Custom measurement system design and qualification, a case study

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ABSTRACT

Like high-volume manufacturers, specialty manufacturers need to measure important product quality characteristics. However, they often discover that off-the-shelf measurement systems, many of them designed for high volume purposes, do not meet their needs. When this happens, they have no choice but to design and qualify their own equipment. This case study outlines the development of a custom measurement system by a diverse team of people at Samson Rope Technologies, a high performance rope manufacturer.

Samson needed the system to measure the tensile strength of twisted HMPE (high modulus polyethylene) yarns used as sub-units in demanding ship mooring, tug and other rope applications. Samson faced four fundamental measurement challenges:

- multi-ton break strengths
- intrinsically slippery and difficult to grip
- twisted in 2 directions (S, Z)
- test is destructive

Unfortunately, readily-available tensile testing grips sold by instrument manufacturers were unable to provide acceptable results. This left Samson Rope with only one choice – in-house custom grip development

This paper outlines the process approach taken by the development team and how JMP dramatically improved the team's creative thinking process. The first step was to use fundamental engineering principles and *the-wisdom-of-colleagues* to identify controllable factors and safe experimental ranges. The factors and ranges were used in a Definitive Screening experiment to identify key main effects and, with augmentation, to create a useful predictive model of the measurement process. The team followed the grip design optimization with iterative measurement systems analysis (MSA) to fine-tune the testing procedure and improve the system's signal-to-noise ratio.

CASE STUDY PURPOSE

The main intention of this paper is to help others use JMP's Design of Experiments capabilities to develop new measurement equipment and to use JMP's EMP[1] measurement systems analysis method to improve measurement methods. By doing so, the authors hope to positively impact colleagues, acquaintances, Process Engineers, Manufacturing Engineers, Quality Engineers and other process improvement enthusiasts.

RISK, AN IMPORTANT PERSPECTIVE

High performance ropes are used in high risk applications as shown in Figure 1 and 2. Business risk is an important context for measurement system development and in this case, significant effort for improved signal-to-noise ratio was easily justified.

Figure 1, Typical high risk application, mooring

Figure 2, Typical high risk application, arborist

PROCESS OVERVIEW

Manufacturing high-performance rope for high risk applications is a complex process requiring predictable raw materials, optimized process setpoints, predictable processes and effective maintenance. The process starts with multiple HMPE fibers (Figure 3) twisted by a twisting machine (Figure 4) into a yarn (Figure 5)

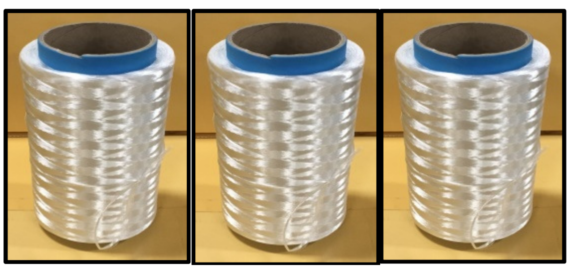


Figure 3, raw material – HMPE fiber

Figure 4, Roblon T300 twister

Figure 5, twisted HMPE yarn, our subunit of interest

As a side note, multiple yarns are then twisted together into a strand and strands (typically 12 of them) are then braided into a finished rope as shown in Figure 6.

Figure 6, Samson EverSteel-X mooring rope

This paper does not include a discussion of rope strength, only the strength of the HMPE yarn subunits.

THE RATIONALE

Tensile testing finished ropes to failure yields much useful information about rope performance. However, anomalies seen during the test may be difficult to diagnose because of the multi-step, complex manufacturing process. For a higher-than-expected result, what was the root cause - raw material, twisting, stranding, braiding, coating or something else?

This quandary pointed toward the need to understand the strength of the twisted yarns themselves. It was initially assumed that off-the-shelf grips were available for the testing. However, we learned that they're not designed for our product of interest. And the testing is destructive, making measurement system characterization more difficult.

