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<td>400 1000</td>
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I. CERTIFICATION OVERVIEW

Professionalizing Quality Education

I KNOW OF NO MORE ENCOURAGING FACT THAN THE UNQUESTIONABLE ABILITY OF MAN TO ELEVATE HIS LIFE BY A CONSCIOUS ENDEAVOR.

HENRY DAVID THOREAU
I. CERTIFICATION OVERVIEW

A little Dilbert® Six Sigma humor with permission of Scott Adams and United Feature Syndicate, Inc.
I. CERTIFICATION OVERVIEW
CERTIFIED SIX SIGMA BLACK BELT

CSSBB Exam

Objective

To provide recognized Six Sigma fundamental training and to prepare persons interested in taking the CSSBB examination.

Eligibility

Eligibility requires two completed projects with signed affidavits or one completed project with signed affidavit and three years work experience within the Six Sigma Body of Knowledge. No education waiver is given.

Duration

The test lasts 4 hours and begins at an advised time (typically 8 or 9 A.M.). The exam is open book and consists of multiple choice questions. Exams are given twice a year.

Other Details

Contact ASQ at (800) 248-1946 or http://www.asq.org
CSSBB Exam (Continued)

Bibliography Sources

The CSSBB student should obtain the bibliography furnished by ASQ. Currently, that list is massive. The sources recommended by the authors include:


I. CERTIFICATION OVERVIEW
CERTIFIED SIX SIGMA BLACK BELT

CSSBB Exam (Continued)

Bibliography Sources (Continued)


I. CERTIFICATION OVERVIEW
CSSBB BODY OF KNOWLEDGE

ASQ Certified Six Sigma Black Belt
Body of Knowledge

The detailed Body of Knowledge is given in the CSSBB Primer pages I-6 through I-17.

I. Enterprise-Wide Deployment (9 Questions)

II. Business Process Management (9 Questions)

III. Project Management (15 Questions)

IV. Six Sigma Improvement Methodology and Tools - Define (9 Questions)

V. Six Sigma Improvement Methodology and Tools - Measure (30 Questions)
I. CERTIFICATION OVERVIEW
CSSBB BODY OF KNOWLEDGE

Body of Knowledge (Continued)

VI. Six Sigma Improvement Methodology and Tools - Analyze (23 Questions)

VII. Six Sigma Improvement Methodology and Tools - Improve (22 Questions)

VIII. Six Sigma Improvement Methodology and Tools - Control (15 Questions)

IX. Lean Enterprise (9 Questions)

X. Design for Six Sigma (DFSS) (9 Questions)
Six Levels of Cognition
Based on Bloom’s Taxonomy (1956)

In addition to content specifics, the subtext detail also indicates the intended complexity level of the test questions for that topic. These levels are based on “Levels of Cognition” (from Bloom’s Taxonomy, 1956) and are presented below in rank order, from least complex to most complex.

- Knowledge Level
- Comprehension Level
- Application Level
- Analysis
- Synthesis
- Evaluation
SIX SIGMA HAS FOREVER CHANGED GE® EVERYONE... IS A TRUE BELIEVER IN SIX SIGMA, THE WAY THIS COMPANY NOW WORKS.

JOHN F. WELCH
FORMER G.E. CHAIRMAN
Enterprise-Wide Deployment

Enterprise-Wide Deployment is reviewed in the following topic areas:

- Enterprise view
- Leadership
- Organizational goals and objectives
- Foundations of Six Sigma

Enterprise view is reviewed in the following topic areas:

- Value of Six Sigma
- Business systems and processes
- Process inputs, outputs and feedback
II. ENTERPRISE-WIDE DEPLOYMENT
   A. ENTERPRISE VIEW
      1. VALUE OF SIX SIGMA

Six Sigma Introduction

Six Sigma is a highly disciplined process that focuses on developing and delivering near-perfect products and services consistently.

Six Sigma is also a management strategy to use statistical tools and project work to achieve breakthrough profitability and quantum gains in quality.

Motorola®, under the direction of Chairman Bob Galvin, used statistical tools to identify and eliminate variation. From Bill Smith’s yield theory in 1984, Motorola® developed Six Sigma as a key business initiative in 1987.

Sigma is a statistical term that refers to the standard deviation of a process about its mean. In a normally distributed process, 99.73% of measurements will fall within ± 3.0 sigma and 99.99966% will fall within ± 4.5 sigma. In a stable attribute distributed process, 99.73% of defective units, or defects, will fall within probability of 0.00135 and 0.99865.

Motorola® is a registered trademark of Motorola, Inc.
Six Sigma Introduction (Continued)

Motorola® noted that many operations, such as complex assemblies, tended to shift 1.5 sigma over time. So a process, with a normal distribution and normal variation of the mean, would need to have specification limits of ± 6 sigma in order to produce less than 3.4 defects per million opportunities.

