Selection of Test Patterns for Model Calibration based on Sensitivity Analysis

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Context

The lithography is one of the key steps in the fabrication of integrated circuits. It consists in transferring the geometric patterns that represents each level of the circuit into a resist on a substrate. As technology advances, the dimensions of these geometric patterns become smaller and smaller, requiring improvements on the precision of the lithography techniques. Standard lithography techniques have reached their physical limits and the industry is currently looking for a solution to continue evolving from one technology node to the next. Electron-beam lithography may be the best option but it presents some issues that impact the final resolution. These issues come mostly from electron forward scattering, backscattering, fogging, resist development, etc.

Applying a rigorous physical model to predict and compensate such effects is not practical due to the amount of data presented in a layout. Therefore, empirical models are used in order to emulate the lithography process and to apply the required compensation (called Proximity Effect Correction - PEC). These empirical models represent the radial exposure intensity distribution induced by a point electron source, commonly named Point Spread Function (PSF).

PEC is required in order to properly delineate dense features as well as meet the required CD uniformity. The correction will even out the non-ideal electron energy deposition using a proper adjustment of the dose and/or geometry of each pattern.
The impulse response of the electron beam, which is called PSF (Point Spread Function), is convoluted with the exposed pattern to compute the 2D repartition of electron energy deposited in the resist. Therefore, the quality of a correction is highly dependent on the quality of the PSF model employed and the accuracy of its parameters.

Since all compensation (PEC) is based on the predictions from the empirical model (PSF), accurately determining the parameters of the PSF is critical to obtain the required resolution for today and future technology nodes.

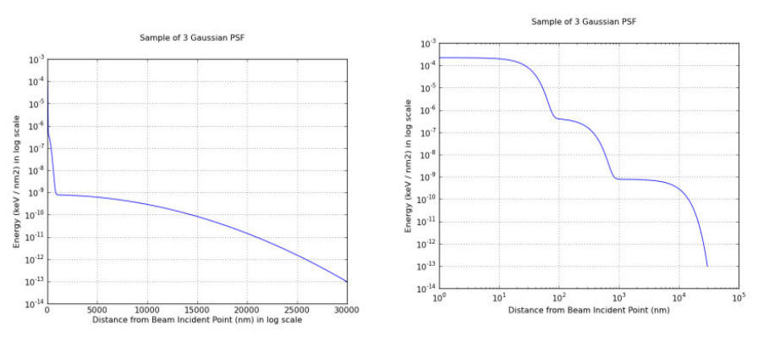
Motivation: *Determine the smallest set of experimental tests sufficient to correctly determine the parameters of any PSF model.*

PSF Models

The global strategy works for any PSF model, but the calibration patterns must adapt

Sum of Gaussians PSF:

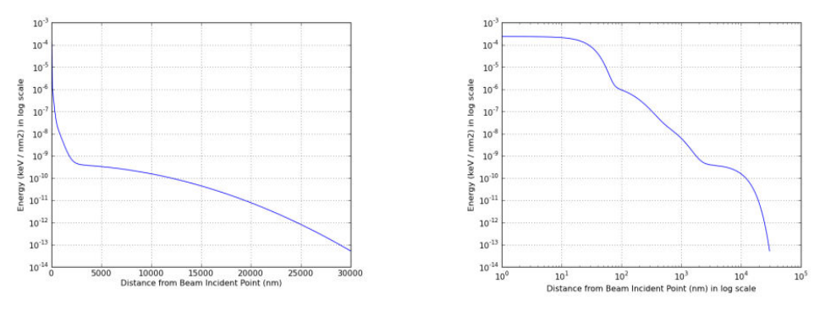
$$\mathrm{PSF}(x) = \frac{1}{1+\sum \eta_i}\left[\frac{1}{\pi\alpha^2}\exp\left(-x^2/\alpha^2\right) + \sum \frac{\eta_i}{\pi\beta_i^2}\exp\left(-x^2/\beta_i^2\right)\right]$$