THE CHALLENGE

In the end, we discovered that off-the-shelf grips (Figure 7) were excellent for testing PET yarns or very small HMPE yarns, but were unsuitable for our HMPE yarns of interest where best-case Intra-class Correlation Coefficient was about 60% even with a fairly wide range of representative product. In some cases, the measurement system was virtually useless as shown in Figure 8.

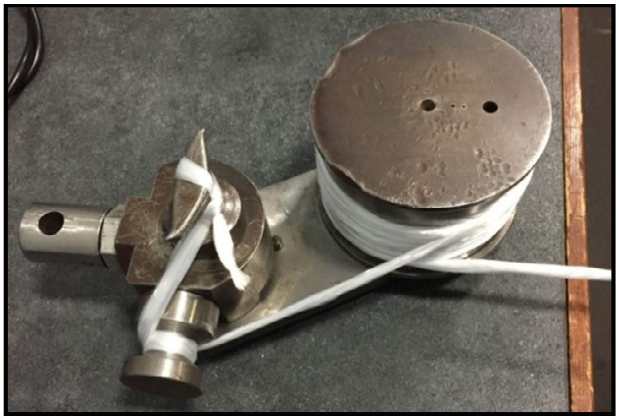


Figure 7, off-the-shelf grips

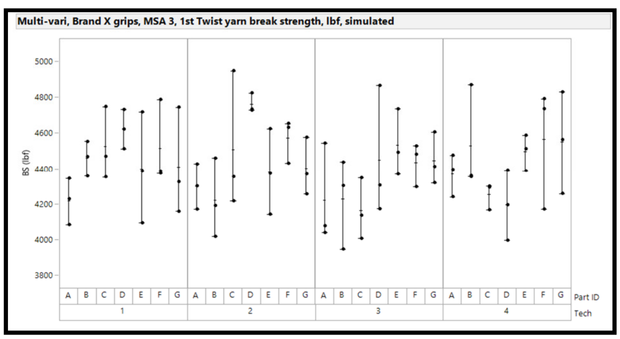


Figure 8, money for nothing

DEVELOPMENT TEAM

The team consisted of an experienced Lab Technician, an R&D Engineer and a Quality Engineer with machining support provided by a Maintenance Technician. It was quickly agreed that the project framework would start with designed experiments to optimize the grip design, followed by EMP measurement systems analysis to optimize the test procedure.

WORK SEQUENCE

SEQUENCE	WHAT WE DID
Prepare	Collect the facts, talk to people
Model cause & effect	Iterative DOE to optimize the grips
Look for trouble	Visual PFMEA[3] and iterative MSA to optimize the test process

Table 1, Work sequence

THE WISDOM OF COLLEAGUES

When working on process improvement, with or without employing statistical methods, Samson's first step is always to seek the sage advice and cooperation of process operators, supervisors and maintenance staff. Discussions always take place on the shop floor or in the maintenance area.

Warning: do not skip this step

DOE, STEP 1 – ZERO IN ON THE GOAL

Another standard process improvement practice is to pay careful attention, up front, to project scope and goal definition. We use a document titled *Checklist for Asking the Right Question*[2] to provide a superb forum for group discussion and joint development of the goal, in this case?

Develop break strength measurement fixtures for twisted yarn type X with a 90% chance to detect desired differences with sample sizes ≤ 5 when tested per SRT-100[4]

DOE TRICK OF THE TRADE

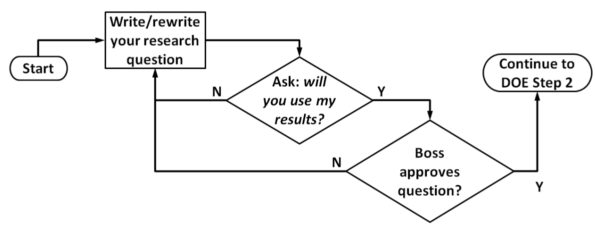


Figure 9, how to avoid disappointment

DOE, STEP 2 – CHOOSE A STRATEGY

Experimenters have three general approaches, strategically-speaking, as shown in Table 2.

