

# Manufacturing Sensor data Analytics: Spatial Data Modeling

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- 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  $g$

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

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

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

## • Spatial Local Denoising

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

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

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

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

## • Step-down Randomness Test

–Test statistics and Control limits

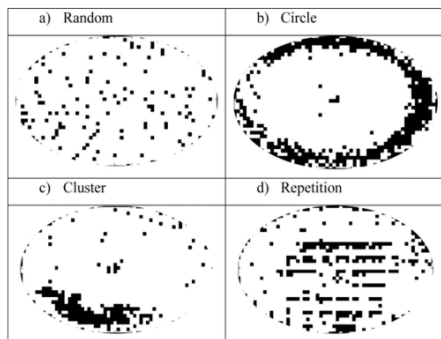
$$Z_1 = \mathbf{y}_r^{(1)T} \mathbf{S}_r^{(1)-1} \mathbf{y}_r^{(1)} \quad CL_1 = \frac{(n-1)r}{(n-r)} F_{\alpha_1}(r, n-r)$$

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

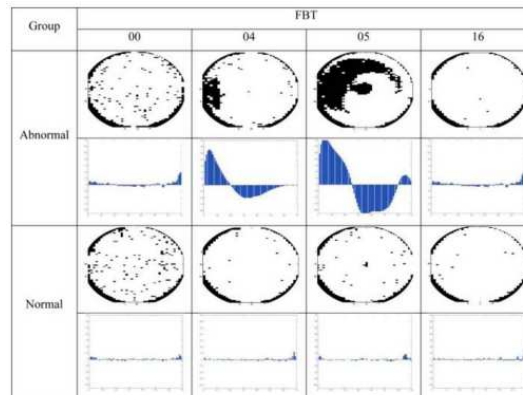
### Comparison of Test performance

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

Binarized FBT maps



Selected denoised FBT maps



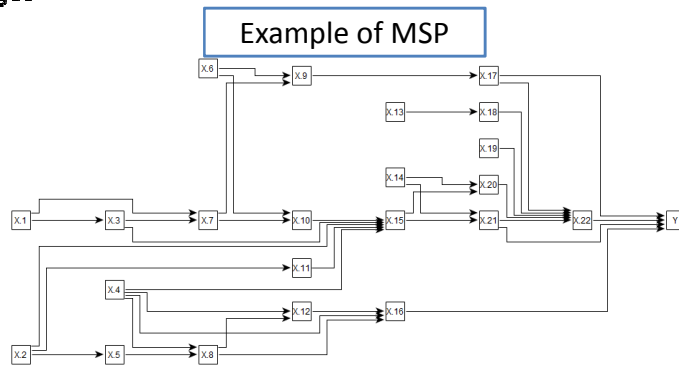
- “Step-Down Spatial Randomness Test for Detecting Abnormalities in DRAM Wafers with Multiple Spatial Maps”, *IEEE TRANSACTIONS ON SEMICONDUCTOR MANUFACTURING* (2016)

# Manufacturing Sensor data Analytics: Multi-stage Modeling

- **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

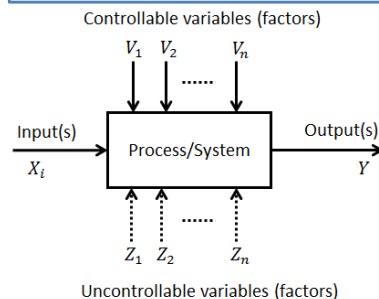


## • Variable Importance in a single stage

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

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

### Anatomy of a Single Stage



- Regression modeling with random forests

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

- Permutation importance for random forests in regression

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

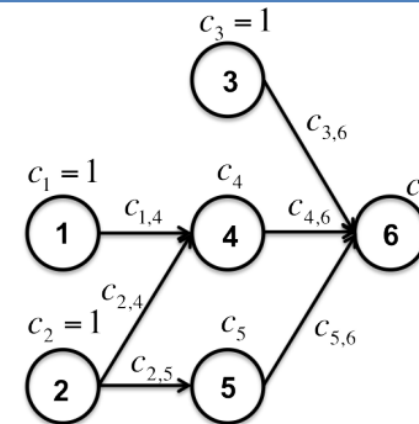
where  $MSE_t = \frac{1}{|O_t|} \sum_{i \in O_t} (y_i - \hat{y}_{i,t})^2$

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

- 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)