

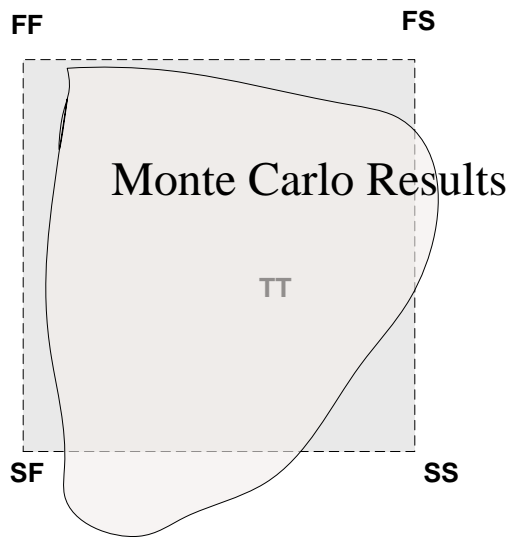
Monte Carlo Analysis

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Monte Carlo VS Corner



MC gives an idea of yield

1. MC gives an idea of yield (or distribution). Corner is much more **extreme** and will give a too pessimistic result.
2. MC is more **accurate** and can get **mismatch information**.

Process & Mismatch: Definition

Monte Carlo

Statistical Variation

☐ Process ☐ Mismatch ☒ All

Sampling Method

Random

Number of Points: 50

Number of Bins:

☐ Auto Stop Using: Significance Test

Target Yield: 99 %

Probability (1-alpha): 95.0 %

Results Database Save Options

☒ Save Process Data

☐ Save Mismatch Data

Other Options

☐ Use Reference Point

☒ Run Nominal Simulation

☒ Save Data to Allow Family Plots

Monte Carlo Seed:

☐ Starting Run Number:

Specify Instances/Devices (Not Specified)

OK Cancel Help

```
parameters rr=1000
statistics {
  process {
    vary rr dist=gauss std=20
  }
}
```

The distributions specified in the **process** block are sampled once per Monte Carlo iteration and are typically used to represent batch-tobatch or process variations.

The distributions specified in the **mismatch** block are sampled on a per subcircuit instance basis and are typically used to represent device-todevice mismatch for devices on the same chip.

In the case where the same parameter is subject to **both process** and **mismatch** variations, the sampled **process** value becomes the mean for the mismatch random number generator for that particular parameter.

```
parameters rr=1000
statistics
  mismatch {
    vary rr dist=gauss std=20
  }
}
```

Process & Mismatch: Example

1. 如果一个参数，例如电阻值rr,只有process的变化，如下：

```
parameters rr=1000
```

```
statistics {  
  process {  
    vary rr dist=gauss std=20 percent=yes  
  }  
}
```

```
r1 1 2 resistor r=rr  
r2 2 0 resistor r=rr  
v0 1 0 vsource dc=2 type=dc
```

MC分析结果，r1和r2均会变化，但变化同步，即V(2)始终为1V；



2. 如果rr只有mismatch的变化，如：
parameters rr=1000

```
statistics {  
  mismatch {  
    vary rr dist=gauss std=20 percent=yes  
  }  
}
```

```
subckt res in out  
r1 in out resistor r=rr  
ends
```

```
x1 1 2 res  
x2 2 0 res
```

MC结果，x1(r1)和x2(r2)变化不同步，即V(2)在1V上下分布取值；

mismatch: 参数rr处于subckt或inline subckt中，才会取值有变化；如果rr处于类似于1中本征器件中，则不会有mismatch的变化。而process的参数处于subckt(inline subckt)还是本征器件中，process的变化都会发生，且变化同步。



How Many Runs Needed: Basically...

Monte Carlo

Statistical Variation
☐ Process ☐ Mismatch ☒ All

Sampling Method
Random

Number of Points 1000

Number of Bins

☐ Auto Stop Using Significance Test

Target Yield 99.7 %

Probability (1-alpha) 95.0 %

Results Database Save Options
☒ Save Process Data
☐ Save Mismatch Data

Other Options
☐ Use Reference Point
☒ Run Nominal Simulation
☐ Save Data to Allow Family Plots

Monte Carlo Seed

☐ Starting Run Number

Specify Instances/Devices (Not Specified)

OK Cancel Help

Basically, The number of runs depends on the accuracy you want to achieve on your yield estimates. If you want to know whether the yield is over **99.7% (3 sigma), 1000 simulations needed...**

How Many Runs Needed: Fortunately...



Monte Carlo

Statistical Variation
☐ Process ☐ Mismatch ☒ All

Sampling Method
Random

Max Number of Points: 2000
Number of Bins:

☒ Auto Stop Using: Significance Test

Target Yield: 93 %
Probability (1-alpha): 90.0 %

Results Database Save Options
☒ Save Process Data
☐ Save Mismatch Data

Other Options
☐ Use Reference Point
☒ Run Nominal Simulation
☐ Save Data to Allow Family Plots
Monte Carlo Seed:
☐ Starting Run Number:

