



Tackling PV Manufacturing Cost

Jeff Cotter

Adjunct A/Prof, ASU and ANU

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JHFC Consulting

High-efficiency silicon solar cells: science, technology, manufacturing

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Tackling PV Manufacturing Cost



Outline

1. My Value Proposition for Tackling PV Manufacturing Costs
2. Accounting for the Cost of Goods Manufactured
3. Tackling COGM; An Example
4. Manufacturing Science of Solar Cells Course

Tackling PV Manufacturing Cost



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Tackling PV Manufacturing Cost (COGM)

Jeff's value proposition for tackling COGM:

1. Improving cost of goods manufactured improves cash flow

$$\textit{cash flow} = \textit{revenue} - \textit{COGS}$$

Cash is King.

Tackling PV Manufacturing Cost (COGM)

Jeff's value proposition for tackling COGM:

1. Improving cost of goods manufactured improves cash flow
2. Improvements are typically small in \$/Wp terms

0.5% EOL yield loss $\approx +0.0025/W_p$ to COGM

Tackling PV Manufacturing Cost (COGM)

Jeff's value proposition for tackling COGM:

1. Improving cost of goods manufactured improves cash flow
2. Improvements are typically small in \$/Wp terms, *however*, they can very often be applied to the whole manufacturing base.

0.5% EOL yield loss $\approx +0.0025/W_p$ to COGM
–\$0.0025/Wp to COGM \approx 5Y NPV of ~\$10M
(for a 1 GW deployment)

Tackling PV Manufacturing Cost (COGM)

Jeff's value proposition for tackling COGM:

1. Improving cost of goods manufactured improves cash flow
2. Improvements are typically small in \$/W_p terms, *however*, they can very often be applied to the whole manufacturing base.
3. There are ample opportunities for improvement, especially when considering the whole span of the PV value stream....

Imagine a gap-to-entitlement of \$0.50/W_p

Capture 5% YoY over 5 years \approx \$0.11/W_p over 5 years

Tackling PV Manufacturing Cost (COGM)

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3. There are ample opportunities for improvement, especially when considering the whole span of the PV value stream....
4. Well organized, effective engineering teams can run concurrent projects

10 small \$0.0025/Wp projects \approx \$0.025/Wp per year

Tackling PV Manufacturing Cost (COGM)

Jeff's value proposition for tackling COGM:

1. Improving cost of goods manufactured improves cash flow
2. Improvements are typically small in \$/Wp terms, *however*, they can very often be applied to the whole manufacturing base.
3. There are ample opportunities for improvement, especially when considering the whole span of the PV value stream....
4. Well organized, effective engineering teams can run concurrent projects
5. Small projects can be completed in a short timeframe, especially compared to new platform or platform improvement projects

New Platform Development: ~ 10-20 years

Platform Improvement: ~ 1-5 years

COGM Improvement: ~ 1-5 quarters

Tackling PV Manufacturing Cost

Tackling COGM is compelling, and PV engineers have a vital role to play in collaboration with Cost Accountants:

Cost Accountants own the business of *accounting* for COGM,

However, PV Engineers own the business of *improving* COGM.

Therefore, we PV Engineers must be well-equipped with the right skills and knowledge to get this job done right and fast.

Tackling PV Manufacturing Cost

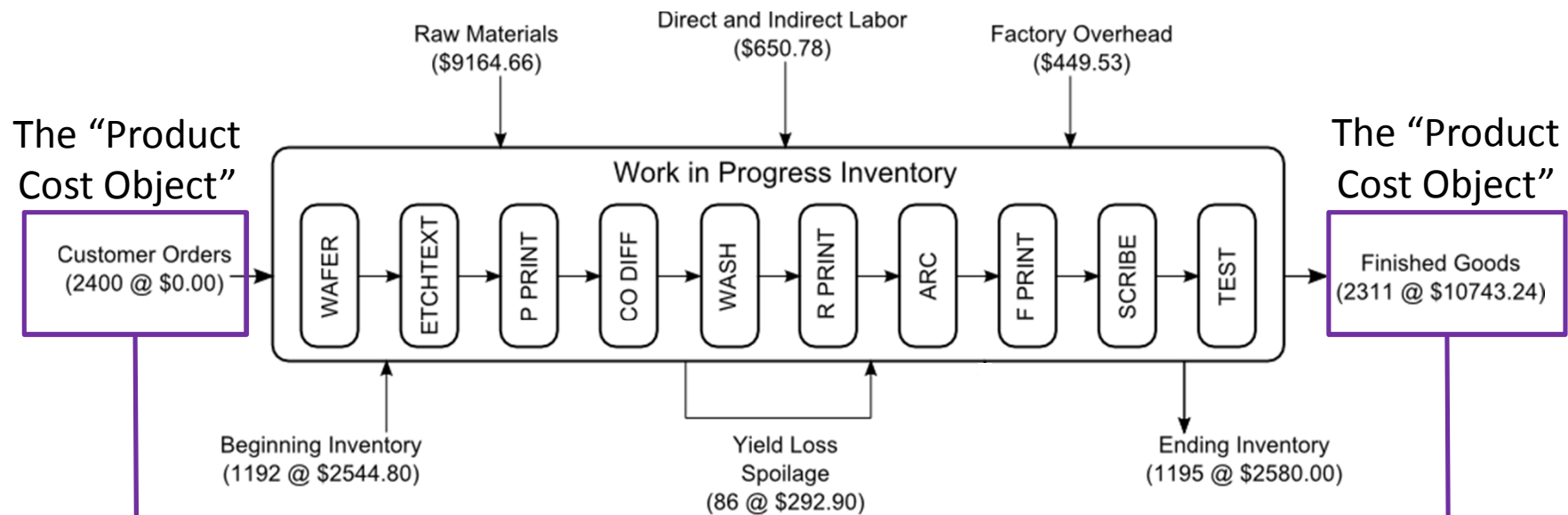


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Accounting for the COGM

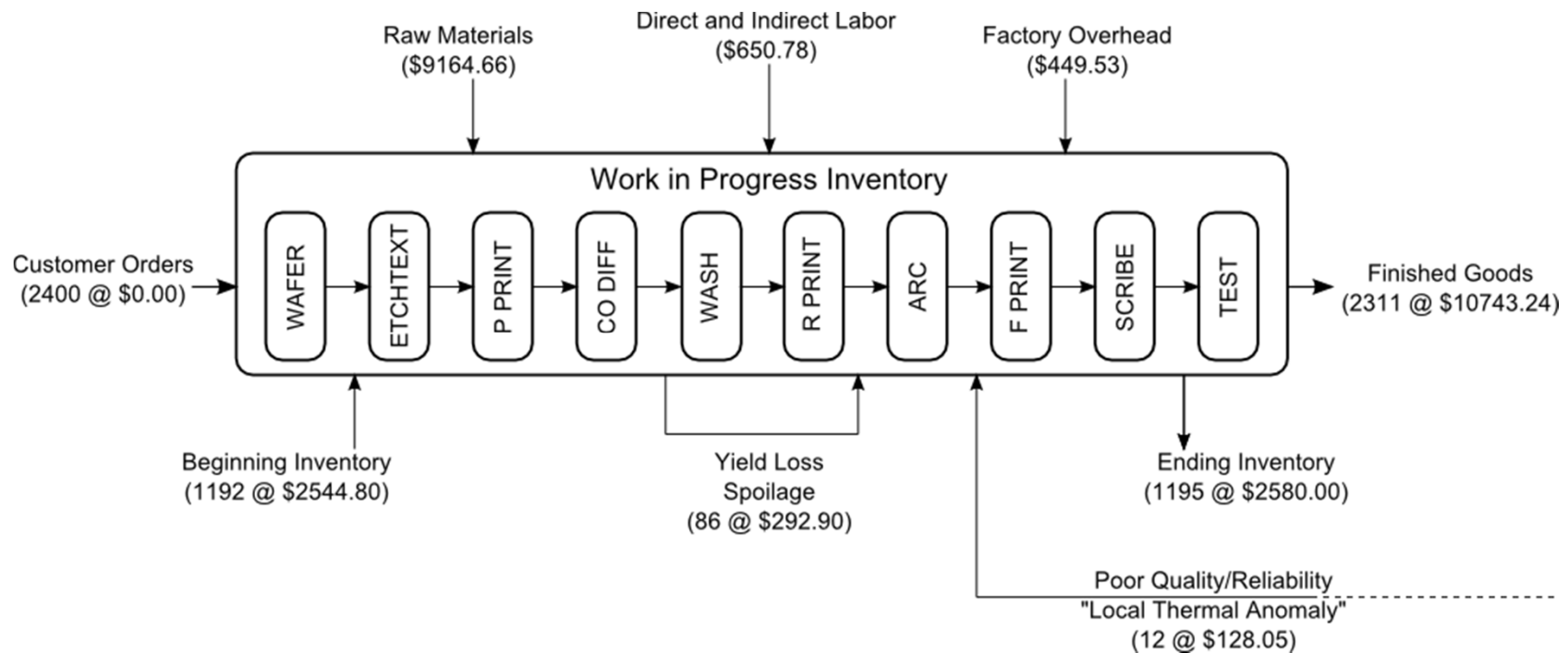
Cost Flow Diagram (an Engineer's POV)



$$\text{COGM} = \text{Beg Inventory} - \text{End Inventory} + \text{Sum of All Cost Contributors}$$

Accounting for the COGM

Cost Flow Diagram (an Engineer's POV)



$$\text{Unit COGM} = \frac{\text{COGM}}{\text{Number of Good Units Produced}}$$

$$\text{Performance COGM} = \frac{\text{COGM}}{\text{Number of Good Watts Produced}}$$

Accounting for the COGM

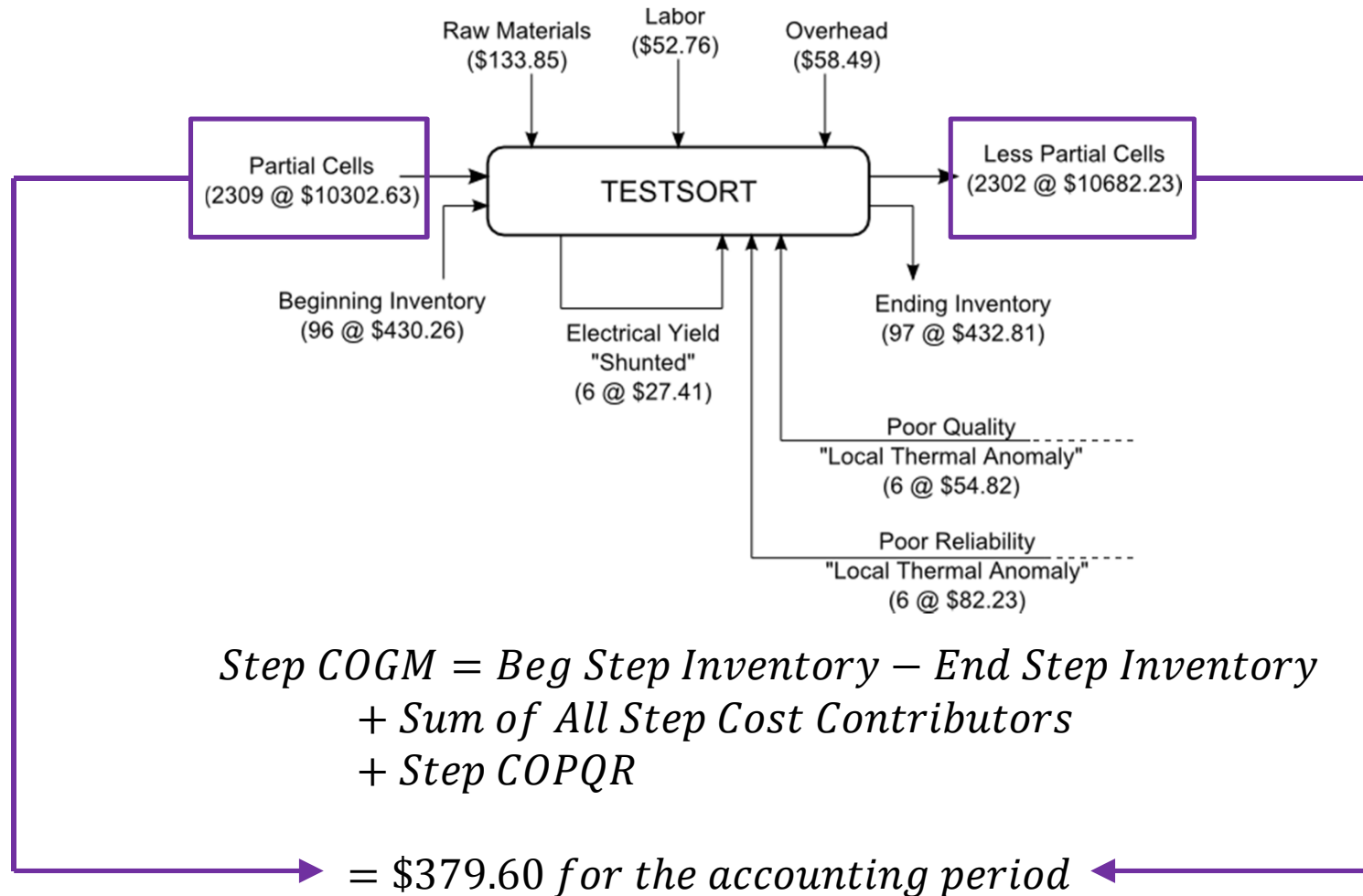
T-account (a Cost Accountant's POV)

Work in Process Control

Type	Description	AssociatedAccount	Quantity	Unit	DebitAmt	CreditAmt
BAL	Beginning Balance				\$0.00	
BAL	Beginning WIP Inventory		1192	units	\$2544.80	
DM	Al(r) Paste	LINE/RMIC	3140.000	g	\$816.40	
DM	Ag(f) Paste	LINE/RMIC	1958.333	g	\$1067.29	
DM	Wafers	LINE/RMIC	2400	pcs	\$4872.00	
DM	Ag(r) Paste	LINE/RMIC	1737.551	g	\$860.09	
DM	Subtotal				\$7615.78	
IDM	R2 Print Screen	LINE/RMIC	0.654	screen	\$15.78	
IDM	F1 Print Screen	LINE/RMIC		screen	\$17.09	
	Product Electrical Spoilage	LINE/WIPC	5	units	\$22.08	\$22.08
SPOIL	Product Mechanical Spoilage	LINE/WIPC	81	units	\$270.82	\$270.82
SPOIL	Product Metrology Spoilage	LINE/WIPC	0	units	\$0.00	\$0.00
SPOIL			86	units	\$292.90	\$292.90
PCO	Product Cost Objects (Acquired)	CUST/ORDRS	2400	units	\$0.00	
PCO	Product Cost Objects (Dispatched)	LINE/FGIC	2311	units		\$10229.76
PCO	Subtotal				\$0.00	\$10229.76
BAL	Ending WIP Inventory		1195	units		\$2580.00
BAL	Ending Balance					\$0.00

Accounting for the Step COGM

Step Cost Flow Diagram (the Process Engineer's POV)



