Empower R2R Controller Design and Implementation with Data Analytics

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APCSM Conference

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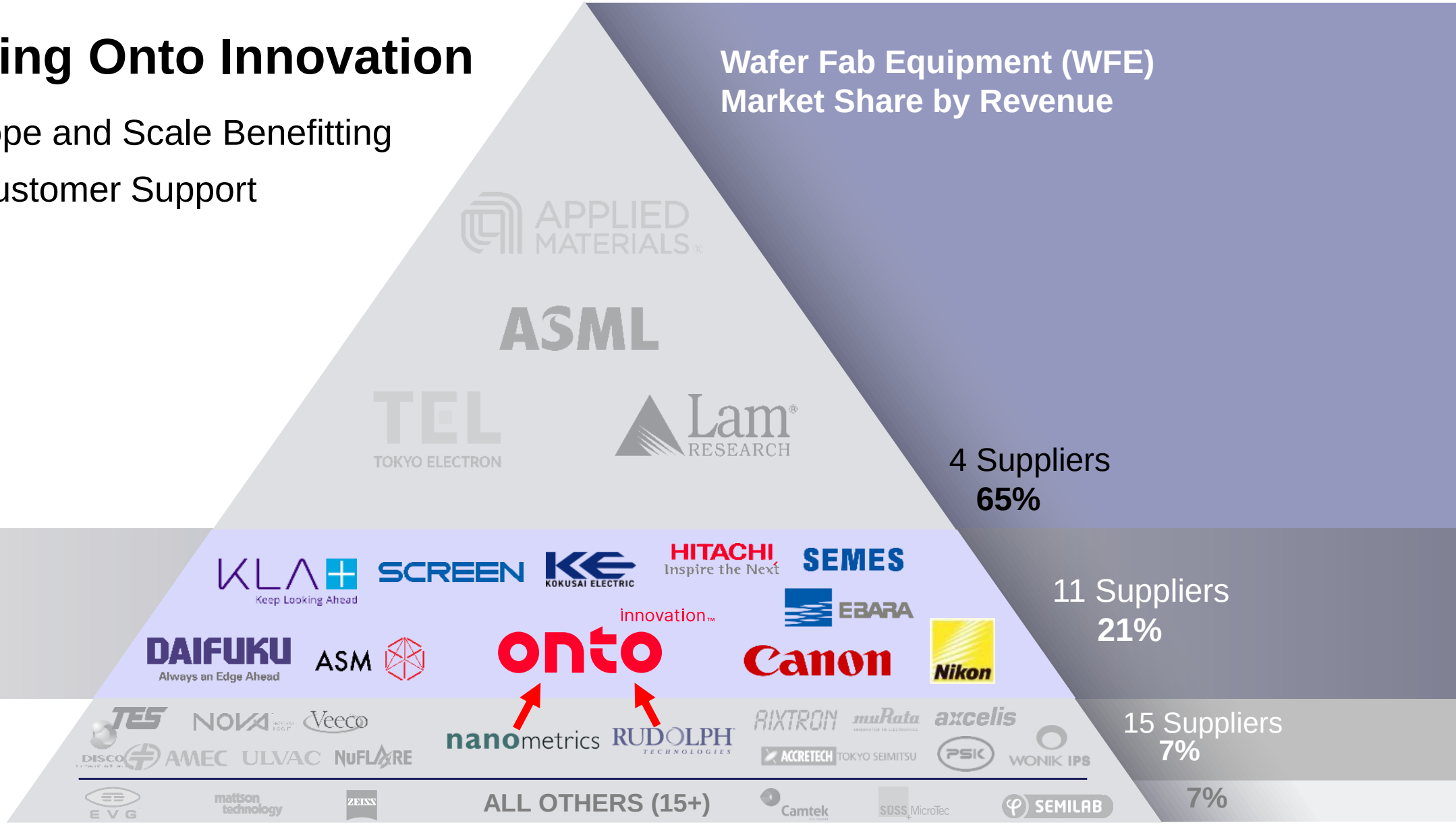
Outline

- Introduction to Onto Innovation
- R2R control overview
  - Threaded control vs. Non-threaded control
- CVD process R2R case study
  - Use of data analytics to facilitate controller design and implementation
- Conclusion

