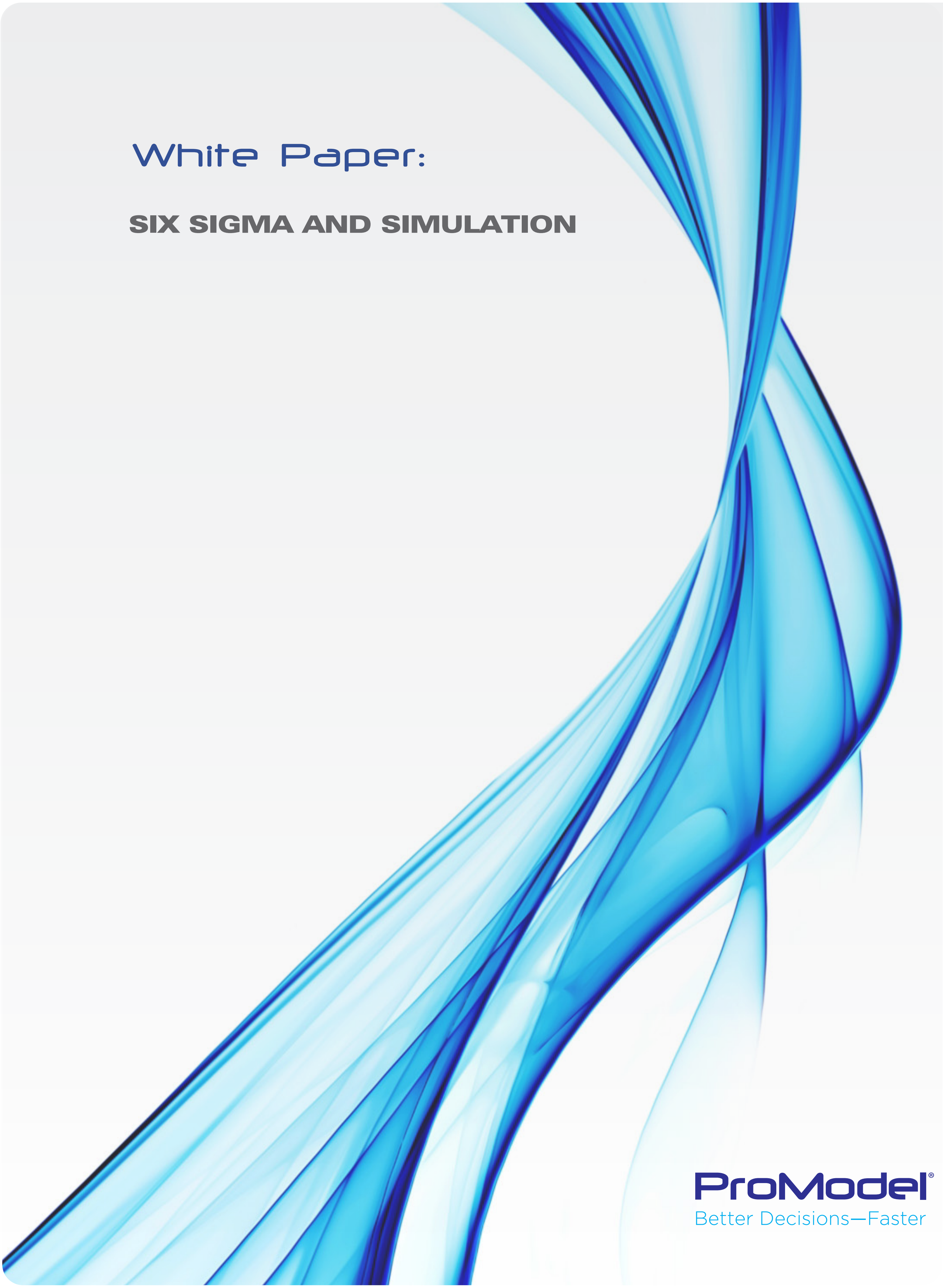
White Paper:

SIX SIGMA AND SIMULATION



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Six Sigma and Simulation

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WHAT IS SIX SIGMA?

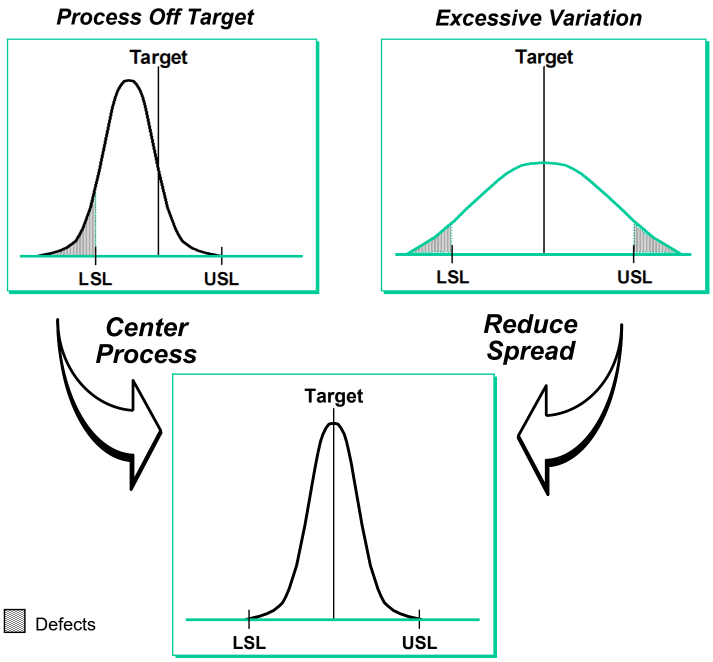
In simple terms Six Sigma is a disciplined program or methodology for improving quality in all aspects of a company's products and services. In many ways it represents that latest step in the evolution of the Total Quality Management movement begun by W. Edwards Deming in the 1950's. The Six Sigma program is credited to Dr. Mikel Harry, a statistician who is co-founder and a principle member of the Six Sigma Academy in Scottsdale, Arizona. Early corporate adopters of the program include Motorola in the 1980's, and other technology-based firms such as General Electric, Texas Instruments and Allied Signal.