Accounting for the Step COGM

Step T-account

F1_PRINTDRYFIRE

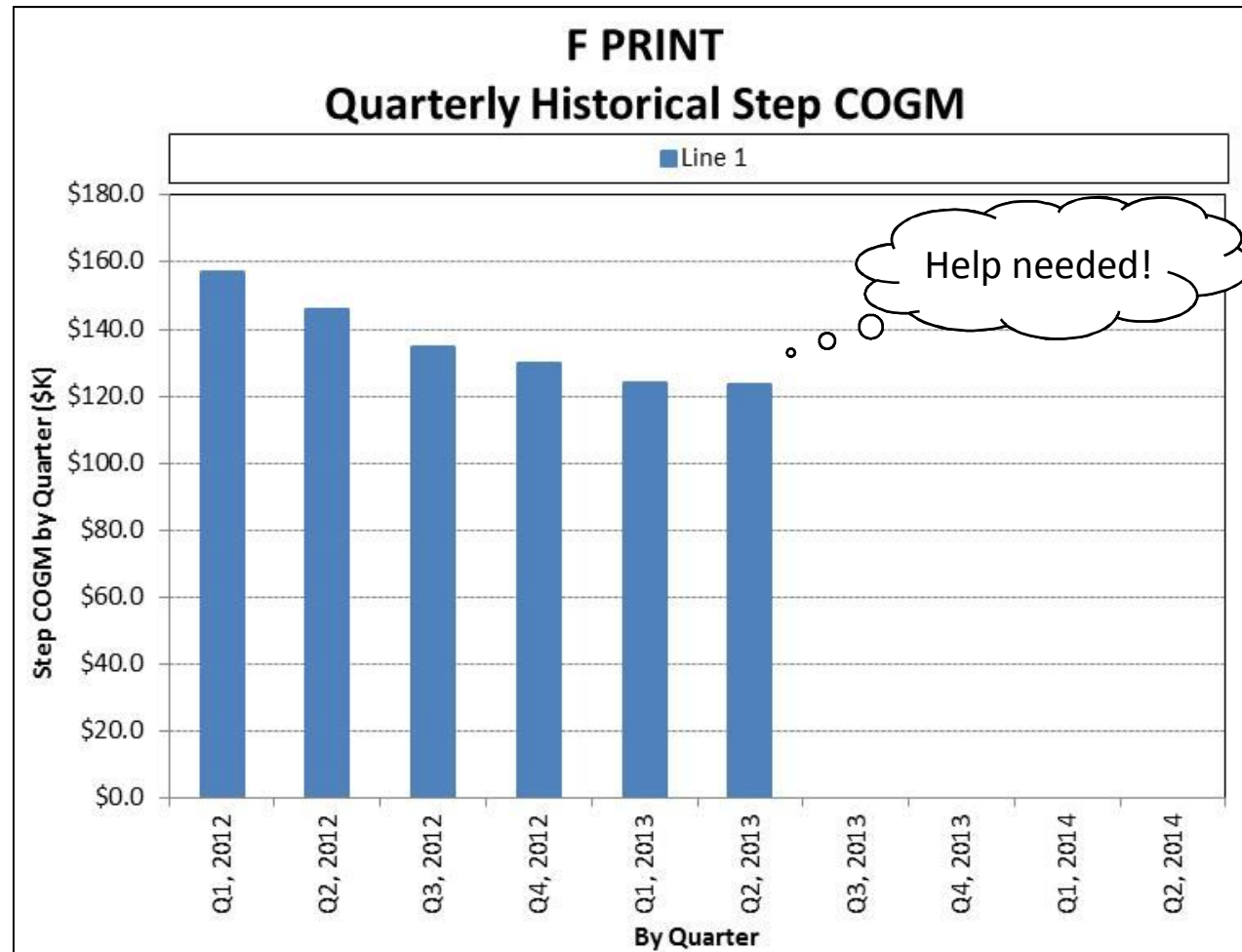
Type	Description	AssociatedAccount	Quantity	Unit	DebitAmt	CreditAmt
DM	Ag(f) Paste	LINE/RMIC	1958.333	g	\$1067.29	
DM	Subtotal				\$1067.29	
IDM	F1 Print Screen	LINE/RMIC	0.712	screen	\$17.09	
IDM	Subtotal				\$17.09	
DL	Operator L3	LINE/VOHC	5.88	hour	\$82.25	
DL	Subtotal				\$82.25	
IDL	Supervisor	LINE/FOHC	0.96	hour	\$19.20	
IDL	Subtotal				\$19.20	
FOH	Depreciation	LINE/FOHC	\$31.31	dollars	\$31.31	
FOH	Compressed, Dry Air	LINE/FOHC	12.000	m3	\$3.36	
FOH	Electricity (FOH)	LINE/FOHC	23.00	kwhr	\$2.00	
FOH	Subtotal				\$36.67	
VOH	Electricity (VOH)	LINE/VOHC	47.00	kwhr	\$4.09	
VOH	Subtotal				\$4.09	
SPOIL	Product Metrology Spoilage			units	\$0.00	\$0.00
	Product Mechanical Spoilage	WIPC/F1_PRINTDRYFIRE	4	units	\$16.81	\$16.81
SPOIL	Product Electrical Spoilage	WIPC/F1_PRINTDRYFIRE	0	units	\$0.00	\$0.00
SPOIL	Subtotal		4	units	\$16.81	\$16.81
PCO	Product Cost Objects (Acquired)	WIPC/ARC	2349	units	\$8646.96	
PCO	Product Cost Objects (Dispatched)	WIPC/ESCRIBE	2346	units		\$9876.45
PCO	Subtotal				\$8646.96	\$9876.45
BAL	Ending WIP Inventory	WIPC/F1_PRINTDRYFI...	99	units		\$364.43

Tackling PV Manufacturing Cost

A well design and maintained Cost Accounting system is very useful to engineers and their managers...

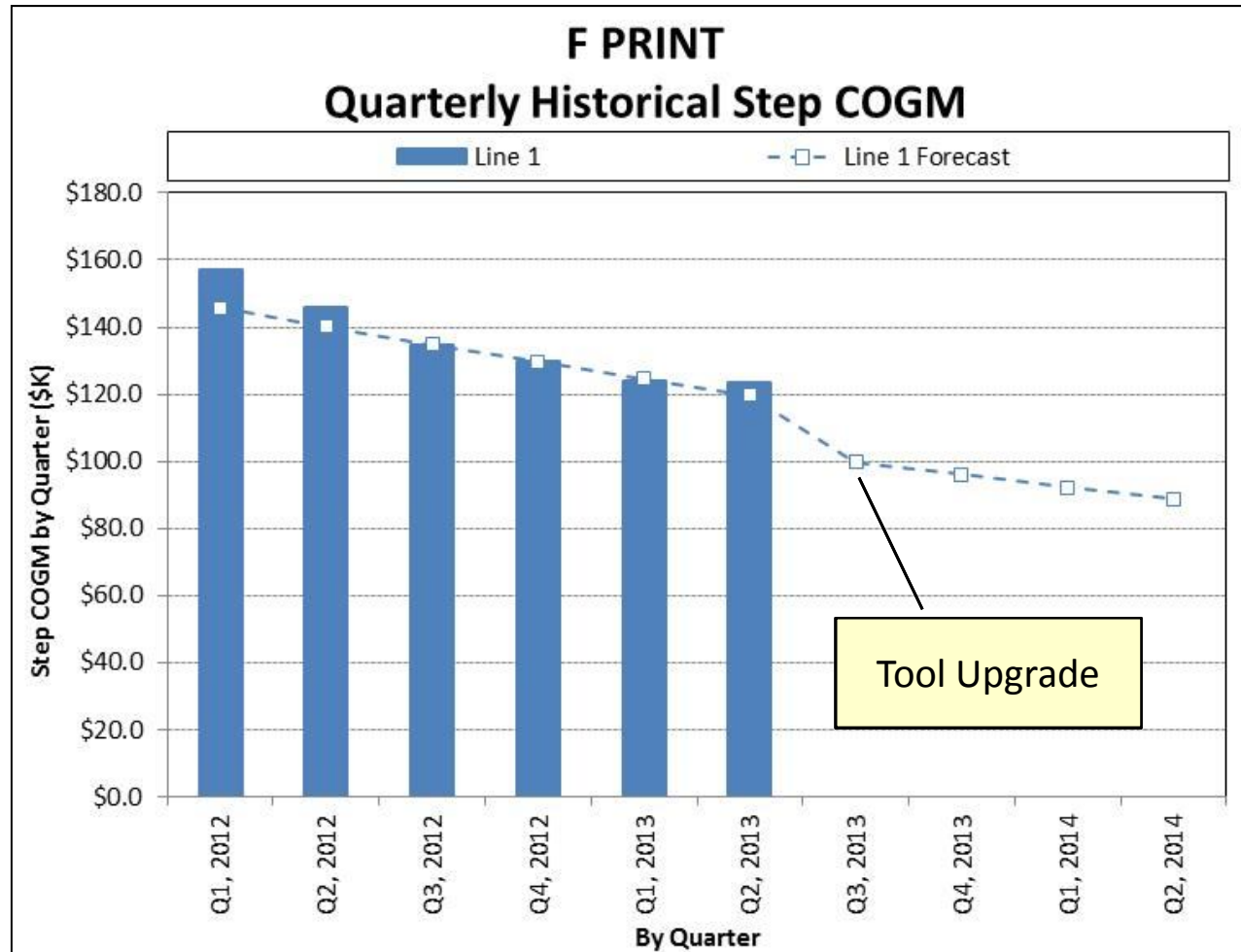
Accounting for COGM

1. Historical Monitoring



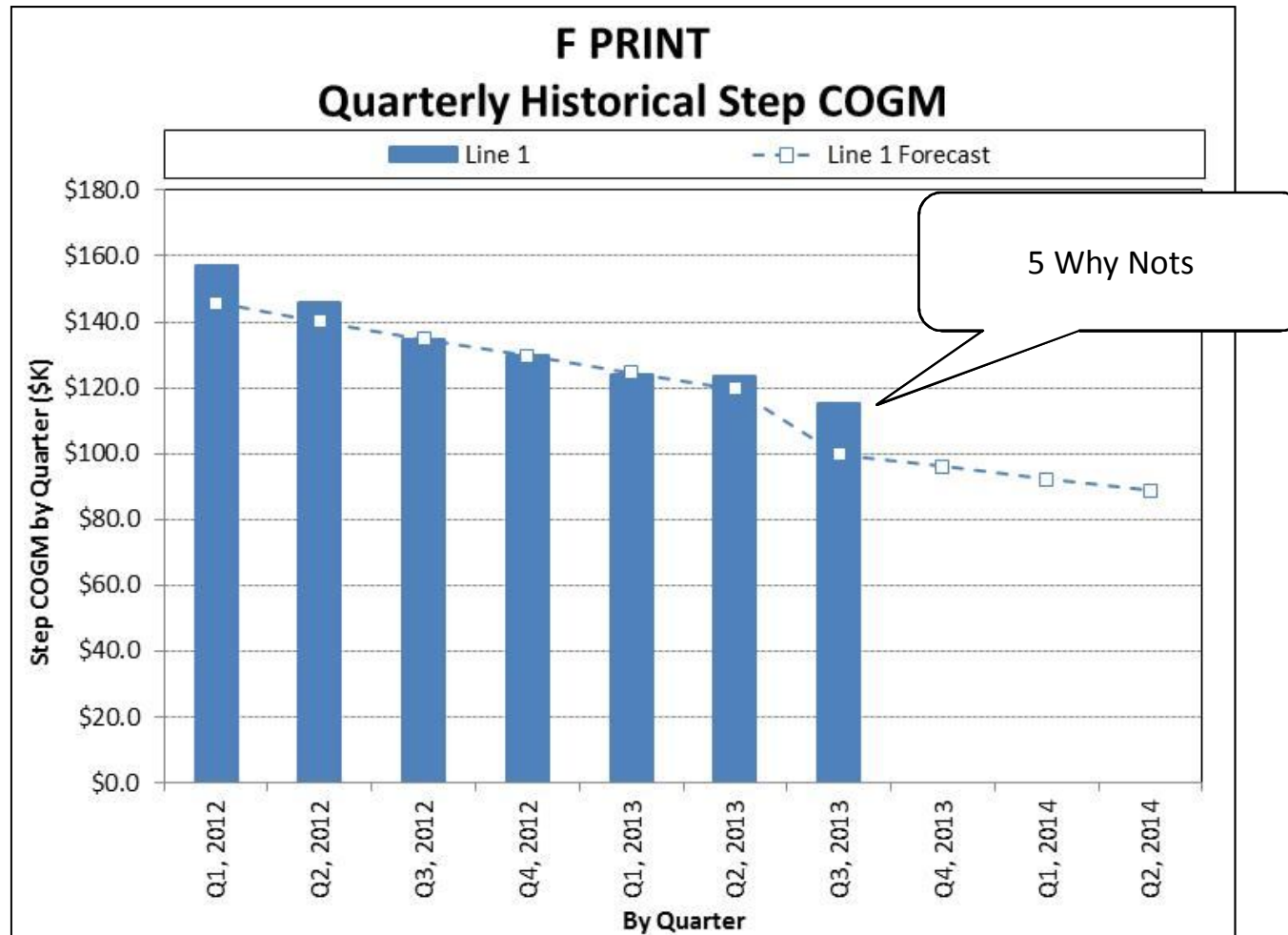
Accounting for COGM

2. Cost Projection and Prediction



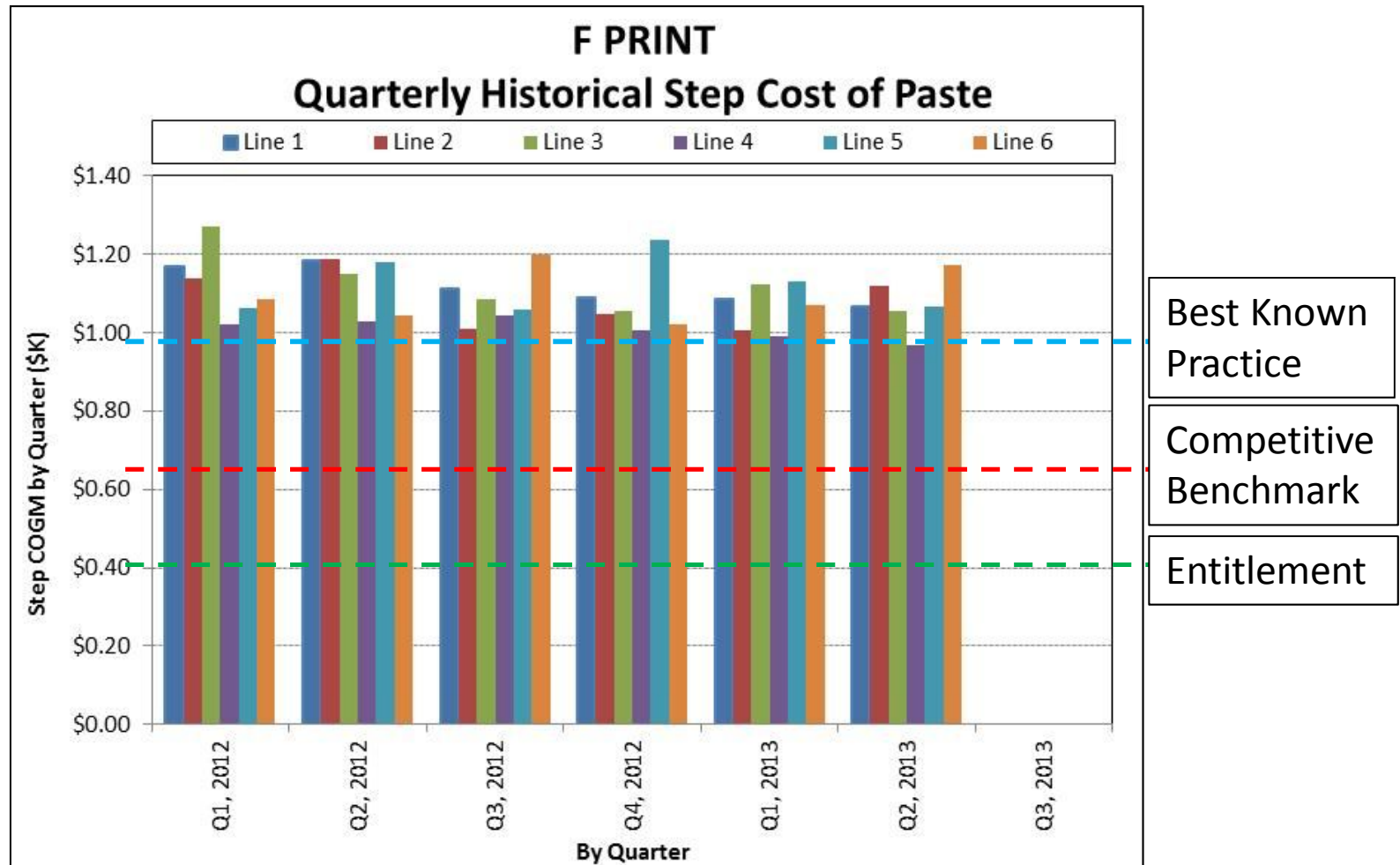
Accounting for COGM

3. Cost Validation



Accounting for COGM

4. Benchmarking



Accounting for COGM

A properly accounted-for COGM enables

1. Historical Monitoring
2. Prediction and Validation
3. Benchmarking – Internal, Competitive, Entitlement
4. Engineering road-mapping, planning project prioritization
5. Compelling argument and alignment within the business
6. Accountability, visibility and feedback to the correct engineering teams
7. Application of “pain and suffering” in the right places/to the right engineering teams
8. And more...

PV Engineers should have a good working knowledge of cost accounting principles and practice!