Introducing Onto Innovation

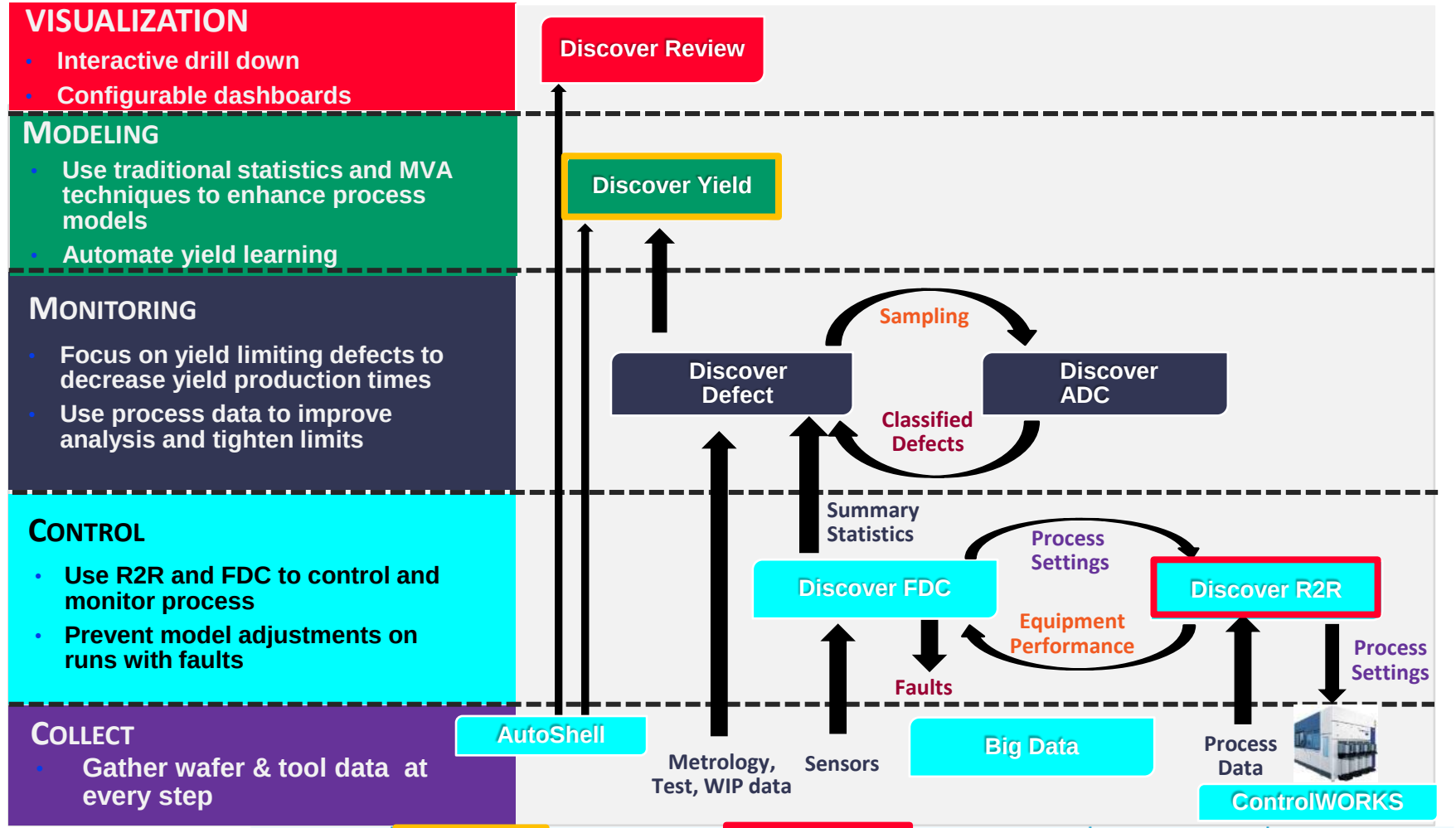
Greater Scope and Scale Benefitting

R&D and Customer Support

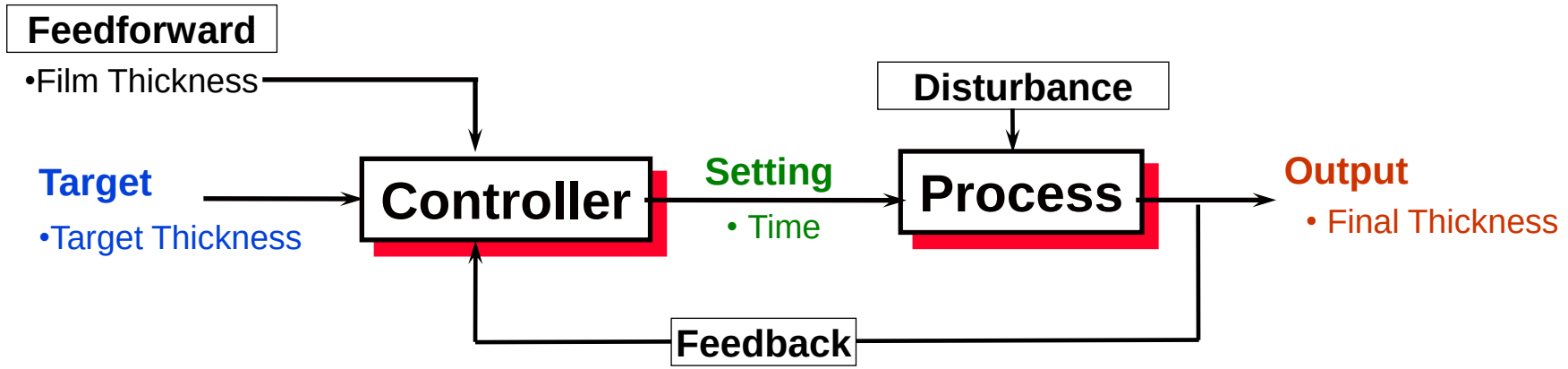


Source: Company Rank Order based on 2018 Share of Total WFE Revenue, Gartner Market Share Data, May 2019

Onto Innovation Software Solutions



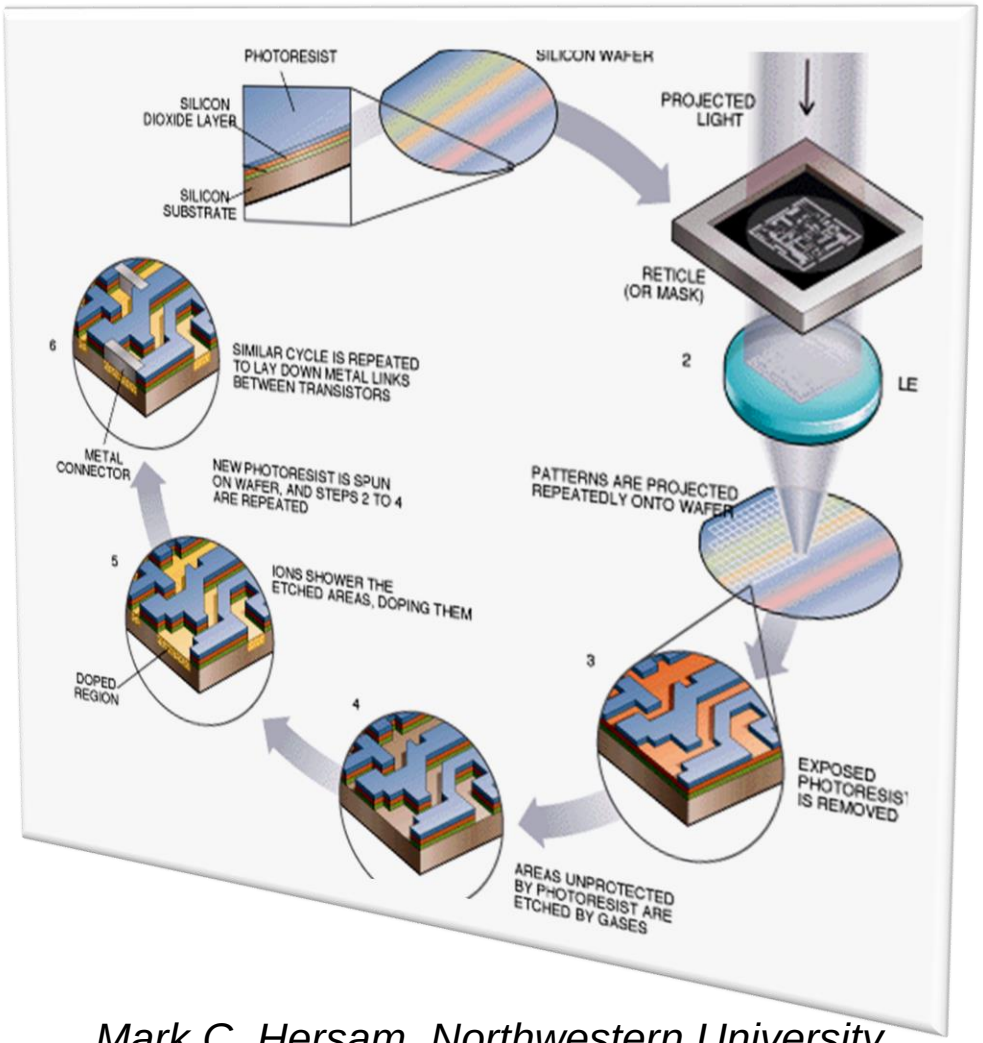
Run-to-Run Control



- Feedforward Control (Open-Loop Control)
  - A disturbance is measured, and the measurement is used to decide how to adjust a setting to keep output on target
  - No output measurement, cannot account for unmeasured disturbances
- Feedback Control (Closed-Loop Control)
  - An output is measured and the measurement is used to decide how to adjust a setting to keep output on target
  - Don’t need to know disturbances, so don’t measure them

How Run-to-Run Control Can Help

- Drive processes to target
  - Achieve proper film thickness, uniformity, stress, CD, overlay
  - Increase process capability (Cp&Cpk) and yield
- Reduce OoC/OoS, rework, pilot & monitor runs,
  - Increase tool up time
  - Increase throughput and reduce cycle time
- Allow tools to run longer between PM
  - Increase time between replacements
  - Reduce consumables
- Make adjustments automatically
  - Reduce engineering time
  - Eliminate human error

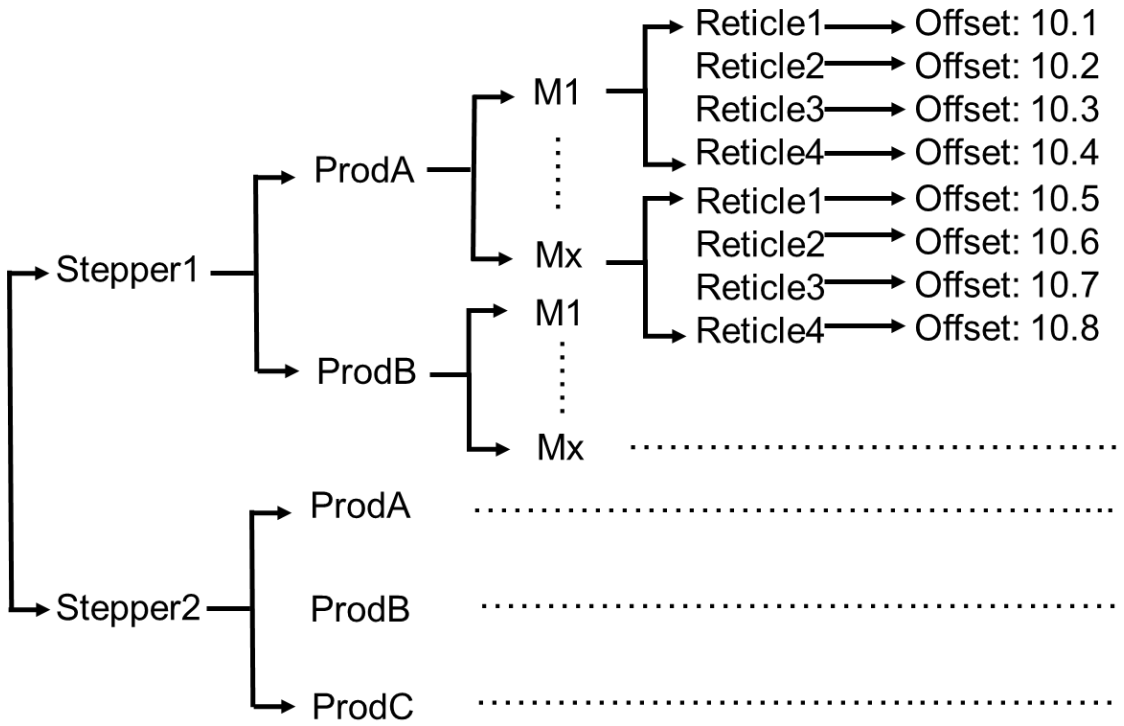


Mark C. Hersam, Northwestern University

Partitions (Threads)