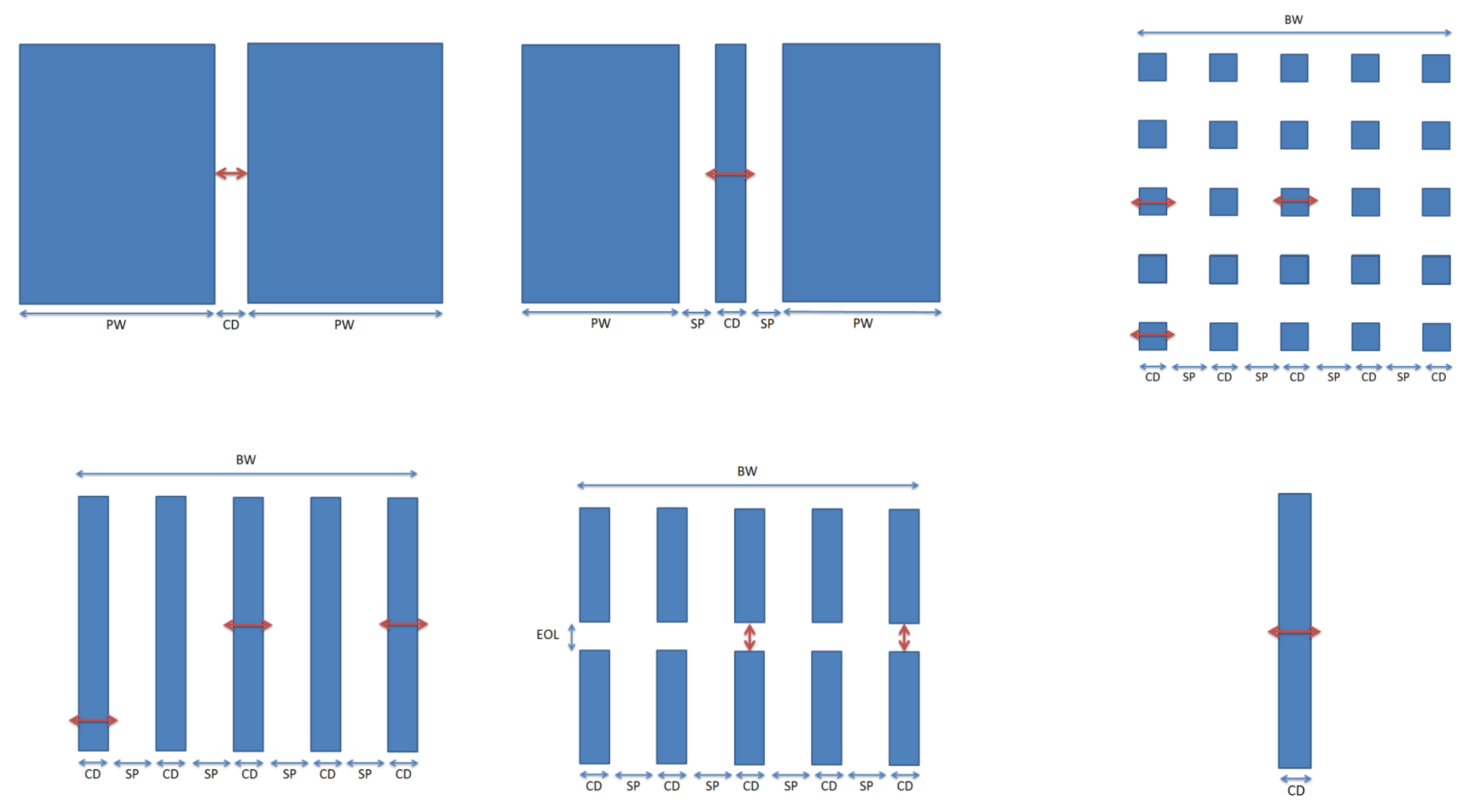
Sum of Gaussians and Gammas PSF:

$$\mathrm{PSF}(x) = \frac{1}{1+\sum \eta_j+\sum \eta_i}\left[\frac{1}{\pi\alpha^2}\exp\left(-x^2/\alpha^2\right) + \sum \frac{\eta_j}{2\pi\kappa_j\theta_{j1}} x^{\kappa_j-1}\frac{\exp\left(-x/\theta_{j1}\right)}{\Gamma(\kappa_j)\theta_j^{\kappa_j}} + \sum \frac{\eta_i}{\pi\beta_i^2}\exp\left(-x^2/\beta_i^2\right)\right]$$