STRATEGY	TYPICAL DESIGN	ESSENTIALS
Comprehensive	I-Optimal	RSM, more work
Reserved	Factorial	Conserves resources
Screening	Definitive Screening	Use for 5+ factors, possible to augment

Table 2, DOE strategies

The team recognized the need to study at least 9 factors of interest. Clearly, this was a job for Definitive Screening and we chose to add 2 blocks with center runs (to estimate response curvature) and 4 extra runs[5].

These factors will be referred to as X_1 to X_9. One factor was categorical, the rest were continuous. A few examples (ref Fig 7):

- Capstan diameter
- Capstan surface coefficient of friction

DOE, STEP 3A - CREATE A PLAN

JMP's sequence for creating a Definitive Screening Design (DSD) is straightforward. In the first screen, we input the process factors, ranges and the desired response (Figure 10).

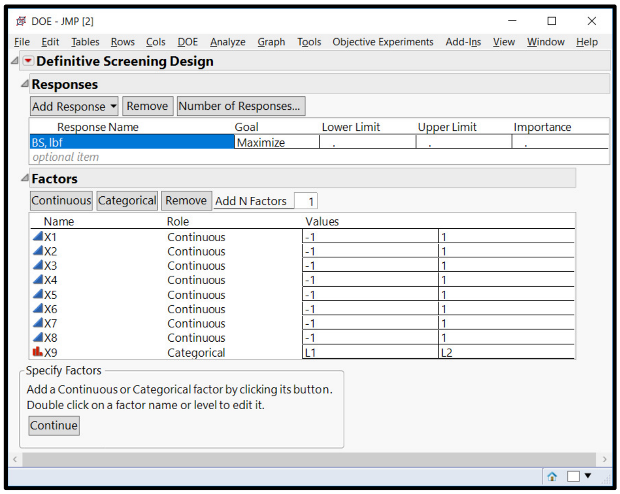


Figure 10: create the plan

In the subsequent screen, we choose options like blocking and doing a bit of extra work to estimate quadratic effects (Figure 11)

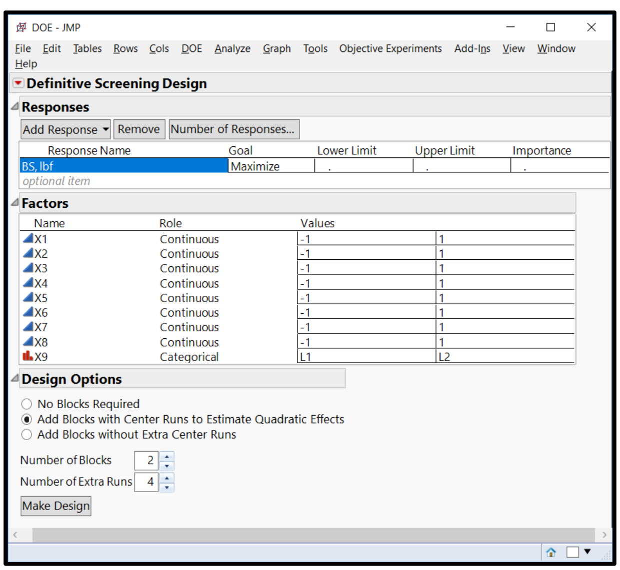
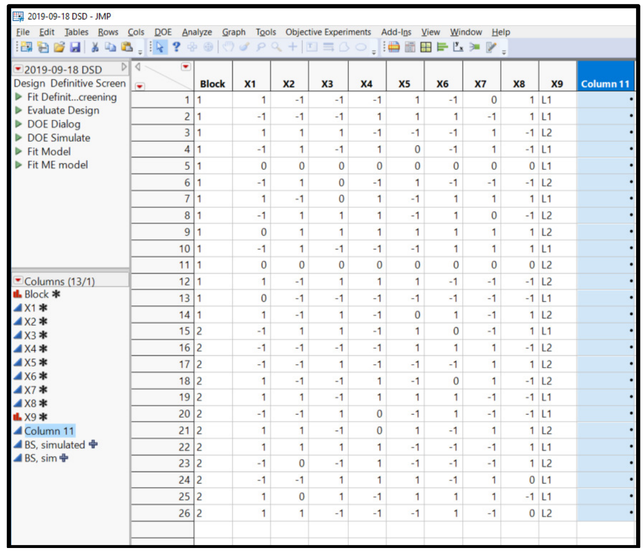