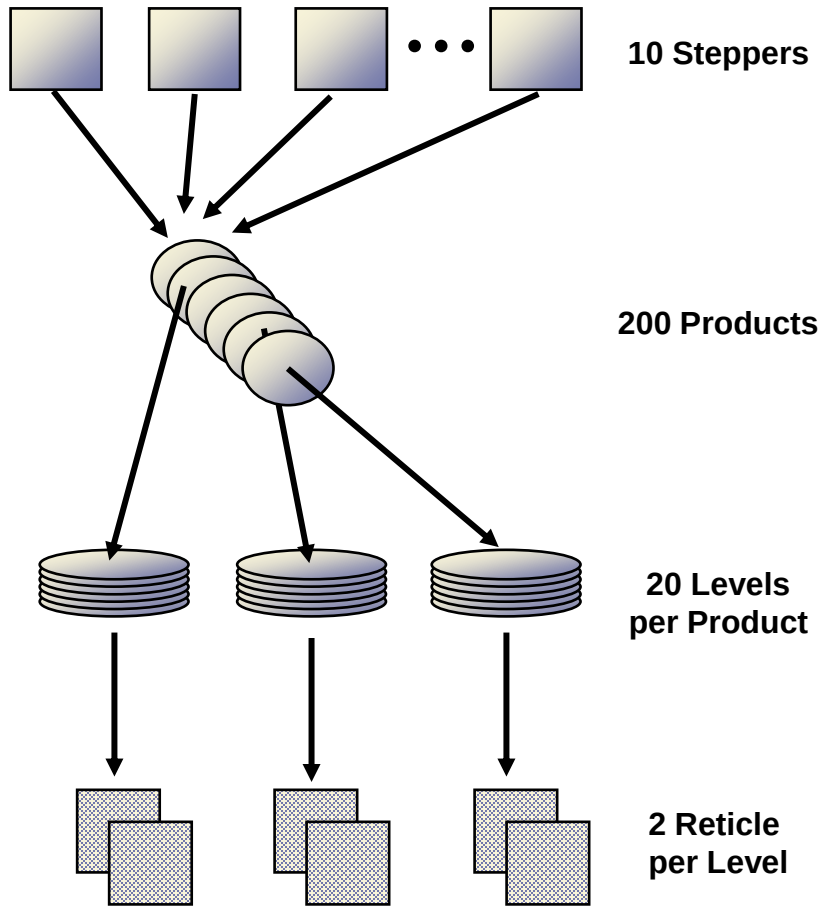
- Unique combinations of manufacturing context attributes, e.g., machine, product, layer, etc.
- Each partition has individual control loop using data only from itself.

- Proper definition of partitions separates disturbances into different groups (partitions) so that variability within each partition should be much smaller than the overall variability.
- Over-definition of partitions may undermine controller performance and lead to large number of partitions and data poverty.



High-Mix Challenges and Solutions

- Hard to keep low-running products updated if they require their own partition
  - Track time and number of wafers/runs since partition was last tuned
    - Control-oriented dispatching to help ensure partition state will be updated *(e.g., Anderson and Hanish, IEEE Trans. Semicond. Manuf., 2008)*
    - Require send-ahead/pilot if last tuning was long ago *(e.g., Krumanocker and Yelverton, APC Conference, 2015)*
  - Similar partitions (e.g., reticles) can be combined into a partition group that share data with each other
  - Controller flexible enough to allow partition criteria change
  - Hierarchical partition definitions *(e.g., Yelverton and Agrawal, SPIE, 2014; Sun, APC Conference, 2017)*



= 80,000 Interactions

MP_AlignmentOffset_Prim1	Layer, MetToTool, Product, RefTool, Reticle
MP_AlignmentOffset_Prim2	Layer, Product, RefTool, Reticle
MP_AlignmentOffset_CR1	Layer, Product, Reticle
MP_AlignmentOffset_CR2	Layer, Product
MP_AlignmentOffset_CR3	Customer, Layer, Process

```
if(timeSinceLastTune(MP_AlignmentOffset_Prim1)<(3600*24*180)) then
(MP_AlignmentOffset_Prim1) else(

if(timeSinceLastTune(MP_AlignmentOffset_Prim2)<(3600*24*180)) then
(MP_AlignmentOffset_Prim2) else(

if(timeSinceLastTune(MP_AlignmentOffset_CR1)<(3600*24*180)) then
(MP_AlignmentOffset_CR1) else(

if(timeSinceLastTune(MP_AlignmentOffset_CR2)<(3600*24*180)) then
(MP_AlignmentOffset_CR2) else(

if(timeSinceLastTune(MP_AlignmentOffset_CR3)<(3600*24*180)) then
(MP_AlignmentOffset_CR3) else(

C_AlignmentSettingsTable)))))
```

Non-Threaded Control

e.g., Wang et al, APC Conference, 2013

- Maintain state vector X(k) with an element for each independent context
- Measured output predicted by linear combination of states based on context of run

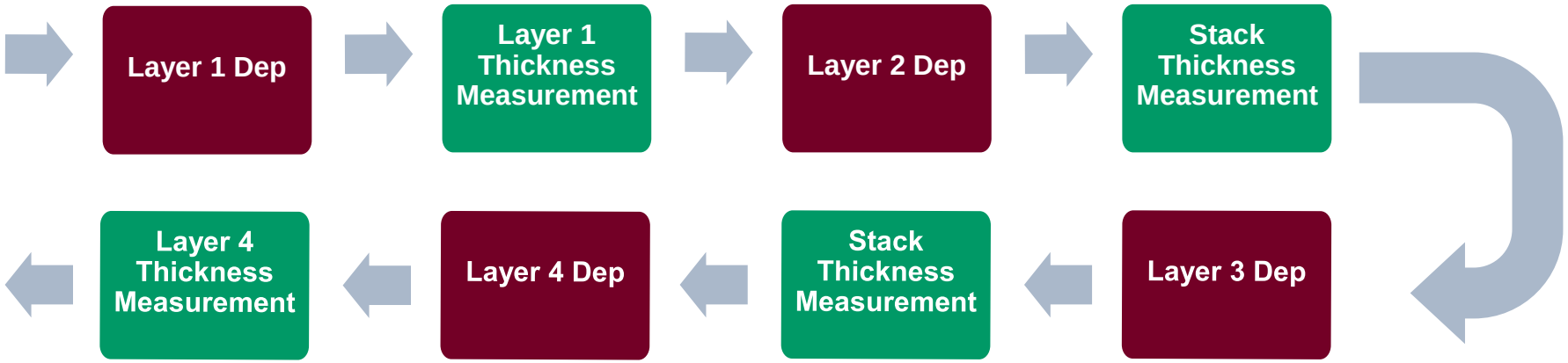
$$X = \begin{bmatrix} Tool1 \\ Tool2 \\ \vdots \\ Layer1 \\ Layer2 \\ \vdots \\ Product1 \\ Product2 \\ \vdots \end{bmatrix}$$

$$y = [1\ 0 \cdots 0\ 1 \cdots 1\ 0 \cdots] \bullet X + u = Tool1 + Layer2 + Product1 + u$$

- Share information between partitions, therefore potentially less send-ahead/pilot wafers
  - Controller performance may deteriorate without frequent model update
    (e.g., Zou et al, APC Conference, 2014)
- Less straightforward implementation; not for strong non-linear interaction among states
  - Not practical for production use when numbers of states change
  - Threaded control works as well when noise is present
    (e.g., Hanish, AEC/APC Symposium, 2005)