specially developed for EUV applications



Experimental Test Patterns

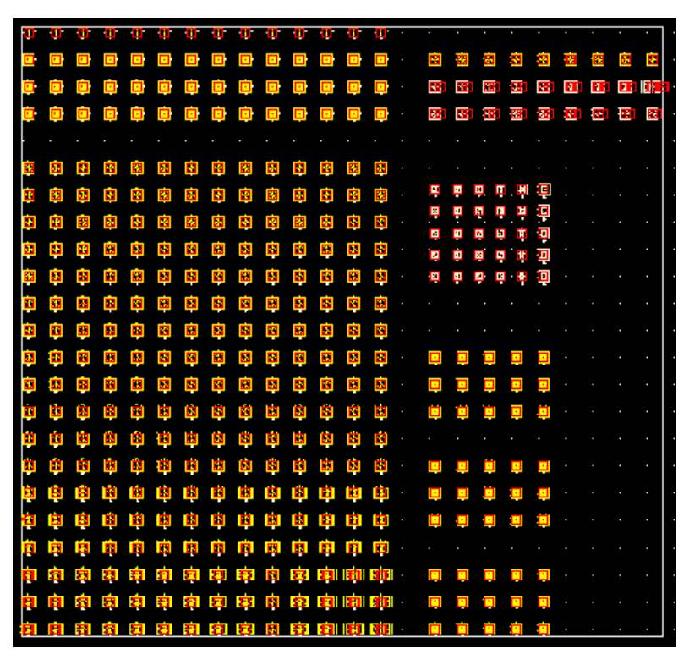


All those variations may lead to thousands of patterns.

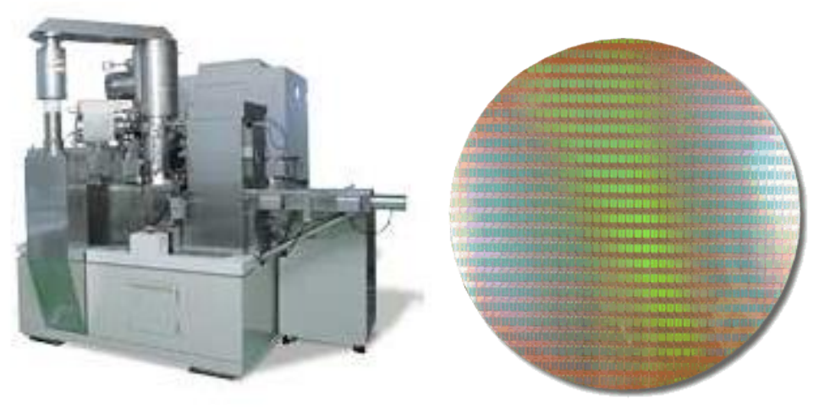
Preliminary results indicate that process and metrology variability may be addressed with fewer patterns.

But what are the patterns to keep?

