SWAP TESTS

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BACKGROUND

One of the challenges in manufacturing is when a product defect occurs intermittently and its source is unknown. The defect could be from a given process, or from one of the machines or operators within a process step (there could be more sources). The natural inclination is to create a designed experiment to determine the source of the defect. However, this ends up not practical for several reasons, mainly because of the intermittent aspect of the defect.

For batch processing, the design technique "Swap Tests" can be used to successfully design experiments to isolate the problem area creating the defect. It can be employed for any number of processes and is only limited by a minimum batch size required based upon the design. If managed correctly, the design will not create any downtime for Operations.

HISTORY

Typical designed experiments (DOE's) are specially constructed to isolate signals from random error through statistical methods. Factors are purposefully changed to see a change in performance (signal). However, all of these design techniques expect that the process is stable. By definition, an intermittent defect indicates instability in a process. Therefore, standard DOE techniques are not appropriate or practical for a variety of reasons, including:

1. Intermittent defects occur under normal operating conditions so there are no variables to change.
2. It is intermittent so the likelihood that it is caught in a special experiment is low.
3. Within an operation there are hundreds of potential variables (processes, machines, people, etc.) so confounding exists.
4. The causal factor may not be included in the experiment since it is unknown.

5. A DOE often creates downtime, especially the larger the experiment. Given the defect is intermittent, without finding the source this may cast a negative light on the power of DOE's for future use.

The author was introduced to the concept of a swap test by Motorola in 2000. The author took the initial concept and expanded it to a suite of designs, as well as probabilities of success based upon the rate of defects. It is applicable in batch manufacturing operations but not in standard continuous operations where the work-in-progress is undisturbed.

EXAMPLE:

In the production of silicon wafers for semiconductor manufacturing, there are four major Process areas:

1. Crystal Pulling (creating a silicon ingot)
2. Wafering (slicing the wafers from the ingot)
3. Polishing (polishing the wafers)
4. Epitaxy (applying an ultrapure layer of silicon to the wafer)

Within each Process above there are multiple process steps. Both wafer and device manufacturing are batch operations, with new batches being created multiple times throughout.

A new, infrequent problem was detected at the customer (device manufacturer) that could not be detected in-house. This problem was new to both customer and supplier. All wafers passed all specified tests and specifications at the supplier. The defect would only be detected when the wafers were actually field tested at the customer; the supplier could not test internally. Despite product traceability, because of the confounding of batches there was no way to determine which Process caused the end-user problem.

A four process swap-test was employed as a joint project between supplier and customer. Of the 16 mini-batches run, 4 mini-batches were found to have defects. With the structure that the swap test provides, it was determined that the source of the problem was in the Crystal area (see Appendix for analysis). Further investigation determined the root cause was in the last step of the Crystal area. Without the structure of the swap test methodology, this problem may never have been solved and potentially could have resulted in lost business.

SWAP TEST TECHNIQUE:

To illustrate the simplest swap, an operation has front end and back end processes. An infrequent defect is detected at the end of the line inspection and there is no knowledge as to whether it comes from the front end or the back end of Operations. A swap test with two Processes is created.

Steps:

1. Determine minimum size of swap test.
    - K = # of processes to be tested (in this example 2)
2. Determine minimum number of batches (mini-batches).
    - K^2 is the minimum number of batches required (in this example $2^2 = 4$)
3. K^2 "mini-batches" (A, B, C, and D) are combined into K Master Batches (Batch 1 and Batch 2).
4. Run Master Batch 1 through Process 1.
    - All of the mini-batches inside Master Batch 1 should be run as closely together as possible
5. Run Master Batch 2 through Process 1.
    - There should be as much of a "delay" as possible between processing Master Batch 1 and Master Batch 2. Depending upon the production layout, a "delay" could constitute:
        - Time for the problem to come and go
        - Different machines to process the batches
        - Different people to process the batches
6. After both Master Batches have been processed through Process 1, the mini-batches are "swapped" to create new Master Batches. <u>This is not a random activity</u>. Tables are provided in this paper for Swap Tests up to 4 Processes, but can be reproduced for any number of processes.
7. After new Master Batches are created, then run each Master Batch through Process 2, ensuring there is a proper "delay" between Master Batches.
8. Inspect the product at the end of line for the defect. Record for each mini-batch whether or not the defect was present.
    - If the defect was not present in any Mini-Batch, rerun the experiment.
    - If the defect was present in all Mini-Batches, rerun the experiment.
    - Where the defect is present in some Mini-Batches and not in others, to each Mini-Batch assign a 1 or 0 (present or not). Calculate the sum of each Master Batch for each Process.
9. The defect is present in the Process where each Master Batch is either 0 or the total possible. All other Processes will have a mixture of possible sums in the Master Batches.