Figure 11: finalize the plan

JMP creates a work plan in tabular form as shown in Figure 12. Note that multiple factor levels change from one run to the next, unlike the misguided *One-Factor-At-A-Time* method.



	Block	X1	X2	X3	X4	X5	X6	X7	X8	X9	Column 11
1	1	1	-1	-1	-1	1	-1	0	1	L1	•
2	1	-1	-1	-1	1	1	1	-1	1	L1	•
3	1	1	1	1	-1	-1	-1	1	-1	L2	•
4	1	-1	1	-1	1	0	-1	1	-1	L1	•
5	1	0	0	0	0	0	0	0	0	L1	•
6	1	-1	1	0	-1	1	-1	-1	-1	L2	•
7	1	1	-1	0	1	-1	1	1	1	L1	•
8	1	-1	1	1	1	-1	1	0	-1	L2	•
9	1	0	1	1	1	1	1	1	1	L2	•
10	1	-1	1	-1	-1	-1	1	1	1	L1	•
11	1	0	0	0	0	0	0	0	0	L2	•
12	1	1	-1	1	1	1	-1	-1	-1	L2	•
13	1	0	-1	-1	-1	-1	-1	-1	-1	L1	•
14	1	1	-1	1	-1	0	1	-1	1	L2	•
15	2	-1	1	1	-1	1	0	-1	1	L1	•
16	2	-1	-1	-1	-1	1	1	1	-1	L2	•
17	2	-1	-1	1	-1	-1	-1	1	1	L2	•
18	2	1	-1	-1	1	-1	0	1	-1	L2	•
19	2	1	1	-1	1	1	1	-1	-1	L1	•
20	2	-1	-1	1	0	-1	1	-1	-1	L1	•
21	2	1	1	-1	0	1	-1	1	1	L2	•
22	2	1	1	1	1	-1	-1	-1	1	L1	•
23	2	-1	0	-1	1	-1	-1	-1	1	L2	•
24	2	-1	-1	1	1	1	-1	1	0	L1	•
25	2	1	0	1	-1	1	1	1	-1	L1	•
26	2	1	1	-1	-1	-1	1	-1	0	L2	•

Figure 12: the work plan

DOE, STEP 3B: EXECUTE THE PLAN

Here are a few *tricks-of-the-DOE-trade* worth considering when collecting the data per the DSD plan.

- Do the work yourself, where practical
- Always do at least one practice run
- Record nuisance variables like ambient temperature, %RH, etc.
- Enter response data directly into the JMP Data Table, if possible
- Take photos and videos, where practial
- Beware arbitrary deadlines, a steady, flexible pace is best.

DOE, STEP 4A: EVALUATE RESULTS

JMP provides world-class graphics to help keep us on track. Figure 13 provide quick, graphical feedback on the ability of our predictive model to, well, predict results.