Model Calibration Procedure



Set of Calibration Patterns

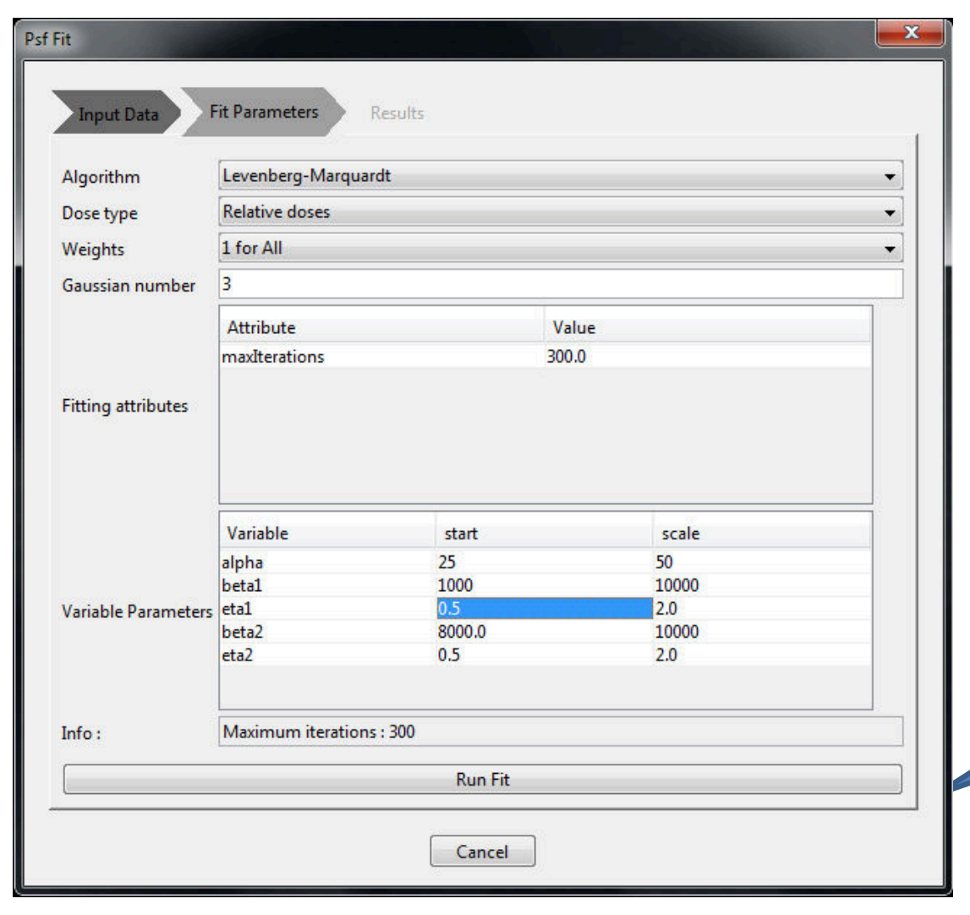


Wafer Exposure

CD-SEM Metrology

Optimization Algorithm

$$MSE = \frac{1}{N}\sum(data - model\ \mathrm{result})^2$$



Algorithm: Levenberg-Marquardt
Dose type: Relative doses
Weights: 1 for All
Gaussian number: 3

Fitting attributes:

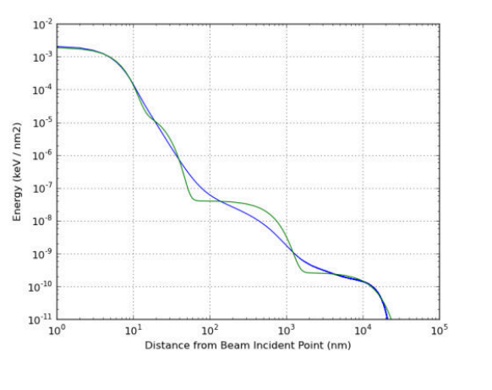
Attribute	Value
maxIterations	300.0

Variable Parameters:

Variable	start	scale
alpha	25	50
beta1	1000	10000
eta1	0.5	2.0
beta2	8000.0	10000
eta2	0.5	2.0

