

# **Experimental Test Strategy For Six Sigma Levels of Process Improvement**

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## **ABSTRACT**

Several progressive test strategies are taught in the literature with regard to applying Design of Experiments (DOE) to process understanding and improvement. These strategies typically utilize DOE's in a progressive fashion to move key control factor process settings toward optimal conditions (variation and mean). While these strategies are well known and accepted techniques for optimizing a process, they intrinsically promote a limited understanding of the process as a whole. Companies today that are striving to become "Six Sigma" need a more reasonable understanding of all possible process control variables. This paper introduces a new iterative replication test strategy and display methodology entitled Statistical Process Accounting (SPA) that facilitates this need as well as to enable a host of other advantages.

Key Words: Test Methods, Test Standardization, Testing.

## **1. INTRODUCTION**

The emergence of Six Sigma as a quality improvement methodology, philosophy, and metric over recent years is forcing a shift in business needs toward higher levels of process sigma and understanding. Well known companies such as General Electric, Motorola, Ford, and Honeywell claiming Billions of dollars saved as a result of Six Sigma supports this shift in business needs (Niles, 2001). System level industry standards such as ISO 9001:2000, QS9000, FDA QSR's, and others have also been recently shifting towards levels of greater process based understanding and control which also supports this shift in business needs.

The typical non-Six Sigma company is said to naturally fall into a three sigma level of quality. The best companies are still only able to achieve approximately a five sigma level of quality. Achieving a six sigma level (3.4 defects per million opportunities) requires a near perfect quality for all key aspects of doing business. This means that all reasonable forms of possible variation are understood and either controlled or in other ways compensated for. For this to happen either the processes within the company need to be very simple or the company needs to be very thorough in testing and accounting all reasonable process variation.

Test strategies are plans for determining how one or more tests are to be run. They are used to enable the experimenter to generate a reliable conclusion to hypotheses being tested in an

efficient and efficacious manner. Expectations of test costs, resources available, and likely outcomes are balanced against test objectives in selecting an appropriate test strategy.

## 2. GENERAL APPLICATION

Dr. Douglas Montgomery states that all experiments are Design of Experiments with some just being poorly planned (Montgomery, 1991). Test strategies range from trial-and-error testing through one-factor or variable-at-a-time testing (1FAT, OFAT, or OVAAT) to what is more commonly considered Design of Experiments (DOE; also known as Experimental Design (ED), DOX, or DoE) using pre-planned test arrays and statistical analysis techniques capable of distinguishing between main effects, interaction effects, and experimental error. While there are appropriate situations for any type of test strategy, only DOE allows measurement of interaction effects needed to obtain high levels of complex process understanding.

The following example represents a DOE test array where three factors (A,B, and C) are tested nine different times in accordance with the prescribed settings for each run. For example, run four would be set up with factor A in high level (coded +1), B in high level and C in low level (coded -1) conditions. In this example, response factors of weight and reject quantities would be recorded for each run. Later the entire experiment would be analyzed statistically to provide significance and confidence for each factor and interactions between the three factors.

run	Factor_A	Factor_B	Factor_C	Weight	Rejects
1	-1.0	-1.0	-1.0	_____	_____
2	1.0	-1.0	-1.0	_____	_____
3	-1.0	1.0	-1.0	_____	_____
4	1.0	1.0	-1.0	_____	_____
5	-1.0	-1.0	1.0	_____	_____
6	1.0	-1.0	1.0	_____	_____
7	-1.0	1.0	1.0	_____	_____
8	1.0	1.0	1.0	_____	_____
9	0.0	0.0	0.0	_____	_____

Only a few test strategies are documented in the literature and then typically as planning strategies or not labeled as strategies. Reviewing what is written allows one to classify all test strategies into a priori and a posteriori classifications as follows.

### 2.1. A Priori Test Strategies

A priori strategies are deductive (from the former) and are presupposed by experience or as applied to test strategies, taken typically from subjective information obtained before testing begins.

2.1.1. **A Priori Charting Strategies:** Barton (1997) outlines a priori charting techniques that enable estimation of expected test results prior to testing. They enable optimized test planning of matrix, factor, and factor range selection.