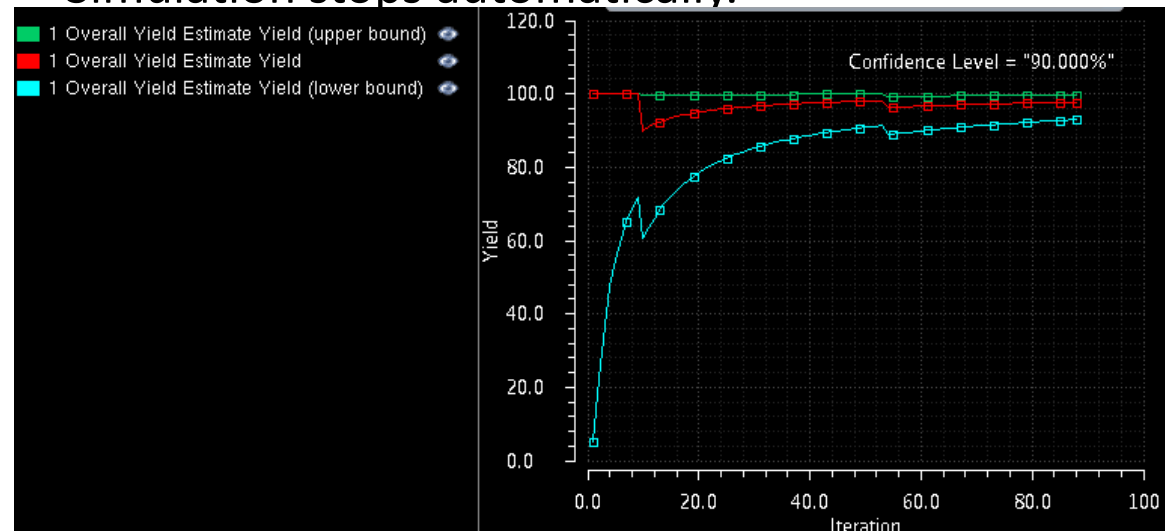
Specify Instances/Devices (Not Specified)

OK Cancel Help

Fortunately, based on Confidence Level (Probability), number of runs can be reduced, when:

Upper bound of yield estimation < Target Yield
Or

Lower bound of yield estimation > Target Yield
Simulation stops automatically.

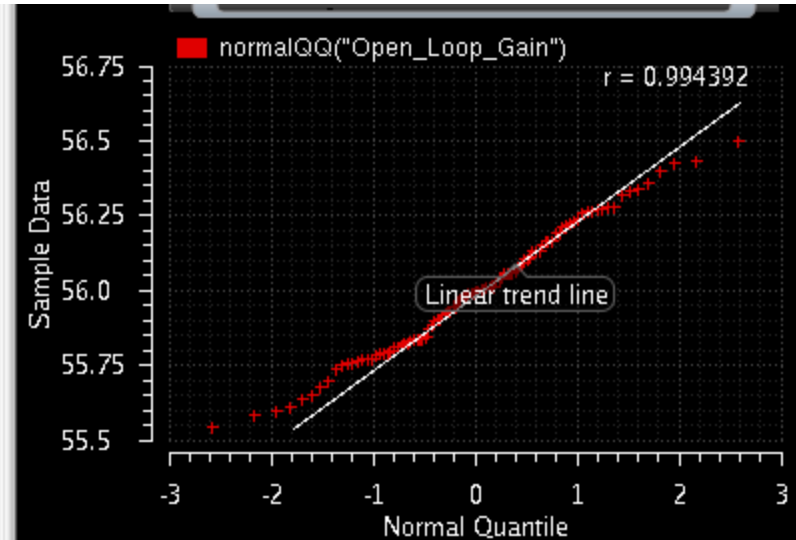
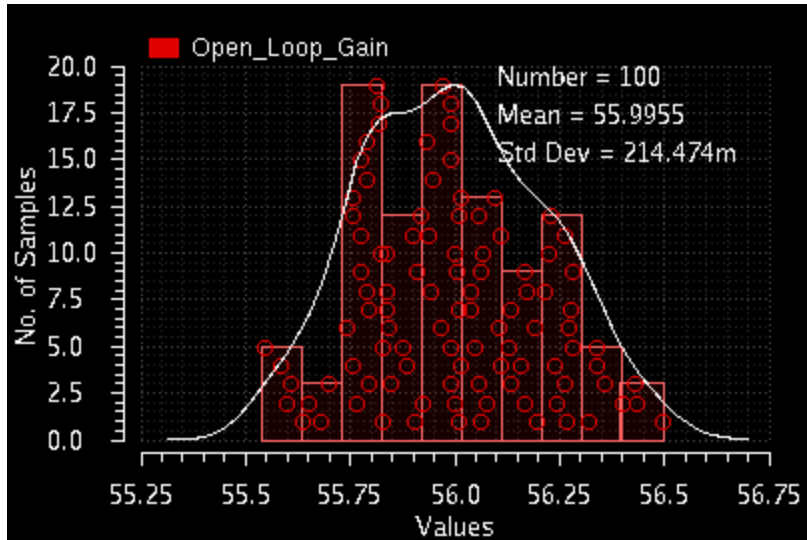


☒ Auto Stop Using: Model Accuracy
(for variance contribution analysis)
R Squared (Goodness of Fit): 90 %

Auto Stop Using Model Accuracy: This option applies a stopping criteria based on the accuracy of the modeling of variation in the outputs, which is due to statistical variation.

How Many Runs Needed: However...

However, in many case, **mean** and **sigma** are of interest.



For normal distribution:

Distribution of X	Probability
[Mean-1*Sigma, Mean+1*Sigma]	68%
[Mean-2*Sigma, Mean+2*Sigma]	95%
[Mean-3*Sigma, Mean+3*Sigma]	99.7%

If 3-sigma range is within specification, **99.7% yield** is guaranteed!

How Many Runs Needed: So...

Monte Carlo

Statistical Variation

☐ Process ☐ Mismatch ☒ All

Sampling Method

Random
Random
Latin Hypercube
Low-Discrepancy Sequence

Number of Bins

☐ Auto Stop Using

Target Yield %

Probability (1-alpha) %

Results Database Save Options

☒ Save Process Data
☐ Save Mismatch Data

Other Options

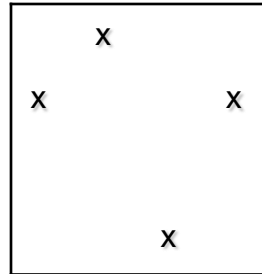
☐ Use Reference Point
☒ Run Nominal Simulation
☐ Save Data to Allow Family Plots

Monte Carlo Seed

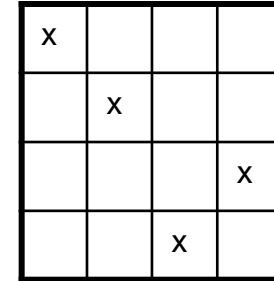
☐ Starting Run Number

Specify Instances/Devices (Not Specified)

So, other sampling method could be used to the same distribution with less sampling point.