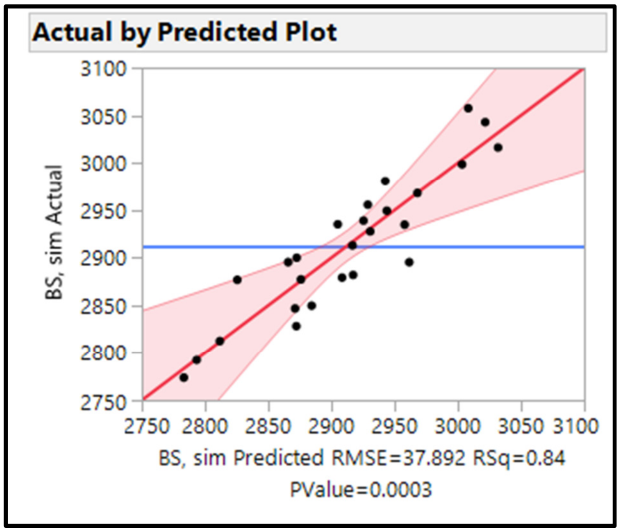
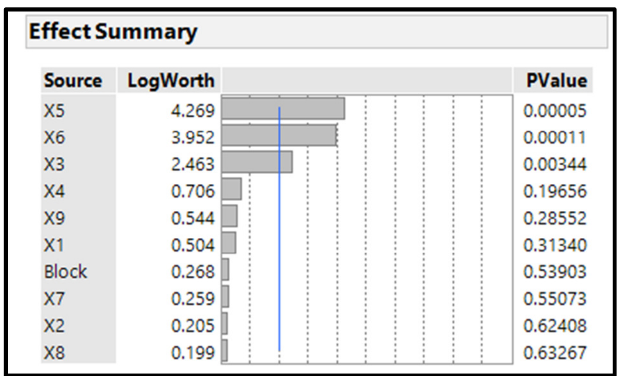


Figure 13: assessing the quality of our model

Likewise for a quick visual graphic that begins to address our goal. See Figure 14.



Source	LogWorth	PValue
X5	4.269	0.00005
X6	3.952	0.00011
X3	2.463	0.00344
X4	0.706	0.19656
X9	0.544	0.28552
X1	0.504	0.31340
Block	0.268	0.53903
X7	0.259	0.55073
X2	0.205	0.62408
X8	0.199	0.63267

Figure 14: discovering what's important

The Effect Summary tells us that factors X_3, X_5 and X_6 have an impact on our desired response (break strength), although we can't be sure yet if there are any interactions present.

DOE, STEP 4A: AUGMENT & REDUCE

Definitive Screening is a major breakthrough in experimental design. For example, we can now take the same data set, augment it if necessary and fit it to a reduced response surface model using only factors X_3, X_5 and X_6 as shown in Figure 15. This is a first order answer to our question – how do we design the grips?

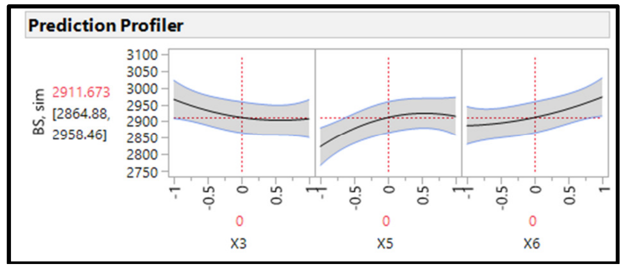


Figure 15: our answer

The first impulse might be to ask JMP to optimize the process settings, but we advise caution. Consider Figure 16, for example.

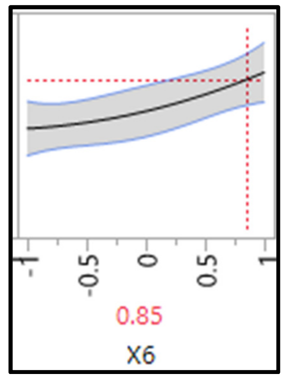


Figure 16: be very, very careful.

One might be tempted to set X_6 =1. However, we have no idea how X_6 behaves beyond a value of 1. However unlikely, it may tail off rapidly and a set point of 1.05 might leave our process in a shambles. To guard against process drift, we suggest a cautious approach keeping X_6 set away from the edge at, say, a value of 0.85 or 0.90.