Tackling PV Manufacturing Cost

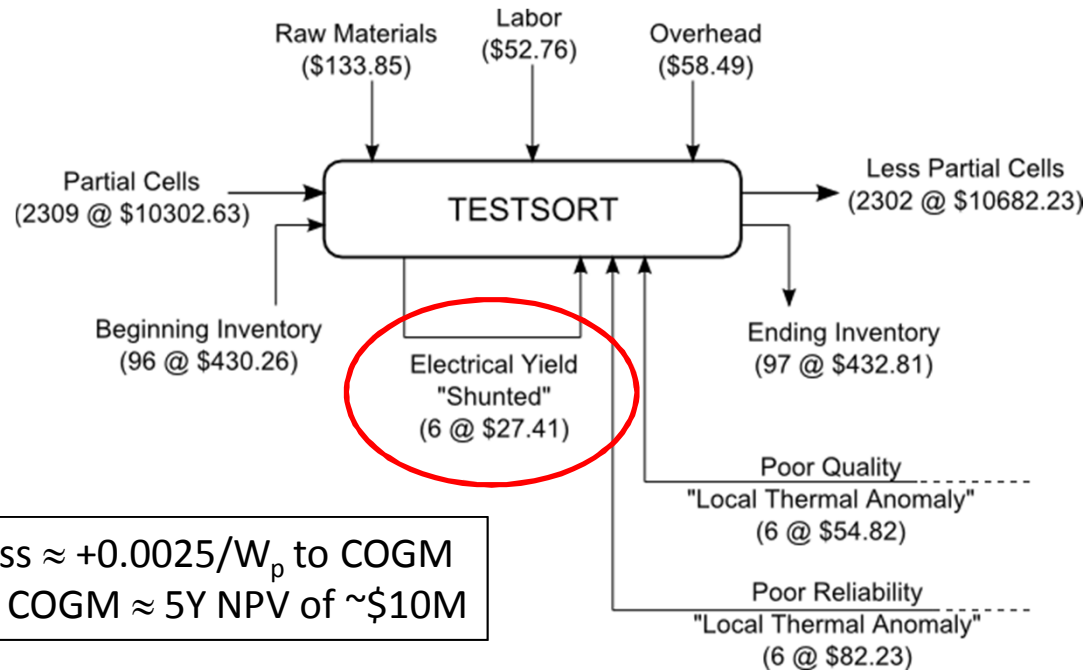


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Electrical Yield “Shunted” Cells

Our story begins at the TESTSORT process...

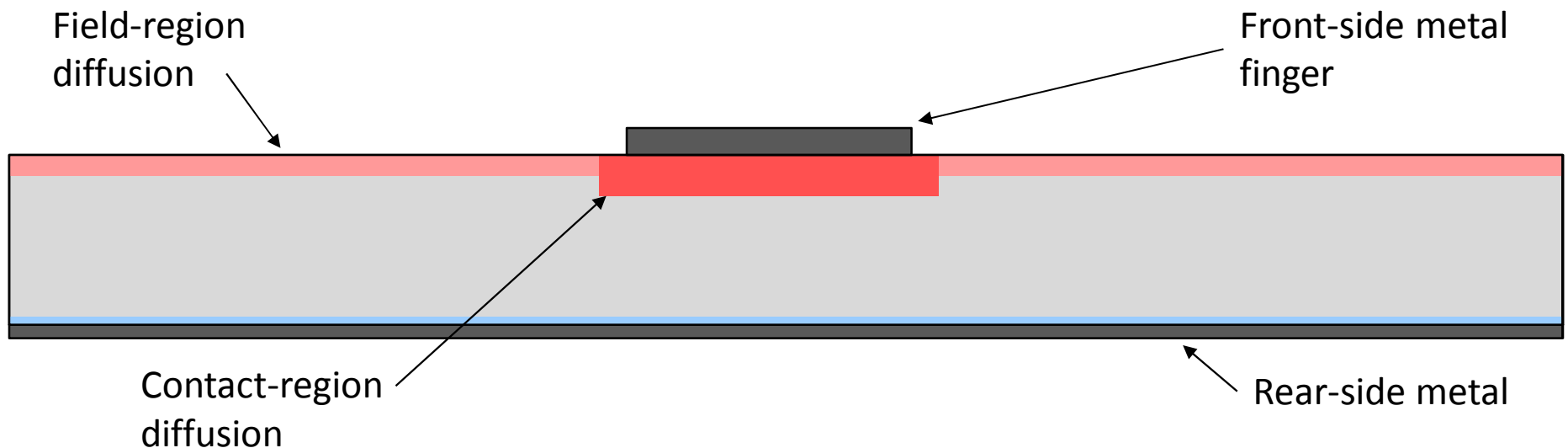


The Test/Yield Engineering team *owns* this cost, so they feel the pain and suffering...

...so, they work very hard to find the root cause of the problem (RC).

Electrical Yield “Shunted” Cells

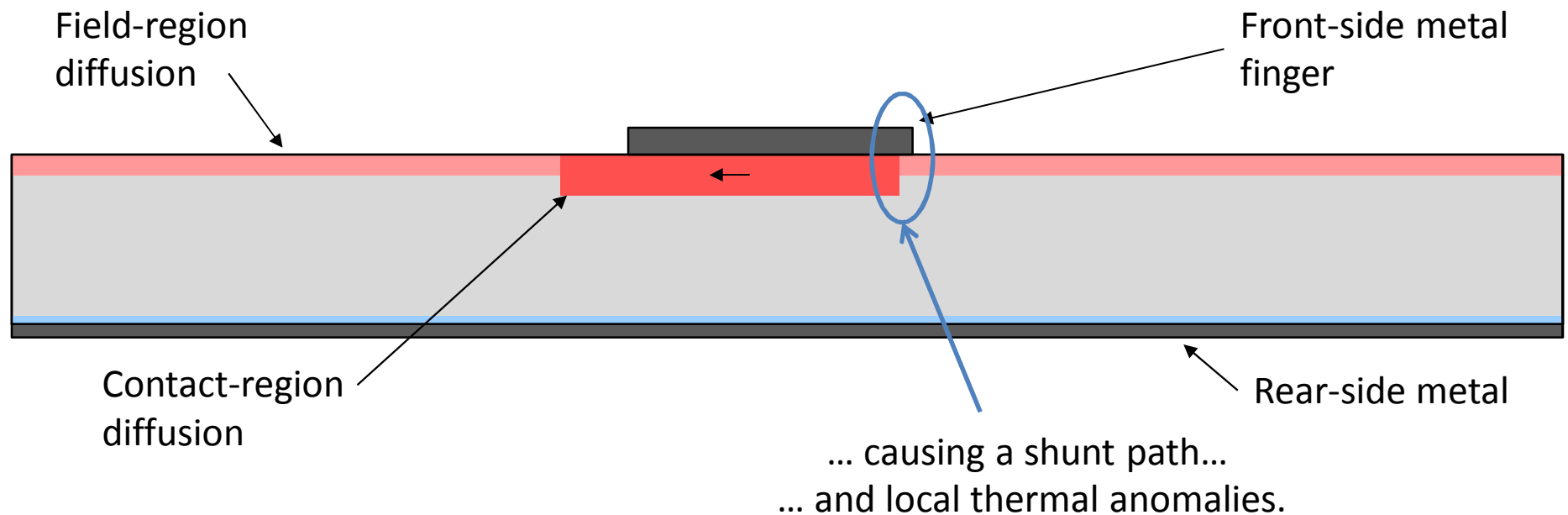
Discovery! The Test/Yield Engineering team finds the RC:



The new Selective Emitter process requires accurate placement of the dopant paste under the front metal paste, however ...

Electrical Yield “Shunted” Cells

Discovery! The Test/Yield Engineering team finds the RC:



The new Selective Emitter process requires accurate placement of the dopant paste under the front metal paste, however ...

... due to Common Cause Variance in the printer alignment, the pattern is sometimes offset from its intended position ...

Tackling PV Manufacturing Cost

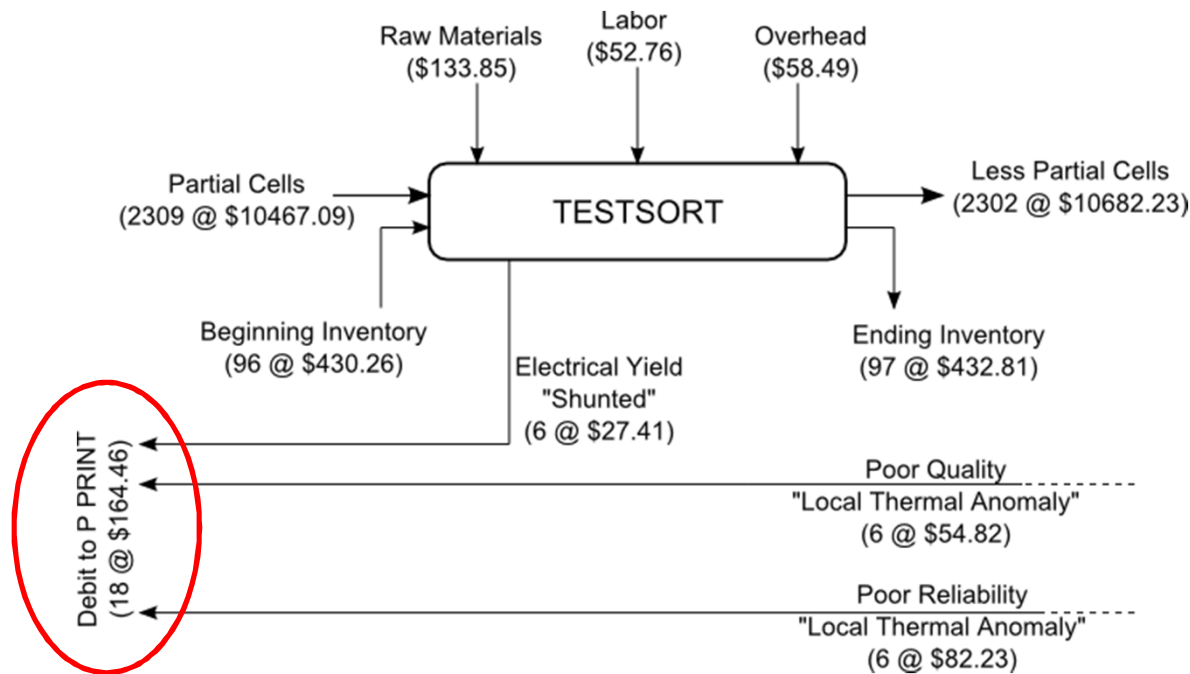


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Electrical Yield “Shunted” Cells

Step 1. Apportion the associated COGM costs *as close as possible* to the point of the root cause.

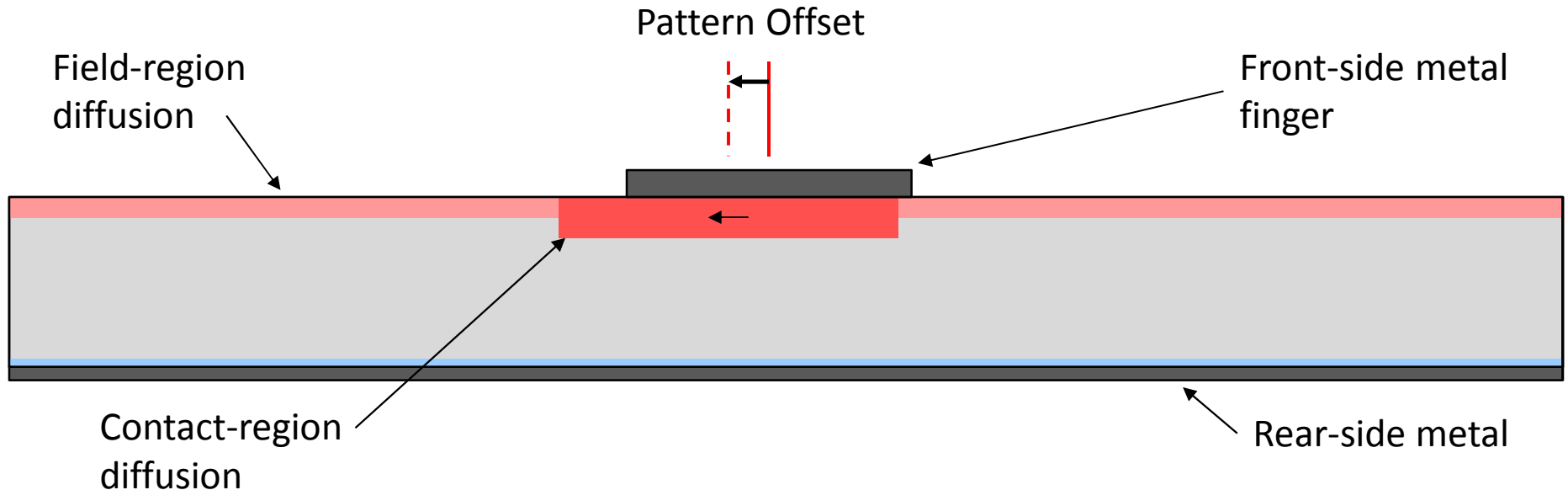


The root cause is not in the TESTSORT process. It is in the P Print process.

Now, the P PRINT Engineers feel the pain and suffering, so they are highly aware of and motivated to find CA.

Electrical Yield “Shunted” Cells

Step 2. Observe the problem *as close as possible* to the point of the root cause.

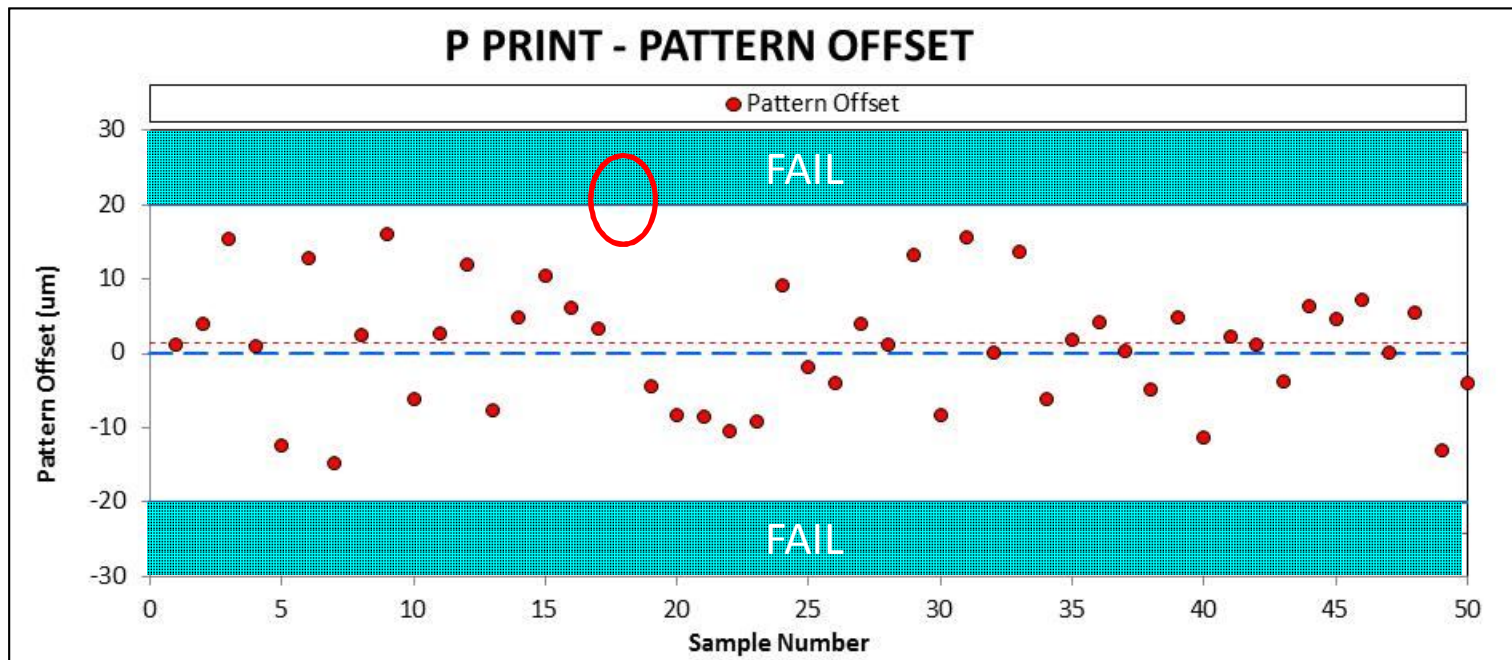


Sample the Pattern Offset

- Every 10 minutes, using a microscope
- Every shift, every day, every P Print tool

Electrical Yield “Shunted” Cells

Step 2. Observe the problem *as close as possible* to the point of the root cause.