Standard Random Sampling



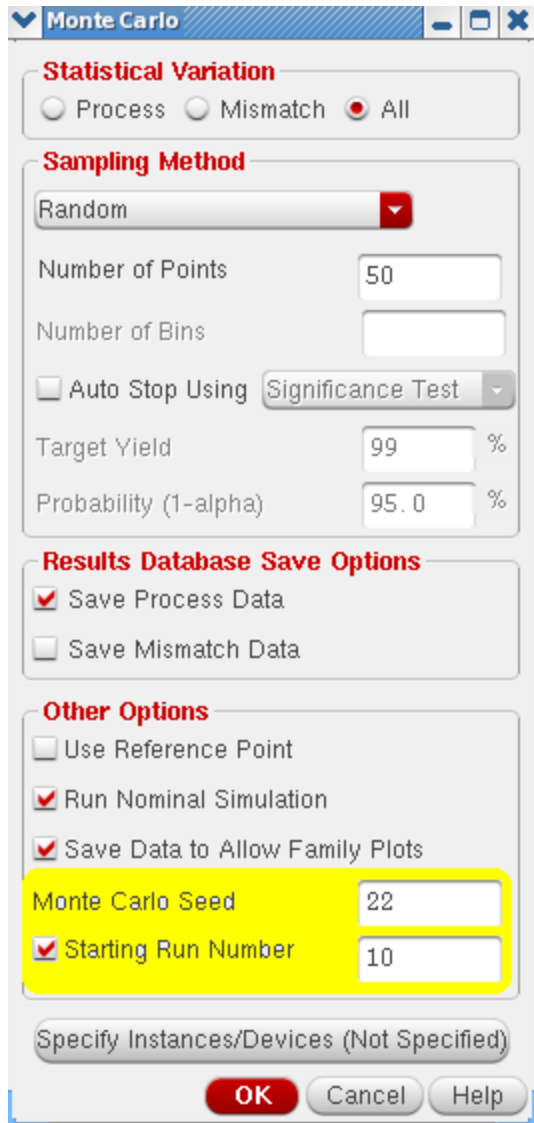
LHS sampling
(need to store samples)

Sampling Method	Number of Runs	Sigma
Random	100	16.5687
Random	1000	20.1577
LHS	100	19.8644
LHS	1000	19.7874

LDS:

Mean: slower than LHS; Sigma: faster than LHS.
Could use Target Yield Stopping Criteria.

How to Reproduce: Seed & firstrun



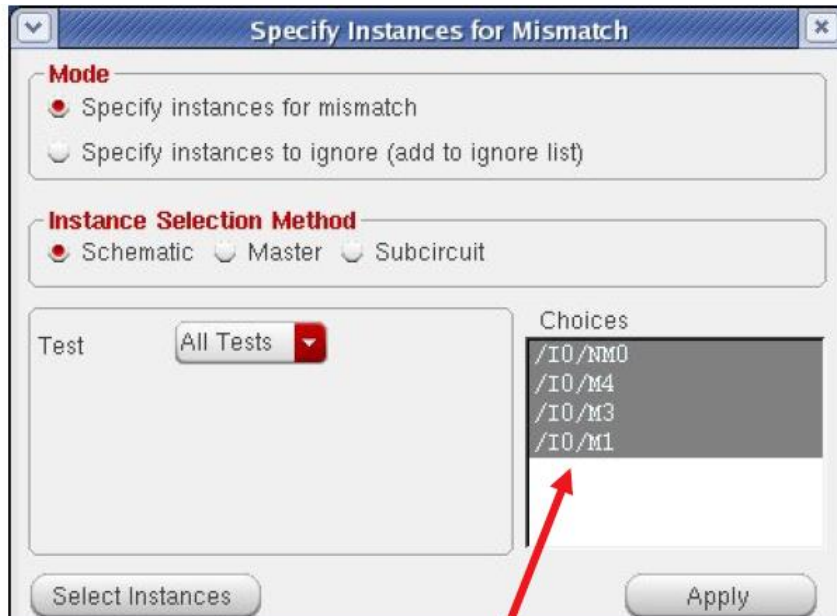
The screenshot shows the 'Monte Carlo' dialog box with the following settings:

- Statistical Variation:** ☐ Process ☐ Mismatch ☒ All
- Sampling Method:** Random (dropdown menu)
- Number of Points:** 50
- Number of Bins:** (empty field)
- Auto Stop Using:** ☐ Significance Test (dropdown menu)
- Target Yield:** 99 %
- Probability (1-alpha):** 95.0 %
- Results Database Save Options:**
 - ☒ Save Process Data
 - ☐ Save Mismatch Data
- Other Options:**
 - ☐ Use Reference Point
 - ☒ Run Nominal Simulation
 - ☒ Save Data to Allow Family Plots
 - Monte Carlo Seed:** 22 (highlighted in yellow)
 - Starting Run Number:** 10 (highlighted in yellow)
- Specify Instances/Devices:** (Not Specified)
- Buttons:** OK, Cancel, Help

By specifying the same seed, you can reproduce a previous experiment. If you do not specify a seed, the value 12345 is used.