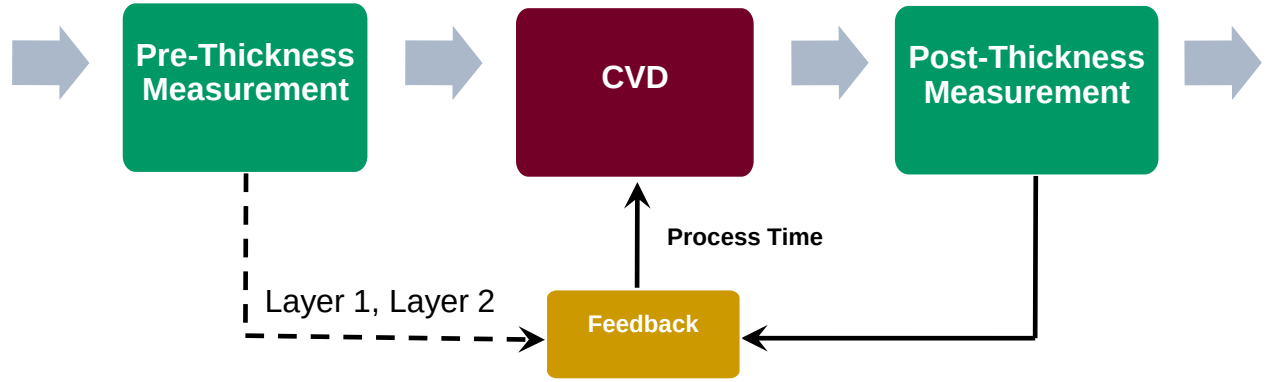
CVD Process Flow

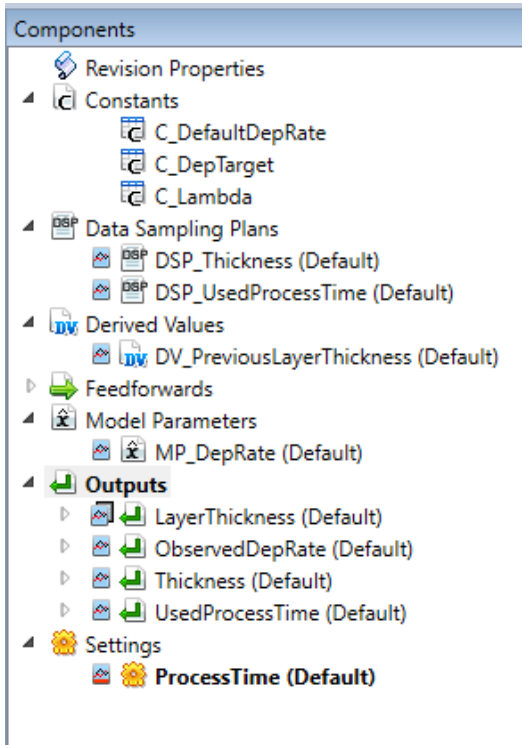
- R2R solution introduced for all product lines with about 14 product families and 4 layers to be controlled.

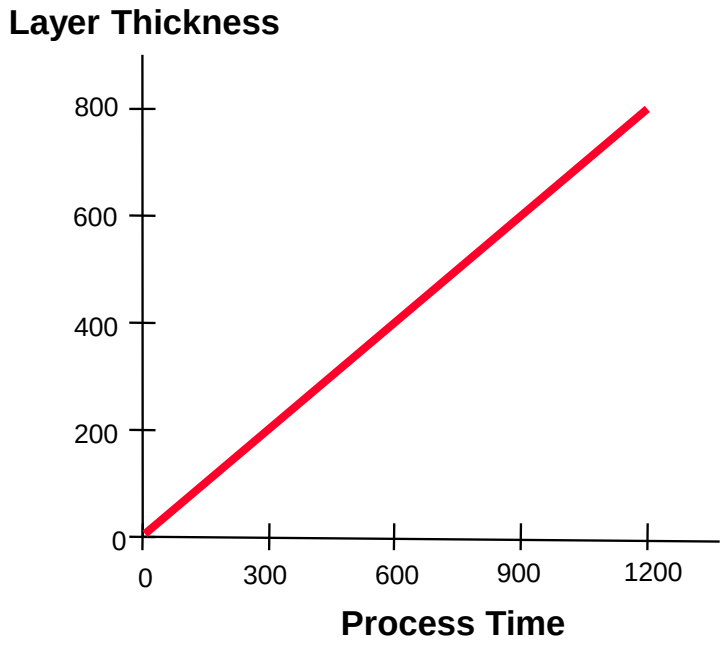


CVD Controller Design

- Process model
  - LayerThickness = *DepRate* * ProcessTime
- EWMA tuner
  - *PredDepRate*(n+1) = (1−λ)**PredDepRate*(n) + λ*ObservedDepRate(n)
- Strategy components
  - Setting: ProcessTime
  - Model parameter: DepRate
  - Feedforward: PreThickness
  - Constant: λ, $Thickness_{tgt}$, DefaultDepRate
  - DSP: DSP_Thickness, DSP_UsedProcessTime
  - Output: $PostThickness_{avg}$, UsedProcessTime
  - Derived output: ObservedDepRate = (PostThk - PreThk) / UsedProcessTime