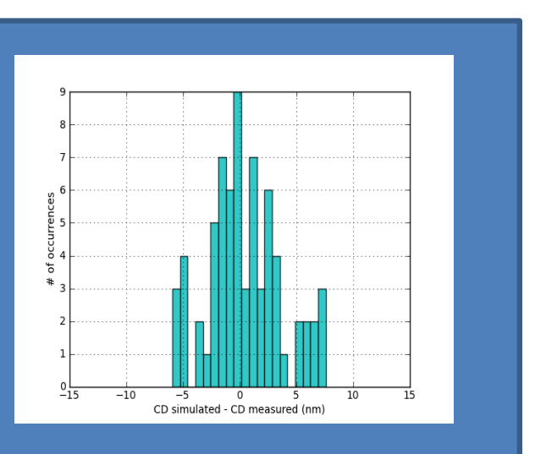
Info : Maximum iterations : 300

Inscale® Calibration Module



α	26,3
β1	1180
η1	0,23
β2	8430
η2	0,57

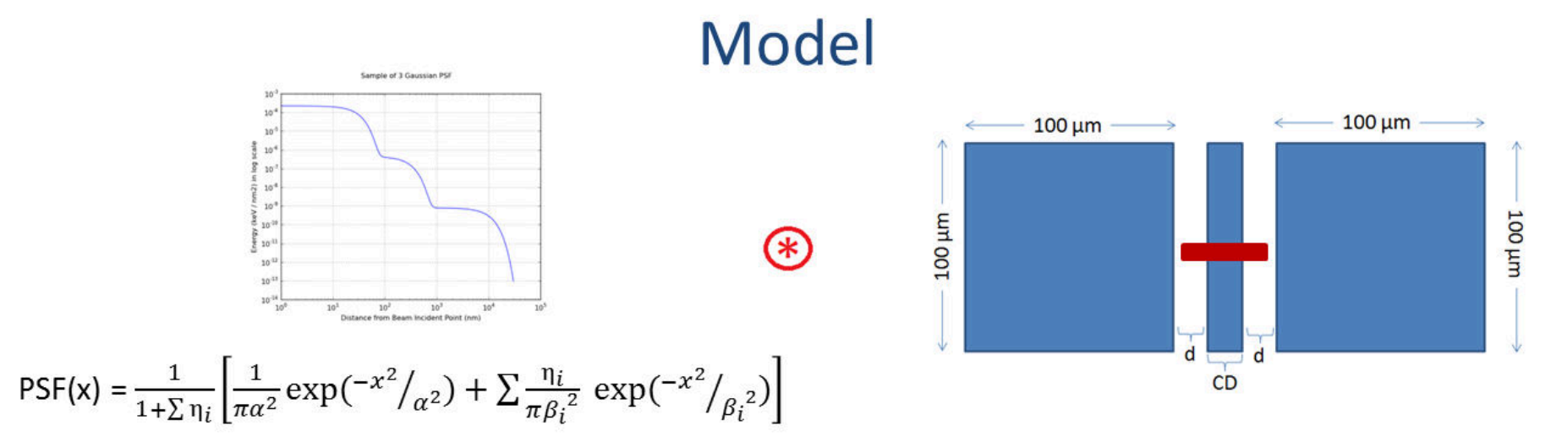
Calibrated Target Model



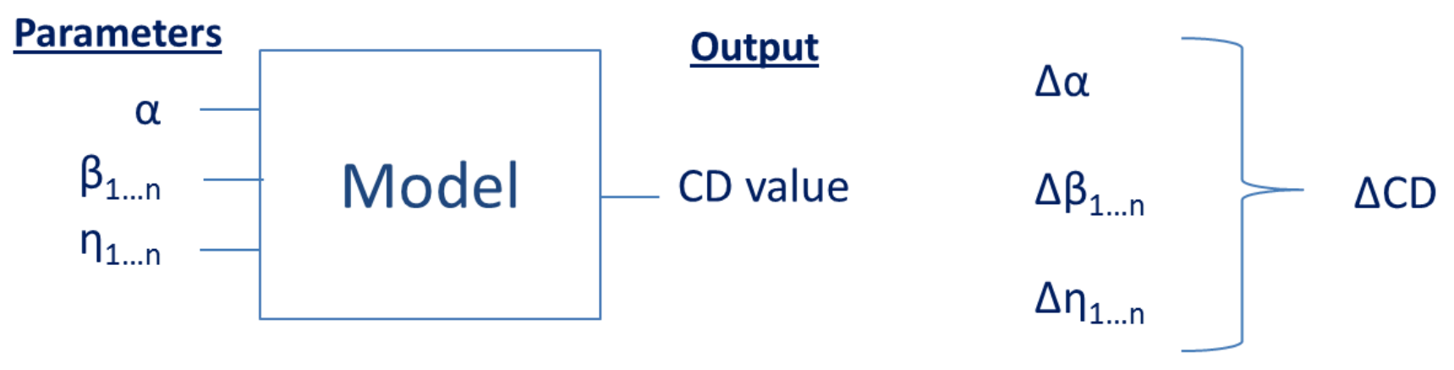
Mean Error and Variance
R2
Adjusted R2
Akaike IC
Correlation Matrix

Calibration/Model Quality Report

Global Sensitivity Analysis



$$\mathrm{PSF}(x) = \frac{1}{1+\sum \eta_i}\left[\frac{1}{\pi\alpha^2}\exp\left(-x^2/\alpha^2\right) + \sum \frac{\eta_i}{\pi\beta_i^2}\exp\left(-x^2/\beta_i^2\right)\right]$$