		Batch 1		Batch 2	
PROBLEM	Process 1	A	B	C	D
	Process 2	A	D	C	B

		Batch 1		Batch 2	
	Process 1	A	B	C	D
PROBLEM	Process 2	A	D	C	B

Example Calculations:

The above figure illustrates a Swap Test with two Processes. The experiment was run and at the end of the line mini-batches B & C were found to have defects.

	Batch 1		**Batch 2**	
Process 1	0	1	1	0
Process 2	0	0	1	1

After summing, the results are as follows

	Batch 1	**Batch 2**
Process 1	1	1
Process 2	0	2

Process 2 would be the source of the defect (Process with defect will either have 0 or 2 (maximum sum)). It could be that the source is now found (a given machine or person), or more research is required but the scope is narrowed to a given area.

Although this seems rather simple, it takes many resources within Production Control to coordinate the management of the Master Batches and Mini-Batches through the operation to ensure success.

CONFOUNDING vs STRUCTURED DESIGN

One of the great challenges in manufacturing is confounding. Unless there is a single machine for each step, product flow will appear in front of the next machine available. There can be potentially thousands of combinations of machines, heads, people, lines, etc. that a given product can see in its assembly.

One of the benefits of traditional Designed Experiments is that the designer purposefully manages the factors and levels to avoid confounding. This care leads to orthogonality (independence) of the factors. The Swap Test works on the same underlying principle of independence. If a swap test is properly designed and conducted, the structure will produce results clearly indicating which Process is the source of the intermittent defect.

PROBABILITIES

Unfortunately, not every test is successful. The less frequent the defect occurs, the more tests are required to be able to isolate the Process creating the defect.

The minimum number of Master Batches is dictated by the number of Processes. If one is doing a swap test with three Processes, then a minimum of three Master Batches are required. However, one can run swap tests with more Master Batches using the swapping theory presented later in the paper.

Using binomial theory, the following table illustrates the likelihood of being successful in detecting the Process that generates the defect given the frequency.

		Probability of Successful Swap Test						
		Master Batches						
Prob (Defect)	Prob (No Defect)	2	3	4	5	6	7	8
0.01	0.99	2%	3%	4%	5%	6%	7%	8%
0.05	0.95	10%	14%	19%	23%	26%	30%	34%
0.10	0.90	18%	27%	34%	41%	47%	52%	57%
0.20	0.80	32%	48%	59%	67%	74%	79%	83%
0.30	0.70	42%	63%	75%	83%	88%	92%	94%
0.40	0.60	48%	72%	84%	91%	95%	97%	98%
0.50	0.50	50%	75%	88%	94%	97%	98%	99%

In an example where a three Process swap test was run with three Master Batches and the frequency of the defect is ~30% of the time, there is a 63% chance of being successful in the first experiment. Depending upon the situation, Operations could decide to improve its odds by running six Master Batches instead of three. This would improve its likelihood of success in the first experiment to 88%. Or it may be easier to manage a smaller number of Master Batches and repeat the experiment. By running the experiment twice with three Master Batches, the probability of detecting it in at least one of the experiments is the same (88%).

The below table shows the probabilities of replications of a two Process Swap Test. Using Binomial theory, one can generate these for any number of Processes.