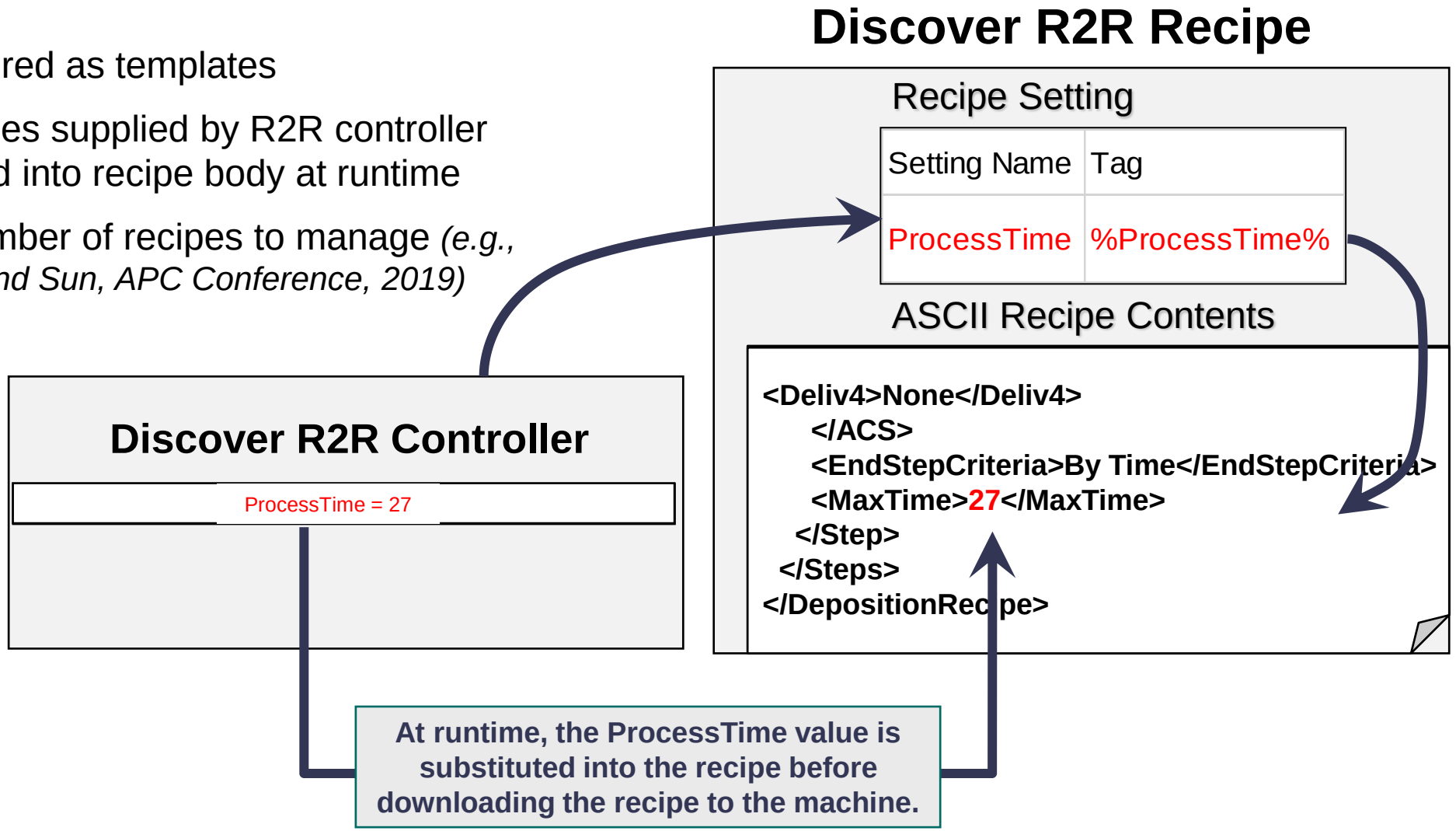






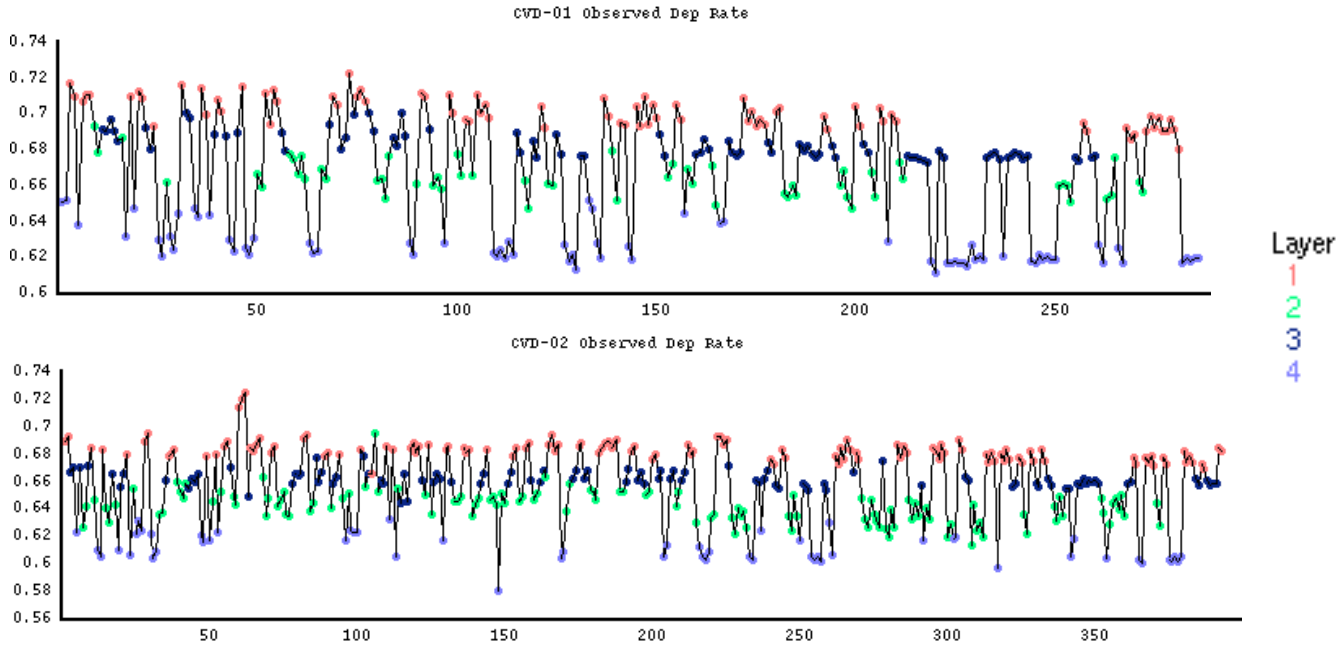
Total R2R/RMS Solution

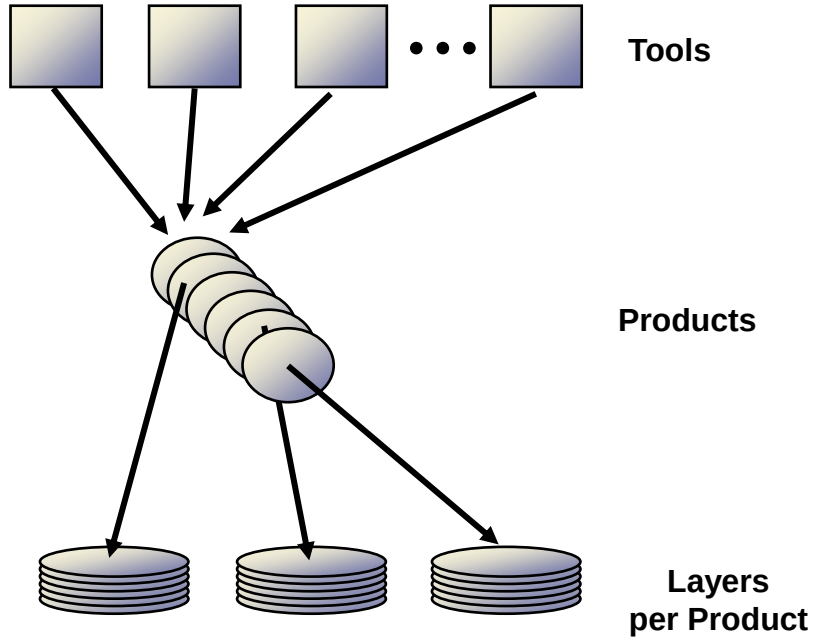
- Recipes stored as templates
- Setting values supplied by R2R controller and inserted into recipe body at runtime
- Reduce number of recipes to manage *(e.g., Echevarria and Sun, APC Conference, 2019)*



Dep Rate Partitioning

- Separate disturbance into machine and material
  - Partition machine disturbance by machine
  - Partition material disturbance by product, layer, etc.
- Partition CVD controller by tool and layer at least
  - Observed dep rate is stratified by layer
  - Variability within each layer is much smaller than overall variability

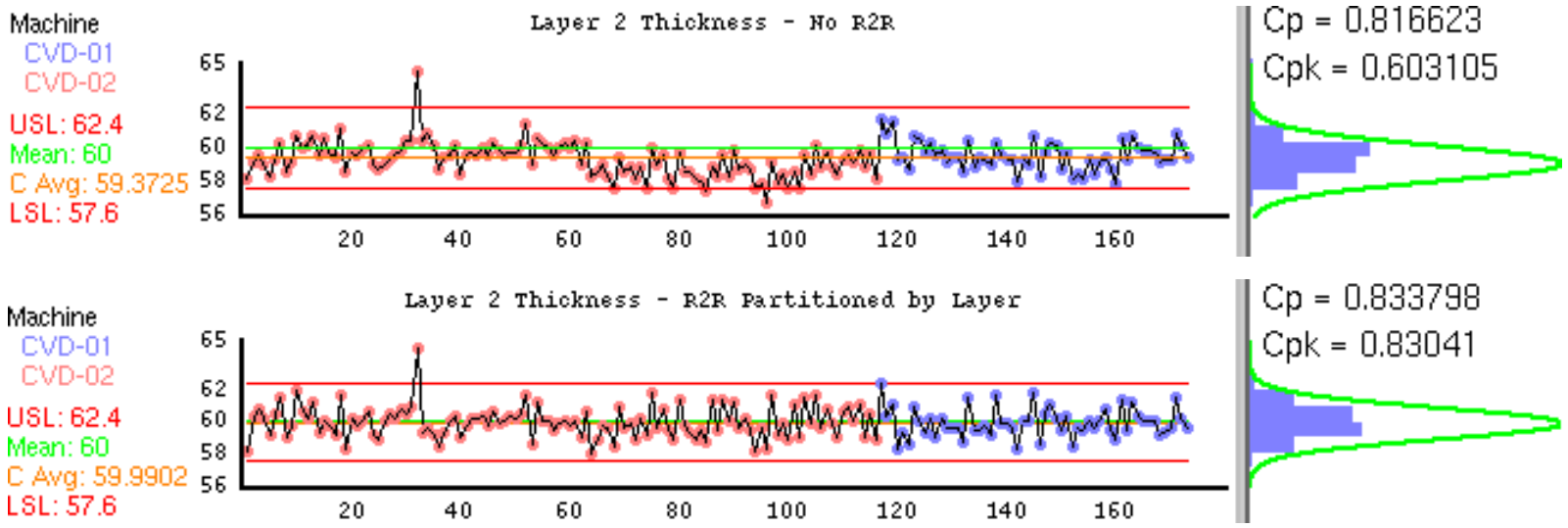




Results with Tool/Layer Partition

- Simulated 679 runs on 2 tools and 4 layers within 2 months
- Results estimated significant reduction in thickness variability which corresponds to up to **+38%** increase in Cpk with optimized λ
- Current thickness data is skewed too. R2R will drive it back to target