Only the paranoid survive[6]
(Andy Grove, 1936-2016)

It's also important to recognize opportunities to make processes robust. Figure 17 shows a highly desirable response curve where the process can be set in the center of a flat spot, thus providing protection against process drift.

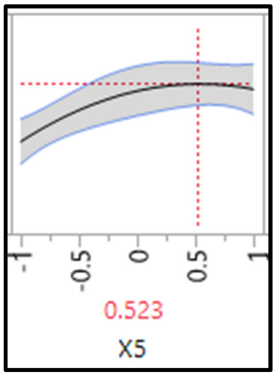


Figure 17: protection against drift in either direction

Based on the knowledge gained in the screening experiment and the known application risk, the team decided to run I-Optimal DOEs using X_3, X_5, X_6 and a new, previously-unstudied factor, X_{10}. The RSM experiments produced the knowledge needed to finalize the grip design.

DOE, STEP 5: ACKNOWLEDGE OTHERS

A key to perpetual DOE success is to acknowledge those that helped you along the way. Failure to do this means you'll get little cooperation and help in the future, understandably so.

DOE COMPARISONS

Screening followed by a comprehensive approach to DOE made sense for this project. Following is a summary or the two options:

ADVANTAGES	DISADVANTAGES
Only practical way to handle large # of factors	Can't define constraints
Augment to "sneak up" on desired model	Can't handle mixtures
Reduce to RSM model	2-level discrete factors only

Table 3, Definitive Screening DOE

ADVANTAGES	DISADVANTAGES
Choose # of replicate runs	More work than DSD
Better RSM models	Typically for <= 5 factors
Can handle mixtures	
Can define constraints	

Table 4, I-optimal DOE

DOE RESULTS

Iterative DOE lead to a tensile grip design that met our goal. In time, we could distinguish desired differences with a sample size of 5. However, optimizing the grip design in a lab & experimental setting is one thing, but getting it to work routinely with multiple operators was a different challenge.

VISUAL PFMEA

A good tool for process improvement is Failure Mode & Effect Analysis (FMEA). It is a structured method designed to help answer two important questions:

- What could go wrong?
- What can we do about it?

However, classic FMEA, with dreary, headache-inducing sessions in conference rooms using Excel spreadsheets with tiny fonts, amounts to cruel and unusual punishment. In response, Samson developed its own visual approach to Safety FMEA, Design FMEA and Process FMEA to reduce the pain of traditional risk analysis. The analysis uses a video (preferred) or photo as the focus for group identification of risk. Figure 18 shows a photo-based example.

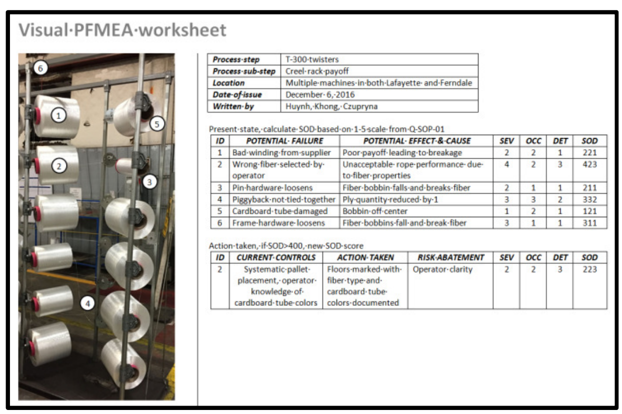


Figure 18: a visual approach to FMEA

The take-away from our P-FMEA was a list of potential measurement method trouble spots that needed to be addressed during the MSA.

THE MSA DESIGN

- 7 parts x 3 operators x 3 measurements
- Graphical analysis

- EMP analysis
- An iterative approach

JMP's highly visual, easy-to-understand MSA output highlights improvement opportunity. Figure 19 shows some concern about repeatability and reproducibility.