This failure rate can be referred to as defects per opportunity (DPO), or defects per million opportunities (DPMO). Figure 2.1 illustrates the ±1.5 sigma shift and Table 2.2 provides some indications of possible defect levels.

![Figure 2.1 The ± 1.5 Sigma Shift](image)
II. ENTERPRISE-WIDE DEPLOYMENT
A. ENTERPRISE VIEW
1. VALUE OF SIX SIGMA

Six Sigma Introduction (Continued)

<table>
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<td>6 sigma</td>
<td>3.4 ppm</td>
</tr>
<tr>
<td>5 sigma</td>
<td>233 ppm</td>
</tr>
<tr>
<td>4 sigma</td>
<td>6,210 ppm</td>
</tr>
<tr>
<td>3 sigma</td>
<td>66,810 ppm</td>
</tr>
<tr>
<td>2 sigma</td>
<td>308,770 ppm</td>
</tr>
<tr>
<td>1 sigma</td>
<td>697,672 ppm</td>
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Table 2.2 Defect Levels

Note that Table II in the Appendix provides defect levels at other sigma values.

It should be noted that the term Six Sigma has been applied to many operations including those with non-normal distributions, for which a calculation of sigma would be inappropriate. The principle remains the same, deliver near perfect products and services by improving the process and eliminating defects. The end objective is to delight customers.
The Six Sigma steps for many organizations are described as DMAIC:

**Define:** Select the appropriate responses (the “Y”s) to be improved.

**Measure:** Data must be gathered to measure the response variable.

**Analyze:** Identify the root causes of defects, defectives or significant measurement deviations whether in or out of specifications. (The “X”s, independent variables).

**Improve:** Reduce variability or eliminate the cause.

**Control:** With the desired improvements in place, monitor the process to sustain the improvements.
II. ENTERPRISE-WIDE DEPLOYMENT
   A. ENTERPRISE VIEW
      1. VALUE OF SIX SIGMA

Six Sigma Results

Motorola\textsuperscript{\textregistered} credits the Six Sigma initiative for savings of $940,000,000 over three years. AlliedSignal\textsuperscript{\textregistered} (now Honeywell\textsuperscript{\textregistered}) reported an estimated $1.5 billion in savings in 1997. GE\textsuperscript{\textregistered} has invested a billion dollars with a return of $1.75 billion in 1998 and an accumulated savings of $2.5 billion for 1999.

Harry reports that the average Black Belt project will save about $175,000. There should be about 5 - 6 projects per year per Black Belt. The ratio of one Black Belt per 100 employees, can provide a 6\% cost reduction per year. For larger companies there is usually one master Black Belt for every 100 Black Belts.

Organizations that follow a Six Sigma improvement process for several years find that some operations achieve greater than Six Sigma quality. When operations reach Six Sigma quality, defects become so rare that individual defects get the full attention necessary to determine and correct the root cause. As a result, key operations frequently end up realizing better than Six Sigma quality.

GE\textsuperscript{\textregistered}, AlliedSignal\textsuperscript{\textregistered} and Honeywell\textsuperscript{\textregistered} are registered trademarks.
II. ENTERPRISE-WIDE DEPLOYMENT
   A. ENTERPRISE VIEW
      1. VALUE OF SIX SIGMA

Typical Six Sigma Training

Potential Black Belts undertake a 4 month training program consisting of one week of instruction each month. A set of software packages are used to aid in the presentation of projects, including Excel or MINITAB™ for the statistics portion.

Potential Black Belts will receive coaching from a Master Black Belt to guide them through a project at their plant. Coaching and guidance from this mentor are valuable for the new Black Belt trainee. This guidance is available during the time between training sessions. The completed project will typically require the trainee to use the majority of tools presented during the training sessions.

Lesser amounts of training will qualify individuals for the Green Belt title.

The training spreads out over 4 months to provide a refresher in statistics for some individuals, or a beginning background in statistics for others. There are portions of the course focusing on team and project management.
## Systems

From an organizational standpoint, a system is defined as a series of actions, activities, elements, components, departments, or processes that work together for a definite purpose.

System effectiveness is a measure of the degree to which a system can be expected to achieve a set of specific (mission) requirements, that may be expressed as a function of performance (availability, dependability and capability).

Subsystems are major divisions of a system that are still large enough to consist of more than one process.
Business Systems

Management leadership is a measure of how senior executives guide the organization and how the organization addresses its responsibilities to the public and practices good citizenship. Listed below are some key management activities:

- Strategic planning
- Customer and market focus
- Information and analysis
- Human resource focus
- Process management
Processes are definable portions of a system or subsystem that consist of a number of individual elements, actions, or steps. Omdahl defines a process as a set of interrelated resources and activities which transform inputs into outputs with the objective of adding value.

Consider Figure 2.3, which illustrates how work and ideas flow within systems.