The central theme of Six Sigma is that product and process quality can be improved dramatically by understanding the relationships between the inputs to a product or process and the metrics that define the quality level of the product or process. Critical to these relationships is the concept of "Voice of the Customer." In other words, quality can only be defined by the customer who will ultimately receive the outputs or benefits of a product or process.

In mathematical terms, Six Sigma seeks to define a transfer function, $y = f(x_1, x_2, \ldots, x_n)$, between the quality metrics of a product or process (e.g. the life expectancy of a product, or the % on-time delivery for a fulfillment process), and the inputs that define and control the product or process (e.g. tolerance of a physical dimension or the number of resources available to service customers). The focus of Six Sigma then is two-fold; 1) understand which inputs (x's) have the greatest effect on the output metrics (y's), and 2) control those inputs so that the outputs remain within a specified upper and/or lower specification limit.

In statistical terms, Six Sigma quality means that for any given product or process quality measurement, there will be no more than 3.4 defects produced per 1,000,000 opportunities. An "opportunity" is defined as any chance for nonconformance, or not meeting the required specifications. By comparison, typical quality levels for manufactured products today achieve about 4 Sigma, which translates to about 6,000 defects per 1,000,000 opportunities.

The diagram below shows the results of two poorly performing processes. On the left, the process is off-center, producing outputs that are mostly below the target value. All observations below the lower specification limit (LSL) are considered defects. On the right, the process produces outputs that, on average, are on target, but with great variability. All observations below the LSL or above the USL are considered defects. The goal of Six Sigma is to both center the process and reduce the variation such that all observations of a Critical to Quality (CTQ) measure are within the upper and lower spec limits.



STRUCTURE OF A SIX SIGMA INITIATIVE

To ensure success, a Six Sigma initiative must receive complete buy-in and continuous support from the highest level of a company's leadership team. In addition, a rigorous training program and dedicated staff positions will require the best and brightest minds that can be allocated to the initiative.

Roles and Responsibilities

"Champions" are high-level executives, including VP's or General Managers, who communicate the business case for the initiative, and provide the resources and the motivation necessary to sustain it.

"Master Black Belts" are change agents who lead the initiative in each major division or function of the company. Their primary role is to train and support the Black Belts who will be leading major projects. They also track the success of each project in terms of customer satisfaction and other corporate goals.

"Black Belts" are full-time resources who are dedicated to leading major Six Sigma projects for a period of 18-24 months. They receive rigorous training and mentor Green Belts on the use of Six Sigma tools and methods.

"Green Belts" are resources who are trained on the concepts of Six Sigma and support the Black Belts in projects involving their own functional areas. Green Belts also lead one or more small projects each year.

Project Selection Criteria

Successful projects share common elements. The following criteria should be considered to ensure a successful project.

- The project clearly relates to the customer and their quality requirements. If the customer doesn't feel the improvements resulting from the project, then much time and effort has been wasted.
- The problem and goal statements are clearly stated and understood by everyone on the project team. Effective problem and goal statements are SMART: Specific, Measurable, Attainable, Relevant and Time Bound.
- Definitions of a "Defect" and an "Opportunity" are clearly stated and understood.
- The project does not presuppose a solution at the outset.
- The project aligns with the business strategy.
- The project makes effective use of the Six Sigma tools.
- The project is data driven.

Evaluation of Project Performance

Just as the level of product and process quality can be defined in measurable terms, so can the success of a Six Sigma project. Projects are evaluated in terms of their:

1) Perceived benefit to the customer
2) Improvement in output performance (Z-value)
3) Financial contribution to the company

SIX SIGMA METHODOLOGY: DMAIC VS. DMADV

Six Sigma has two branches depending on the focus of improvement efforts. For existing products and processes, the DMAIC methodology applies. For new products and processes, the DMADV methodology applies. The first three steps in each case are similar, Define, Measure and Analyze. For DMAIC, the last two steps focus on Improving and Controlling existing product or process inputs. For DMADV, the final steps focus on Designing and Verifying the future product or process inputs.

The DMAIC methodology for existing products and processes consists of the following steps:

- **Define** – Identify the project goals and objectives and the customer’s CTQs. Create a team charter that lists the roles and responsibilities of the team members including, of course, the customer. Define the boundaries of the project, including the products and processes to be examined.

- **Measure** – Select the characteristics of the product or process to be measured (i.e. the outputs). Define the performance standards for those outputs. Create a data collection plan for gathering data on the outputs. Perform a measurement system analysis to determine the capability of all measuring devices to accurately measure the outputs (Y’s).