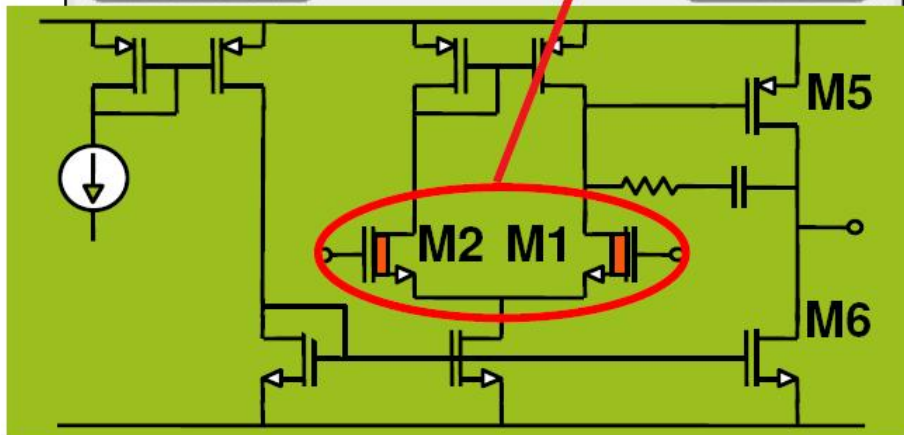
By specifying the first iteration number and the same value for seed, you can reproduce a particular run or sequence of runs from a previous experiment (for example, to examine an outlier case in more detail.)

Mismatch: All or Selected?



Default, **Mismatch** will be run on **All Instances/Devices**.

Furthermore, **Mismatch** of only **Selected Device/Instance** could be considered or ignored in MC.



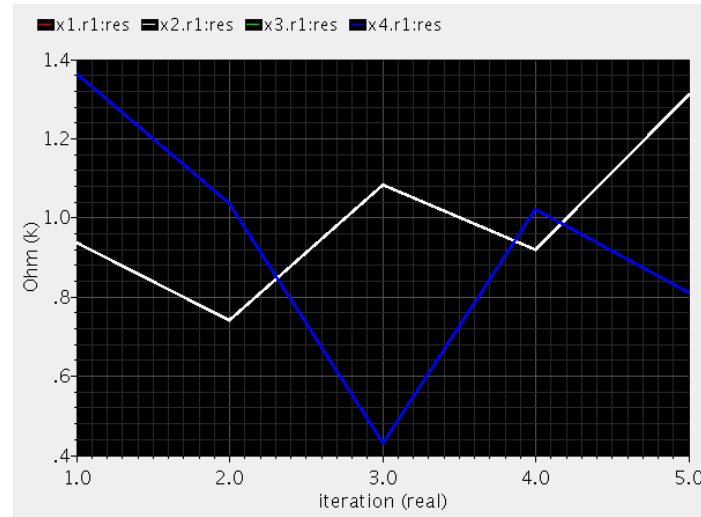
How to Correlate?: $cc=[-1:1]$

```
parameters rr=1000
statistics {
mismatch {
vary rr dist=gauss std=20 percent=yes
}
}
```

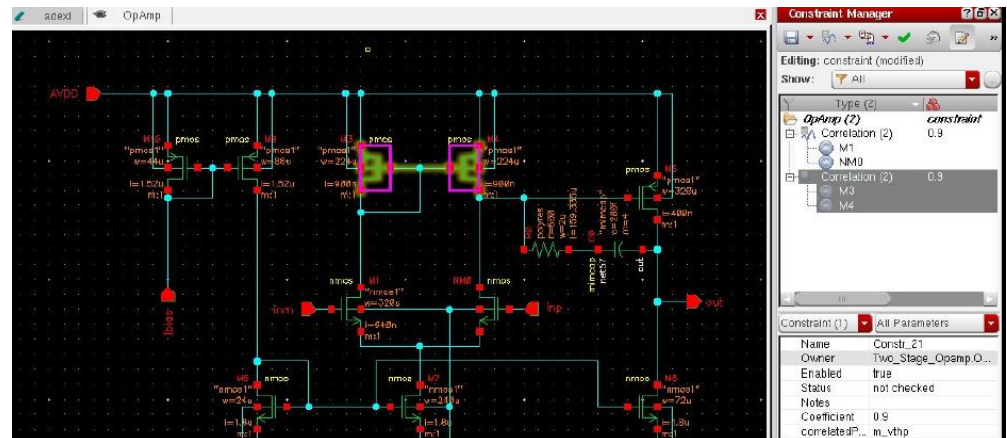
```
statistics {
correlate dev=[x1 x2] param=[rr] cc=1
correlate dev=[x3 x4] param=[rr] cc=1
}
```

```
subckt res in out
r1 in out resistor r=rr
ends
```

```
x1 1 0 res
x2 2 0 res
x3 3 0 res
x4 4 0 res
```



Res in X1 and X2 are exactly the same;
Res in X3 and X4 are exactly the same;



Correlation could also be set in Schematic:
(M1, M2), param: vth, coefficient = 0.9;

How to Simplify: Worst or Specified

Looking for the **worst** sample, fine tune circuit to pass this worst sample.

Looking for the **worst** sample, fine tune circuit to pass this worst sample

ACGain								
Open_Loop_Gain(summary)	100	55.59		56.32	55.97	177.7m	33.6195	
Open_Loop_Gain	100	55.59	> 50	56.32	55.97	177.7m	33.6195	
Phase_Margin(summary)	100	89.71		89.71	89.69	9.483m	2076.42	
Phase_Margin				89.71	89.69	9.483m	2076.42	
Supply_Current(summary)	100	103.2u		103.2u	100.4u	1.209u	-4.4294	
Supply_Current				103.2u	100.4u	1.209u	-4.4294	
UGF(summary)	100	2.407M		2.511M	2.461M	27.36k	35.1421	
UGF	100	2.407M	> 1.5M	2.511M	2.461M	27.36k	35.1421	

Percentile is most least worst sample number.