Figure 2.3  A Hypothetical System Schematic
II. ENTERPRISE-WIDE DEPLOYMENT  
A. ENTERPRISE VIEW  
2. BUSINESS SYSTEMS AND PROCESSES

Business Responsibilities

In today’s world, organizations must keep pace with ever increasing changes. The complexity of the business requires numerous functions in order to be competitive. A brief description of common business functional responsibilities includes the following from Gee:

- Human Resources
- Engineering
- Sales and Marketing
- Finance
- Product Liability
- Manufacturing
- Safety and Health
- Legal and Regulatory
II. ENTERPRISE-WIDE DEPLOYMENT
   A. ENTERPRISE VIEW
      2. BUSINESS SYSTEMS AND PROCESSES

Business Responsibilities (Continued)

- Research and Development (R&D)
- Purchasing
- IT or MIS
- Production Planning and Scheduling
- Quality
- Environmental
- Technology
- Servicing
Cross-Functional Collaboration

Galbraith describes cross-functional efforts as a lateral coordination effort. Departments or functions at the same level (lateral) should be grouped together to produce the required output. The units are all interdependent of each other, if the firm is to succeed.

Schermerhorn provides the following tips for improving subsystem integration:

- Rules and procedures
- Hierarchical referral
- Planning
- Direct contact among managers
- Liaison roles
- Task forces and teams
- Matrix organization
Process Inputs, Outputs and Feedback

Each process consists of inputs and outputs that can be monitored. Measurements of process inputs and outputs can be used to optimize the process being measured.

Process input requirements should be stated so that key measures of input quality can be controlled.

Measurements within the process can also be used to effectively control the process. Once process capabilities are known, output measures can be used to monitor if the process has remained in control. See Figure 2.4 below.

![Figure 2.4 Generalized Process Model](image)
Another key concept in Six Sigma methodology is the SIPOC high level process map in which SIPOC stands for Suppliers, Inputs, Process, Outputs, and Customers.

Figure 2.5 An Expanded SIPOC Model
II. ENTERPRISE-WIDE DEPLOYMENT
   A. ENTERPRISE VIEW
      2. BUSINESS SYSTEMS AND PROCESSES

Process Inputs, Outputs (Continued)

The advantages of using a SIPOC model include:

- A display of cross functional set of activities in a single, simple diagram

- A “big picture” perspective to which additional detail can be added

- A framework applicable to either large organizations or smaller processes

The ultimate goal is to identify essential work flows and sources of variation in work over time. The diagram can also be adapted to a number of essential support processes.

SIPOC captures the key components of success from suppliers, through internal processes and on to key customers.
Organizational Structures

There are several ways to structure a Six Sigma Blackbelt program. Successful programs, however, share a common core of management support, training, reward and reinforcement.

Management Support

It has been said that there are two times when it is difficult to implement an improvement program, when times are bad and when times are good. When times are bad, profitability is low, resources are tight and “strategic” activities take a back seat to “survival.”

When times are good, profitability is high, resources are focused on the current source of cash flow. Improvement may be last on the list of things to do in order to take advantage of the current opportunity.

Skilled managers must be willing to make significant commitments in order to implement and support a successful Six Sigma initiative. Early successes must be exploited to propel the company forward.
Enterprise Leadership (Continued)

Training

The role of training, in the successful implementation of Six Sigma, is fundamental. All companies that implemented successful Six Sigma programs have found that training investments pay back significant benefits. Extensive training is necessary for several levels of individuals and basic training is required for the entire organization.

The relative volume of each diagram level represents the relative number of people receiving training.

Figure 2.6 Six Sigma Training Pyramid
Enterprise Leadership (Continued)

Training (Continued)

In some organizations, black belts are full time positions that report directly to management sponsors, who, in turn, assign specific projects to them.

Green belts are within the normal organizational structure and are typically assigned to process improvement teams as needed.

Black belts have specific mentoring responsibilities, including the development of individuals assigned to them.

Master black belts are responsible for coaching and training black belts in order to make the best use of their skills. Master black belts also train and coach management in order to help them support the black belt program.
II. ENTERPRISE-WIDE DEPLOYMENT
B. LEADERSHIP
   2. SIX SIGMA ROLES & RESPONSIBILITIES

Six Sigma Roles

Black Belts

Six Sigma Black Belts are most effective in full-time process improvement positions. Six Sigma Black Belts are individuals who have studied and demonstrated skill in implementation of the principles, practices, and techniques of Six Sigma for maximum cost reduction and profit improvement.

Black Belts are encouraged to mentor Green Belt and Black Belt candidates.

Master Black Belts

Six Sigma Master Black Belts are typically in full time process improvement positions. They are, first and foremost, teachers who mentor Black Belts and review their projects.

Selection criteria for Master Black Belts includes both quantitative skills and the ability to teach and mentor.
II. ENTERPRISE-WIDE DEPLOYMENT
B. LEADERSHIP
2. SIX SIGMA ROLES & RESPONSIBILITIES

Six Sigma Roles (Continued)

Green Belts

Six Sigma Green Belts are not usually in full-time process improvement positions. Green Belt refers to an individual who has mastered the basic skills and may be Black Belts-in-training. Green Belts must demonstrate proficiency with the core statistical tools by using them for positive financial impact and customer benefits on a few projects.