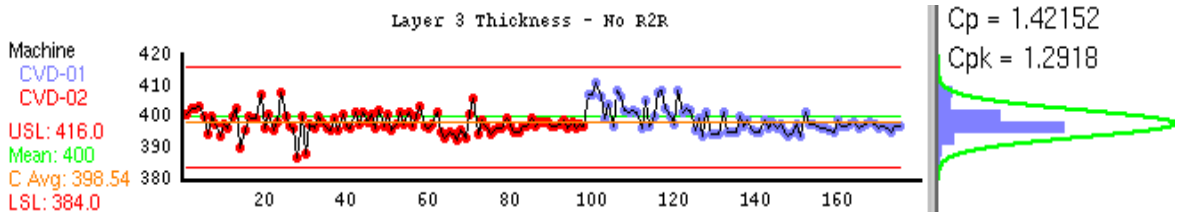
Layer	Cpk Increase	Optimal λ (CVD01, CVD02)
1	9%	0.2, 0.4
2	38%	0.3, 0.3
3	24%	0.3, 0.1
4	4%	0.5, 0.2

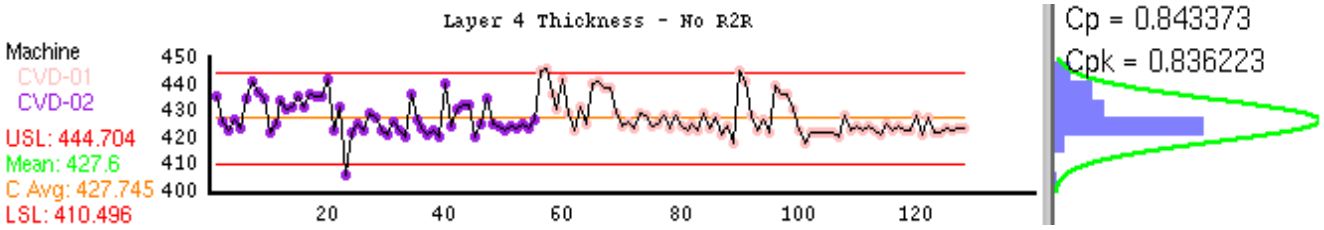


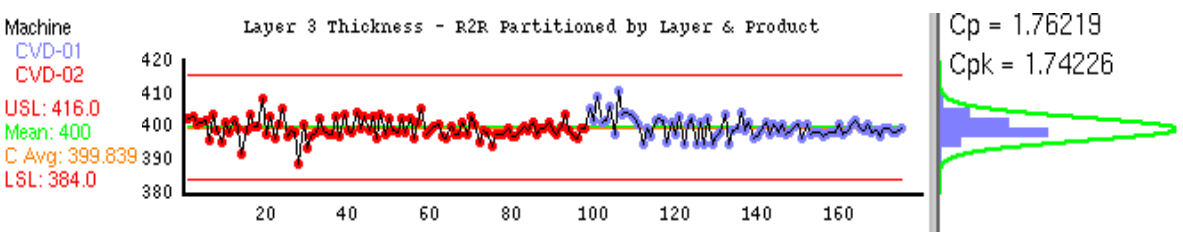
Results with Tool/Layer/Product Partition

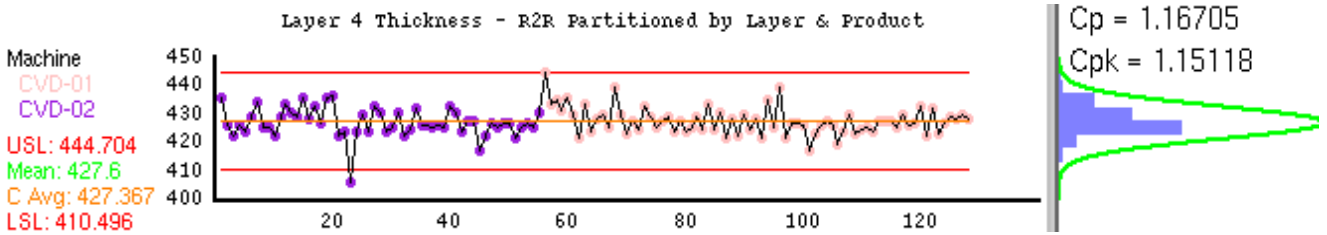
- Significant further Cpk improvement at Layer 3 & 4
- Controller performance deteriorates for Layer 1 & 2
- Process engineer raised concern about data starvation for low-running products

Layer	Cpk Increase	Optimal λ (CVD01, CVD02)
1	3%	0.5, 0.4
2	35%	0.2, 0.5
3	**35%**	0.5, 0.5
4	**37%**	0.7, 0.7





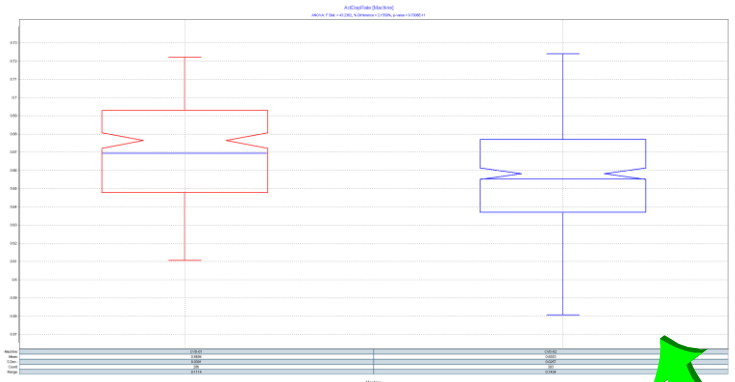


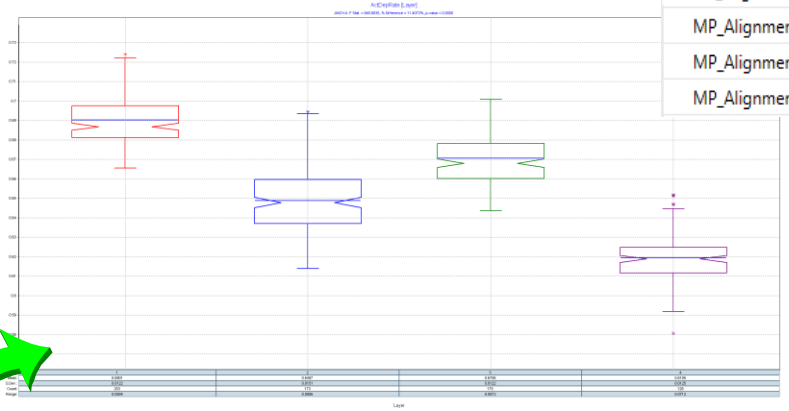


ANOVA for Dep Rate in Discover Yield

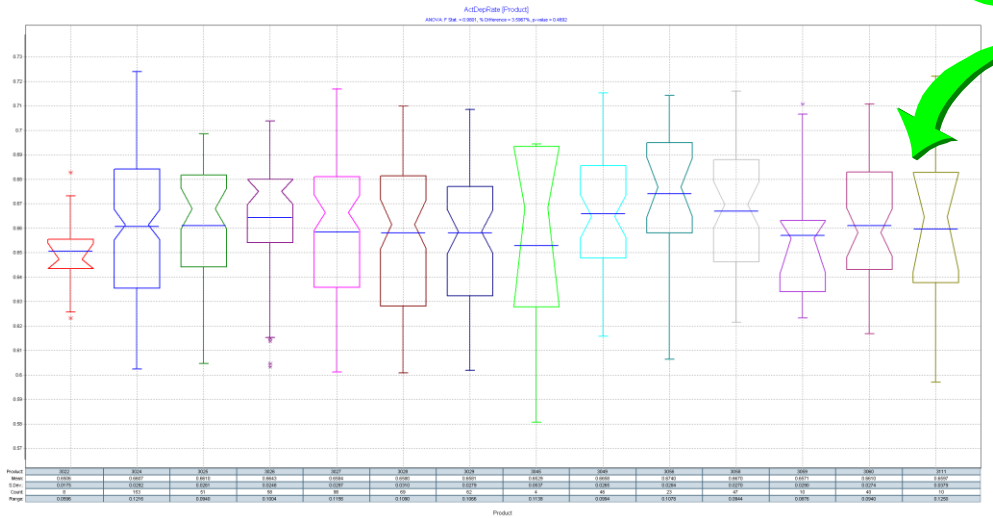
- Verifies significant dep rate variability in Layer and Tool but less variability in Product
- Guides design of partition scheme and prioritizes sources of disturbances