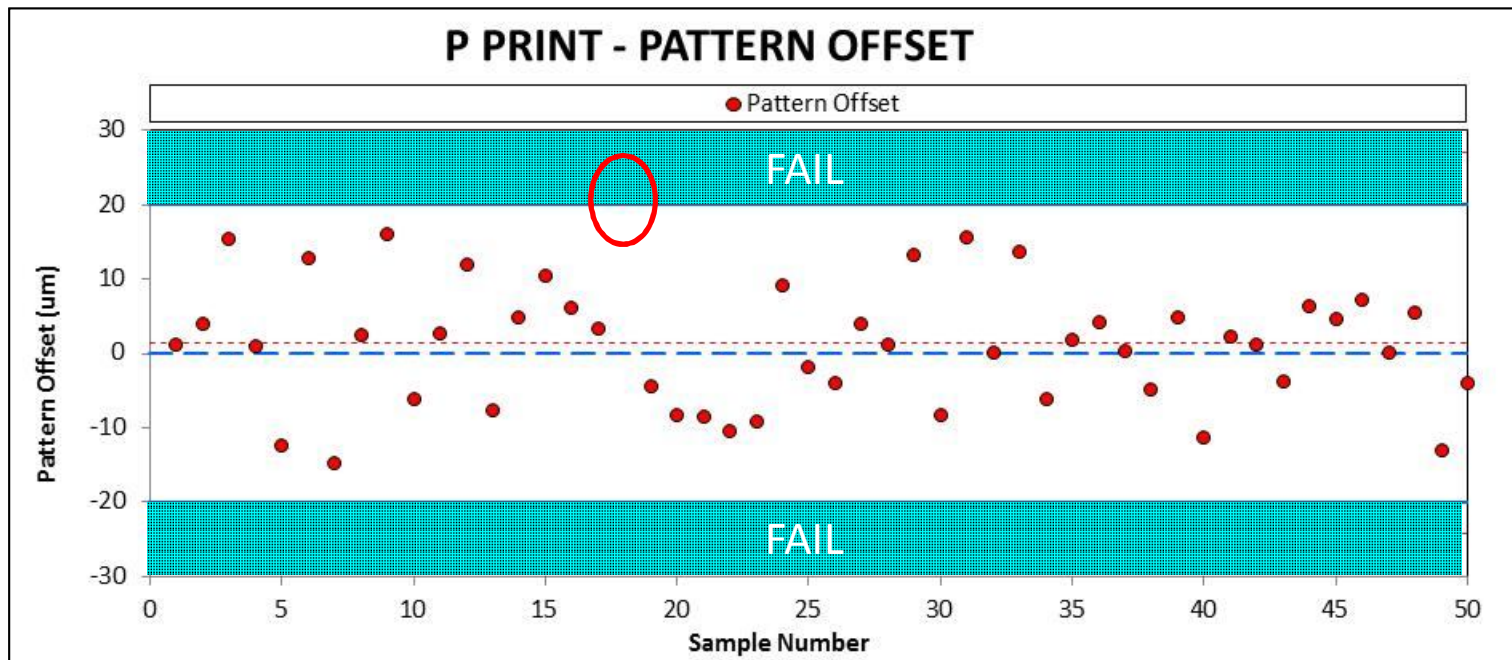


OOS AP:

- OOS – Stop the tool and call the P Print Engineers immediately

Electrical Yield “Shunted” Cells

Step 3. Contain the problem *as close as possible* to the point of the root cause.

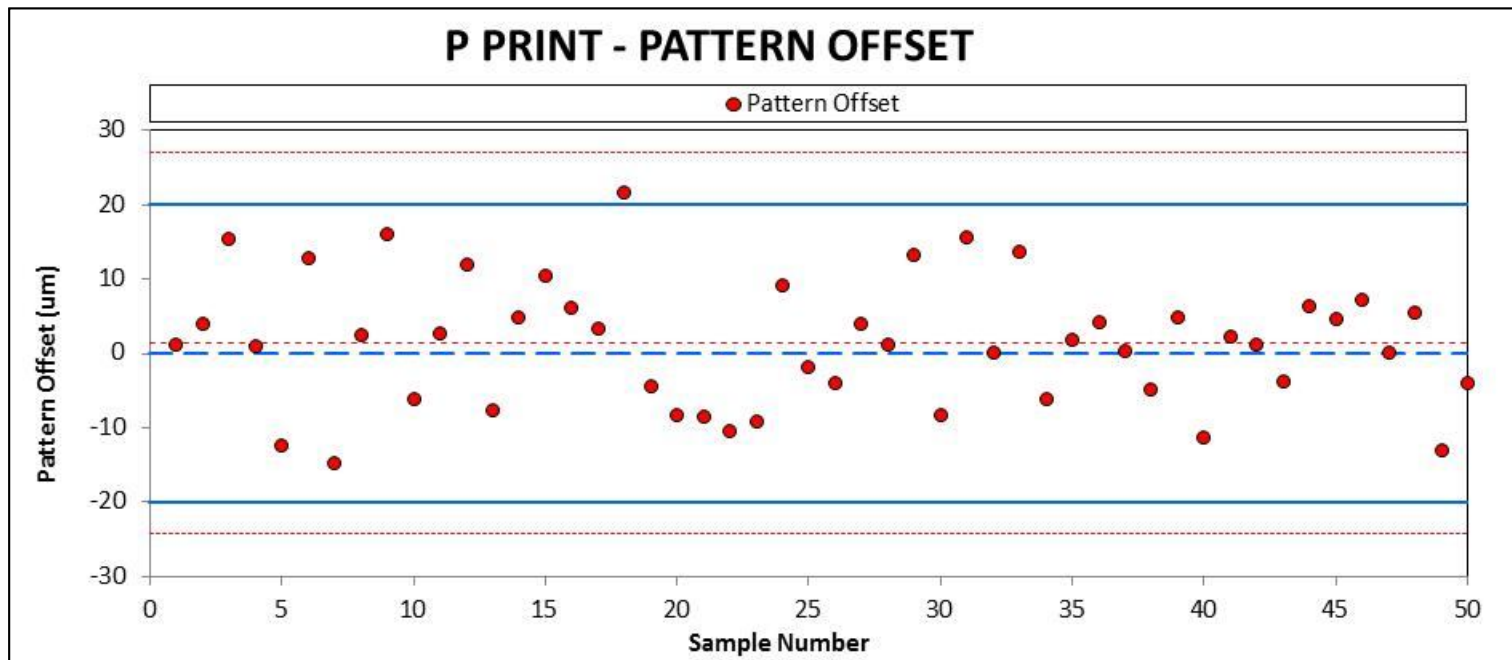


OOS AP:

- OOS – Stop the tool and call the P Print Engineers immediately
- Reject all OOS wafers as spoilage

Electrical Yield “Shunted” Cells

Step 3. Contain the problem *as close as possible* to the point of the root cause.



Target Pattern Offset to zero:

- Adjust Tool Offset Parameter
- No opportunity here

T-test concerning the average

$$H_0: \mu_{PO} = 0.0 \text{ um}$$

$$T_{crit} = 2.01$$

$$T_{stat} = 0.98 \text{ (p-val} = 0.332)$$

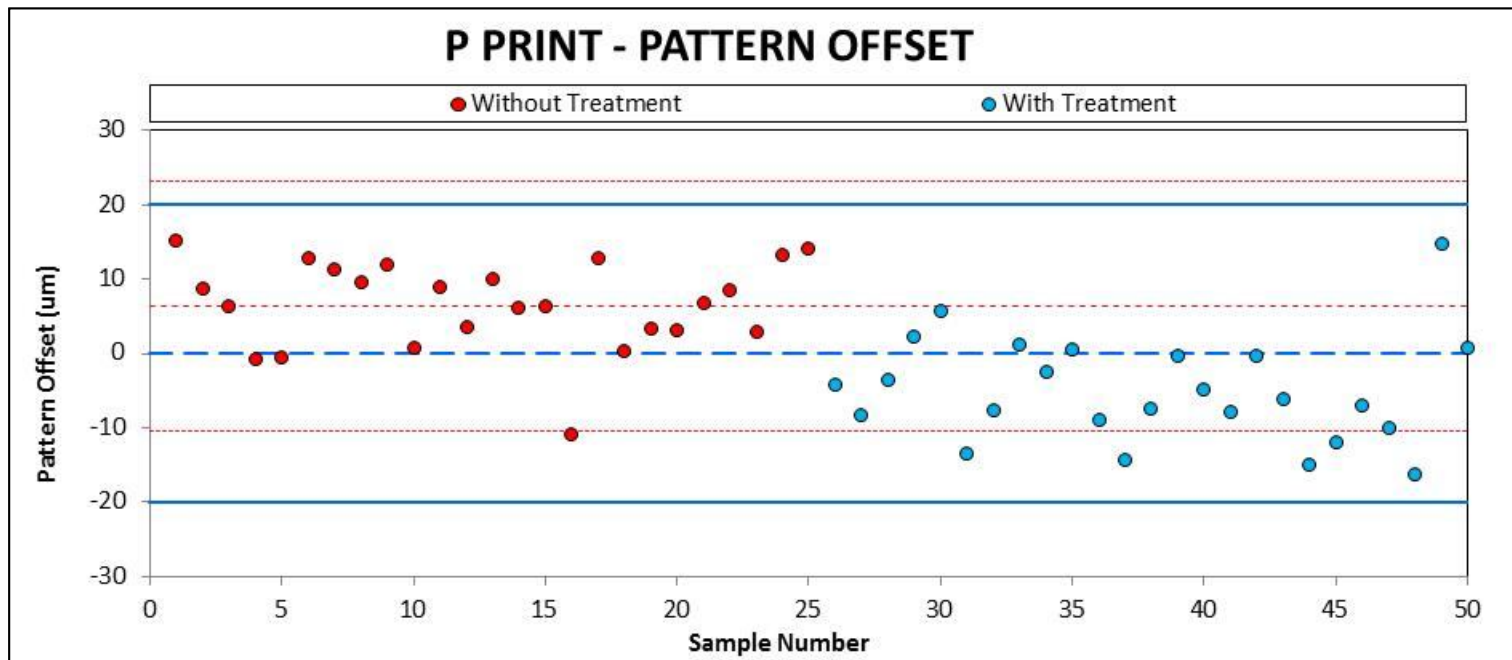
$$\text{Precision} = 2.0 \text{ um}$$

Fail to Reject, 95% conf, ± 2.0 um precision

No evidence of average Pattern Offset $\neq 0$ um

Electrical Yield “Shunted” Cells

Step 3. Contain the problem *as close as possible* to the point of the root cause.



Reduce Pattern Offset std dev:

- Perform Full Tool Maintenance
- No opportunity here

F-test concerning the standard deviations

$$H_0: \sigma^2_{\text{Before}} = \sigma^2_{\text{After}}$$

$$F_{\text{crit}} = 1.38$$

$$T_{\text{stat}} = 0.71 \text{ (p-val} = 0.611)$$

Fail to Reject, 95% conf

No evidence of improved standard deviation

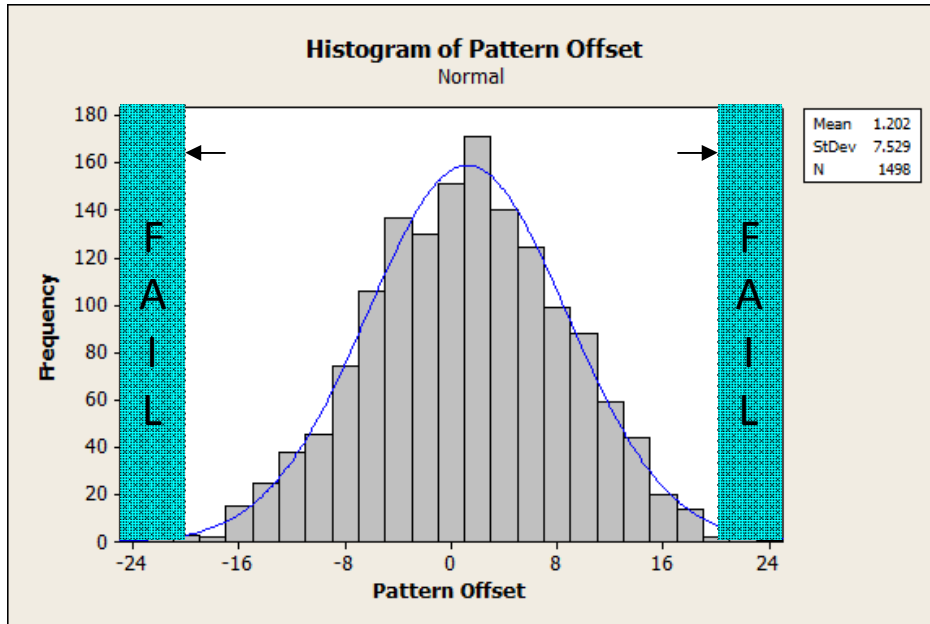
Electrical Yield “Shunted” Cells



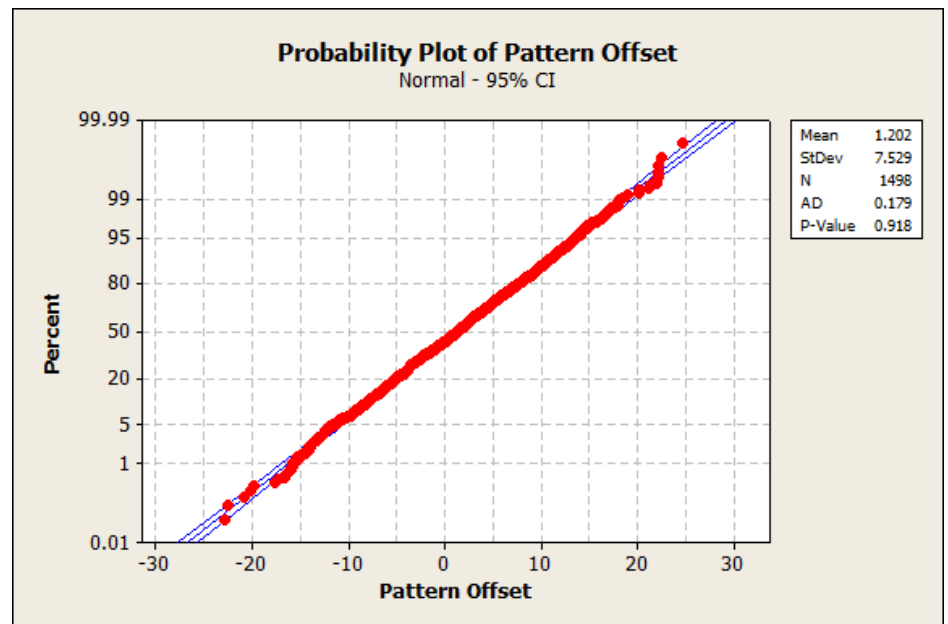
Reducing variance = 

Electrical Yield “Shunted” Cells

Step 4. Contain the problem with “Design for Capability”



Develop a Population Model ...



... don't forget to check adequacy!