Green Belts operate under the supervision and guidance of a Black Belt or Master Black Belt.

Executive Sponsors

Executive sponsorship is a key element in an effective Black Belt program. Executive leadership sets the direction and priorities for the organization.

Executives typically receive training that includes a Six Sigma program overview, examples of successful deployment and strategies, and tools and methods for definition, measurement, analysis, improvement, and control.
II. ENTERPRISE-WIDE DEPLOYMENT
   B. LEADERSHIP
      2. SIX SIGMA ROLES & RESPONSIBILITIES

Six Sigma Roles (Continued)

Champions

Six Sigma Champions are typically upper level managers that control and allocate resources to promote process improvements and Black Belt development.

Champions are trained in the core concepts of Six Sigma and deployment strategies used by their organizations. Six Sigma Champions lead the implementation of the Six Sigma Program.

Process Owners

Key processes should have a process owner. A Process Owner coordinates process improvement activities and monitors progress on a regular basis. Process owners work with Black Belts to improve the processes for which they are responsible.

Process owners should have basic training in the core statistical tools but will typically only gain proficiency with those techniques used to improve their individual processes.
II. ENTERPRISE-WIDE DEPLOYMENT
   B. LEADERSHIP
      2. SIX SIGMA ROLES & RESPONSIBILITIES

Six Sigma Roles (Continued)

Six Sigma Structure

<table>
<thead>
<tr>
<th>Functions</th>
<th>Structure Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executive Direction</td>
<td>• Six Sigma Steering Committee</td>
</tr>
<tr>
<td></td>
<td>• Quality Council</td>
</tr>
<tr>
<td></td>
<td>• Executive Steering Council</td>
</tr>
<tr>
<td>Six Sigma Management</td>
<td>• Six Sigma Manager</td>
</tr>
<tr>
<td></td>
<td>• Six Sigma Director</td>
</tr>
<tr>
<td></td>
<td>• Master Black Belt</td>
</tr>
<tr>
<td>Process Owner</td>
<td>• Champion</td>
</tr>
<tr>
<td></td>
<td>• Sponsor</td>
</tr>
<tr>
<td>Sponsor</td>
<td>• Process Owner</td>
</tr>
<tr>
<td></td>
<td>• Champion</td>
</tr>
<tr>
<td>Coach</td>
<td>• Master Black Belt</td>
</tr>
<tr>
<td></td>
<td>• Black Belt</td>
</tr>
<tr>
<td>Team Leader</td>
<td>• Trained Supervisor/Facilitator</td>
</tr>
<tr>
<td></td>
<td>• Black Belt</td>
</tr>
<tr>
<td></td>
<td>• Green Belt</td>
</tr>
<tr>
<td>Team Member</td>
<td>• Associate with Team Training</td>
</tr>
<tr>
<td></td>
<td>• Associate with Process Knowledge</td>
</tr>
<tr>
<td></td>
<td>• Green Belt</td>
</tr>
</tbody>
</table>

Table 2.7 Functions in a Six Sigma Organization
Linking Projects to Organizational Goals

The readiness assessment includes a review of the following areas:

- Assess the outlook and future path of the business
  - Is the strategy course clear for the company?
  - Can we meet our financial and growth goal?
  - Does our organization respond effectively to new circumstances?

- Evaluate the current organizational performance:
  - What are our current overall business results?
  - How effectively do we meet customer requirements?
  - How effectively are we operating?

- Review the capacity for systems change and improvement:
  - How effective are we in managing system changes?
  - How well are our cross-functional processes managed?
  - Are there conflicts in our current efforts with Six Sigma?
II. ENTERPRISE-WIDE DEPLOYMENT
C. ORGANIZATIONAL GOALS AND OBJECTIVES
1. LINKING PROJECTS TO ORGANIZATIONAL GOALS

Linking Projects to Goals (Continued)

The October 1992 Annual Quality Forum found that the best strategy that a company can employ depends upon their current performance level. The recommended strategies for survival is detailed in Figure 2.8:

<table>
<thead>
<tr>
<th>PERFORMANCE</th>
<th>DO</th>
<th>DON’T DO</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOW</td>
<td>Concentrate on basics Use problem solving teams Apply cost management Engage in customer innovation</td>
<td>Empowerment Benchmarking Strategic planning</td>
</tr>
<tr>
<td>MEDIUM</td>
<td>Set goals and monitor them Use process simplification Use department improvement teams Get middle management involved</td>
<td>—</td>
</tr>
<tr>
<td>HIGH</td>
<td>Benchmark other firms Empower employees Communicate strategic plans Continuously improve</td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 2.8 Strategies Based on Performance Level
II. ENTERPRISE-WIDE DEPLOYMENT
C. ORGANIZATIONAL GOALS AND OBJECTIVES
1. LINKING PROJECTS TO ORGANIZATIONAL GOALS

Linking Projects to Goals (Continued)

Harry details a methodology to focus the deployment of Six Sigma projects. There are a considerable number of options, dependent upon the goals and objectives of the organization. Considerations include:

- Focus on project cost savings
- Focus on customer satisfaction deliverables
- Focus on processes
- Focus on problems
- Focus on location (a good way to introduce Six Sigma)
- Focus on design
- Focus on supplier processes
II. ENTERPRISE-WIDE DEPLOYMENT
C. ORGANIZATIONAL GOALS AND OBJECTIVES
2. RISK ANALYSIS

SWOT Analysis

SWOT is an acronym meaning strengths, weaknesses, opportunities and threats.