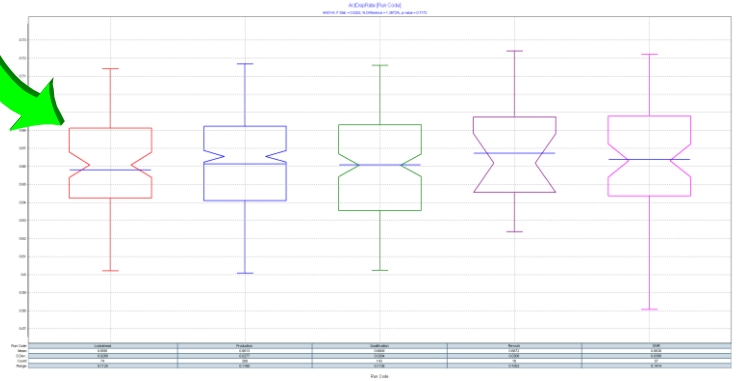
MP_AlignmentOffset_Prim1	Layer, MetToTool, Product, RefTool, Reticle
MP_AlignmentOffset_Prim2	Layer, Product, RefTool, Reticle
MP_AlignmentOffset_CR1	Layer, Product, Reticle
MP_AlignmentOffset_CR2	Layer, Product
MP_AlignmentOffset_CR3	Customer, Layer, Process





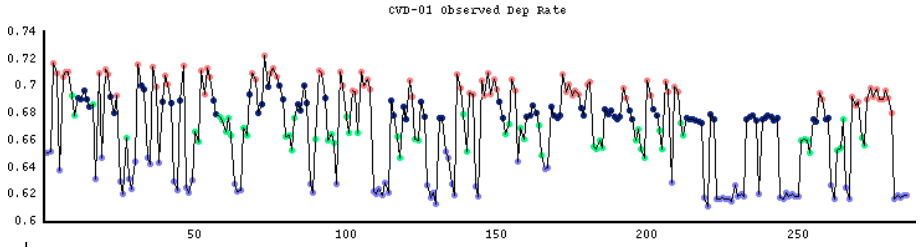
Sub-Grouping	SS (Sub-Grouping)	df	MS	SS (Error)	df	MS	SS (Total)	df	F Stat.	p-value
Layer	0.4350	3	0.1450	0.1153	675	0.0002	0.5503	678	848.6835	0.0000
Machine	0.0330	1	0.0330	0.5173	677	0.0008	0.5503	678	43.2362	9.7006E-11
Product	0.0103	13	0.0008	0.5400	665	0.0008	0.5503	678	0.9801	0.4692
Run Code	0.0017	4	0.0004	0.5486	674	0.0008	0.5503	678	0.5252	0.7172

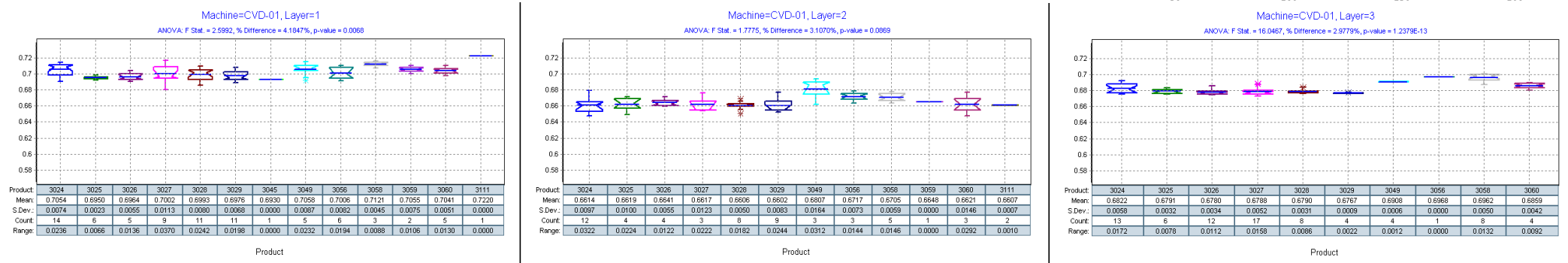


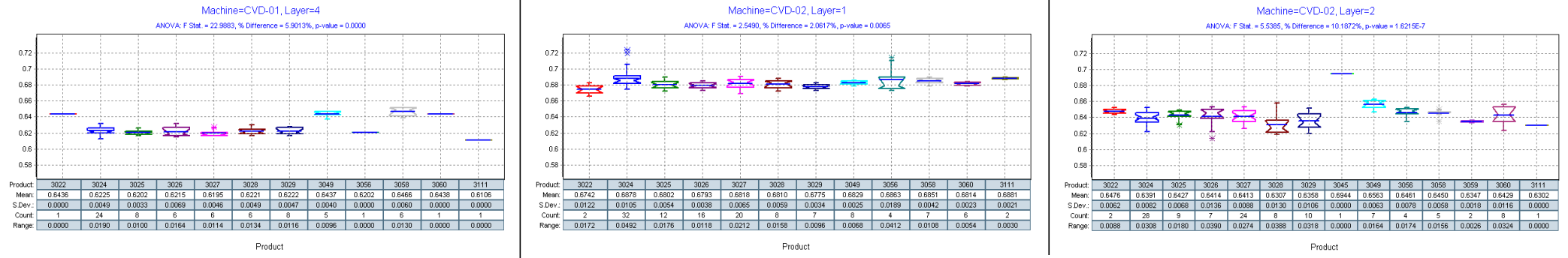


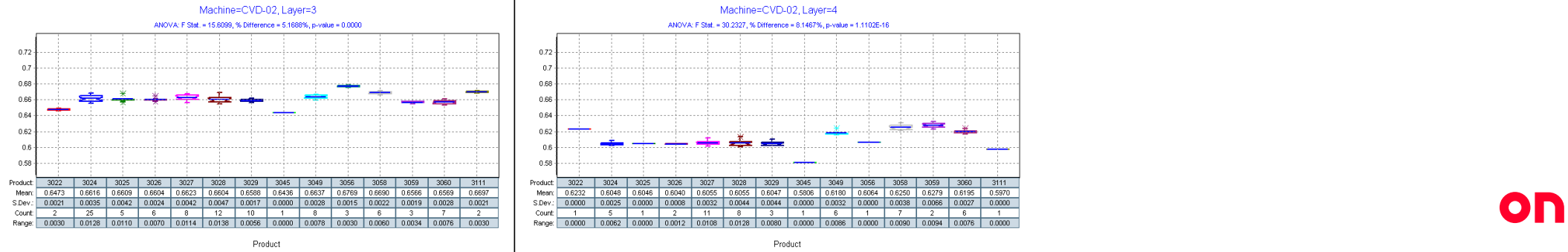
Analyzing Dep Rate Offsets by Product

- Dep rate variability in Product not significant suggests controller remain partitioned by tool/layer to quickly capture trend but dep rate offset can be applied to achieve better control between products