37	ACGain	Supply_Current	101.9u	< 95u	near
37	ACGain	UGF	2.47		
37	ACGain	Phase_Margin	89.		
37	ACGain	Open_Loop_Gain	55.6		
37	ACGain	/V0/PLUS			
37	ACGain	/OUT			
38	ACGain	Supply_Current	102		
38	ACGain	UGF	2.49		
38	ACGain	Phase_Margin	89.6		
38	ACGain	Open_Loop_Gain	56		
38	ACGain	/V0/PLUS			
38	ACGain	/OUT			
39	ACGain	Supply_Current	100.		
39	ACGain	UGF	2.45		
39	ACGain	Phase_Margin	89.		
39	ACGain	Open_Loop_Gain	55.5		
39	ACGain	/V0/PLUS			
39	ACGain	/OUT			
40	ACGain	Supply_Current	99.8		
40	ACGain	UGF	2.41		
40	ACGain	Phase_Margin	89.7		
40	ACGain	Open_Loop_Gain	55.6		
40	ACGain	/V0/PLUS			

Output_Log
View_Netlist
Open_Terminal ...
Job_Log
Plot
Plot_Across_Corners
Plot_Across_Design_Points
Create_Copy_Of_Selected_Corner
Troubleshoot_Point
Open_Debug_Environment ...
Open_Results_Browser ...
Open_Calculator ...
Violations_Display
Create_Statistical_Corner
Print_Statistical_Parameters
Plot_Outputs
Direct_Plot
Print

Anyone of MC samples could be **Specified** to:

Print the statistical parameter of the corner;

Create this MC sample to a single coner;

In-line debug this corner.

Results: Family Plot

Monte Carlo

Statistical Variation
☐ Process ☐ Mismatch ☒ All

Sampling Method
Random

Number of Points: 50
Number of Bins:
☐ Auto Stop Using: Significance Test

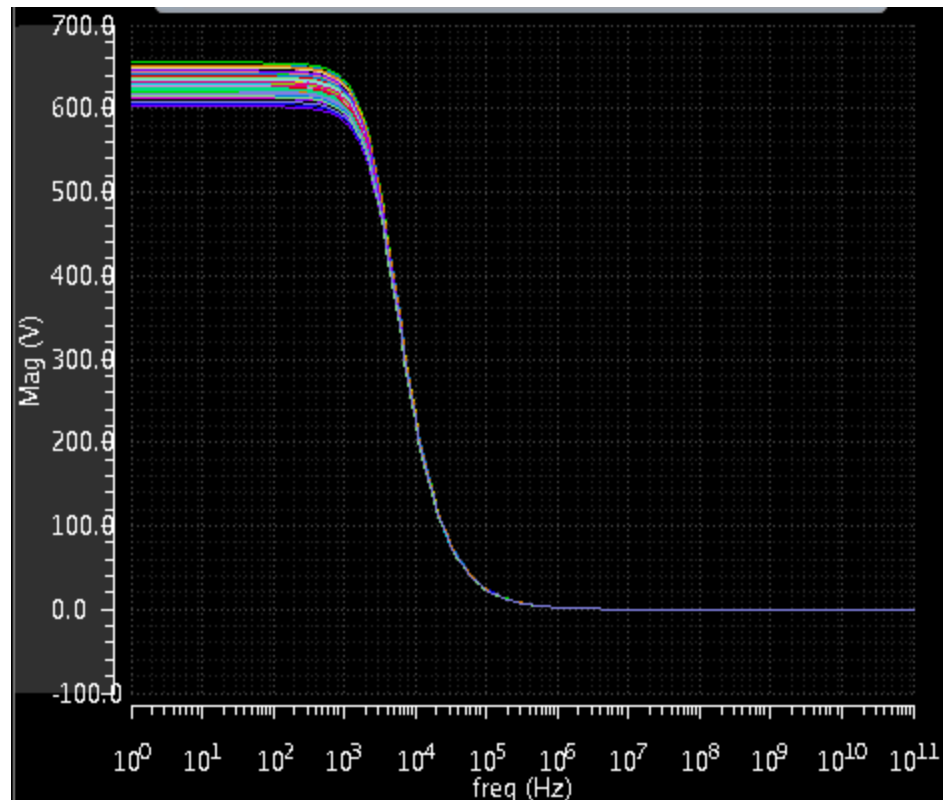
Target Yield: 99 %
Probability (1-alpha): 95.0 %

Results Database Save Options
☒ Save Process Data
☐ Save Mismatch Data

Other Options
☐ Use Reference Point
☐ Run Nominal Simulation
☒ Save Data to Allow Family Plots