SWOT analysis requires that a comprehensive appraisal of internal and external situations be undertaken before suitable strategic options can be determined. Good strategies are built on the strengths of a company and on exploiting opportunities.

Strengths and Weaknesses

A strength is something that the company is good at doing. Some strengths that a company may enjoy include:

- Engineering expertise
- Technical patents
- Skilled workforce
- Solid financial position
- Reputation for quality
Strength and Weaknesses (Continued)

A weakness is something that the firm lacks or is a condition that puts it at a disadvantage. Analysis of weaknesses should cover the following key areas:

- An evaluation of each subunit of business
- The status of tracking or control systems for the critical success indicators.
- An indication of the firm’s level of creativity, risk taking and competitive approach.
- An assessment of the resources available to implement plans.
- An analysis of the current organizational culture and of the firm’s way of doing business.
Opportunities and Threats

The firm must be able to assess the external environment in preparation for challenges. The external environment can include assessment of the following:

- Economic environment
- Socio-political environment
- Social environment
- Technological environment
- Competitive environment

A firm’s external world will provide opportunities and threats. The strategy must match up with:

- Opportunities suited to the firm’s capabilities
- Defenses against external threats
- Changes to the external environment
Knowledge Management

Knowledge management is a process that a firm can use to build their capabilities in maintaining and improving performance. The aim is to continuously improve the firm through the sharing of knowledge. The basic concept is to have the right knowledge, at the right time, at the right place.

It is not sufficient to capture learning and knowledge. Information must also be stored, organized, and readily accessible, to be of value and enhance an organization’s operating performance.

Knowledge management will enhance the core competencies of a firm. The core competencies may be dispersed throughout the firm. Through use of knowledge management systems, competency can be fully leveraged. A definition of core competency from Prahalad follows:

Core competency: “The collective learning in the organization, especially how to coordinate diverse production skills and integrate multiple streams of technologies.”
Knowledge Management (Continued)

Eight factors that contribute to successful knowledge management:

1. Link knowledge management to economic performance
2. Maintain both a technical and organizational infrastructure
3. Develop a standardized flexible knowledge structure
4. Cultivate a knowledge friendly culture
5. Develop a clear purpose and language
6. Change motivational practices
7. Create multiple channels for knowledge transfer
8. Demonstrate senior management support
## Quality History Influencing Six Sigma

Listed below are some well known quality pioneers and what they contributed to both the business and technical foundations of Six Sigma. This list is far from inclusive.

<table>
<thead>
<tr>
<th>Guru</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Philip B. Crosby</td>
<td>Senior manager involvement &lt;br&gt;4 absolutes of quality management &lt;br&gt;Quality cost measurements</td>
</tr>
<tr>
<td>W. Edwards Deming</td>
<td>Plan-do-study-act (wide usage) &lt;br&gt;Top management involvement &lt;br&gt;Concentration on system improvement &lt;br&gt;Constancy of purpose</td>
</tr>
<tr>
<td>Armand V. Feigenbaum</td>
<td>Total quality control/management &lt;br&gt;Top management involvement</td>
</tr>
<tr>
<td>Kaoru Ishikawa</td>
<td>4M (5M) or cause and effect diagram &lt;br&gt;Company wide quality control &lt;br&gt;Next operation as customer</td>
</tr>
</tbody>
</table>

Table 2.10 Major Contributors to the Six Sigma Knowledge Bank
## Quality History (Continued)

<table>
<thead>
<tr>
<th>Guru</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joseph M. Juran</td>
<td>Top management involvement</td>
</tr>
<tr>
<td></td>
<td>Quality Trilogy (project improvement)</td>
</tr>
<tr>
<td></td>
<td>Quality cost measurement</td>
</tr>
<tr>
<td></td>
<td>Pareto Analysis</td>
</tr>
<tr>
<td>Walter A. Shewhart</td>
<td>Assignable cause vs. chance cause cause</td>
</tr>
<tr>
<td></td>
<td>Control charts</td>
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<tr>
<td></td>
<td>Plan-do-check-act</td>
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<tr>
<td></td>
<td>Use of statistics for improvement</td>
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<tr>
<td>Genichi Taguchi</td>
<td>Loss function concepts</td>
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<td>Signal to noise ratio</td>
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<td></td>
<td>Experimental design methods</td>
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<td></td>
<td>Concept of design robustness</td>
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</tbody>
</table>