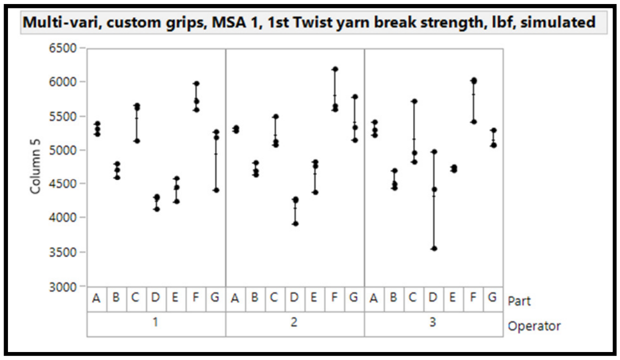


Figure 19: a good start, but not good enough

Referring to the potential trouble spots highlighted in the measurement P-FMEA, the team took action to improve lighting, support fixturing, instructional clarity, accessibility of support tooling and a method to control the bundled fiber twist.

After a few MSA iterations, the signal-to-noise ratio improved and we had our system. See Figure 20.

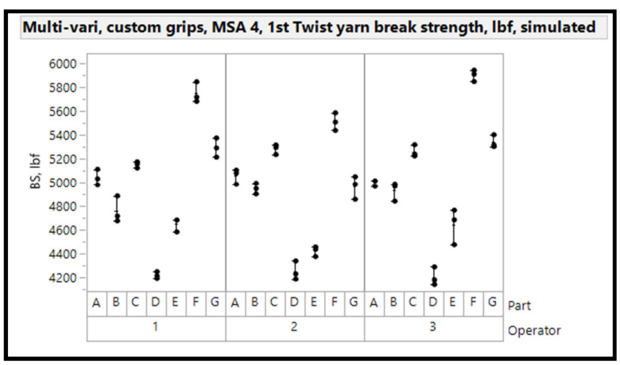


Figure 20: after multiple iterations, a highly useful system

KEYS TO PROJECT SUCCESS

Sweat the Human Elements

A major key to success for measurement system development is to carefully consider human elements. The highest priority in test system design and layout is safety. We used our Visual S-FMEA method to identify and address a long list of potential hazards:

- Sonic (sharp noise at break)
- Electrical
- Cut
- Pinch
- Impact
- Entanglement
- Vibration
- Flying debris
- Ergonomic, exertion
- Repetitive motion
- Falling object
- Thermal
- Inhalation
- Tripping
- Chemical

Careful, paranoid consideration of safety when designing measurement systems (or any other process) is simply not optional.

Other human elements of importance included accommodation of:

- left-handed people
- height variation
- physical strength variation
- variation in visual acuity
- tolerance to noise and other factors

The right mindset

A deliberate, informal approach, based on sound statistical and lean principles, lead to success. There was no Team Leader, no hierarchy and no project formalities. Little time was spent in a conference room. Instead, the work was done by a diverse, focused group of people <u>in the lab, in the machine shop and on the factory floor</u>. Interactions between people were productive and rewarding. Along the way, JMP served as a lynchpin, providing a focal point for data-centric decision-making, supported by clear, convincing graphics.

A word of caution
The development project hit many obstacles. Designed experiments and MSAs, rarely unfold exactly as planned. The *faint-of-heart* should steer well clear of iterative DOE and iterative MSA.

Apply lean principles
Samson has had great success with the application of 5S principles to measurement system design and layout. Chaos and clutter are the enemy of good measurements, thus having a neat, organized workplace results in a better signal-to-noise ratio.

Special mention must be made regarding ambient lighting. In our experience, poor lighting or lighting skewed toward a yellow (2200-2700°K) color temperature can add unwanted noise to measurement systems. 4200°K is a good color temperature for the measurement environment.