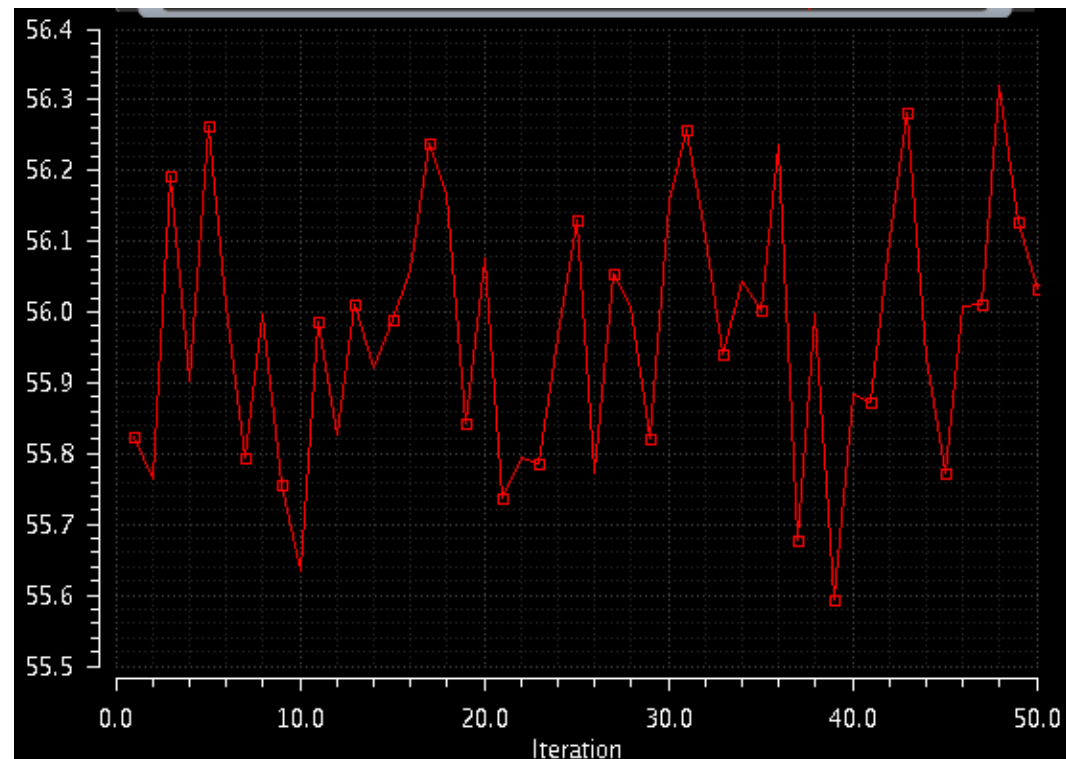
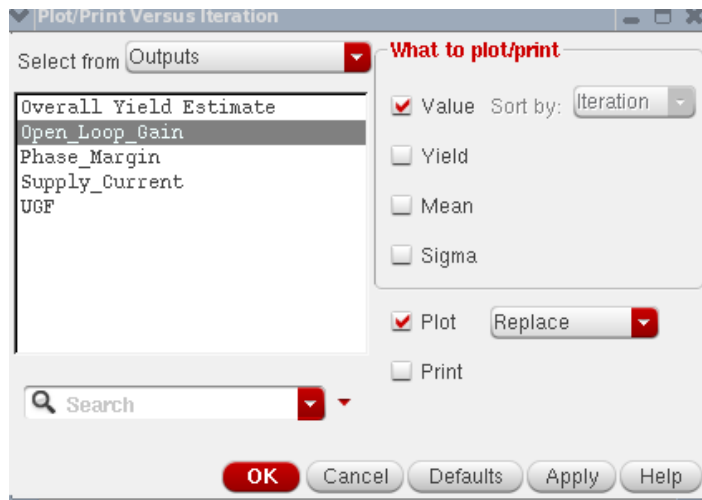
Monte Carlo Seed:
☐ Starting Run Number:
Specify Instances/Devices (Not Specified)

OK Cancel Help

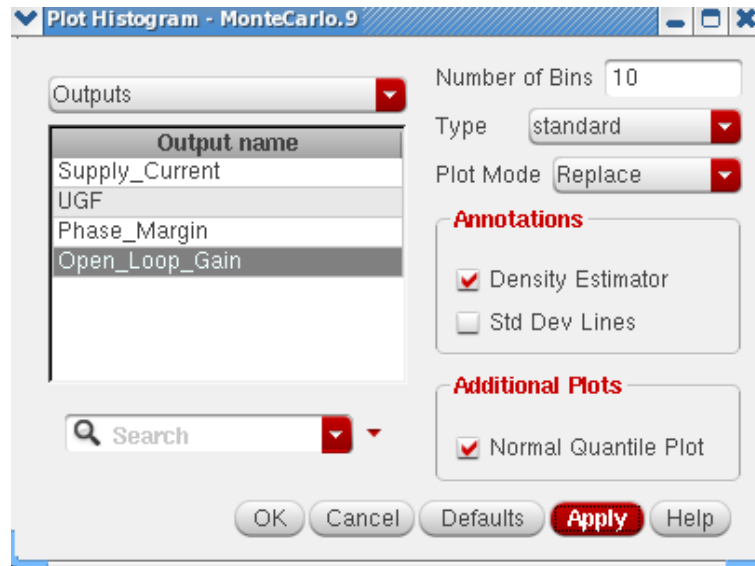


Results: Plot/Print Versus Iteration

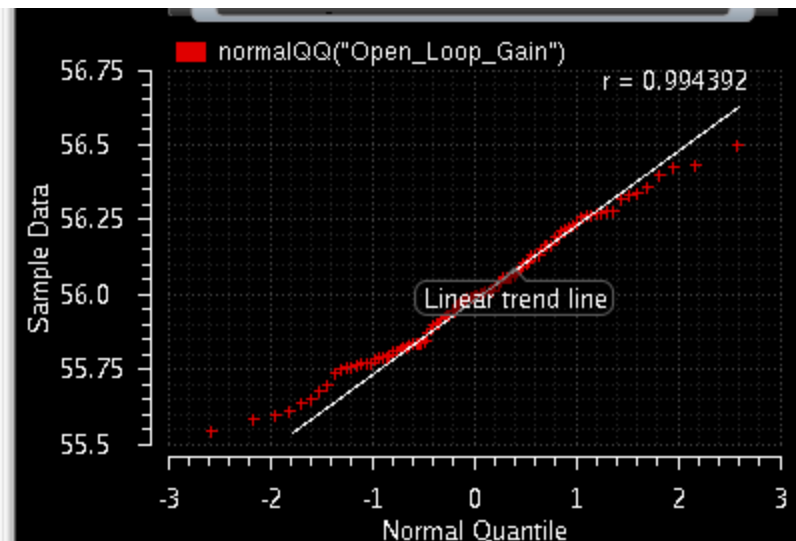
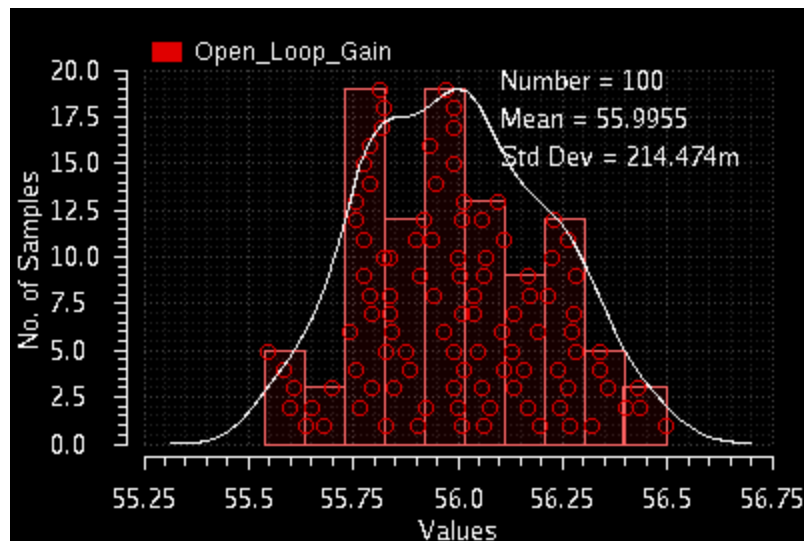
You can print/plot outputs and parameters Vs iterations. In addition, you can also plot or print the mean and sigma values for outputs.