- **Analyze** – Establish the capability of the current product or process in statistical terms (i.e. what is the current sigma quality level). Identify a transfer function that relates the inputs to the outputs. Identify sources of both random cause variation and special cause variation in the inputs (X’s).

- **Improve** – Use Design of Experiment techniques to determine which inputs should be the focus of improvement efforts. Determine the effects of improved inputs on the outputs by performing a sensitivity analysis. Establish acceptable operating tolerances for the inputs.

- **Control** – Perform a measurement system analysis to determine the capability of all measuring devices to accurately measure the inputs. Implement statistical process control measures on the inputs to ensure that they remain within acceptable operating tolerances.

Steps 4 and 5 of the DMADV methodology consist of the following activities:

- **Design** – Generate and verify system and/or subsystem models, allocations and transfer functions. Optimize X's through statistical analysis of variance drivers. Generate purchasing and/or manufacturing specifications and verify measurement systems on the X's.

- **Verify** – Statistically confirm that product/processes match predictions. Develop mfg and supplier control plans. Document product/process capabilities and transition to full production rates.

Each step in the DMAIC and DMADV methodologies requires the use of specific skills and tools to achieve the desired results. For example, in the Define stage the Critical to Quality parameters (CTQ's) are identified using a tool called Quality Function Deployment (QFD). In the Measure stage, a calibration process called Gage R&R is used to determine the capabilities of the output measuring devices. And in the Control stage, Statistical Process Control Charts are used to ensure that system inputs remain within acceptable tolerance levels.

Simulation is a tool that can be used in multiple stages of a Six Sigma project. However, it is typically applied in the Analyze & Improve or Analyze & Design stages. A simulation model becomes a transfer function that relates the critical X's (inputs) to the Y's (outputs). Experimentation with the X's leads to a better understanding of process capability. The next section shows how a simulation model was used to predict the future-state performance of a manufacturing process.

CASE STUDY: CYCLE TIME REDUCTION FOR GENERATOR FIELD MACHINING

Background:

A manufacturer of industrial power generation equipment produces five types of generators. A key component of each unit is the rotating Field that turns inside the generator. Current planning cycles for Field machining range from 73 to 124 business days, depending on product type. The Field machining area has been experiencing rising WIP levels and inflated cycle times due to capacity constraints in the system. The process is expected to be stressed even further due to increased volumes in the coming year. A solution to achieve the required throughput and maintain acceptable cycle times must be found.

Define:

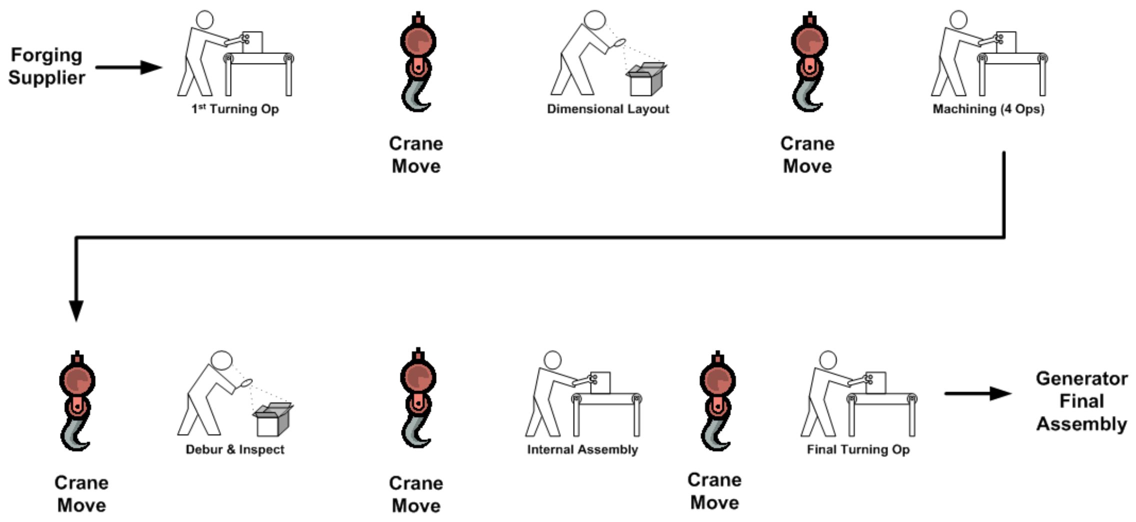
In this stage we answer the following questions: who is the customer, who is on the project team, and what are the boundaries of the process? The results of the Define stage are as follows:

Customer – Generator Final Assembly Production Manager (Internal Customer)

Team – Black Belt, Machinists & Shift Foreman, Production Control Staff, Forging Supplier

Process Boundaries – All Process Steps from Receipt of Forging through delivery to Final Assembly

Field Machining Process



The process consists of 9 steps, with bridge crane movements between each operation. Also, each operation may be performed at multiple locations in multiple areas, which increases the demands on the cranes. If a move is made from one bay to another then two crane moves will be required in addition to a rail car move.

All machines have preventive maintenance schedules in addition to random breakdowns.

All work is inspected before moving to the next operation in order to eliminate additional rework steps.

Setups are required at each step in the process whenever the previous and current product types differ.