		Probability of Successful Swap Test		
		Replications of Two Processes		
Prob (Defect)	Prob (No Defect)	1	2	3
0.01	0.99	2%	4%	6%
0.05	0.95	10%	19%	26%
0.10	0.90	18%	34%	47%
0.20	0.80	32%	59%	74%
0.30	0.70	42%	75%	88%
0.40	0.60	48%	84%	95%
0.50	0.50	50%	88%	97%

SWAPPING THEORY

Swapping theory is simple. Once the pattern is established, additional master batches can be easily added and is only limited by Operations' ability to manage the master and mini batches.

Two Processes: (shown above in the examples)

Three Processes:

The table below graphically shows the following:

1. In the first "swap" (from Process 1 to Process 2)
   a. Keep "first" mini-batch from the first Master Batch.
   b. Move the other two mini-batches to the next Master Batch.
   c. Repeat for each Master Batch.
   d. When you get to the last Master Batch, move the other two mini-batches to the first Master Batch.
2. In the second "swap" (from Process 2 to Process 3)

a. Keep the “first” mini-batch and one of the mini-batches that had been moved before.
b. Move the final mini-batch to the next Master Batch.
c. Repeat for each Master Batch.
d. When you get to the last Master Batch, move the other mini-batch to the first Master Batch.

3. Run Master Batches through Process 3.

		Batch 1	Batch 2	Batch 3
PROBLEM	Process 1	A B C	D E F	G H I
	Process 2	A H I	D B C	G E F
	Process 3	A H F	D B I	G E C

		Batch 1	Batch 2	Batch 3
	Process 1	A B C	D E F	G H I
PROBLEM	Process 2	A H I	D B C	G E F
	Process 3	A H F	D B I	G E C

		Batch 1	Batch 2	Batch 3
	Process 1	A B C	D E F	G H I
	Process 2	A H I	D B C	G E F
PROBLEM	Process 3	A H F	D B I	G E C

Probability of Successful Swap Test
Master Batches

Prob (Defect)	Prob (No Defect)	3	4	5	6	7	8	9
0.01	0.99	3%	4%	5%	6%	7%	8%	9%
0.05	0.95	14%	19%	23%	26%	30%	34%	37%
0.10	0.90	27%	34%	41%	47%	52%	57%	61%
0.20	0.80	48%	59%	67%	74%	79%	83%	87%
0.30	0.70	63%	75%	83%	88%	92%	94%	96%
0.40	0.60	72%	84%	91%	95%	97%	98%	99%
0.50	0.50	75%	88%	94%	97%	98%	99%	100%

Probability of Successful Swap Test
Replications of Three Processes

Prob (Defect)	Prob (No Defect)	1	2	3
0.01	0.99	3%	6%	9%
0.05	0.95	14%	26%	37%
0.10	0.90	27%	47%	61%
0.20	0.80	48%	74%	87%
0.30	0.70	63%	88%	96%
0.40	0.60	72%	95%	99%
0.50	0.50	75%	97%	100%

Four Processes

		Batch 1	Batch 2	Batch 3	Batch 4
PROBLEM	Process 1	A B C D	E F G H	I J K L	M N O P
	Process 2	A N O P	E B C D	I F G H	M J K L
	Process 3	A N K L	E B O P	I F C D	M J G H
	Process 4	A N K H	E B O L	I F C P	M J G D

		Batch 1	Batch 2	Batch 3	Batch 4
	Process 1	A B C D	E F G H	I J K L	M N O P
PROBLEM	Process 2	A N O P	E B C D	I F G H	M J K L
	Process 3	A N K L	E B O P	I F C D	M J G H
	Process 4	A N K H	E B O L	I F C P	M J G D

		Batch 1	Batch 2	Batch 3	Batch 4
	Process 1	A B C D	E F G H	I J K L	M N O P
	Process 2	A N O P	E B C D	I F G H	M J K L
PROBLEM	Process 3	A N K L	E B O P	I F C D	M J G H
	Process 4	A N K H	E B O L	I F C P	M J G D