Results: Histograms

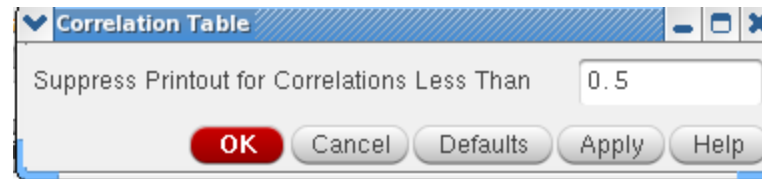


Histograms and Normal Quantile for the outputs and statistical parameters from Monte Carlo results can be plotted.



Results: Print Correlations

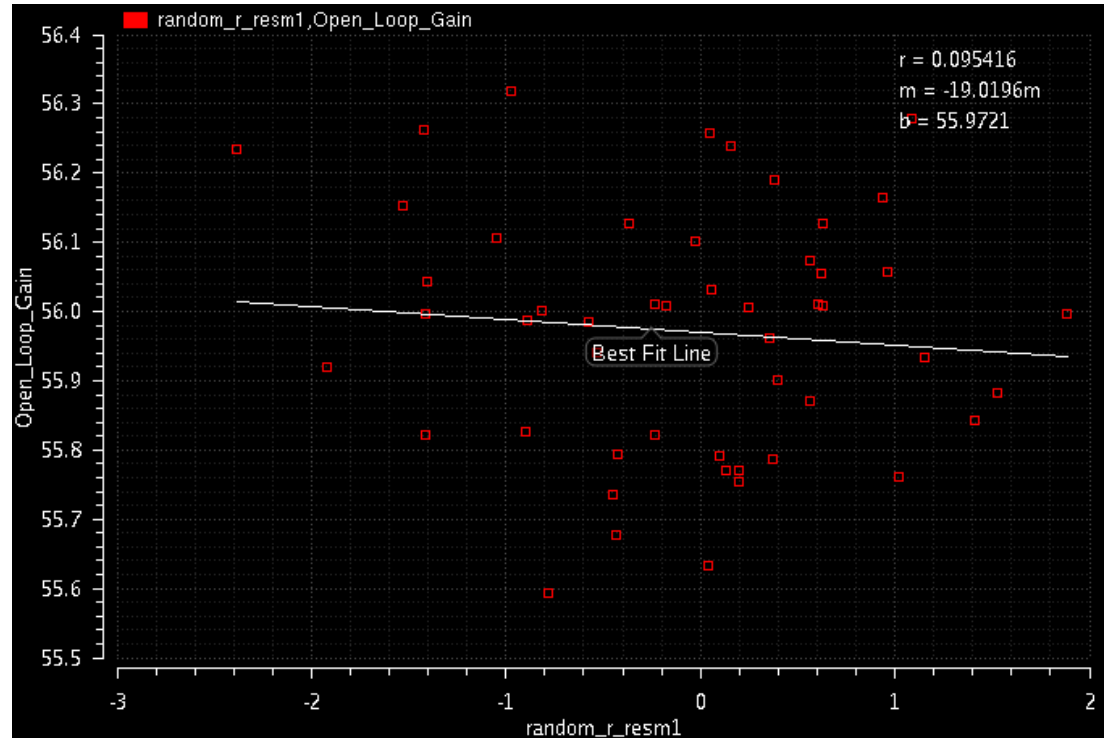
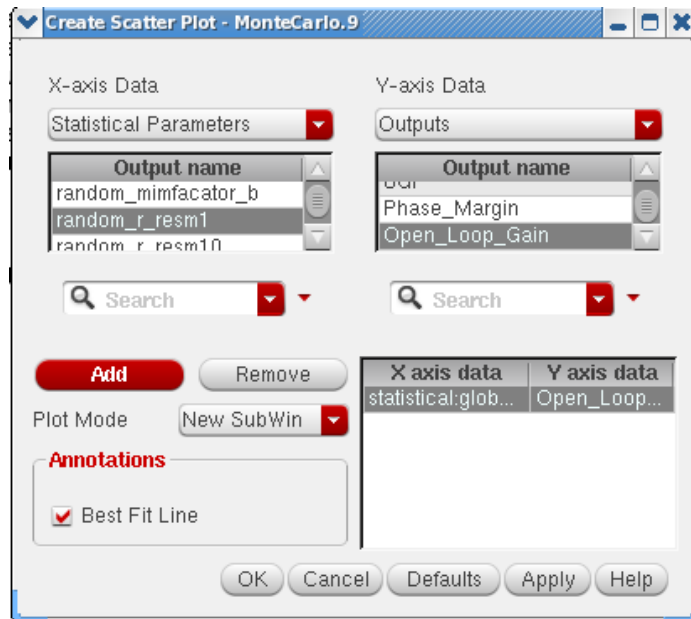
To print a table showing the correlation coefficients of each parameter with each of the other parameters sorted from most correlated to least correlated for each combination of parameters, do one of the following:



param #1	param #2	corr-coef	mean1	stdev1	mean2	stdev2	size
Open_Loop_Gain	Phase_Margin	-8.8258e-01	5.5974e+01	1.7769e-01	8.9690e+01	9.4828e-03	50
Phase_Margin	Open_Loop_Gain	-8.8258e-01	8.9690e+01	9.4828e-03	5.5974e+01	1.7769e-01	50
Phase_Margin	UGF	-5.8355e-01	8.9690e+01	9.4828e-03	2.4614e+06	2.7358e+04	50
Supply_Current	UGF	5.6272e-01	1.0035e-04	1.2087e-06	2.4614e+06	2.7358e+04	50
UGF	Phase_Margin	-5.8355e-01	2.4614e+06	2.7358e+04	8.9690e+01	9.4828e-03	50
UGF	Supply_Current	5.6272e-01	2.4614e+06	2.7358e+04	1.0035e-04	1.2087e-06	50
random14	random_mimfacator_b	-5.4720e-01	-4.6825e-02	1.0441e+00	1.8636e-01	1.0370e+00	50
random_mimfacator_b	random14	-5.4720e-01	1.8636e-01	1.0370e+00	-4.6825e-02	1.0441e+00	50

Results: Scatter Plot

A scatter plot could depict the relationship between the pairs of outputs or parameters in the Monte Carlo results.



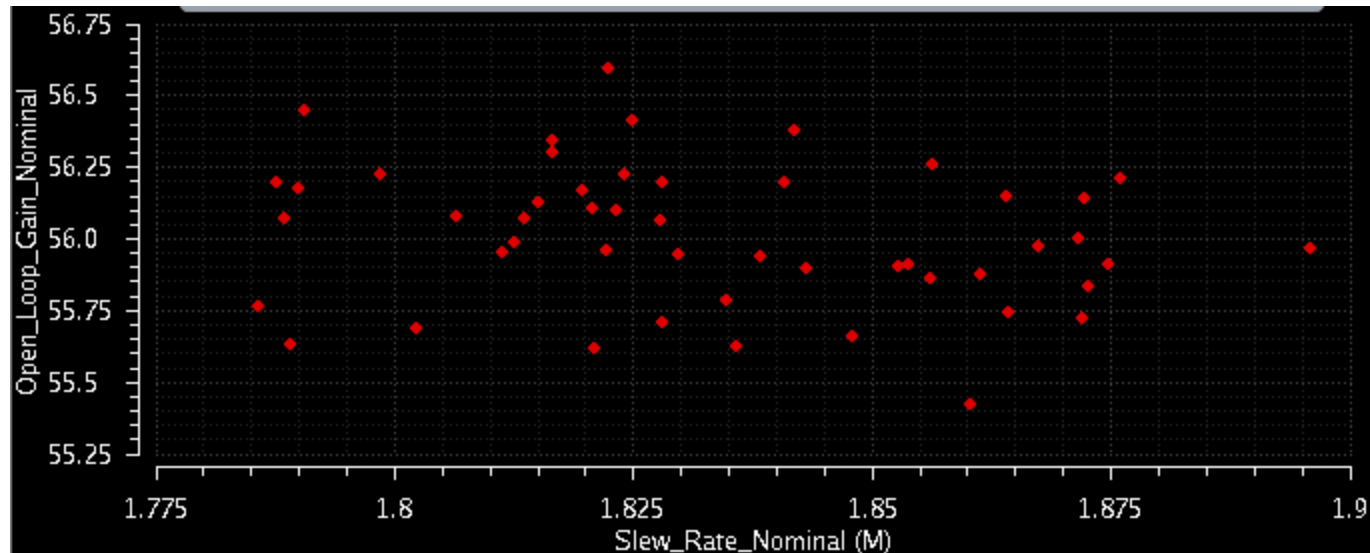
r shows the correlation coefficient. The value of **r** ranges between -1.0 and 1.0.

b is the constant value and **m** is the value of slope in the linear equation describing the best fit line of the plotted data. The linear equation that is used to find the best fit line is $y = \mathbf{b} + \mathbf{m}x$.

Results: Sensitivity

	Average(Mag)	Slew_Rate Nominal (Top 100.0%)	Supply_Current Nominal (Top 100.0%)	UGF Nominal (Top 100.0%)	Phase_Margin Nominal (Top 100.0%)	Open_Loop_Gain Nominal (Top 100.0%)
Slew_Rate_Nominal	1		N.A.	N.A.	N.A.	N.A.
Open_Loop_Gain_Nominal	0.67211	N.A.				
Phase_Margin_Nominal	0.67723	N.A.				
UGF_Nominal	0.66554	N.A.				
Supply_Current_Nominal	0.52186	N.A.				

Sensitivity Tab could be used to creat scatter-like plot between specs from 2 different testbenches. For example: “Slew_Rate” comes from “Slew_Rate” testbench, “Open_Loop_Gain” comes from “ACGain” testbench. Double-clicking the boxes in the table, scatter-like plot can be got.



Use Machine Farms



- ADE XL distributes Monte Carlo on a farm of machines or processors based on
 - # of tests
 - # of corners
 - # of Monte Carlo samples
- Example: 2 tests, 3 corners (+nominal), 100 samples, 20 processors
 - Total sims: 800
 - Sims / machine: 40 simulations

END