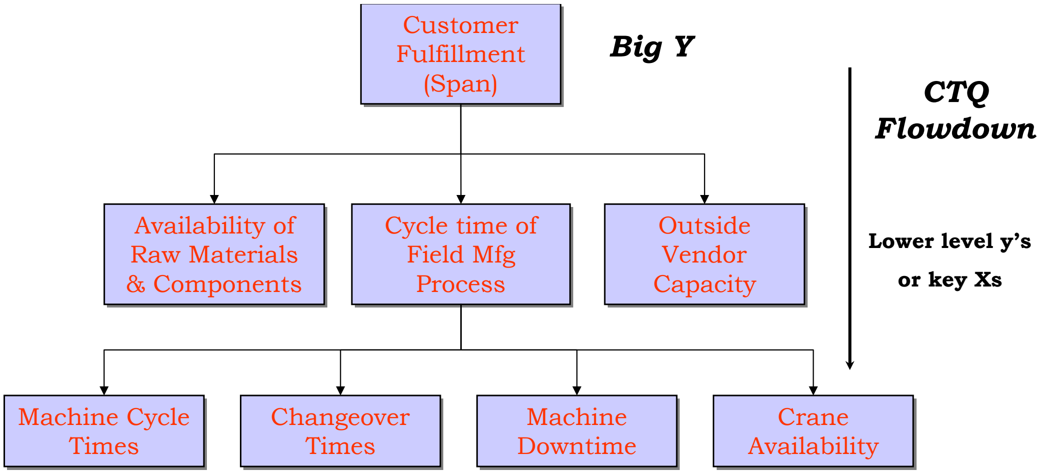
Measure:

In this stage we select the characteristics of the product or process to be measured, we define the performance standards for those outputs, and we perform a “CTQ Flowdown” to understand the relationship between the inputs and outputs.

Primary CTQ – Cycle Time, from receipt of forging through delivery to Generator Final Assembly

Performance Target – 0 days late from Master Schedule plan (Span = 0)

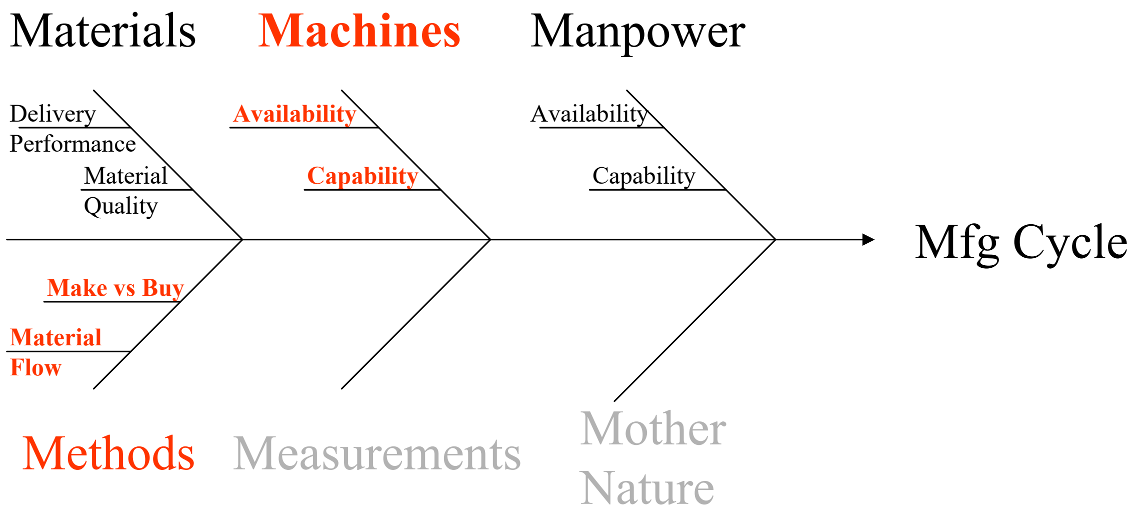
CTQ Flow Down:



$$\text{Mfg Cycle} = f(X_1, X_2, X_3, \ldots)$$

The diagram above shows how our primary CTQ, Mfg Cycle, is a function of parameters which are under our control, such as machining times, changeover times, downtimes and crane availability. Other factors, such as product mix and holiday schedules must also be taken into account.

Another tool used to show the relationship between inputs and outputs is a fishbone diagram like below.