Table 2.10 Major Contributors to the Six Sigma Knowledge Bank
Statement on quality:

Quality is conformance to requirements

Philip Crosby preached four absolutes of quality management:

1. Quality means conformance to requirements
2. Quality comes from prevention
3. The quality performance standard is zero defects
4. Quality measurement is the price of nonconformance

The four absolutes of quality management are basic requirements for understanding the purpose of a quality system.
Philip B. Crosby (Continued)

Philip Crosby also developed a 14 step approach to quality improvement:

1. Management Commitment
2. Quality Improvement Team
3. Measurement
4. Cost of Quality
5. Quality Awareness
6. Corrective Action
7. Zero Defects Planning
8. Employee Education
9. Zero Defects Day
10. Goal Setting
11. Error Cause Removal
12. Recognition
13. Quality Councils
14. Do it All Over Again
Dr. W. Edwards Deming  
(1900 - 1993)

The Fourteen Obligations of Top Management:

1. Create constancy of purpose for improvement of products and service
2. Adopt a new philosophy; we are in a new economic age
3. Cease dependence upon inspection as a way to achieve quality
4. End the practice of awarding business based on price tag
5. Constantly improve the process of planning, production, and service - this system includes people
6. Institute training on the job
7. Institute improved supervision (leadership)
8. Drive out fear
9. Break down barriers between departments
10. Eliminate slogans/targets asking for increased productivity without providing methods
11. Eliminate numerical quotas
12. Remove barriers that stand between workers and their pride of workmanship; the same for all salaried people
13. Institute programs for education and retraining
14. Put all emphasis in the company to work to accomplish the transformation
II. ENTERPRISE-WIDE DEPLOYMENT
   D. HISTORY OF ORGANIZATIONAL IMPROVEMENT

Dr. W. Edwards Deming

Seven Deadly Diseases That Management Must Cure:

1. Lack of constancy of purpose to plan a marketable product and service to keep the company in business and provide jobs
2. Emphasis on short-term profits
3. Personal evaluation appraisal, by whatever name, for people in management, the effects of which are devastating
4. Mobility of management; job hopping
5. Use of visible figures for management, with little or no consideration of figures that are unknown or unknowable
6. Excessive medical costs
7. Excessive costs of warranty, fueled by lawyers that work on contingency fees

Among other educational techniques, Deming promoted the parable of the red beads, the PDCA cycle and the concept of 85% management (system) versus 15% operator controllable improvement approach.
Dr. W. Edwards Deming (Continued)

Deming’s Chain Reaction

Deming shared the following chain reaction with Japan in the summer of 1950:

Improve quality $\rightarrow$ Decrease costs (less rework, fewer delays) $\rightarrow$ Productivity Improves $\rightarrow$ Capture the market with better quality and price $\rightarrow$ Stay in business $\rightarrow$ Provide jobs.

Deming’s chain reaction is summarized by Delavigne and Robertson as the following series of events:

1. The quality and productivity rise
2. Costs decrease
3. The time required for development and production is reduced
4. Management begins to know their cost, “they have a system”
5. Increased division of labor and specialization occurs
6. The near-term future is more predictable
7. The standard of living rises
8. The system has a future and can provide “jobs and more jobs”
II. ENTERPRISE-WIDE DEPLOYMENT
D. HISTORY OF ORGANIZATIONAL IMPROVEMENT

Dr. Armand V. Feigenbaum
(1920 - )

Statement on Total Quality Control:

An effective system for integrating the quality development, quality maintenance, and quality improvements of the various groups in an organization so as to enable production and service at the most economical levels allowing for full customer satisfaction.

Feigenbaum is generally given credit for establishing the concept of “total quality control” in the late 1940’s at General Electric. His TQC statement was first published in 1961, but at that time, the concept was so new, that no one listened.

The TQC philosophy maintains that all areas of the company must be involved in the quality effort. The quality effort has generally only affected the shop floor people, but must extend to all sections of the company. Products must not only be made quicker and faster, but also sold faster.
Dr. Armand V. Feigenbaum (Continued)

The success of TQC includes these principles:

- TQC is a company wide process, all functions are involved
- Quality is what the customer says it is
- Quality and production costs are in partnership ... higher quality will equate with lower costs
- Both individual and team zeal are required
- Quality is a way of managing, providing a continuous and relentless emphasis on quality through leadership
- Quality and innovation can work together in product development
- As an ethic, all of management must be involved in quality, not just the specialist
- Requires continuous improvement, the use of new and existing technologies
- Is the most cost-effective, least capital intensive route to productivity and is implemented with both customers and suppliers
Dr. Kaoru Ishikawa  
(1915 - 1989)

Statement on total quality control:

To practice quality control is to develop, design, produce, and service a quality product that is most economical, most useful, and always satisfactory to the consumer.