Sobol’ Sensitivity Indices

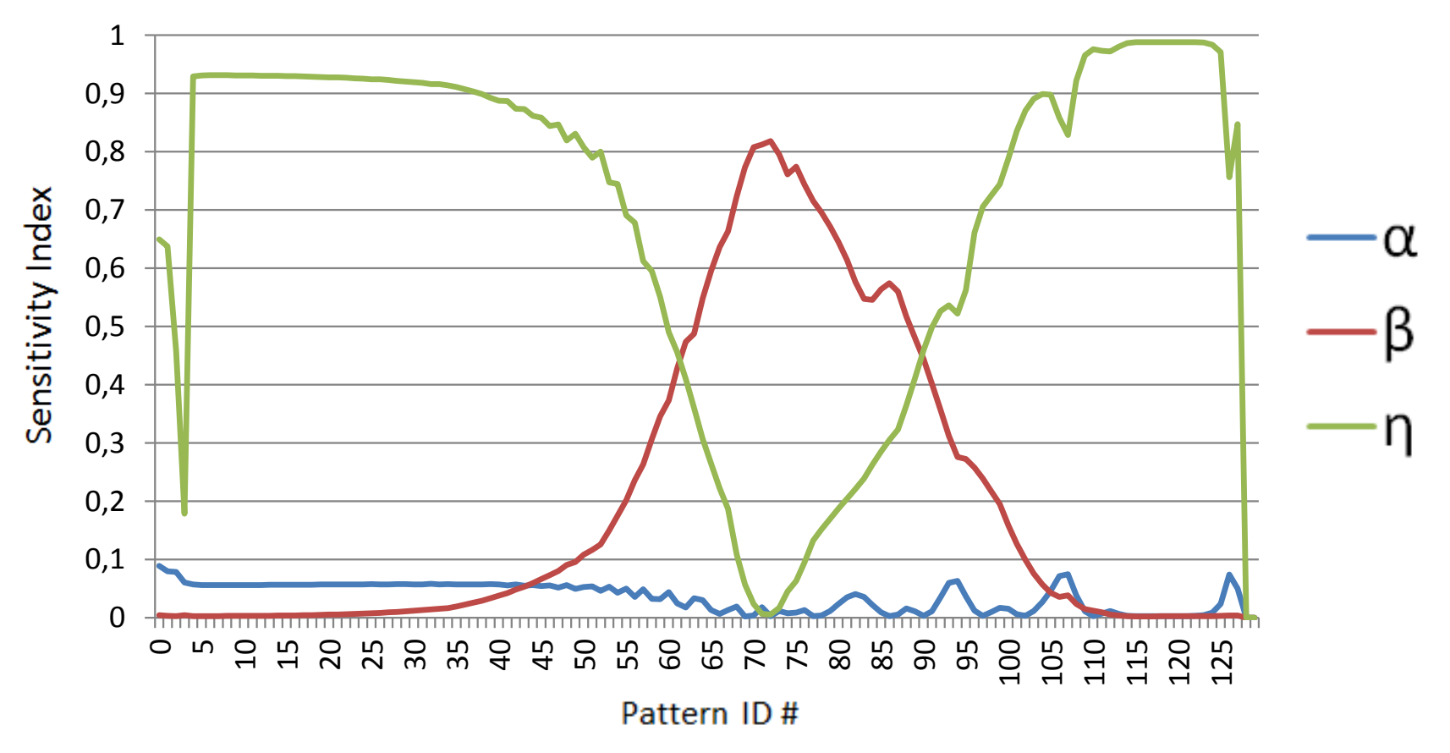
$$S_{i_1\ldots i_s} = \frac{D_{i_1\ldots i_s}}{D}\ , \qquad D = \int f^2 dx - f_0^2 \qquad D_{i_1\ldots i_s} = \int f_{i_1\ldots i_s}^2 dx_{i_1} \ldots dx_{i_s}$$