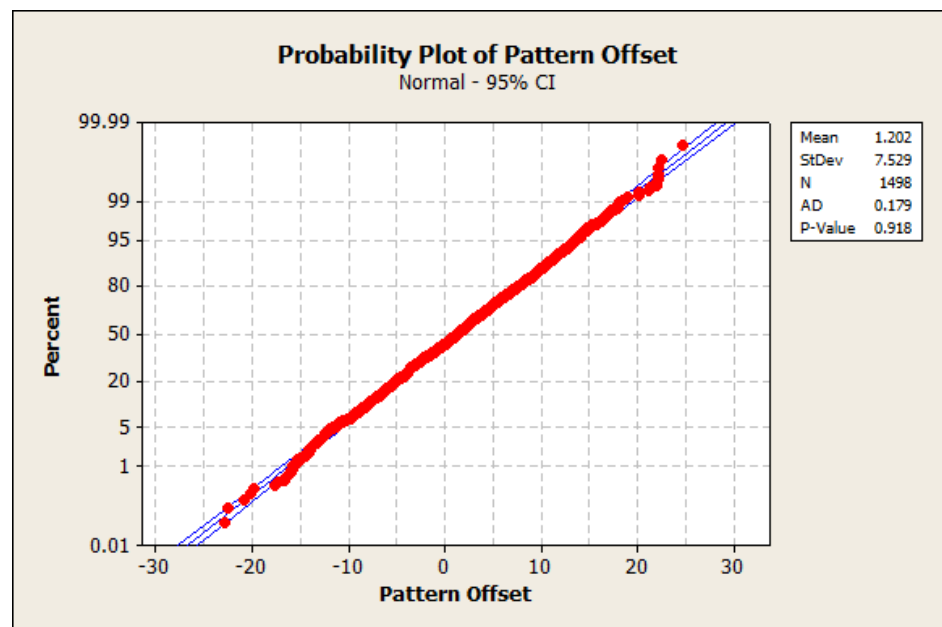
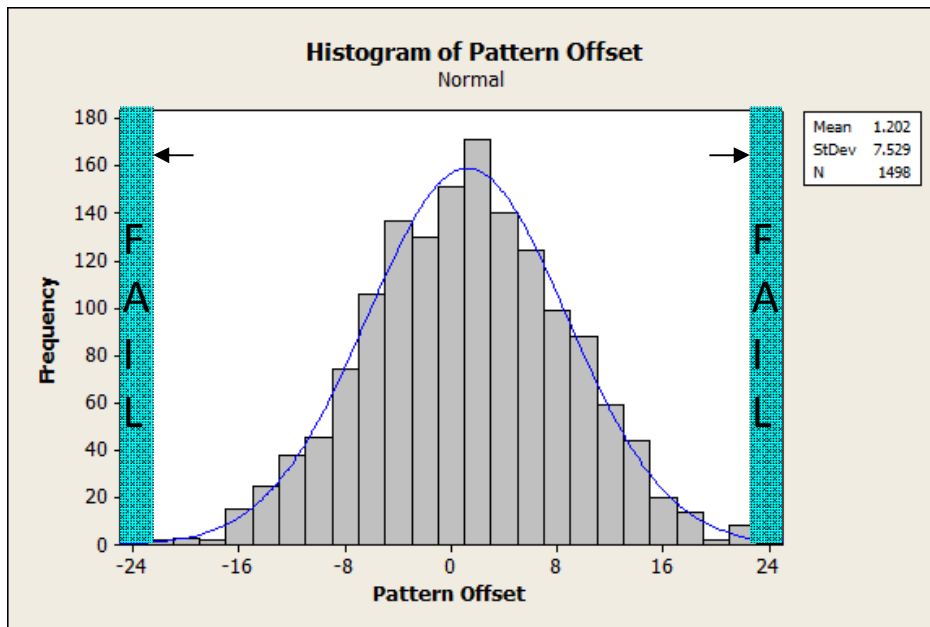
Change the specification ... to achieve desired capability (aka yield loss)

- Current capability $CpK = 0.929$ -- equivalent to 0.55% yield losses
- Change the specification to achieve $CpK = 1.500$ -- equivalent to 2700 dppm

How? Change the mask design! Increase the Buffer Width.

Electrical Yield “Shunted” Cells

Step 4. Contain the problem with “Design for Capability”

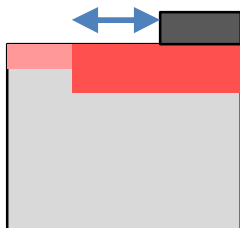


Develop a Population Model ...

... don't forget to check adequacy!

How? Change the mask design!

Increase the Buffer Width!



Design for Capability

$$CpK = 1.5 = (USL - LSL)/6\sigma$$

$$\sigma = 7.529 \text{ um (from the population model)}$$

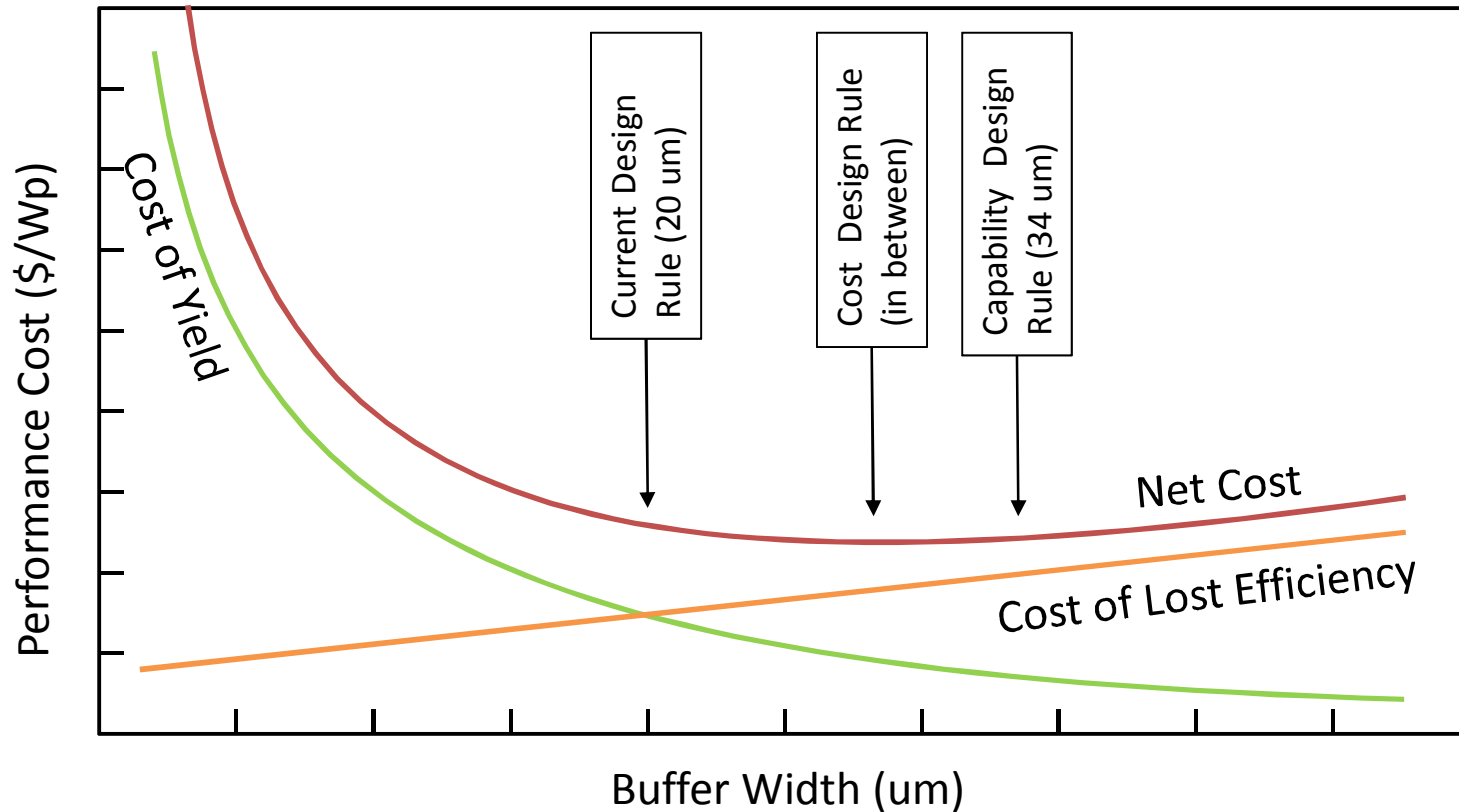
$$USL - LSL = 1.5 * 6 * \sigma = 67.7 \text{ um}$$

Capable design rule for P PRINT Buffer Width

$$= 67.7 / 2 = 33.8 \text{ microns (each side)}$$

Electrical Yield “Shunted” Cells

Step 5. Contain the problem with “Design for Cost”

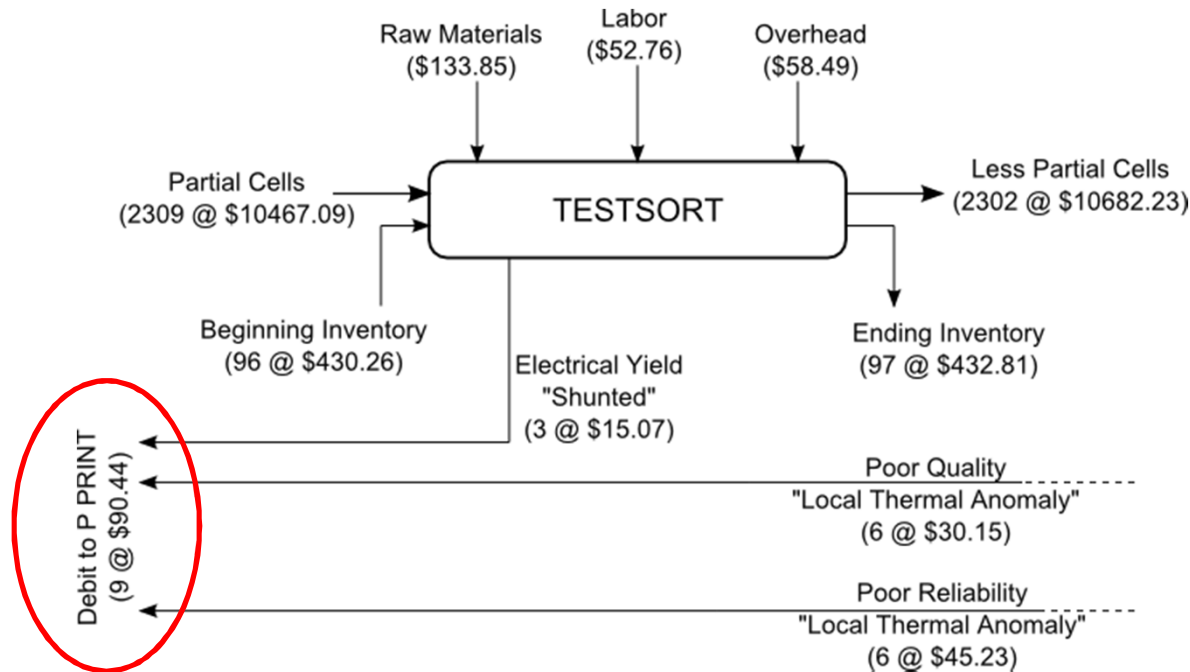


Let's use our device physics and cost accounting skills predict cost of the Buffer Width DR in terms of lost efficiency.

Find the lowest net cost. Deploy containment.

Electrical Yield “Shunted” Cells

Step 6. Validate the containment.



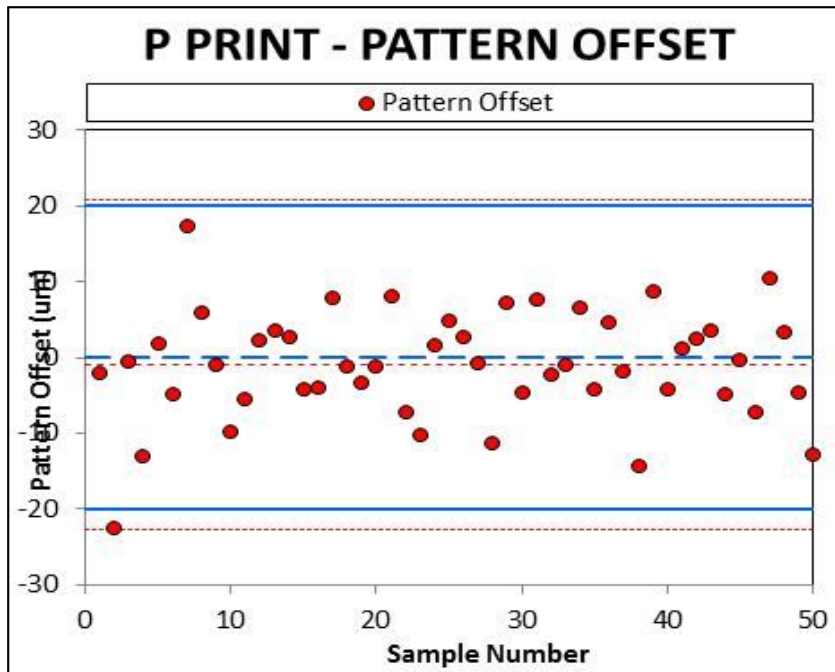
We captured half of the opportunity (5500 dppm down to 2700 dppm) and gave up a little bit of efficiency. COPQR also improved, since they had the same root cause.

However, this is **CONTAINMENT** only, not **ROOT CAUSE CORRECTIVE ACTION**.

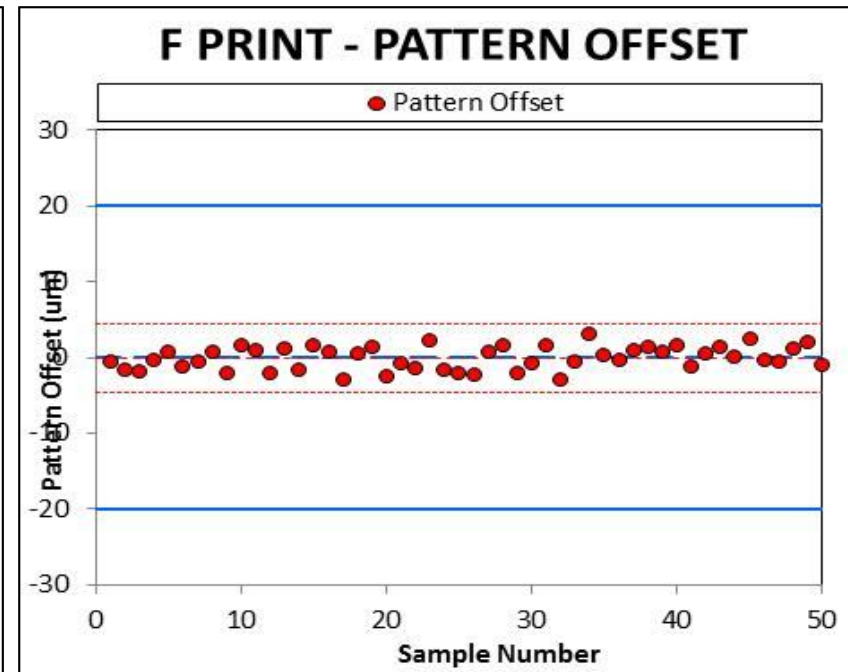
We are not finished!

Electrical Yield “Shunted” Cells

Step 7. Find the root cause of variance in Pattern Offset.



P PRINT Tool



F PRINT Tool

Benchmarking printer tools reveals that the F PRINT Tool (that prints the top metal), has significantly better variance!

Why is F PRINT better? It's a different tool manufacturer

What's different? Almost everything

Which are important? – Unsure - parts, speeds, pressures, handlers, vision, etc.

Electrical Yield “Shunted” Cells

Step 8. Determine which factors are the root cause(s) for high Pattern Offset variance in P PRINT.

Brainstorm sources of variance:

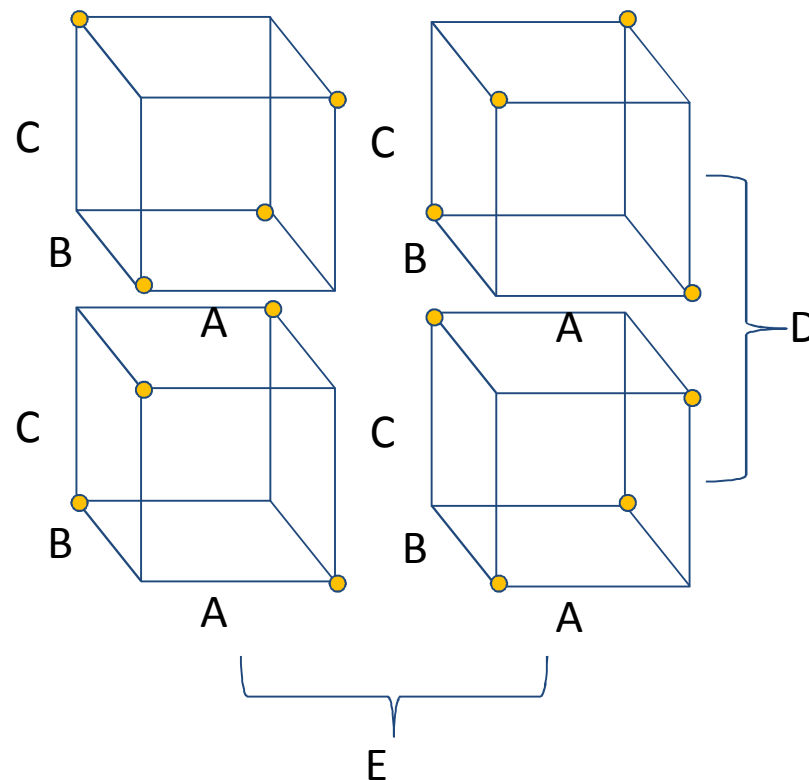
1. Printing Speed
2. Printing Down Force
3. Emulsion Thickness
4. Paste Viscosity
5. Thermal Expansion
6. Transport Speed
7. Pickup Speed
8. Etc.

Too many! Use Multi-factor Factorial Experiment Design with Statistical Analysis of Variance (aka DOE with ANOVA).

Electrical Yield “Shunted” Cells

Step 8. Design a factorial experiment ...

5 factors – Half fractional factorial Screening DOE Topology



Test all 5 candidate factors with 16 legs (experiments).