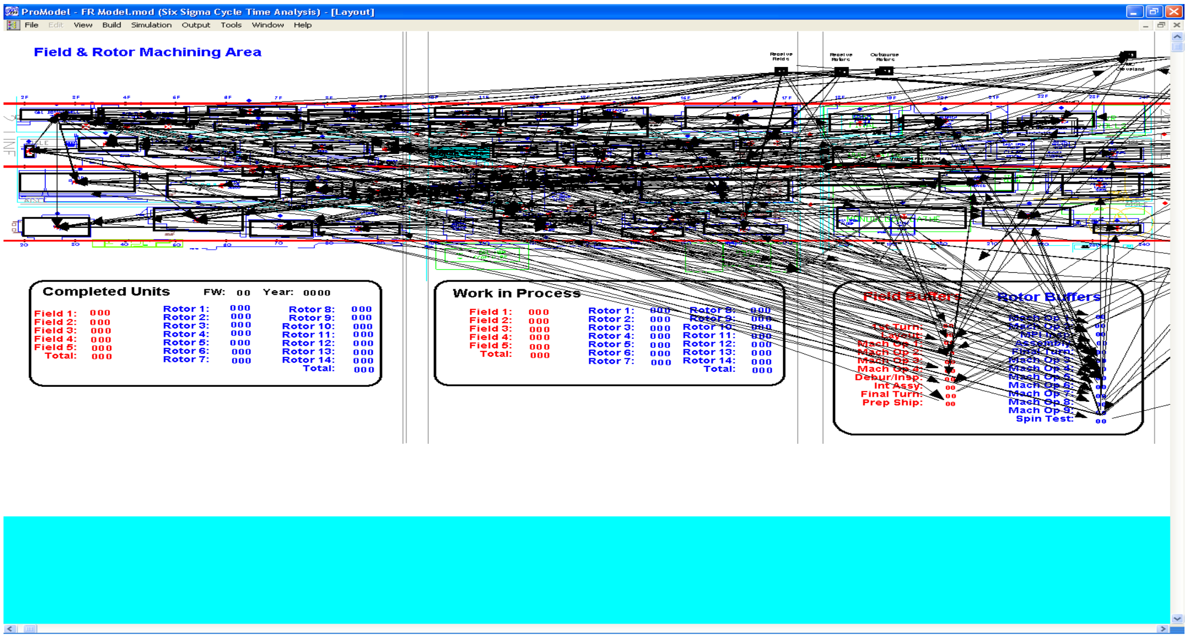
Analyze:

In this stage we seek to establish the capability of the current process in statistical terms, i.e. what is the current sigma quality level (Z-score). Then we seek to develop an accurate transfer function that relates the inputs to the outputs, so that realistic delivery dates can be determined and on-time delivery of each Field can be assured. Finally, we identify sources of both random and special cause variation in the inputs, and perform experiments to understand their effects on the outputs.

The current method for determining delivery dates is a manual process, using project management-type software to sequence and schedule each customer order through every step of the process. While this method provides a good estimate of the expected completion date, it does not account for the realities of both random and special cause variation in the process. The typical way to account for these delays is to add a cushion factor to each operation time, resulting in an extended cycle time.

In addition to the inherent inaccuracies of the current planning method, the process is time intensive. Each time a major disruption occurs, like an unplanned downtime at a bottleneck machine, the planning process must be repeated.

In order to determine the current process capability, we must have a transfer function that accurately relates the inputs to the outputs. For a simple system, with minor process variation and dedicated resources (no interdependencies), a spreadsheet calculation can be used to create the transfer function. However, the complexity of most manufacturing systems requires a more robust model that takes into account these realities. The picture below shows the complexity of the process routing, where each arrow represents a potential move from one machine or queue to another, across two manufacturing bays.



Completed Units FW: 00 Year: 0000

Field 1: 000
Field 2: 000
Field 3: 000
Field 4: 000
Field 5: 000
Total: 000
Rotor 1: 000
Rotor 2: 000
Rotor 3: 000
Rotor 4: 000
Rotor 5: 000
Rotor 6: 000
Rotor 7: 000
Rotor 8: 000
Rotor 9: 000
Rotor 10: 000
Rotor 11: 000
Rotor 12: 000
Rotor 13: 000
Rotor 14: 000
Total: 000

Work in Process

Field 1: 000
Field 2: 000
Field 3: 000
Field 4: 000
Field 5: 000
Total: 000
Rotor 1: 000
Rotor 2: 000
Rotor 3: 000
Rotor 4: 000
Rotor 5: 000
Rotor 6: 000
Rotor 7: 000
Rotor 8: 000
Rotor 9: 000
Rotor 10: 000
Rotor 11: 000
Rotor 12: 000
Rotor 13: 000
Rotor 14: 000
Total: 000

Field Buffers

1st Turn: 00
Layout: 00
Mach Op 1: 00
Mach Op 2: 00
Mach Op 3: 00
Mach Op 4: 00
Debur/Insp: 00
Int Assy: 00
Final Turn: 00
Prep Ship: 00

