# Manufacturing Sensor data Analytics: Spatial Data Modeling

sponsored by SAMSUNG ELECTRONICS

- Defects on semiconductor wafers
  - –Spatial defect patterns contain useful information about issues during integrated circuit fabrication
  - –Promptly detecting abnormal wafers is an important way to increase yield and product quality

- Objective
  - –Develop an algorithm for detecting abnormal DRAM wafers more accurately in semiconductor manufacturing

- Binarized FBT maps
  - –A generalized joint count-based statistics

$$T^{(k)}(g) = p^{(k)} {c_{00}}^{(k)}(g) + (1 - p^{(k)}) {c_{11}}^{(k)}(g)$$

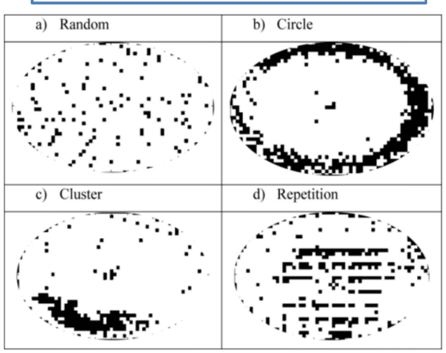
  - –The test statistic corresponding to the spatial lag g

$$Z_T^{(k)}(g) = \frac{T^{(k)}(g) - c^{(k)}(g) p^{(k)} (1 - p^{(k)})}{\sqrt{c^{(k)}(g) \left(p^{(k)}\right)^2 \left(1 - p^{(k)}\right)^2}} \sim N(0, 1)$$

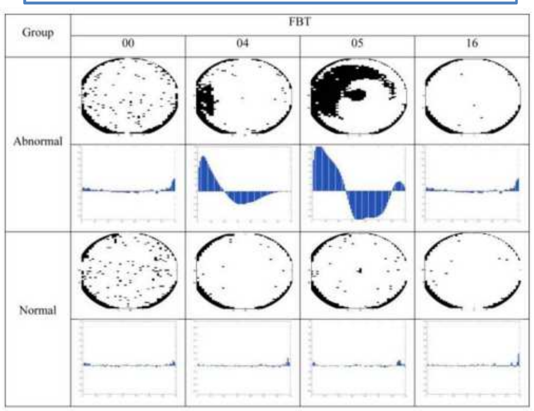
  - –The orginial FTB value of $i$-th functional chip of $k$-th FTB map

$$\hat{f}_h^{(k)}(u) = \frac{1}{n_f * h^{(k)}} \sum\nolimits_{i=1}^{n_f} K\left(\frac{u^{(k)} - u_i^{(k)}}{h^{(k)}}\right) \quad \text{where} \quad h^{(k)} = \left(\frac{4\hat{\sigma}^{(k)^5}}{3n_f}\right)^{\frac{1}{5}} \approx 1.06\hat{\sigma}^{(k)} (n_f)^{-\frac{1}{5}}$$

Binarized FBT maps




Selected denoised FBT maps




- Spatial Local Denoising
  - –Case 1) De-Noising the Interior of the Binarized FBT Map

$$R^{(k)}(i,j) = \frac{1}{t^2} \sum\nolimits_{m=-t}^{t} \sum\nolimits_{n=-t}^{t} x_{i,j}^{(k)} x_{i+m,j+n}^{(k)}$$

  - –Case 2) De-Noising the Edges of the Binarized FBT Map

$$R^{(k)}(i,j) = \frac{1}{N(i,j)} \sum_{m=-t}^{t} \sum_{n=-t}^{t} x_{i,j}^{(k)} x_{i+m,j+n}^{(k)} A(i+m, j+n)$$

- Step-down Randomness Test
  - –Test statistics and Control limits

$$Z_1 = {\boldsymbol{y}_r}^{(1)T} \boldsymbol{S}_r^{(1)-1} {\boldsymbol{y}_r}^{(1)} \qquad CL_1 = \frac{(n-1)r}{(n-r)} F_{\alpha_1}(r, n-r)$$

$$Z_k = \frac{T_k^2 - T_{k-1}^2}{1 + T_{k-1}^2/(n-1)} \qquad CL_k = \frac{(n-1)r}{(n-kr)} F_{\alpha_k}(r, n-kr),\ k = 2, 3, \ldots, N$$