Electrical Yield “Shunted” Cells

Step 8. ...then analyse the results with ANOVA methods

Analysis of Variance for Pattern Offset (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	5	268.44	268.44	53.688	1.07	0.388
A	1	60.52	60.52	60.518	1.21	0.277
B	1	43.48	43.48	43.477	0.87	0.356
C	1	127.99	127.99	127.995	2.56	0.116
D	1	14.20	14.20	14.202	0.28	0.597
E	1	22.25	22.25	22.246	0.44	0.508
2-Way Interactions	10	287.36	287.36	28.736	0.57	0.827
A*B	1	38.37	38.37	38.375	0.77	0.386
A*C	1	26.06	26.06	26.055	0.52	0.474
A*D	1	106.08	106.08	106.083	2.12	0.152
A*E	1	4.06	4.06	4.057	0.08	0.777
B*C	1	10.60	10.60	10.604	0.21	0.648
B*D	1	29.53	29.53	29.532	0.59	0.446
B*E	1	56.63	56.63	56.630	1.13	0.293
C*D	1	14.73	14.73	14.731	0.29	0.590
C*E	1	1.04	1.04	1.038	0.02	0.886
D*E	1	0.26	0.26	0.260	0.01	0.943
Residual Error	48	2404.22	2404.22	50.088		
Pure Error	48	2404.22	2404.22	50.088		
Total	63	2960.02				

All 5 candidate factors *fail to show* significant influence on Pattern Offset Variance - keep looking!

Electrical Yield “Shunted” Cells

Step 9. Develop a fault tolerant process recipe.

Brainstorm important process factors:

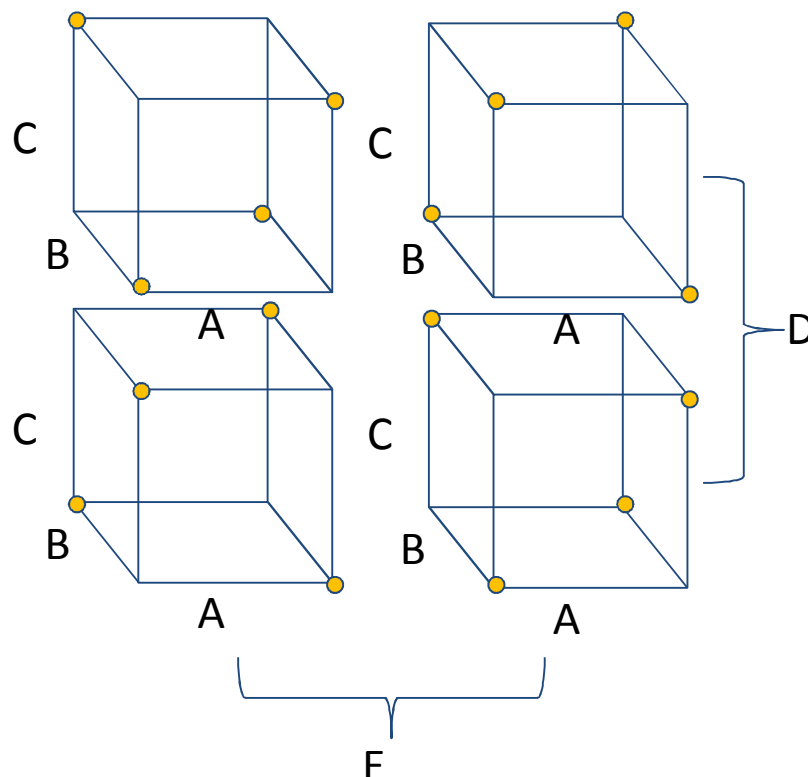
1. F PRINT Paste Formulation
2. F PRINT Firing Temperature
3. F PRINT Firing Time
4. CO DIFF Pre-dep Time
5. CO DIFF Pre-dep Temperature
6. CO DIFF Drive Time
7. CO DIFF Drive Temperature
8. Etc.

Too many! Design a Screening DOE and augment to RSM DOE to find the optimum process recipe.

Electrical Yield “Shunted” Cells

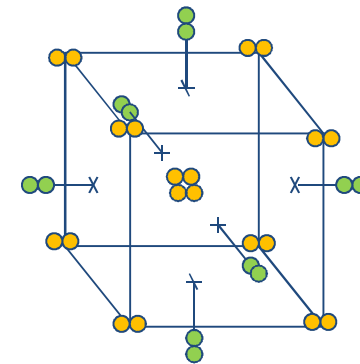
Step 9. First, screen for the significant process factors, then build a polynomial regression model.

5 factors – Half fractional factorial
Screening DOE Topology



Screen for the significant factors

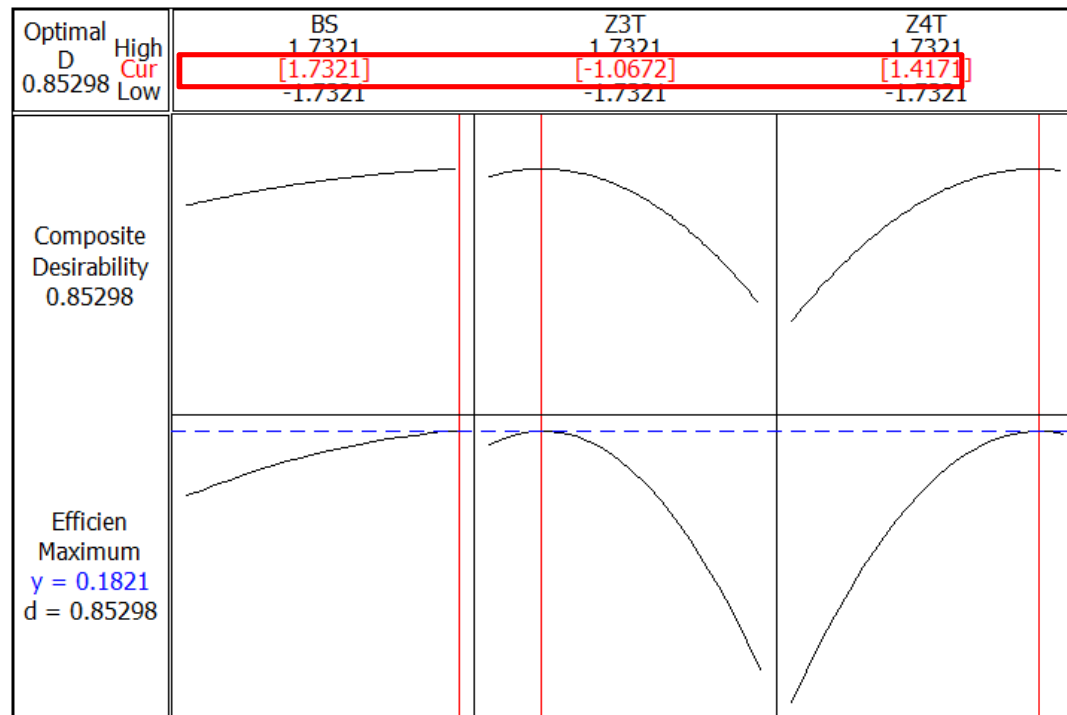
3 factors – Full factorial
RSM DOE Topology



Model the process, then optimize

Electrical Yield “Shunted” Cells

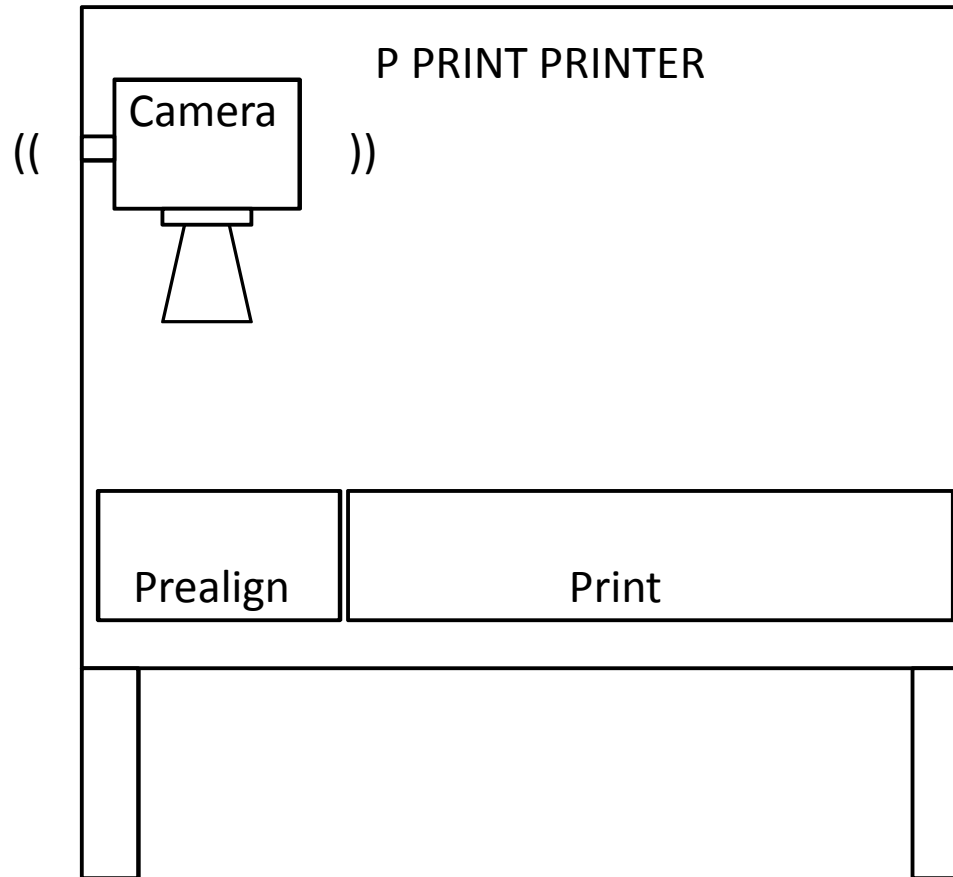
Step 9. Eventually, use the regression model to optimize for a fault tolerant process recipe



3 Factor Polynomial Regression Model Optimizer

Electrical Yield “Shunted” Cells

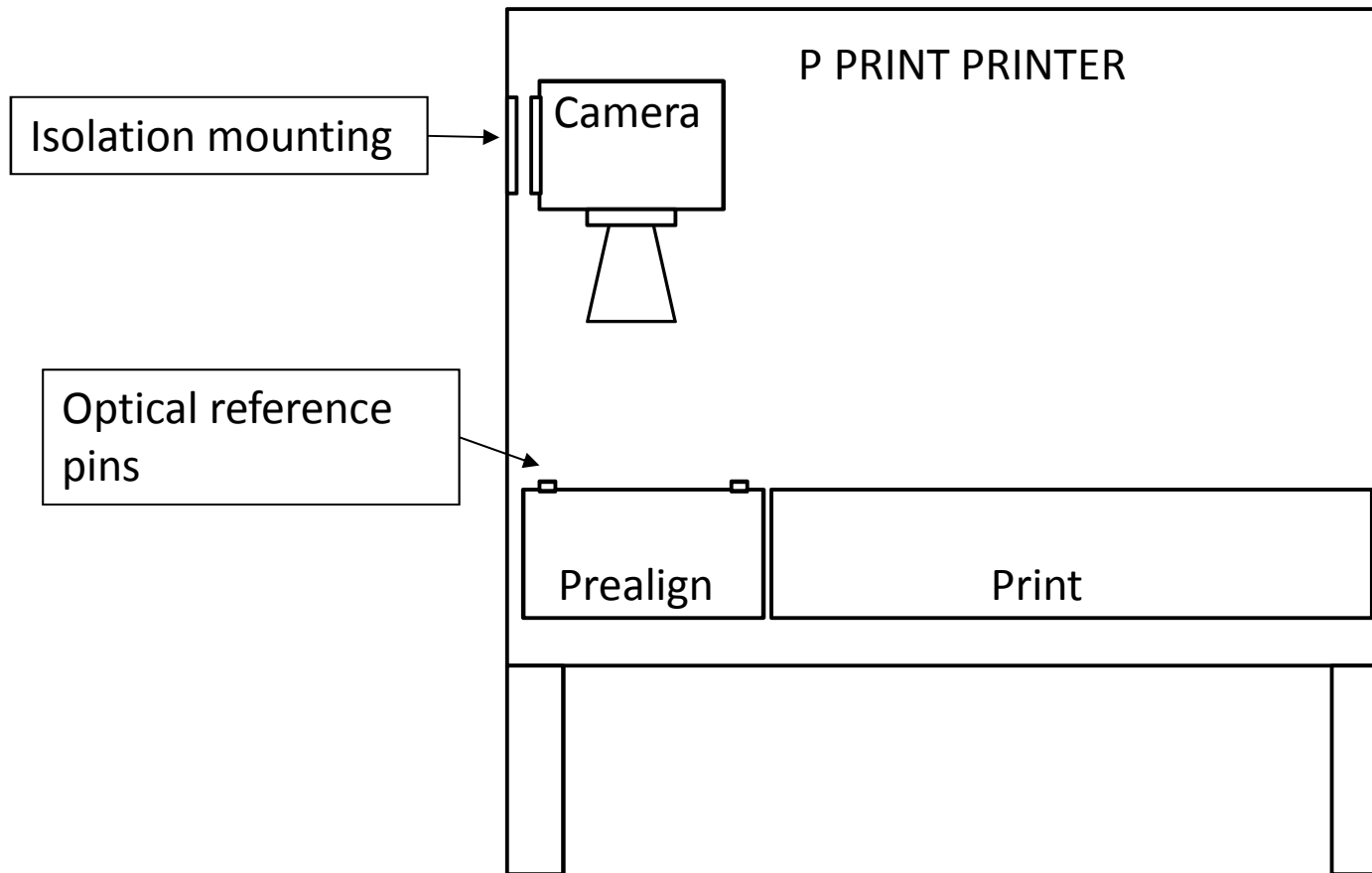
Step 10. Discovery!! of root cause of Pattern Offset variance.



Root Cause: Impulse action of automation is shaking the pre-alignment camera, confusing the alignment software.

Electrical Yield “Shunted” Cells

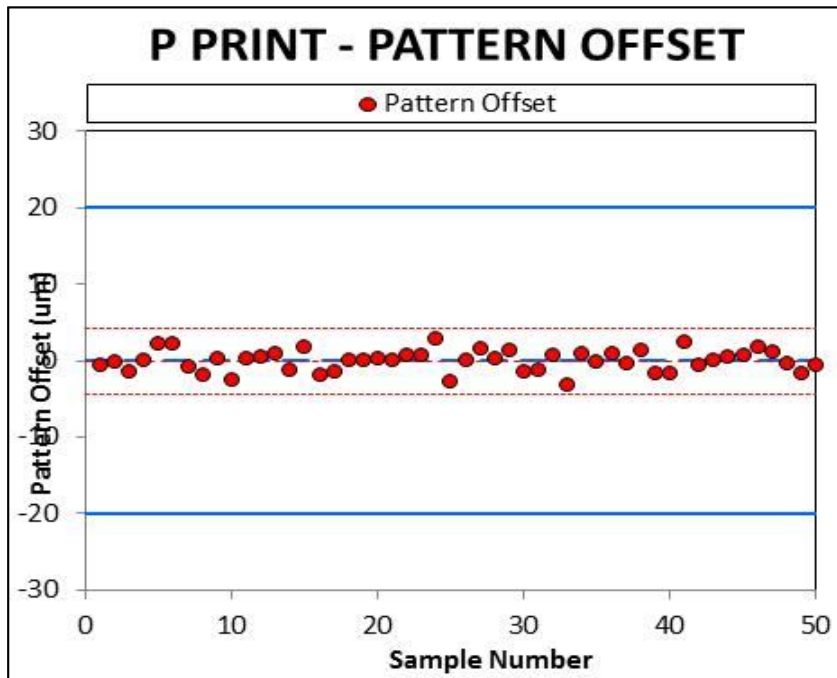
Step 11. Invention!! of Corrective Action!