2.1.2. **Taguchi's Resolution III Test Strategy:** Taguchi (1993) has been quoted for saying "dig wide not deep" in reference to this strategy where low-resolution test

matrices are selected where interaction effects are not likely to occur. A related example would be to choose a Latin Squares matrix when no interaction effects are suspected. Test costs to obtain interaction effects that don't likely exist are minimized.

- 2.1.3. **Direct Selection of Response Surface Matrices:** Although not advised in the literature, direct selection of response surface matrices can reduce the costs of screening testing when the factors to be tested are well understood prior to testing.
- 2.1.4. **Constrained Variable:** When several variables are known in advance to add up to 100% of the variation in a given situation, mixture experiments are most efficiently used.
- 2.1.5. **Confounded Design Selection:** Selecting complex experimental designs with known design confounding in an effort to efficiently match test environments where some interactions are known to exist.
- 2.1.6. **Virtual Experimentation Strategies:** Tom Pyzdek (2000) outlines strategies using pre-existing data in what he calls "virtual" DOE testing. This technique is similar to Barton's charting techniques.

## 2.2. A Posteriori Test Strategies

A posteriori strategies are derived from facts or reasoning (from the latter) or as applied to test strategies, taken from data obtained through prior testing. The following list of strategies has been compiled by the author from literature as well as personal experience.

- 2.2.1. **Iterative Test Space Progression:** The first two of the following strategies are sometimes considered to be the same strategy. Both methods prescribe adjusting the experimental space until a "sweet spot" is reached.
  - 2.2.1.1. **Evolutionary Operation (EVOP):** EVOP is an acronym for evolutionary operation. Once present conditions are understood, sequential testing is leveraged off of that knowledge by predicting and then testing more optimized theoretical conditions.
  - 2.2.1.2. **Path of Steepest Ascent:** Similar to EVOP where an optimized slope is followed along the steepest slope toward optimization.
  - 2.2.1.3. **Test Range Reduction:** Refers to methods for narrowing in on optimized test ranges by beginning with very wide "reasonable extreme" test ranges for all factors tested and then reducing those ranges in subsequent tests depending upon measured effects and process needs. Changing the test range may also require changes to the design power of subsequent experiments in order to maintain or increase confidence in the results.
- 2.2.2. **Iterative Model Progression:** There are several of these strategies. Most are well documented in the literature as follows:
  - 2.2.2.1. **Screening to response surface methodology (RSM):** This method is the most commonly taught strategy in the literature (Montgomery, 1991). It begins with screening experiments to weed out significant factors and follows-up with Response Surface Methodologies (RSM) to optimize those factors.
  - 2.2.2.2. **Iterative Power / Resolution Progression Testing:** Similar to Taguchi's Resolution III test strategy. Starts with statistically weak

designs with intentions of augmenting it later if needed. Small screening experiments are often replicated later into higher power screening experiments as needed. Data can be used twice using assumptions (1990).

- 2.2.3. **Iterative Replication:** There are at least three of these types of strategies as follows:
- 2.2.3.1. **Retest Strategies:** Factor replication where one or more factors from previous tests are replicated during subsequent testing. SPA is a retest strategy. See statistical process accounting below.
  - 2.2.3.2. **Test Factor Quantity Selection:** Test replication where many small experiments are preferred over a few large experiments. In essence, many aspects of testing are replicated in an effort to improve overall efficiency.
  - 2.2.3.3. **High Power / Small Test Range:** Sometimes referred to as a “passive approach”. Strategy where very small test factor ranges are offset using large run arrays. This is useful for large run experiments are performed on production material using very small factor test ranges as only previously validated tolerances can be tested in order to sell the final product and minimize test costs.
- 2.2.4. **Shainin’s Visual Strategies:** Analysis of experiments using a variety of visual charting methods such as “multi-vari plots” and “paired comparison plots” (Bhote, 2000).

### 3. STATISTICAL PROCESS ACCOUNTING (SPA)

For simplicity sake, the test strategy being introduced in this paper will be entitled Statistical Process Accounting (SPA) throughout the remainder of this paper.