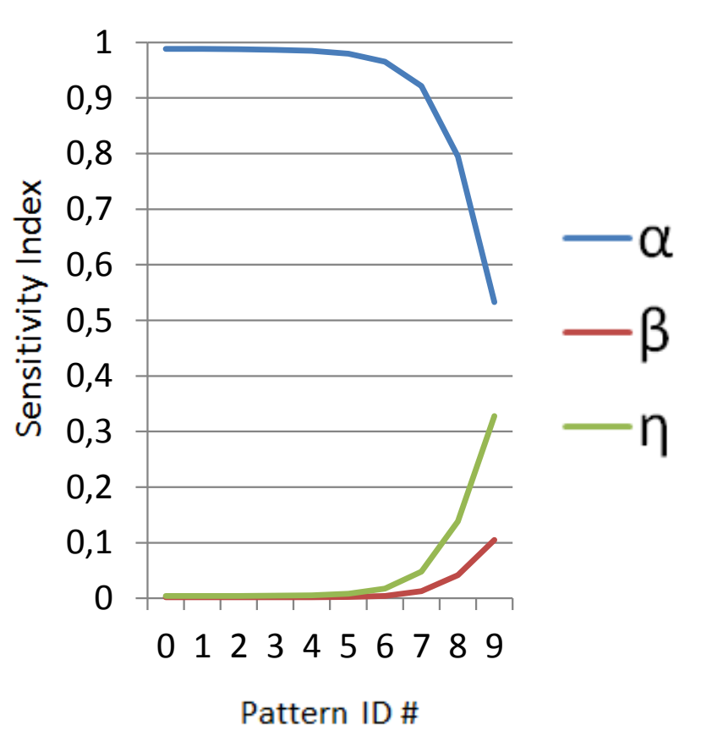
Total Sensitivity Indices may be used as well with a small additional cost!
25% more simulations!

Results

Sum of 2 Gaussians PSF:

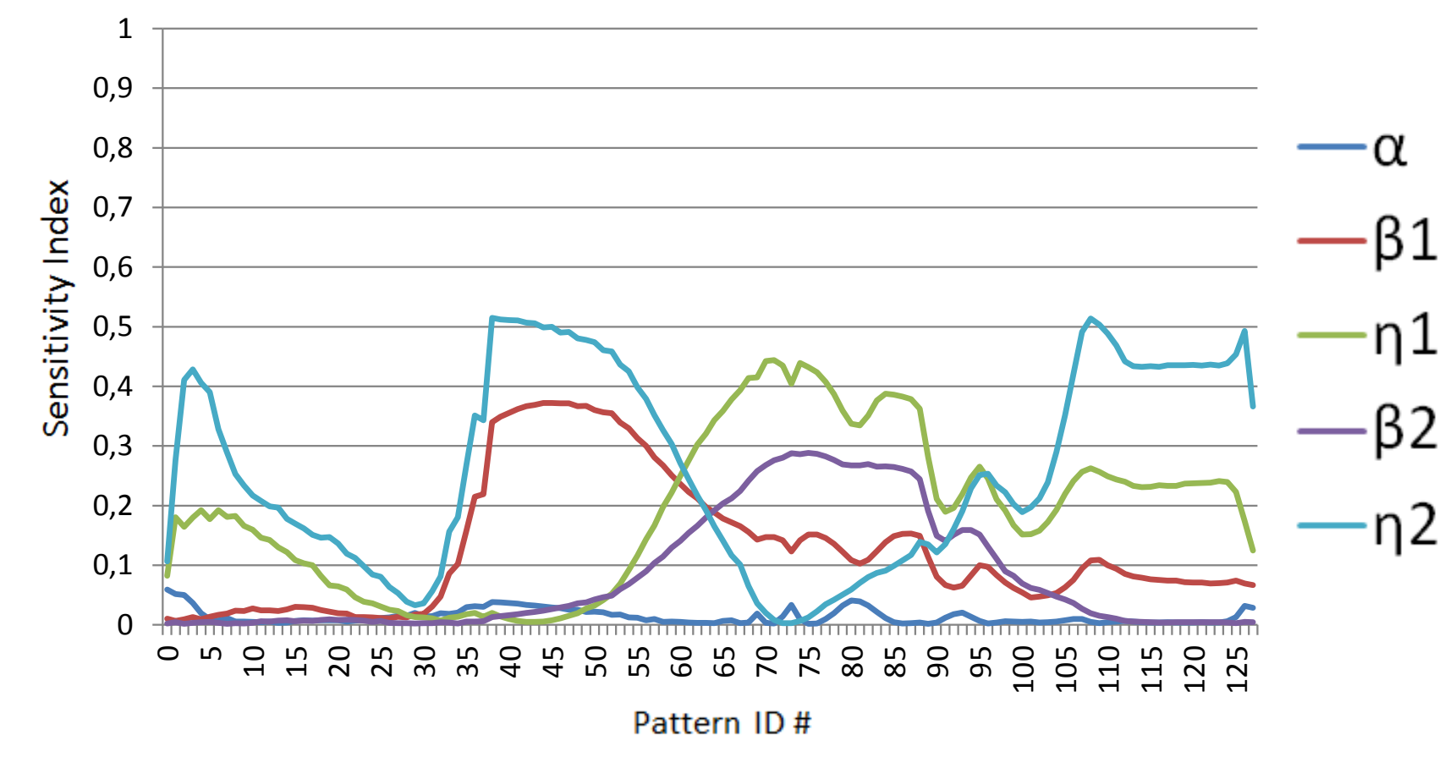
$$\mathrm{PSF}(x) = \frac{1}{\pi(1+\eta)}\left[\frac{1}{\alpha^2}\exp\left(-x^2/\alpha^2\right) + \frac{\eta}{\beta^2}\exp\left(-x^2/\beta^2\right)\right]$$