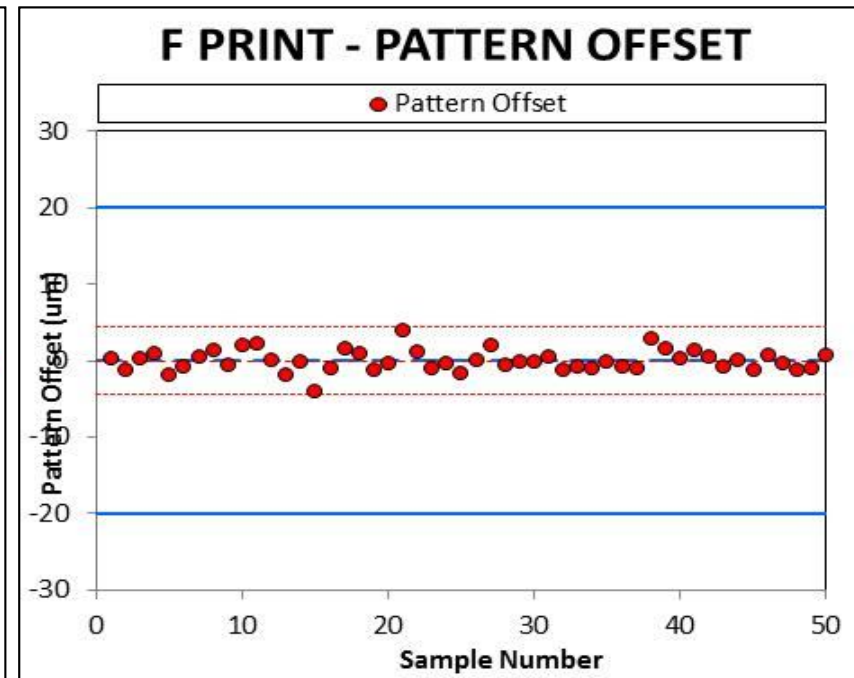
Corrective Action: Isolation mounting and optical reference pins.

Electrical Yield “Shunted” Cells

Step 12. Validation the corrective action!



P PRINT Tool



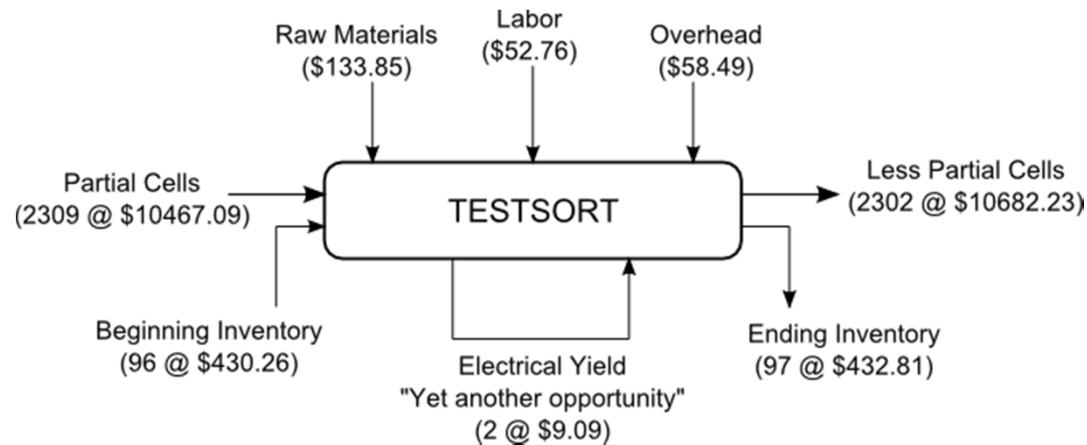
F PRINT Tool

Validation:

1. Matching variance
2. Zero EY loss at TESTSORT attributed to Pattern Offset
3. Zero Quality and Reliability returns (the “Local Thermal Anomaly” has same root cause)

Electrical Yield “Shunted” Cells

Step 12. Validate the corrective action! Check the COGM.



We captured the full opportunity (5500 dppm down to 0 dppm)

COPQR for “Local Thermal Anomaly” also eliminated.

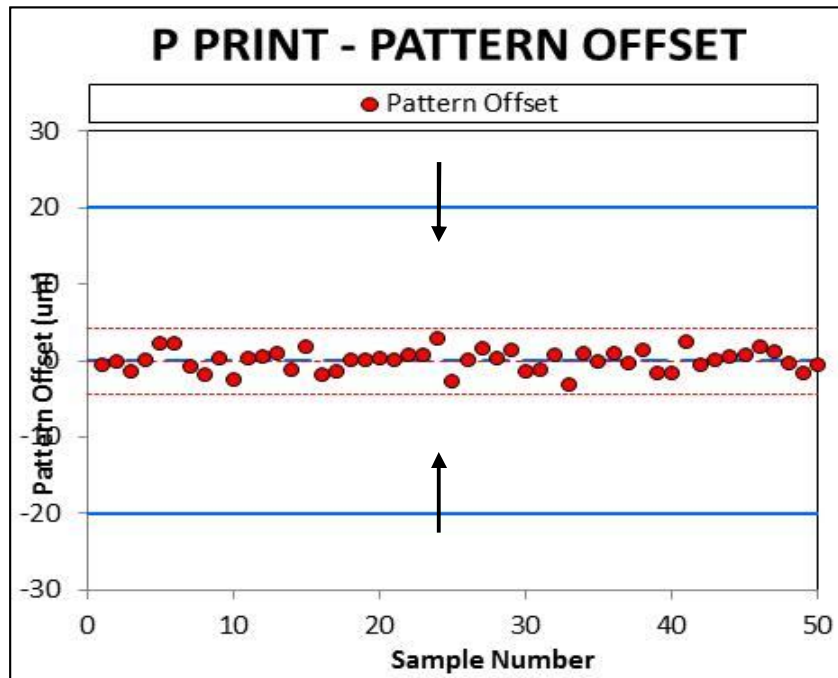
ROOT CAUSE identified; CORRECTIVE ACTION deployed.

P Print Engineers return to a happy, normal life?

Not yet. There is more to do.

Electrical Yield “Shunted” Cells

Step 12. Monetize the new excess process capability



P PRINT Tool

New Process Capability

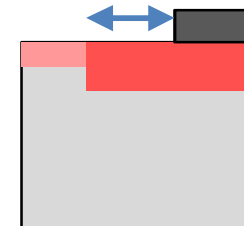
$$CpK = (USL - LSL)/6\sigma = 6.02$$

Excess Capability = \$\$\$ Opportunity!!

Excess Capability:

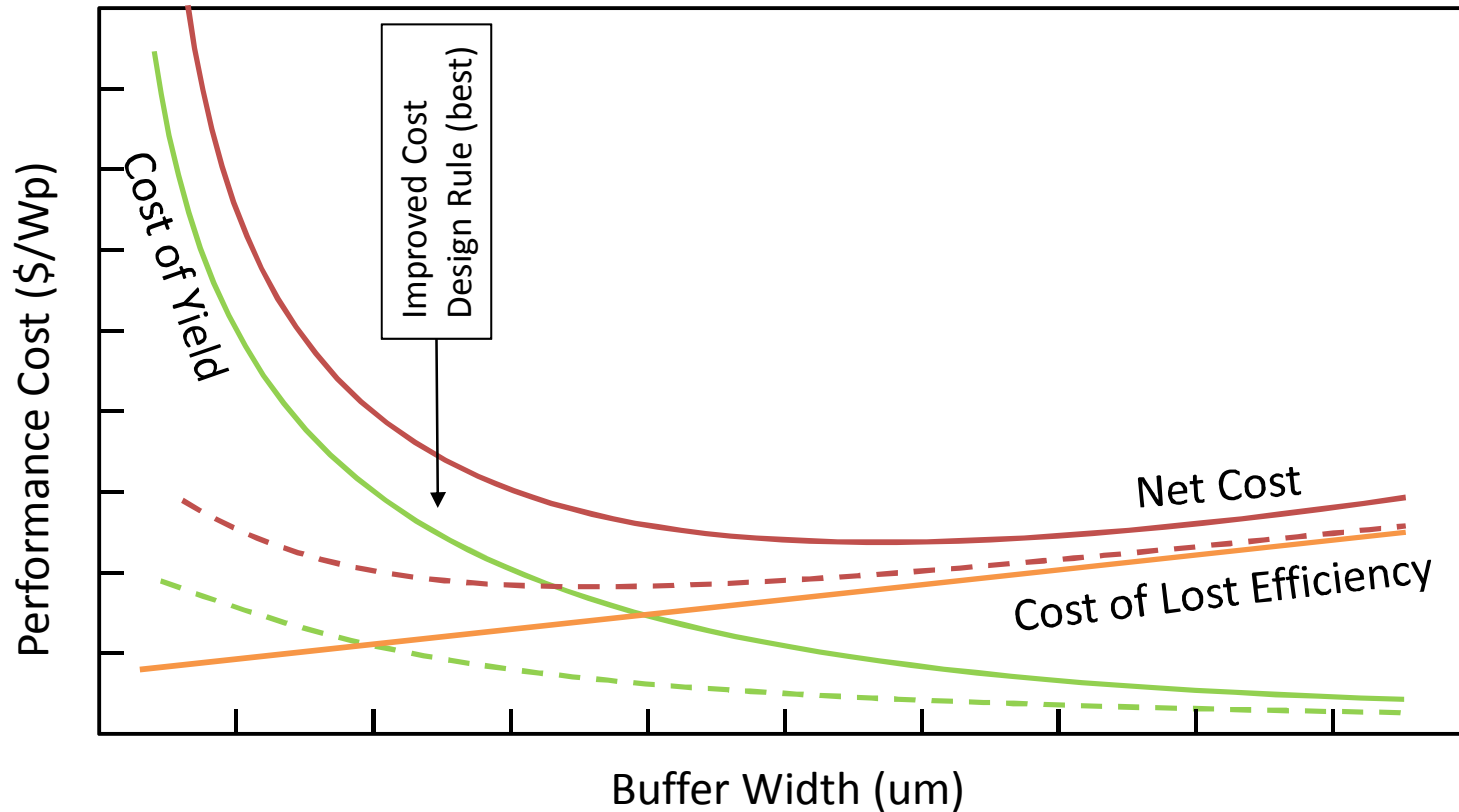
1. Opportunity to lower/raise the target closer to the spec limits
2. Opportunity to decrease the spec limit window

Decrease the Buffer Width!



Electrical Yield “Shunted” Cells

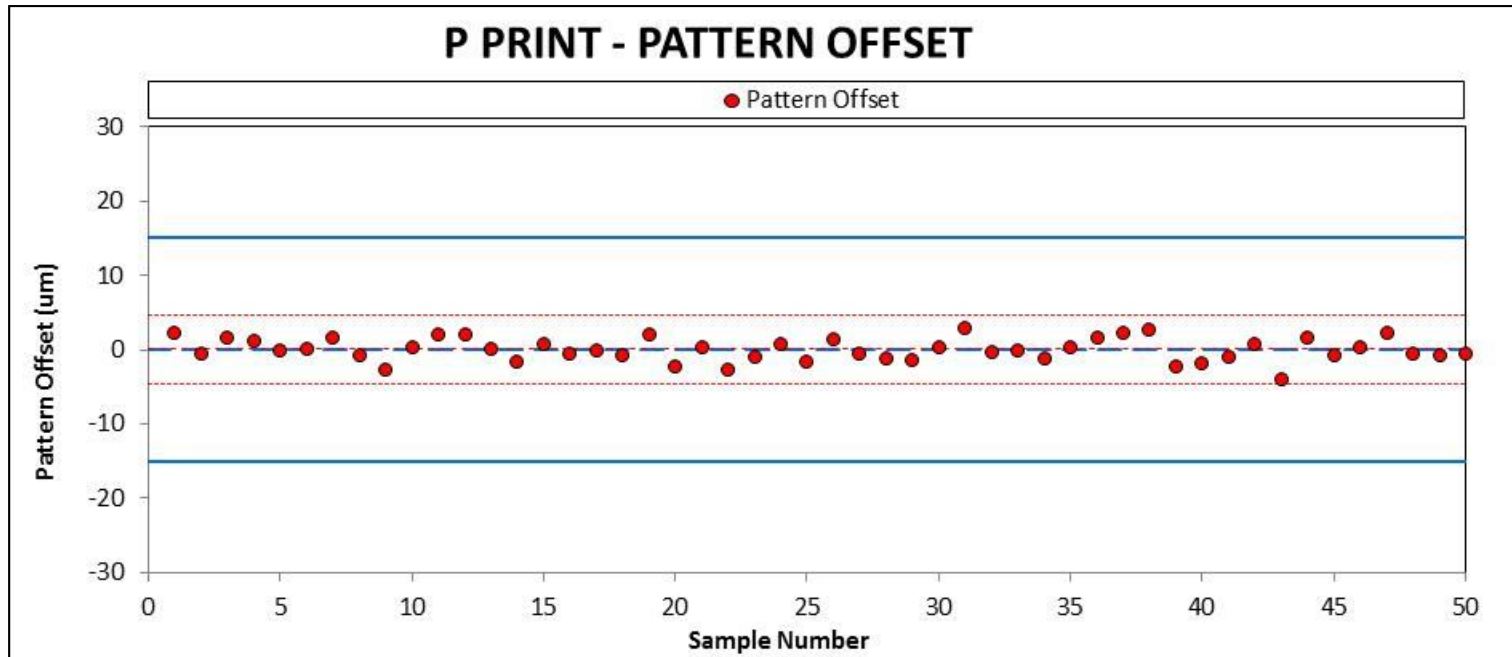
Step 13. Re-apply “Design for Cost” principles



Claim both low yield losses AND high efficiency!!

Electrical Yield “Shunted” Cells

Step 14. Finally, perfection.



But, one more thing to do. Who can name it?

Electrical Yield “Shunted” Cells

Step 14. Finally, one more thing to do

But, one more thing to do. Who can name it?

Eliminate the P PRINT chart.

Electrical Yield “Shunted” Cells

Step 15. Final project validation

Project NPV

\$0.0055/Wp COGM savings, on 800 MW capacity

NPV = \$14M

Project Costs

Line Time Charges = \$150,000

Materials and Supplies = \$50,000

Eng/Tech Labor = \$180,000

Tool Upgrades = \$320,000

Total = \$700,000

ROI = 26.8

DISCLAIMER: Figures, examples, numbers cited in all of these example are made up.

Tackling PV Manufacturing Cost



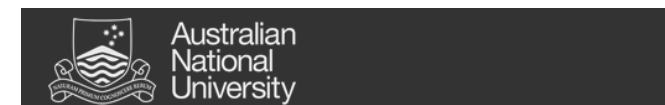
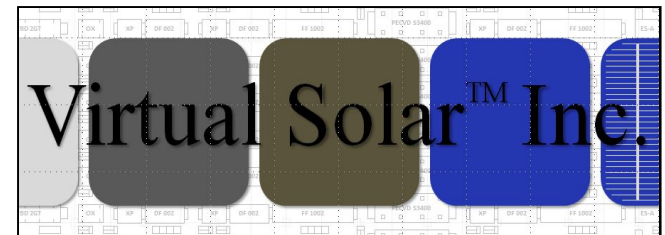
Outline

1. My Value Proposition for Tackling PV Manufacturing Costs
2. Accounting for the Cost of Goods Manufactured
3. Tackling COGM; An Example
4. Manufacturing Science of Solar Cells Course

The Virtual Cell Fab Project

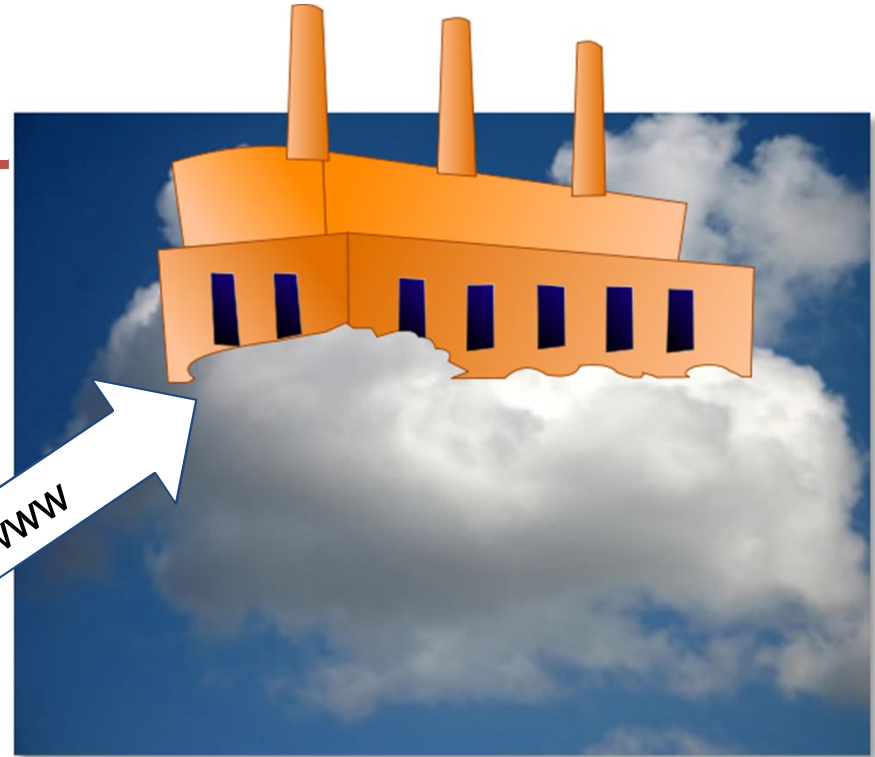
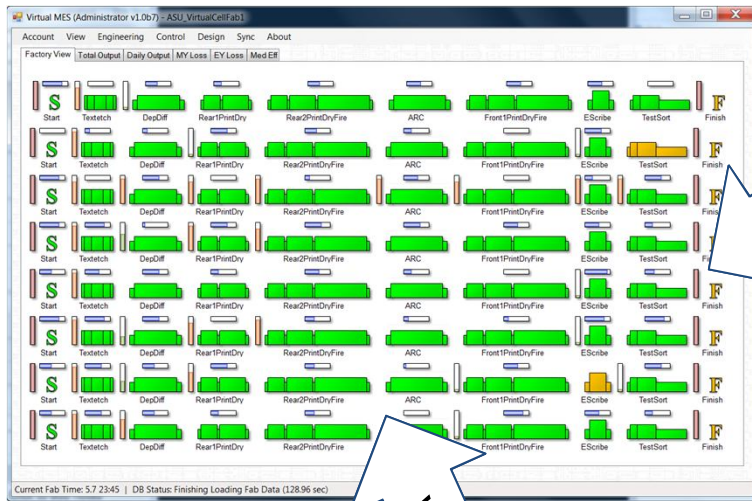
The VCF Project