SPA is an iterative replication / retest strategy and display methodology that can be combined with other test strategies but can also be considered unique for the following reasons:

1. Factors are re-tested for the unique underlying purpose of combining all DOE’s from a single process as if they were samples taken from that process. Assumptions can also be used to skip re-testing if the experimenter is willing to assume added risks of missing important long term variation.
2. It encourages the experimenter to investigate factors that might not be tested using any other strategy because the goal of SPA is to develop a master process control settings key as opposed to simply finding a significant factor, solving a problem, etc. As the table matures, everything tested is displayed so that both important and non-important factor effects are displayed.
3. One can argue that it is the only test strategy that is both a priori and a posteriori because it works throughout the entire process of brainstorming test factors to final reporting.
4. It allows correlation of production costs with key factor settings.
5. It provides a unique means for validating a process as it provides a master process control settings key developed using reliable and accepted test methods. Optimized control

settings are outlined in the final table. Note that final product validation involves actual customer conditions over all forms of reasonable variation testing.

SPA can also be considered a methodology as it utilizes spreadsheet tables as outlined in three stages and in chronological order as follows:

1. **Stage I: Control Factor Selection Table Development:** SPA begins with factor selection. Traditional test preparation should have already been performed (i.e. define the test objective, determine process stability and control, determine response factors to be used, etc.). Factors may be selected using traditional means such as brainstorming teams using cause and effect diagrams, affinity diagrams, etc. Once all reasonable control factors are brainstormed and selected, they are entered in to a simple spreadsheet, prioritized, and sorted in order of likelihood of producing an effect on the response. This becomes a stage I SPA table. The stage I table is therefore a table outlining what factors should be tested and how using “best guess” efforts of team-based decision making.

The figure 1 Stage I SPA table example below outlines eleven factors that were outlined during a brainstorming session as most likely being important to controlling the response factor of “void rejections”. The actual test factor names have been coded (A-H) in order to protect proprietary information. The fishbone area columns are optional but in this case helps one recognize that all common cause areas have been covered (i.e. 5Ms). Once test range and unit details are determined, the team subjectively evaluates each factor based on estimated factor significance, ease of test, and risk importance in order to sort the entire table by the factor of those columns (priority). Note that the team rated factor H (manpower related) when tested between 1 and 10 seconds as being the most important factor to test first because it had a high risk associated with it (Risk), a high probability in their minds of producing significant results (Sig. Est.), and they believed it would be easy to test (Ease).

<b>SPA Stage I Table Example</b>										Estimated Priority Sort			
<b>Comments:</b> Process Line A-3													
<b>Response Factor:</b> Void Rejections													
	Test Factors	Fishbone Areas					Test Range			Estimated Priority			
		Man	Mach	Meas	Meth	Misc	(-)	(+)	Units	Sig. Est. (0-9 high)	Ease (0-9 high)	Risk (0-9 high)	Priority (Mult.)
1	H	x					1	10	Seconds	8	9	9	648
2	B		x				2	4	Seconds	8	8	8	512
3	K		x				0	2	Rotation	7	9	8	504
4	I			x			2	8	Seconds	6	8	8	384
5	F		x				10	25	Seconds	6	8	7	336
6	E		x				2	7	Seconds	6	8	7	336
7	G				x		2	25	Seconds	7	7	6	294
8	A	x					-0.2	0.2	Volts	5	7	6	210
9	D		x				2	7	Seconds	5	7	6	210
10	J		x				25	40	Seconds	5	6	5	150
11	C					x	22	45	Seconds	5	6	5	150

Figure 1: Stage I SPA Table Example

While the table above was developed using data from a proprietary process, one envisions the process being composite part manufacturing and the goal being to eliminate voids as they are often sources of stress concentrations and fracture initiation. For example, factors might be raw material quality of reinforcements and resins, including the ratio of these two items in pre-pregs. Lay-up factors in laminates are concerns, factory temp and humidity may be factors, particularly if the pre-pregs have been refrigerated. Orientation of the laminates, curing time, temperature and pressure are all important variables in such fabrication. Note that continuous variables such as these last three mentioned very commonly result in interaction effects which make DOE's very important.

2. **Stage II: Test Results Table Conversion:** Once the stage I table is initiated, testing begins in accordance with existing methods and strategies as appropriate. Each new test contains one or more factors that have been previously tested.