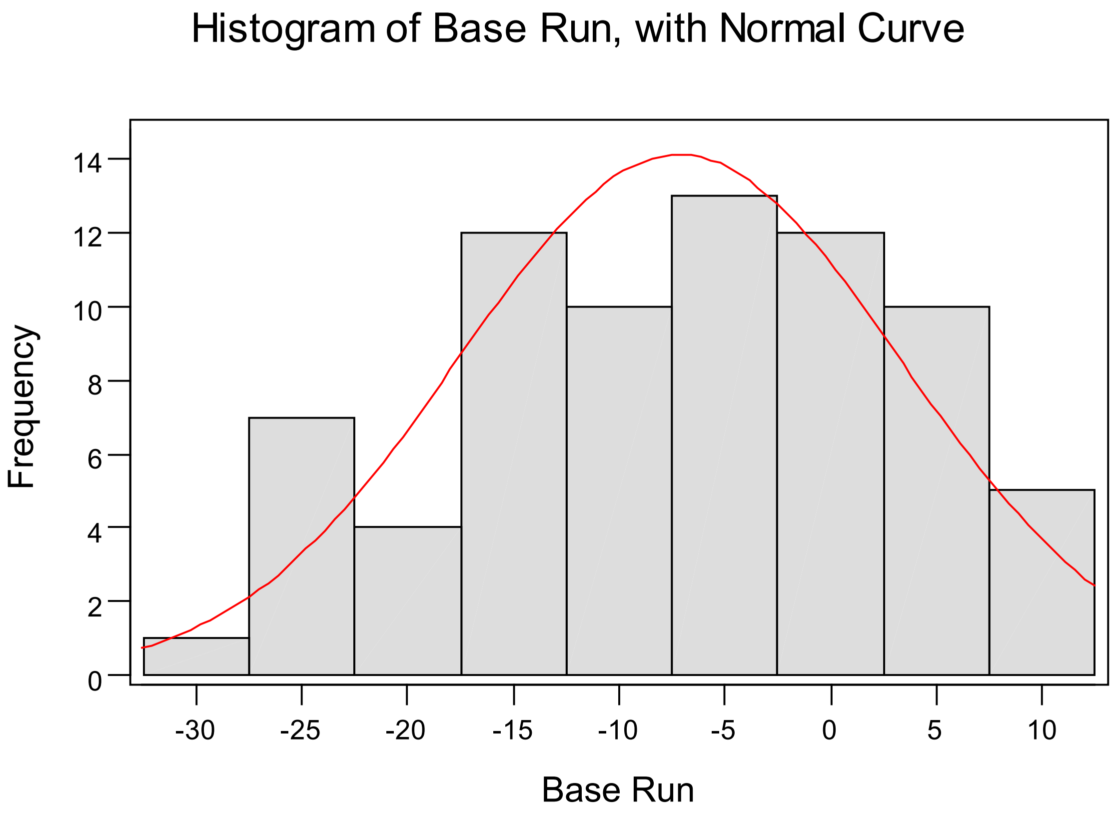
Rotor Buffers

Mach Op 1: 00
Mach Op 2: 00
MPI Insp: 00
Assembly: 00
Final Turn: 00
Mach Op 3: 00
Mach Op 4: 00
Mach Op 5: 00
Mach Op 6: 00
Mach Op 7: 00
Mach Op 8: 00
Mach Op 9: 00
Spin Test: 00

The process is made even more complicated by the fact that most machines are shared between Field mfg and other components. In this case, steam turbine rotors are also produced in the same area. Adding random machine downtimes and setup times that are dependent on the current and previous part types, it is easy to see that no spreadsheet calculation will adequately reflect the complexities of the Field and Rotor machining process. Therefore, a simulation model was built to represent the current-state process and predict future-state performance under several proposed process improvements.

The simulation model included all operations in the Field and Rotor machining processes. However, before the model could be used to test future-state scenarios, it had to be validated against actual historical production data. This task was performed and some refinements were made until the model outputs were very close to the results from the actual system.

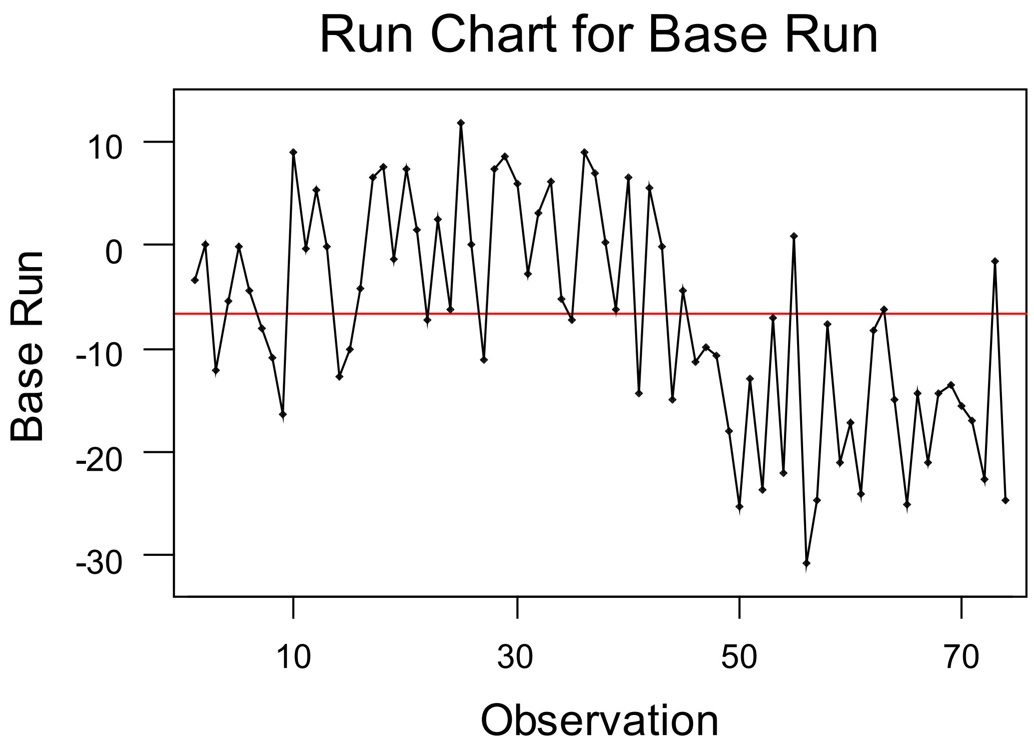
The outputs of the simulation provide both total cycle times and deviations from planned cycle times for each Field and Rotor processed. However, our primary concern in this model was Field cycle times, so they are the focus of this analysis. A first view of the Field data is seen through a histogram showing the distribution of the deviations from planned cycle times. The chart below shows an approximate normal distribution with a mean value of 7.15 days early. The standard deviation of 10.47 days and the range of 31 days early to 12 days late reflect a process with great variation.



```
Variable              N       Mean     Median     TrMean      StDev    SE Mean
Base Run             74      -7.15      -6.72      -6.98      10.47       1.22

Variable        Minimum    Maximum         Q1         Q3
Base Run         -30.92      11.81     -14.60       0.36
```