Modified Controller Design

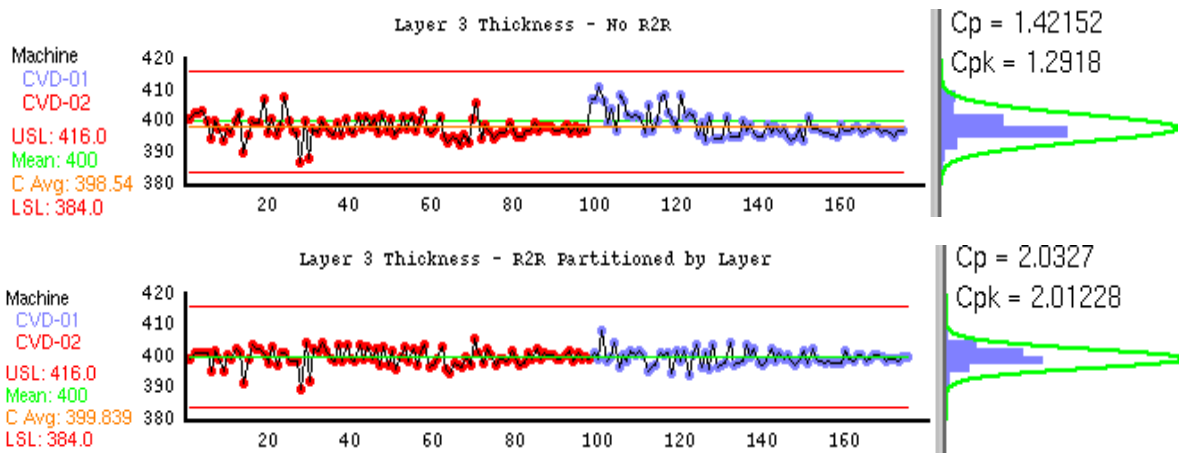
- Process model
  - LayerThk = ($DepRate_{tool/layer}$ + $Offset_{tool/layer/product}$) * ProcessTime
- EWMA tuner
  - *PredDepRate*(n+1) = (1−λ) * *PredDepRate*(n) + λ * (ObservedDepRate(n) – Offset)
- Sample dep rate offset from YMS

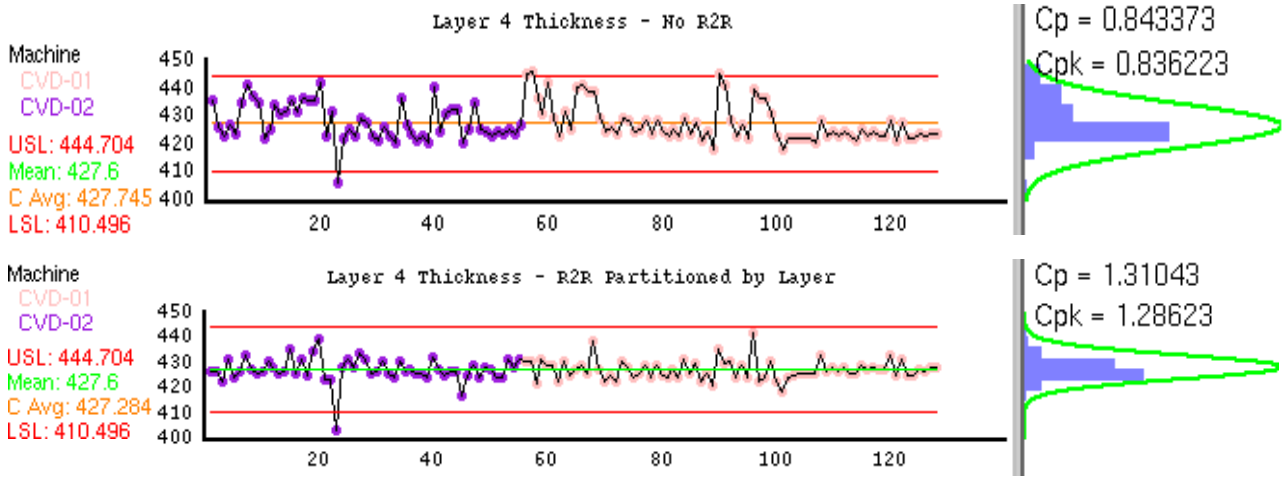
	Indexing			
Name	Layer	Machine	Product	Value
C_DepRateOffset	*	*	*	0
C_DepRateOffset	2	CVD-01	3049	0.016
C_DepRateOffset	2	CVD-01	3056	0.008
C_DepRateOffset	2	CVD-01	3058	0.006
C_DepRateOffset	3	CVD-01	3049	0.008
C_DepRateOffset	3	CVD-01	3058	0.014
C_DepRateOffset	4	CVD-01	3049	0.018
C_DepRateOffset	4	CVD-01	3058	0.02
C_DepRateOffset	2	CVD-02	3028	-0.012
C_DepRateOffset	2	CVD-02	3029	-0.006
C_DepRateOffset	2	CVD-02	3049	0.014
C_DepRateOffset	3	CVD-02	3056	0.014
C_DepRateOffset	3	CVD-02	3058	0.006
C_DepRateOffset	4	CVD-02	3024	-0.008
C_DepRateOffset	4	CVD-02	3027	-0.006
C_DepRateOffset	4	CVD-02	3028	-0.006
C_DepRateOffset	4	CVD-02	3049	0.006
C_DepRateOffset	4	CVD-02	3058	0.012
C_DepRateOffset	4	CVD-02	3060	0.008

Results with Modified Control Model

- Significant further improvement for Layer 2, 3 & 4 even comparing to partition by tool/layer/product
- Handles low-running products better

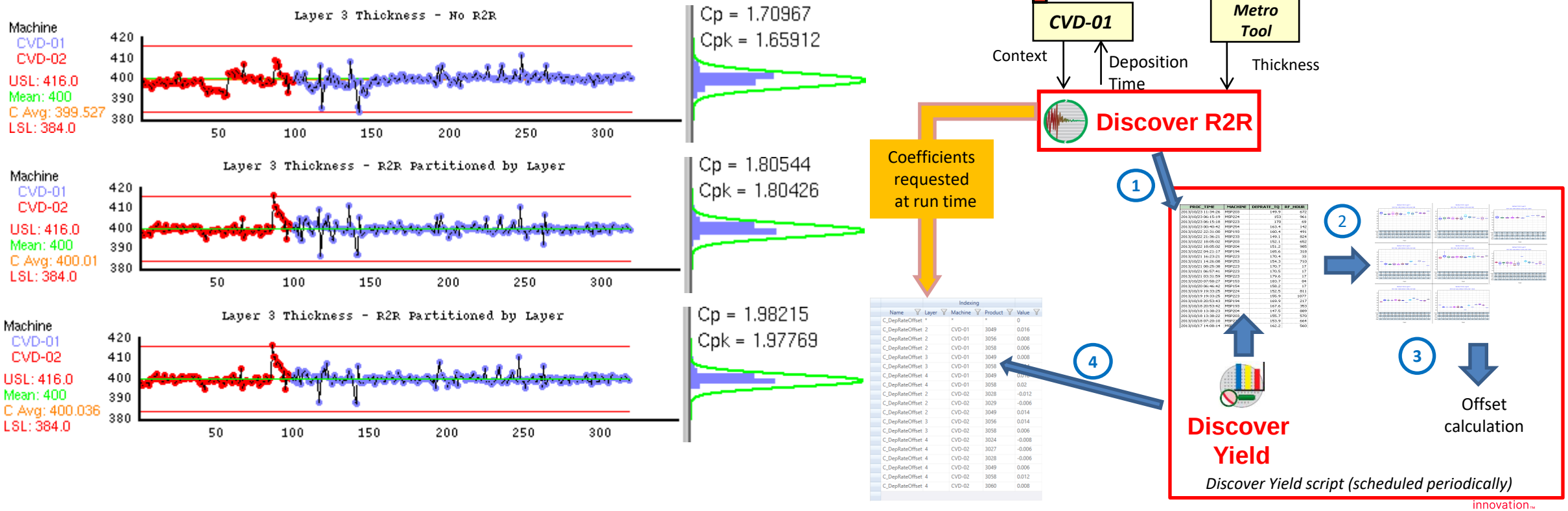
Layer	Cpk Increase	Optimal λ (CVD01, CVD02)
1	9%	0.2, 0.4
2	48%	0.2, 0.2
3	56%	0.2, 0.2
4	54%	0.2, 0.2





Frequent Offset Update Maintains Controller Performance

- Simulated modified control model with new production data
- Controller performance deteriorates as old products phased out and new products coming in
- Obtaining new dep rate offsets by product helps maintain controller performance
- YMS can periodically re-analyze offsets and update R2R model



Summary

- Traditionally, R2R controllers handle disturbances with partitions/control threads

- Data analytics can be employed to
  - Guide design of partition scheme and prioritize sources of disturbances
  - Improve control model with offsets within partition to achieve better control
  - Re-analyze offsets periodically to help maintain controller performance

- Results from CVD process showed significant Cpk improvements

Thank You

谢谢 | 謝謝	ありがとう	Obrigado
Danke	감사합니다	Merci

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