As factors previously outlined and or newly identified are tested, the stage one table is converted into a stage two table. Additional columns for significance and confidence are added; a column for the test number is added. Additional rows listing interaction test results are added, and the statistical confidence column instead of the priority column now is used to sort the stage II table.

The a priori table becomes an a posteriori table at this point as "best guess" sorting turns into "statistical confidence" sorting. The stage II table is therefore a table outlining factors that really are and really are not important as measured through testing within the conditions surrounding the DOEs outlined in the table. New columns are revealed to enable entry of DOE measured significance (i.e. effect), confidence calculated from statistical analysis p-values (1-p), test plan numbers for further information, and optional error tolerance information. New rows are also added to list important interaction effects that are measured. For example row two in the table below outlines the interaction of factors A and B as measured during DOE #53. Details are listed to be found in test plan #53.

Figure 2 below shows how the table in figure 1 was changed to become a stage II table. One can see in this example how the team was correct regarding factor H. We can now state from this example that factor H controlled 24 void rejects over the range tested during test #53 with 99.8% confidence.

<b>SPA Stage II Table Example</b>						Measured Priority Sort				
<b>Comments:</b> Process Line A-3										
<b>Response Factor:</b> Void Rejections										
Test Factors	Test Range		Units	Orig.Est. Priority (Mult.)	Test Plan#	Measured Priority Moving Low to High			Confidence	
	(-)	(+)				Significance	Error Tol.(+/-)	P-value		
1	H	1	10	Seconds	53	24	2.36	0.002	99.80%	
2	53AB	-	-	-	53	22	2.36	0.0026	99.74%	
3	B	2	4	Seconds	48	84.3	11.34	0.005	99.50%	
4	K	0	2	Rotation	53	13	2.36	0.0118	98.82%	
5	I	2	8	Seconds	49	69.7	18.78	0.034	96.60%	
6	57AB	-	-	-	57	36	13.23	0.0702	92.98%	
7	F	10	25	Seconds	51	9	3.4	0.0773	92.27%	
8	E	2	7	Seconds	41	48.5	18.5	0.079	92.10%	
9	G	2	25	Seconds	54	11	4.54	0.0937	90.63%	
10	41AB	-	-	-	41	39.5	18.5	0.122	87.80%	
11	A	-0.2	0.2	Volts	55	15	7.46	0.1378	86.22%	
12	48AB	-	-	-	48	37	19.64	0.1509	84.91%	
13	D	2	7	Seconds	41	29.5	18.5	0.209	79.10%	
14	J	25	40	Seconds	52	19	6.71	0.2131	78.69%	
15	C	22	45	Seconds	52	15	6.71	0.2639	73.61%	

Figure 2: Stage II SPA Table Example

- Stage III: Master Process Key Table Conversion:** Once the table is nearly complete, additional columns can be added to outline other ways of estimating process understanding. The table now becomes a final stage III master process settings key that can be used to provide evidence of process validation, understanding / maturity, estimate cost control effects of key process variables, outline weak areas yet to be optimized, etc.

New optional columns can be added outlining additional information such as weighted or total cost control during the test, signal to noise ratios, application or maintenance notes, highlighted best settings, etc. The stage III table is therefore the most mature form of table outlining everything necessary to understand how to control costs surrounding the given response factor.

Figure 3 below shows how the table in figure 2 was changed to become a stage III table. One can see in this example how factor H is best placed at 10 seconds and that during test it controlled \$341 in rejects. Also note that while it measured with the highest confidence, it was not the most significant factor for controlling cost in the process. Factor B controlled almost \$1200.