Ishikawa stated that total quality control had been practiced in Japan since 1958. To reduce confusion between Japanese-style total quality control and western total quality control, he called the Japanese method the company-wide quality control (CWQC). There are 6 main characteristics that make CWQC different:

1. More education and training in quality control
2. Quality circles are really only 20% of the activities for CWQC
3. Participation by all members of the company
4. Having QC audits
5. Using the seven tools and advanced statistical methods
6. Nationwide quality control promotion activities
Dr. Kaoru Ishikawa (Continued)

CWQC involves the participation of workers from top to bottom of the organization and from the start to the finish of the product life cycle. CWQC requires a management philosophy that has respect for humanity. There must be acknowledgment that the worker can contribute to the success of the company through suggestions, creativity, and worthwhile ideas.

One of the first concepts that western management took back to their own shores was the quality circle. Quality circles were originally study groups that workers formed together in their department to study the quality concepts.

Quality circles involve members from within the department. The circle solves problems on a continuous basis. Circle membership changes dependent upon the task or project under consideration.

Ishikawa also wrote that he originated the concept: “Next operation as customer.” The separation of departments was referred to as sectionalism.

The fishbone diagram is also called the Ishikawa diagram in honor of Kaoru Ishikawa.
II. ENTERPRISE-WIDE DEPLOYMENT
D. HISTORY OF ORGANIZATIONAL IMPROVEMENT

Dr. Joseph M. Juran
(1904 - )

Statement on quality:

Adopt a revolutionary rate of improvement in quality, making quality improvements by the thousands, year after year.

Juran’s basics for success can be described as follows:

- Top management must commit the time and resources for success. CEOs must serve on the quality council.
- Specific quality improvement goals must be in the business plan and include:
  - The means to measure quality results against goals
  - A review of results against goals
  - A reward for superior quality performance
  - The responsibility for improvements must be assigned to individuals
  - People must be trained for quality management and improvement
  - The workforce must be empowered to participate in the improvement process
Juran has felt that managing for quality requires the same attention that other functions obtain. Thus, he developed the Juran or quality trilogy which involves:

- Quality planning
- Quality control
- Quality improvement

Juran sees these items as the keys to success. Top management can follow this sequence just as they would use one for financial budgeting, cost control, and profit improvement.

For any project, quality planning is used to create the process that will enable one to meet the desired goals. The concept of quality control is used to monitor and adjust the process. Chronic losses are normal in a controlled state, while the sporadic spike will cause investigations. Eventually, only quality improvement activities will reduce the chronic losses and move the process to a better and improved state of control and that’s the “last word.”
Dr. Walter A. Shewhart
(1891 - 1967)

Quote:

“Both pure and applied science have gradually pushed further and further the requirements for accuracy and precision. However, applied science, particularly in the mass production of interchangeable parts, is even more exacting than pure science in certain matters of accuracy and precision.”

Abstract:

Bell Telephone’s engineers had a need to reduce the frequency of failures and repairs. In 1924, Shewhart framed the problem in terms of “assignable-cause” and “chance-cause” variation and introduced the “control chart” as a tool for distinguishing between the two.

Bringing a production process into a state of “statistical control,” where the only variation is chance-cause, is necessary to manage a process economically.
Dr. Walter A. Shewhart (Continued)

The Shewhart Cycle

The Shewhart cycle (PDCA) or Deming (PDSA) is a very helpful procedure to follow for improvement at any stage.

Figure 2.11 The Shewhart or Deming Cycle

1. Plan - What changes are desirable? What data is needed?

2. Do - Carry out the change or test decided upon, preferably on a small scale.

3. Check - Observe the effects of the change or the test.

4. Act - What we learned from the change should lead to either (a) improvement of any, or all stages and (b) some activity to better satisfy the customer either internal, or external. The results may indicate that no change at all is needed.
Dr. Genichi Taguchi  
(1924 - )

Statement on quality: Quality is related to the financial loss to society caused by a product during its life cycle.

Taguchi’s system is a system to optimize the design of products and processes in a cost-effective manner. Taguchi’s plan takes a different view of product quality:

1. The evaluation of quality. Use the loss function and signal-to-noise ratio as ways to evaluate the cost of not meeting the target value.

2. Improvement of quality and cost factors. Use statistical methods for system design, parameter design, and tolerance design of the product.