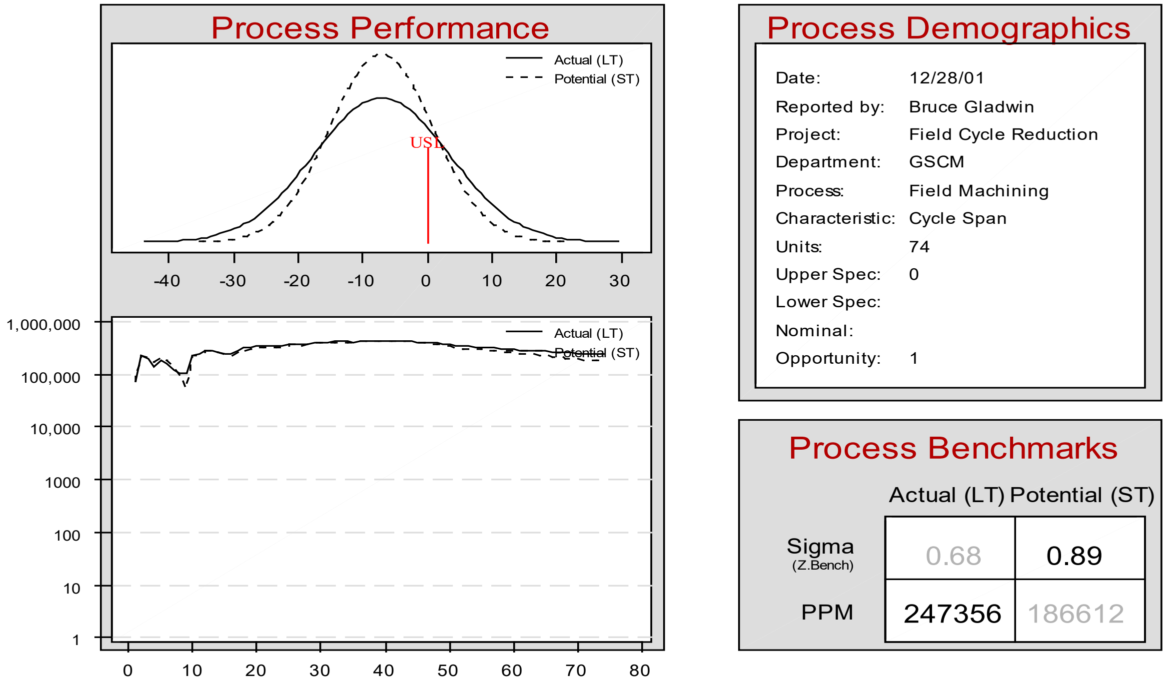
The next step in the analysis was to create a Run chart showing the number of days early or late for each Field over the 75 week production schedule. A run chart provides insight beyond the summary statistics, such as trends over time. The chart below shows that most of the late deliveries would occur between week 10 and week 45. The improvement after week 45 is due to additional machinery coming on line.



```
Number of runs about median:      24.0000        Number of runs up or dow n:      48.0000
Expected number of runs:          38.0000        Expected number of runs:         49.0000
Longest run about median:          9.0000        Longest run up or dow n:          4.0000
Approx P-Value for Clustering:     0.0005        Approx P-Value for Trends:        0.3901
Approx P-Value for Mixtures:       0.9995        Approx P-Value for Oscillation:   0.6099
```

Beyond the summary statistics and the run chart there are several excellent statistical tools available to perform a complete Six Sigma analysis on process data. The charts below were created using Minitab®. They show that our current process has a Z-value of only .89! In practical terms, this means that nearly 25% of all observations were greater than our target of 0 days late.

Report 1: Executive Summary



Process Demographics

Date: 12/28/01
Reported by: Bruce Gladwin
Project: Field Cycle Reduction
Department: GSCM
Process: Field Machining
Characteristic: Cycle Span
Units: 74
Upper Spec: 0
Lower Spec:
Nominal:
Opportunity: 1

Process Benchmarks

	Actual (LT)	Potential (ST)
Sigma (Z.Bench)	0.68	0.89
PPM	247356	186612

It is obvious from the run chart above that something must be done to prevent late deliveries in weeks 10 through 45. From our CTQ Flowdown, we know that we have some degree of control over machine cycle times, changeover times, downtimes and crane availability. However, at this point we do not know which of these factors will have the greatest impact on overall cycle time.

Improve:

In this stage of the analysis we used Design of Experiment (DOE) techniques to determine which inputs should be the focus of our improvement efforts. A discussion with the project team identified a set of experiments to help understand the sensitivity of the cycle times to each of three control parameters: changeover times, machine downtimes and crane move times. Machine cycle times were considered to be too difficult or too costly to reduce.

Experiment Table

Run 1 0/0/0	Run 2 30/0/0	Run 3 30/30/0	Run 4 30/0/30
Run 5 0/30/0	Run 6 0/30/30	Run 7 0/0/30	Run 8 30/30/30

2k Factorial DOE for Field Cycle Time

Run 1 = Base Run

Factor	Level 1	Level 2
Changeover:	0%	30%
Downtime:	0%	30%
Crane Time:	0%	30%

Levels represent the % reduction in average time for each parameter.