In addition, respect for people is another lean principle to keep in mind during measurement system development and layout. For example, if the measurement system operator is put under pressure by people hovering about during the measurements or by ill-informed supervisors setting arbitrary productivity expectations and the like, the result will almost certainly be more noise. Samson coined the term "Orwellian Bias" to make our point about the need for a respectful, stress-free environment for test personnel.

Use JMP graphics to manage Managers
While steady progress is a requirement for process improvement specialists, the rate of progress must be kept in balance with the need to get things right. Pressure to cut corners and speed up is common and understandable.

One remedial tactic is to use JMP's excellent graphics as the main progress reporting tool. Our experience indicates they convey a clear statement of progress and they work far better than written reports and bullet lists. Here are a few examples:

- Variability charts with partial DOE results, by block as shown in Figure 21
- Variability charts with partial MSA results, by operator/part

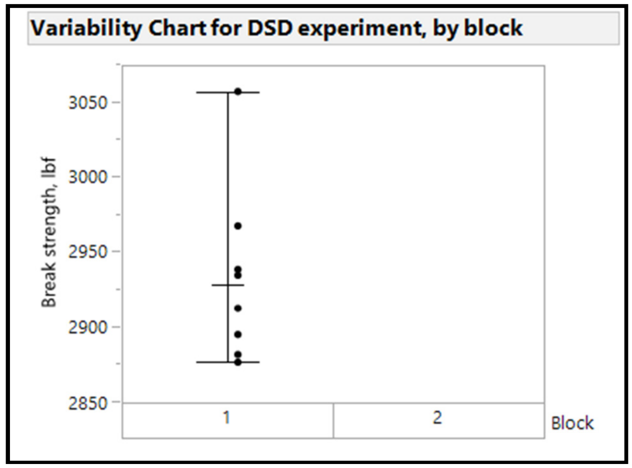


Figure 21: partial DOE results, for reporting purposes only

These charts may not be useful for analytic purposes, but they can be useful for other purposes.

ENTROPY IS INSIDIOUS & EVIL

Entropy is an unfortunate fact of industrial life. As a countermeasure to long-term equipment degradation and employee turnover and to acknowledge the risk inherent in the use of high-performance ropes, the team developed a daily validation routine. At the beginning of each day, a technician does the following:

- perform 3 breaks of a "standard yarn" with a well-characterized break strength
- plot the results immediately on an X-bar-R control chart. See Figure 22.
- interpret the control chart, look for measurement process signals
- proceed with actual product measurement in the absence of control chart signals.
- stop immediately in the presence of control chart signals and address the process shift before proceeding

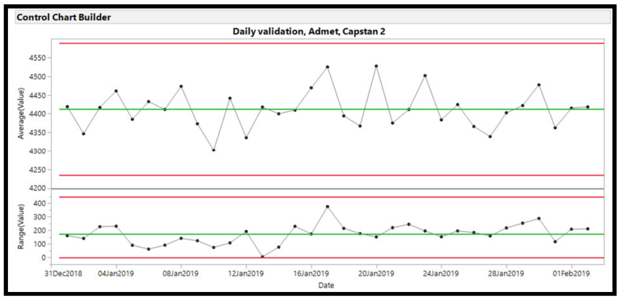


Figure 22: daily system validation

FINAL RESULTS

The custom grips and highly-tuned measurement process method have served Samson well for more than a year. We successfully identified cause-and-effect relationships that were vital to optimize the grip design and we successfully tuned our measurement method to yield the best signal-to-noise ratio. The insight gained from sub-component strength measurements is a foundation of important continuous improvement and process troubleshooting work.

In addition, due to the statistical approach taken, a number of measurement nuances were discovered during the project, providing Samson with a potential competitive advantage.

EPILOGUE

This case study is another clear demonstration of the philosophical underpinnings of statistical thinking, i.e. to treat all work (including measurements) as a process, that all processes vary and that the key to success is a statistical approach and variation reduction.

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AUTHOR BIOGRAPHIES

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