		Batch 1	Batch 2	Batch 3	Batch 4
	Process 1	A B C D	E F G H	I J K L	M N O P
	Process 2	A N O P	E B C D	I F G H	M J K L
	Process 3	A N K L	E B O P	I F C D	M J G H
PROBLEM	Process 4	A N K H	E B O L	I F C P	M J G D

Probability of Successful Swap Test

		Batches								
Prob (Defect)	Prob (No Defect)	4	5	6	7	8	9	10	11	12
0.01	0.99	4%	5%	6%	7%	8%	9%	10%	10%	11%
0.05	0.95	19%	23%	26%	30%	34%	37%	40%	43%	46%
0.10	0.90	34%	41%	47%	52%	57%	61%	65%	69%	72%
0.20	0.80	59%	67%	74%	79%	83%	87%	89%	91%	93%
0.30	0.70	75%	83%	88%	92%	94%	96%	97%	98%	99%
0.40	0.60	84%	91%	95%	97%	98%	99%	99%	100%	100%
0.50	0.50	88%	94%	97%	98%	99%	100%	100%	100%	100%

Probability of Successful Swap Test

		Replications of Four Processes		
Prob (Defect)	Prob (No Defect)	1	2	3
0.01	0.99	4%	8%	11%
0.05	0.95	19%	34%	46%
0.10	0.90	34%	57%	72%
0.20	0.80	59%	83%	93%
0.30	0.70	75%	94%	99%
0.40	0.60	84%	98%	100%
0.50	0.50	88%	99%	100%

LIMITATIONS

There are few limitations, other than operationally within a manufacturing facility of creating swaps and managing the work-in-progress. These techniques work successfully in any batch operation where batches are free to flow to any piece of equipment or operator within a process.

Potential limitations could include:

- Time-sensitivity between processes
- Defect would turn on and off within a Master Batch

Swap Tests could be used with quantitative data rather than qualitative data, although the user would have to be careful in drawing conclusions as to where the problem existed.

CONCLUSION

These designs offer Operations the ability to run carefully designed experiments to pinpoint the source of intermittent defects without disrupting regular production. Standard DOE techniques require stability to understand the impact of different factors. Using the knowledge of the frequency of the defect, the number of general Process areas and associated constraints, the experiment can be designed to maximize potential success. These tests can be expanded to any size, limited only by Operations' ability to manage the test and work-in-progress.

REFERENCES:

- The author would like to thank the Motorola Corporation for introducing the concept of swap tests (four processes/four master batches). There is no documentation or publications on this topic that could be found. Expansion upon the initial concept is the work of the author (number of processes, probabilities of success).
- Binomial Distribution (countless sources): http://www.itl.nist.gov/div898/handbook/eda/section3/eda366i.htm

APPENDIX

In the 4 Swap Test example, Mini-Batches A, B, C, D, I, J, K, L had defects. Mini-Batches E, F, G, H, M, N, O, P did not. The sums for each Master Batch at each Process were calculated.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	1	1	1	0	0	0	0	1	1	1	1	0	0	0	0
1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1
1	0	1	1	0	1	0	0	1	0	1	1	0	1	0	0
1	0	1	0	0	1	0	1	1	0	1	0	0	1	0	1

Process 1	4	0	4	0
Process 2	1	3	1	3
Process 3	3	1	3	1
Process 4	2	2	2	2

Whichever Process has 0's and 4's (the maximum number of Mini-Batches), this is the Process where the intermittent defect is being generated.

Note: If Mini-Batches E, F, G, and H also had defects but M, N, O, P then we will have several Processes with 4 Mini-Batches in a Master Batch with defects.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
1	0	0	0	1	1	1	1	1	1	1	1	0	1	1	1
1	0	1	1	1	1	0	0	1	1	1	1	0	1	1	1
1	0	1	1	1	1	0	1	1	1	1	0	0	1	1	1

Process 1	4	4	4	0
Process 2	1	4	4	3
Process 3	3	2	4	3
Process 4	3	3	3	3

Although Process 2 and 3 have at least one Master Batch with 4, the problematic Process is the one with either 0's or 4's.