<b>SPA Stage III Table Example</b> Measured Priority Sort Including Optimization Information														
<b>Comments:</b> Process Line A-3														
<b>Response Factor:</b> Void Rejections														
Test Factor	Test Range		Test Units	Test Plan#	Significance	Error Tol.(+/-)	P-value	Confidence	Optimization Information			Signal to Noise	Sig.> Conf.	Of Note >Sig.
	(-)	(+)							Best Setting or Optimum	Cost Control	Unit Cost = \$14.25			
1	H	1	10	Sec	53	24	2.36	0.002	99.80%	H at 10s	\$341.32	0.25		
2	53AB	-	-	-	53	22	2.36	0.0026	99.74%	H10:00K	\$312.68	0.3		
3	B	2	4	Sec	48	84.3	11.34	0.005	99.50%	B at 4s	\$1,195.27	0.58	x	
4	K	0	2	Rot	53	13	2.36	0.0118	98.82%	No rotation	\$183.06	0.16		x
5	I	2	8	Sec	49	69.7	18.78	0.034	96.60%	I at 8sec	\$959.46	0.43		
6	57AB	-	-	-	57	36	13.23	0.0702	92.98%	57Aat22:5C	\$476.99	0.15		
7	F	10	25	Sec	51	9	3.4	0.0773	92.27%	F at 20s	\$118.34	0.07		x
8	E	2	7	Sec	41	48.5	18.5	0.079	92.10%	E at 5s	\$636.53	0.1		
9	G	2	25	Sec	54	11	4.54	0.0937	90.63%	G at 2 sec	\$142.06	0.05		
10	41AB	-	-	-	41	39.5	18.5	0.122	87.80%	41E at 5:7D	\$494.20	0.04	x	
11	A	-0	0.2	Volt	55	15	7.46	0.1378	86.22%	A at 0.2v	\$184.30	0.03		
12	48AB	-	-	-	48	8	19.64	0.1509	84.91%	48A at 12:4B	\$96.80	0.05		
13	D	2	7	Sec	41	22	18.5	0.209	79.10%	D at 7s	\$247.98	0.07	x	
14	J	25	40	Sec	52	7	6.71	0.2131	78.69%	J at 40s	\$78.49	0.05		
15	C	22	45	Sec	52	5	6.71	0.2639	73.61%	C at 45s	\$52.45	0.05		

Figure 3: Stage III SPA Table Example

### 3.1. EVALUATION OF BENEFITS

**Advantages of SPA:**

- It captures more long-term variation than traditional test strategies because important test factors are retested over time.
- It can be combined with other test strategies to minimize test costs.
- It promotes measuring all suspected control factors, thus measuring both what is and is not important to the process.
- SPA facilitates justification of multiple DOE's at the beginning of the program and therefore DOE implementation efforts.
- It attracts management's attention as the development of the master key allows an understanding of the overall knowledge and process maturity to be understood by management.
- SPA serves as a unique communication tool to quickly communicate details of process understanding.
- Very useful for explaining optimal settings in large or complex processes.

**Disadvantages of SPA:**

- Requires the use of an additional assumption that performing DOE's on a process already under control is the equivalent of taking samples from that process as long as the control factor levels being tested are within the normal operating ranges of that process. Whether we realize it or not, all test strategies depend upon assumptions such as:
  - Capturing all variation in or between samples
  - The data is normally distributed.
  - Data gathering errors are equally distributed or sample distributions approach the normal distribution in accordance with the central limit theorem.
  - Changes between factor test levels (combinations) are adequate.

- Possibly propagates more of a false sense of understanding of process control if long term variation is not captured.
- Not as appropriate for small and or simple processes without interaction effects.

**Major differences between SPA and traditional strategies are as follows:**

- Promotes testing of all reasonable suspect factors. Factors suspected by the “process experts” may be measured not to be important.
- Enables more comprehensive comparison of experimental error as retesting captures more long term error / variation.
- Promotes testing of previously measured variables. This allows us to utilize the assumption that by re-testing, one can compare DOE information from different DOEs as if they are samples taken from a process over time.
- Promotes development of process key which may include cost information.

## **4. SUMMARY AND RECOMMENDATIONS**

SPA has been used many times by this author over many diversified processes, companies, products, and industry types. This technique has been used in problem solving, process improvement, and research and development efforts to save what is estimated to be in excess of \$350M dollars in potential losses or lost opportunities.

SPA was developed in an effort to reach management's attention while facilitating DOE implementation, process understanding, validation, and quality improvement. After reviewing the advantages and disadvantages, ease of use, and practicality of SPA, one can see why this author will continue to use it as his preferred test strategy.

The use of this strategy and methodology is encouraged in an effort to promote holistic understanding of processes, cut overall rejection rates, and improve process profitability.

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