- Led by Jeff Cotter with ASU QESST, UDel and ANU as affiliated institutes (to date)
- Goal: Develop curricula that informs undergraduate engineering students about PV manufacturing science
 - Design of Experiments
 - Regression Modeling
 - Hypothesis Testing
 - Chart Models
 - Population Models
 - Cost Accounting Analysis
 - SPC and Control Charts
 - Cost/Capability Design Principles
 - Analysis of Variance
 - And More
- Centerpiece: The VCF and VMES software simulation package
 - Captures the manufacturing context
 - Models (approximately) the physics/chemistry of solar cell fabrication
 - Models (in detail) the cost and statistic variation typical of solar cell manufacturing
 - Supports teaching and learning activities related to manufacturing science

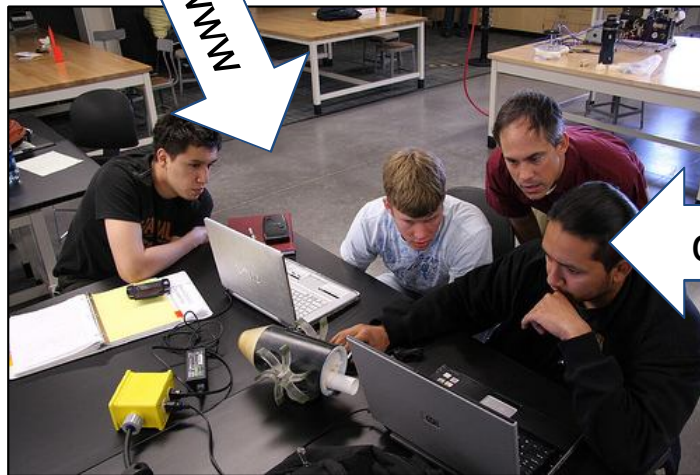


Virtual Solar Inc.

Virtual Manufacturing Execution System (Client Software)



Virtual Solar Cell Fab (Server Software)



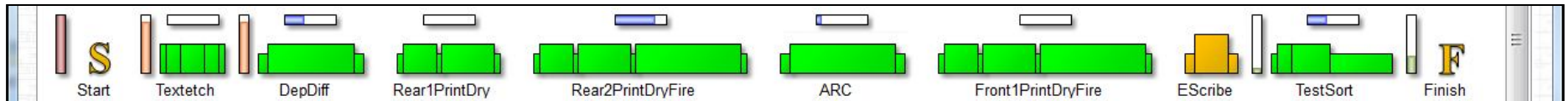
Engineering Students



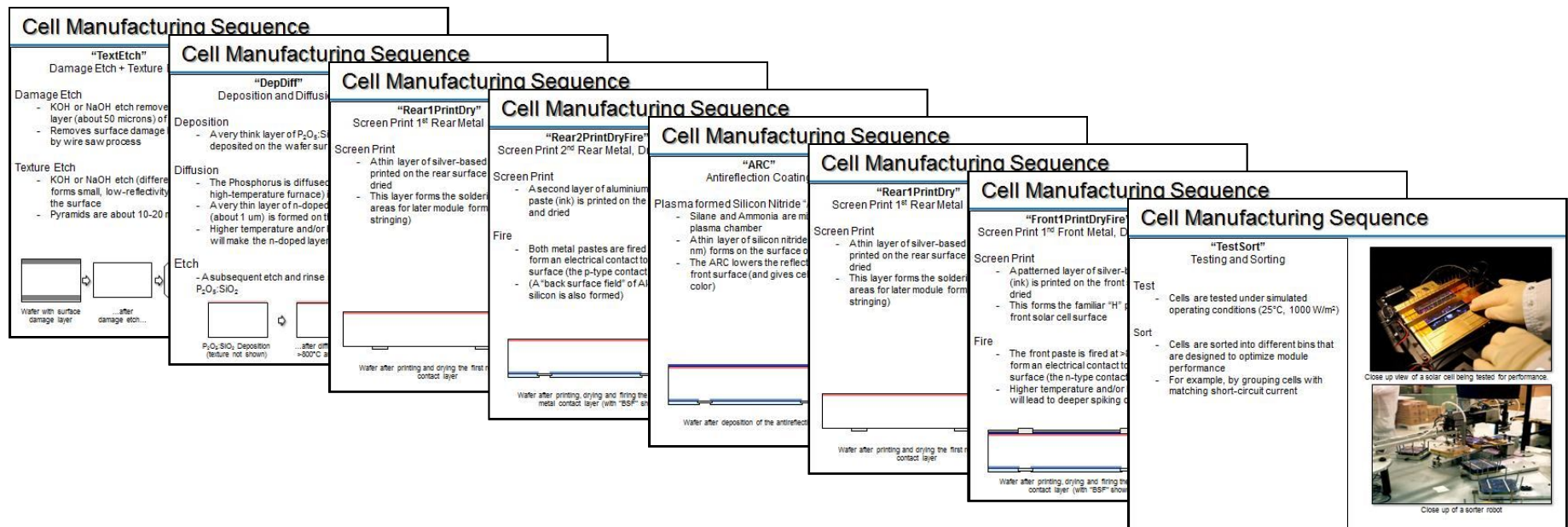
Learning Activities

The Virtual Cell Fab (Server)

A simple, 8-step, screen-print solar cell production sequence...

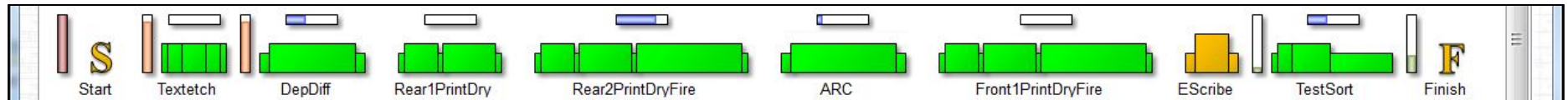


...with very simple process models, but very sophisticated statistical and operational models...



The Virtual Cell Fab (Server)

A simple, 8-step, screen-print solar cell production sequence...



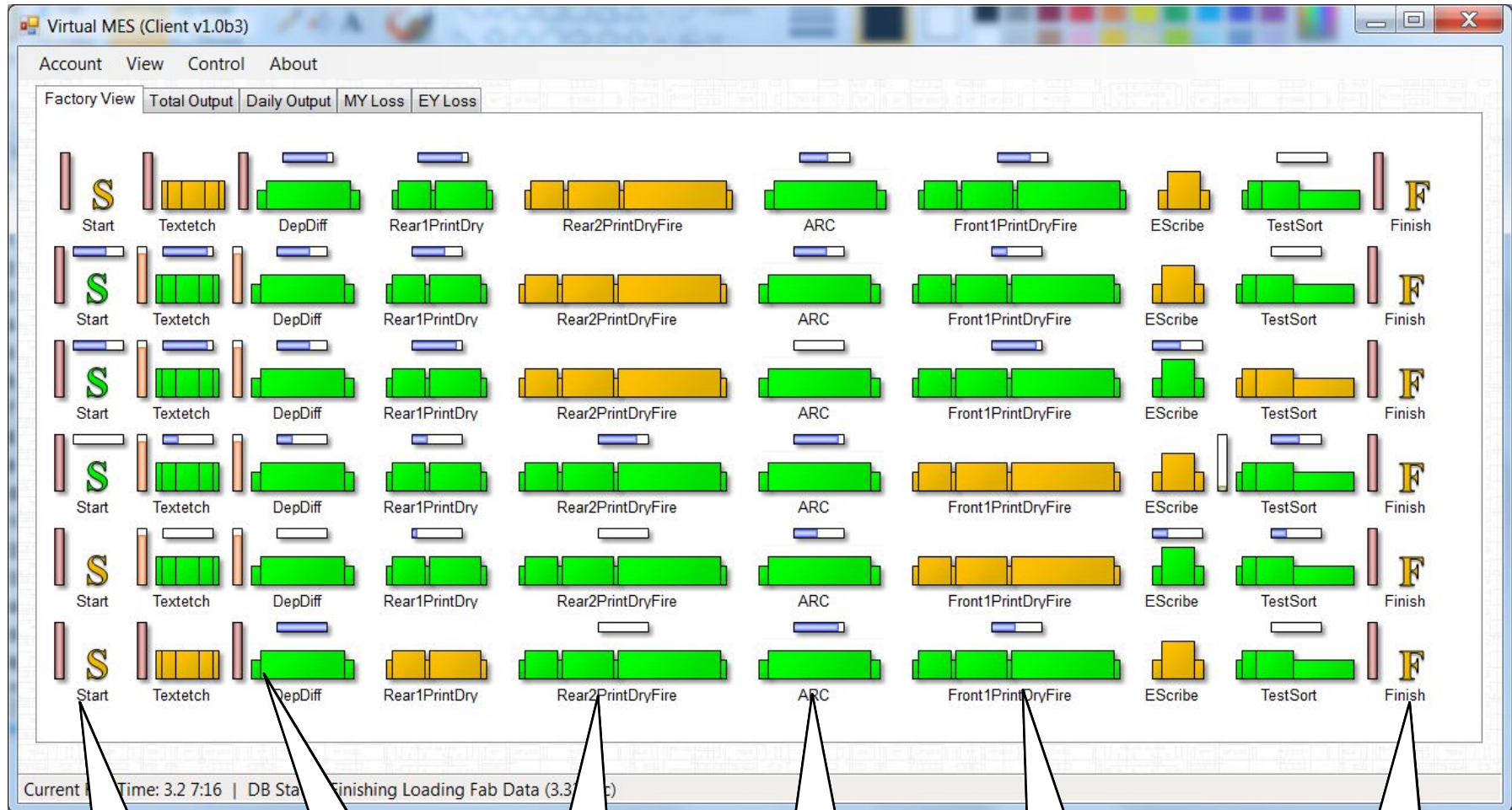
...and a full cost-accounting system complete with T-Accounts, Accounting Schedules, Cash Flow Diagrams and a Working Capital Account.

Schedule of Cost of Goods Manufactured

Description	Period Cost	Unit Cost	Performance Cost
Cost of Goods Manufactured			
- Beginning WIP Inventory	\$2451.53	\$1.0567	\$0.4121
- Manufacturing Costs			
- DM	\$7671.79	\$3.3068	\$1.29
- IDM	\$1186.23	\$0.5113	\$0.20
- DL	\$478.48	\$0.2062	\$0.08
- IDL	\$117.60	\$0.0507	\$0.02
- FOH	\$422.29	\$0.1820	\$0.07
- VOH	\$27.38	\$0.0118	\$0.00
- Total Manufacturing Costs	\$9903.77	\$4.2689	\$1.6649
- Ending WIP Inventory	(\$2482.61)	(\$1.0701)	(\$0.4174)
- Quantity of Goods Manufactured / Total Power Manufactured		2320	5948.4
Cost of Goods Manufactured	\$9872.69	\$4.2555	\$1.6597

The Virtual Manufacturing Execution System (Client)

Software: A fully functional “Virtual MES” client interface to the VCF



Multiple production lines, each managed by a small team of specialist “process engineers”...

Engineering Split Lots

Tool Inventory and Status

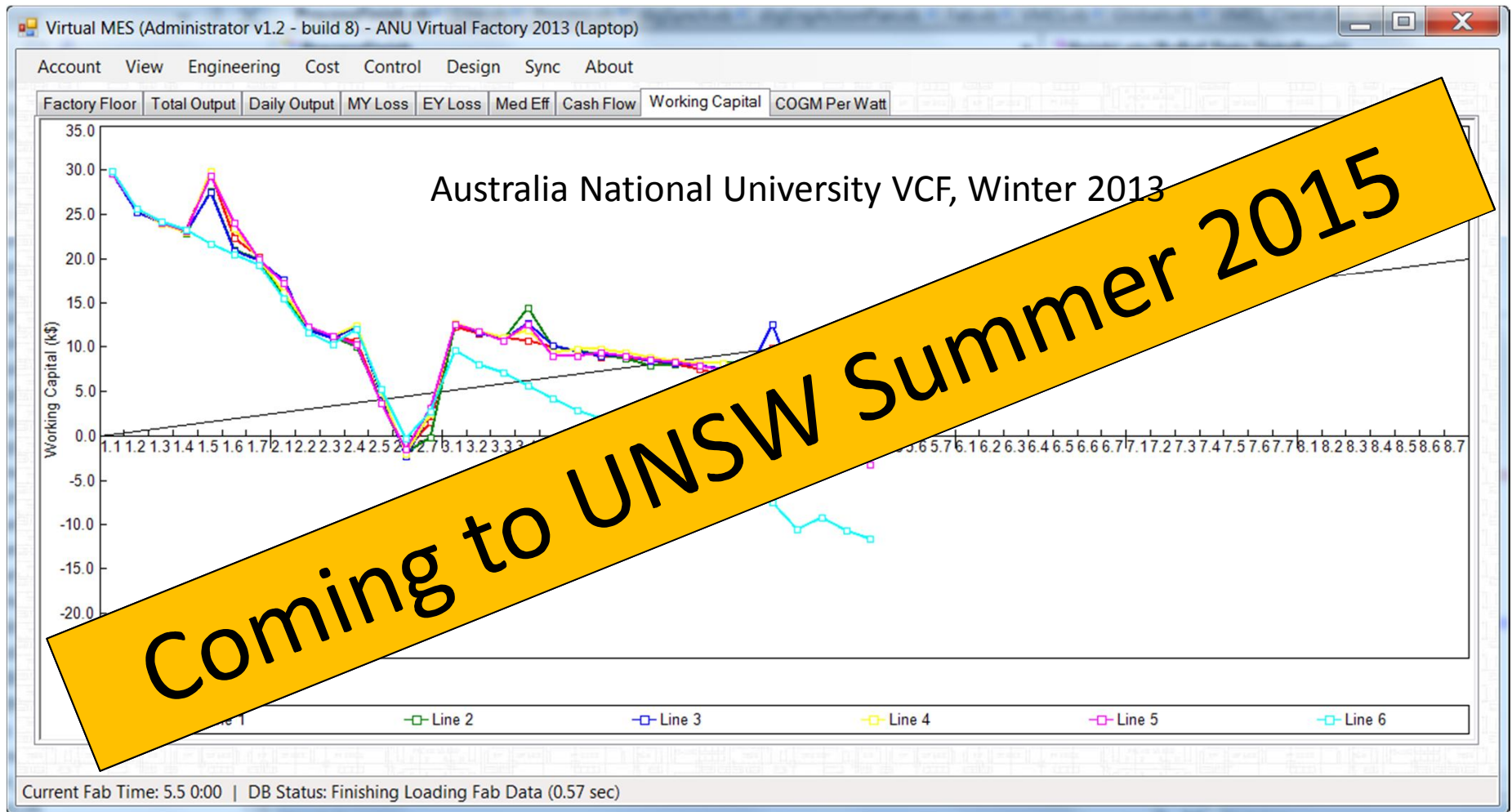
Cost Accounting

Plan Engineering Activities

Line Metrics Output, Yield, Eff, etc

EOL Data Collection/Analysis

With a Compelling Context



Can you save Virtual Cells Inc?



Thanks!