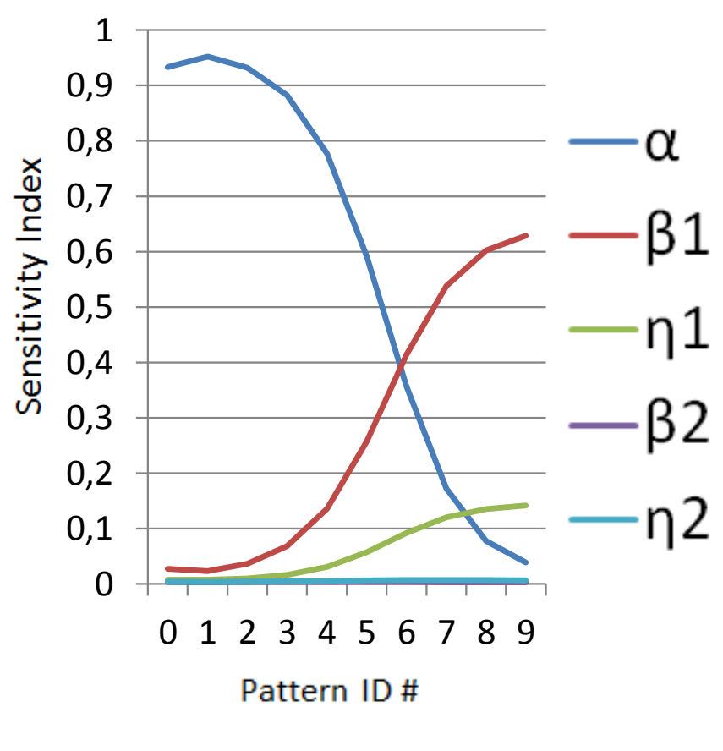




Sum of 3 Gaussians PSF:

$$\mathrm{PSF}(x) = \frac{1}{\pi(1+\eta_1+\eta_2)}\left[\begin{array}{c}\frac{1}{\alpha^2}\exp\left(-x^2/\alpha^2\right) + \\ \frac{\eta_1}{\beta_1^2}\exp\left(-x^2/\beta_1^2\right) + \\ \frac{\eta_2}{\beta_2^2}\exp\left(-x^2/\beta_2^2\right)\end{array}\right]$$





Conclusions

- Sensitivity Analysis may be used to better determine the set of test patterns that should be used for a calibration procedure.
- Preliminary results shown that reducing the number of patterns respecting this approach does not impact the quality of the calibrated model.
- Further studies must be performed in order to evaluate the potential of using sensitivity information inside the calibration algorithm.

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