The results of the DOE showed that total cycle times were least affected by changeover times, while crane times had the greatest impact. However, none of the parameters by themselves could achieve the 90% target DPMO reduction that the team had established. This meant that the process would require simultaneous improvements in two or more factors. Considering this in Runs 3, 4, 6 and 8, we see that both Run 6 and Run 8 could provide the required DPMO reduction.

Results Table: DPMO

Run 1 247,356	Run 2 224,386	Run 3 72,795	Run 4 30,748
Run 5 121,242	Run 6 12,762	Run 7 61,384	Run 8 8,505

Run 1 = Base Run

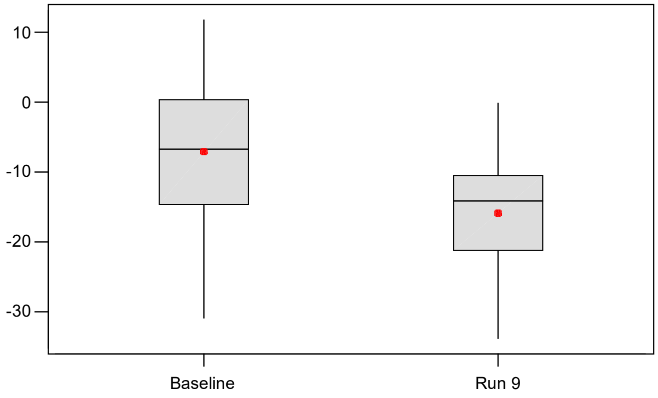
At this point in the Improve stage the project team had to consider the feasibility of reducing both crane move times and machine downtimes by 30%. It was determined that crane move times, which consisted mostly of time waiting for a crane to be available, could be reduced 30% by changes in crane operator staffing schedules. However, it was determined that machine downtimes could not be reduced by 30% in the short-term. Therefore, additional scenarios were proposed and those experiments run on the model.

In the end, it was found that the combination of a 30% reduction in crane move times, plus a 10% reduction in machine downtimes could still provide the 90% DPMO reduction that the team required. A Six-Sigma analysis on the final scenario (Run 9) is shown below. The analysis shows a reduction in the mean cycle time of 8.65 days, and a reduction in the standard deviation of 2.46 days. Therefore, the improved state includes both a reduction in variation and a shift in the mean.

The final Z-value of the improved process is 2.67. Although this is much better than the baseline Z-value of 0.89, it is apparent that achieving a truly six sigma process will require continuous improvement!

Boxplots of Baseline and Run 9

(means are indicated by solid circles)



2 Sample t-test

$$H_0: \mu_1 = \mu_0$$

$$H_1: \mu_1 \neq \mu_0$$

P-value < .05, so we reject the null hypothesis that $\mu_1 = \mu_0$

```
           N      Mean     StDev   SE Mean
Baseline  74      -7.2      10.5       1.2
Run 9     73    -15.85      8.04      0.94


95% CI for mu Baseline - mu Run 9: ( 5.7,  11.74)
T-Test mu Baseline = mu Run 9 (vs not =): T = 5.65  P = 0.0000  DF = 136
```

Control:

The final step in this DMAIC project was to ensure that the vital inputs (i.e. changeover times, machine downtimes and crane move times) would stay within the limits defined in the DOE. It was determined that the best way to accomplish this as quickly as possible was to launch two separate DMAIC projects. The first project was focused on reducing crane move times by 30%, while the second project was focused on reducing machine downtimes by 10%. Both of these projects used Statistical Process Control techniques that tracked the values of the inputs listed above over time. Whenever, the inputs were determined to be out of bounds, immediate attention would be given to correct the situation and bring the process back under control.

CONCLUSION

Six Sigma is a disciplined program or methodology for improving quality in all aspects of a company's products and processes. The primary concept is to define quality metrics (CTQ's) that are important to a customer and then understand the relationships between the inputs to the product or process and the outputs (metrics). This is done by determining a transfer function between the inputs, i.e. Y = F(X1, X2, X3,…Xn). Once the transfer function is known, experiments can be performed on the X's to understand their effects on the Y's.

Simulation is just one of many tools used in a Six-Sigma initiative. Within the Analyze and Improve stages of a DMAIC project, or the Analyze and Design stages of a DMADV project, simulation is a powerful tool because of the following value and benefits it provides:

1) Simulation takes into account process variances, uncertainties and interdependencies
2) Simulation can test many alternative solutions quickly and easily
3) Models can be developed with little risk and no disruption to existing processes
4) Simulation takes the subjectivity and emotion out of decision making
5) Animation features make simulation a good tool to help "sell" others on the best solutions
6) Reusable models encourage continuous improvement
7) Impact on upstream or downstream customers/operations/processes can be considered

ABOUT THE AUTHOR

Bruce Gladwin is currently the manager of consulting services for ProModel Corporation's Manufacturing and Logistics Group. He has over 16 years experience in process analysis and simulation of manufacturing and service systems. He spent five years with General Electric, at both the Global Research Center and the Power Systems Division in Schenectady, NY. He received his Six Sigma training while at GE and is a Certified Six-Sigma Black Belt. Bruce has a B.S. in Systems Engineering from the University of Arizona and an MBA from Brigham Young University.

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