Comparison of Test performance

| *Test Method* | *Procedure of the randomness test* | | | *Accuracy* | | |
|---|---|---|---|---|---|---|
| | Binarization | De-noising | Test | Normal | Abnormal | All |
| A | No | No | Single test | 0.50 | 0.56 | 0.52 |
| B | Normal | Proposed denoising | Step-down | 0.84 | 0.79 | 0.81 |
| C | Otsu | Proposed denoising | Step-down | 0.17 | 0.88 | 0.51 |
| D | KDE | No | Step-down | 0.78 | 0.79 | 0.78 |
| E | KDE | Median Filter | Step-down | 0.83 | 0.75 | 0.79 |
| F | KDE | Proposed denoising | Bonferroni | 0.92 | 0.71 | 0.81 |
| G | KDE | Proposed denoising | Step-down | 0.91 | 0.90 | 0.91 |

- "Step-Down Spatial Randomness Test for Detecting Abnormalities in DRAM Wafers with Multiple Spatial Maps", *IEEE TRANSACTIONS ON SEMICONDUCTOR MANUFACTURING* (2016)

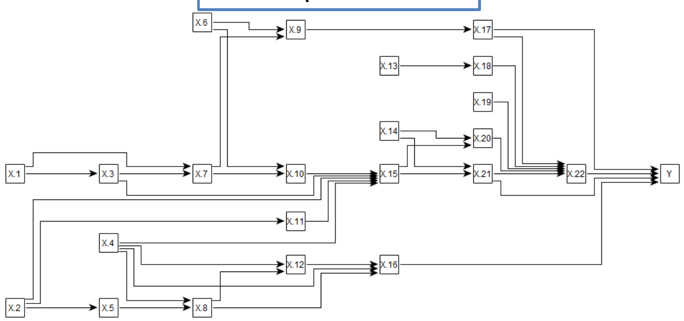
# Manufacturing Sensor data Analytics: Multi-stage Modeling

sponsored by

- Multi-stage manufacturing process (MSP)
  - A number of stages, which are related to each other via an intricate network of complex relationships
  - A given preceding stage usually affects the final stage through a cascade of both direct and indirect input/output contributions, each of which is hard to model parametrically

- Objective
  - Assess stage variable importance in manufacturing processes characterized by a hierarchy of technical relationships between stages

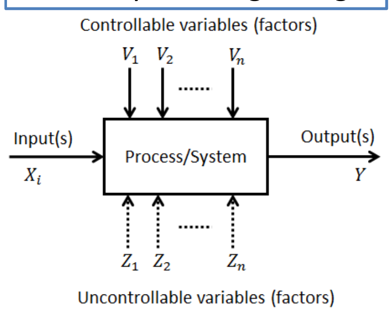
Example of MSP




- Variable Importance in a single stage
  - Assess the relative influence that input variables of a given set have on a certain output variable of interest $Y$

$$Y = f(V_1, \ldots, V_n, Z_1, \ldots, Z_n, X_i) + \varepsilon$$

Anatomy of a Single Stage




- Regression modeling with random forests

$$\max_{j,v} SS_{X_j,v} = \frac{1}{|U|}\sum_{i \in U}(y_i - \bar{y}_U)^2 - \left[\frac{1}{|S_1^{j,v}|}\sum_{i \in S_1^{j,v}}\left(y_i - \bar{y}_{S_1^{j,v}}\right)^2 + \frac{1}{|S_2^{j,v}|}\sum_{i \in S_2^{j,v}}\left(y_i - \bar{y}_{S_2^{j,v}}\right)^2\right]$$

- Permutation importance for random forests in regression

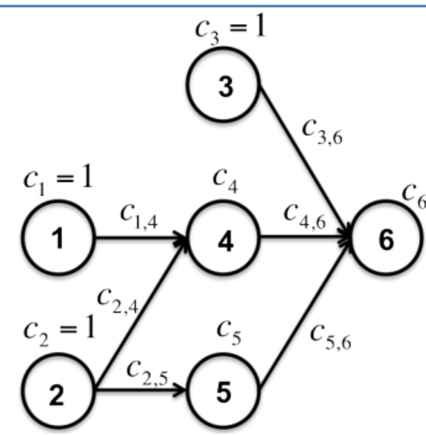
$$I_j^{Perm} = \frac{1}{T}\sum_{t=1}^{T}(MSE_{t,\pi_j} - MSE_t)$$

where
$$MSE_t = \frac{1}{|O_t|}\sum_{i \in O_t}(y_i - \hat{y}_{i,t})^2$$

$$MSE_{t,\pi_j} = \frac{1}{|O_t|}\sum_{i \in O_t}(y_i - \hat{y}_{i,t,\pi_j})^2$$

- Stage importance within a multi-stage process
  1) Local relative contribution assessment
  2) Global relative contribution assessment via integration of local relative contribution assessments
  3) Overall procedure for the assessment of stage importance

Contribution Coefficients in a Given Network




- “Integrated Variable Importance Assessment in Multi-Stage Production Processes“ (Under revision)