3. Monitoring and maintaining quality. Reduce the variability of the production line.

Robustness derives from consistency. Robust products and processes demonstrate more insensitivity to those variables that are noncontrollable. Building parts to target (nominal) is the key to success. We should work relentlessly to achieve designs that can be produced consistently and demand consistency from the factory.
II. ENTERPRISE-WIDE DEPLOYMENT QUESTIONS

2.2. Using Six Sigma methodology, a company at 4.5 sigma would have a failure rate of:

a. 3.4 ppm  c. 1350 ppm
b. 233 ppm   d. 6210 ppm

2.8. The function of a coach in a Six Sigma organization is most likely to be filled by which of the following:

I. Steering committee members
II. Process owners
III. Master black belts
IV. Black belts

a. I and II only  c. III and IV only
b. II and III only  d. I, II, III and IV

2.13. A company struggling with low performance in terms of quality, profitability and productivity is considering a Six Sigma initiative. A decision to proceed would be considered:

a. Smart, they have a lot of low lying fruit
b. Unwise, they probably can’t afford the effort
c. Unwise, they need to attend to basic activities first
d. Smart, they obviously need the Six Sigma structure

Answers: 2.2 c, 2.8 c, 2.13 c
II. ENTERPRISE-WIDE DEPLOYMENT

QUESTIONS

2.16. A SWOT analysis developed by top management is the ideal way to prepare for a strategic plan, EXCEPT for the fact that:

a. One person generates it
b. It does not incorporate everyone's strengths
c. The voice of the customer is a weakness
d. There is lack of diversity in top management thinking

2.19. One of Dr. Deming's 14 points for Management states, “Cease dependence upon inspection as a way to achieve quality.” The underlying tenet of this statement is which of the following?

a. Many American companies employ too many inspectors; perhaps 5 - 10% of the work force
b. Quality should be built into the product, not inspected in
c. In most cases, the workers should perform his/her own inspection and not rely on someone else
d. Most manual inspection will miss 10 -20% of defects under typical working conditions

2.21. Which of the following quality luminaries would be most clearly identified as a proponent of improvement and breakthrough projects?

a. Ishikawa c. Juran
b. Deming d. Crosby

Answers: 2.16 d, 2.19 b, 2.21 c
IT WOULD BE EASY TO DISMISS SIX SIGMA AS A FAD IF IT WEREN'T FOR THE CALIBER OF THE RESULTS ITS PRODUCING AND THE COMPANIES ADOPTING IT.

PANDE, NEUMAN AND CAVANAGH
III. BUSINESS PROCESS MANAGEMENT

A. PROCESS VS FUNCTION

INTRODUCTION

Business Process Management

Business Process Management is reviewed in the following topic areas:

- Process vs. functional view
- Voice of the customer
- Business results

Process versus functional view is reviewed in the following topic areas:

- Process elements
- Owners and stakeholders
- Project management and benefits
- Project measures
Business Process Management (Cont.)

Business Process Management (BPM) is a fundamental concept of Six Sigma. Efforts to improve individual process components are replaced by systematic methods to understand, control and improve overall business results. These methods have evolved from the basic tenets of quality and continuous improvement to address specific business objectives.

W. Edwards Deming defined quality in general terms as a product or service that provides value and enjoys a sustainable market. In order to help us understand, control and improve the business process, he described the familiar Supplier – Process – Customer model, with several key concepts:

- Process inputs, controls, and outputs are interdependent
- Statistical methods can improve process control and guide improvements
- Process feedback can be used to redesign products and processes, and improve overall business results
Business Process Management (Cont.)

Deming’s Theory of Profound Knowledge also appears in four related parts to help guide the continual improvement process:

- Appreciation of a system and the interdependence of system components
- Knowledge about variation and the power of statistical thinking and methods
- Theory of knowledge, the essential key to learning
- Psychology, the powerful effects of human factors on system performance

BPM is focused on understanding, controlling, and improving business processes to create value for all stakeholders. Six Sigma builds on classic concepts to ensure results.
III. BUSINESS PROCESS MANAGEMENT
A. PROCESS VS FUNCTION
INTRODUCTION

Business Process Management (Cont.)

Juran’s Quality Handbook provides more details about business processes in the following definition:

A business process is the logical organization of people, materials, energy, equipment, and information into work activities designed to produce a required end result (product or service).

Juran also defines three principal dimensions for measuring the quality of this process:

- Effectiveness: how well the output meets customer needs
- Efficiency: the ability to be effective at least cost
- Adaptability: the ability to remain effective and efficient in the face of change

Six Sigma programs strive to manage the entire business process to maximize these goals for the overall business. Six Sigma’s business focus represents a major extension of traditional quality improvement programs.
Business Process Management (Cont.)

Figure 3.1 illustrates a traditional Business Process. Traditional management structures are built around functional organizations (vertical silos). The obvious objective is to control and improve each individual function with respect to its own local goals and objectives.
Process Elements

The major elements that constitute the core processes of an organization are shown below:

<table>
<thead>
<tr>
<th>Suppliers</th>
<th>Inputs</th>
<th>Processes</th>
<th>Outputs</th>
<th>Customers</th>
</tr>
</thead>
</table>

SIPOC is an acronym for the five major elements in the diagram:

Supplier: The person or organization providing resources to the process of concern

Input: The information, materials, or service provided

Process: The set of action steps that transforms the inputs into outputs by adding customer value.

Output: The final product or service resulting from the process

Customer: The person, process or organization that receives the output
A closer investigation of the SIPOC model shows how Six Sigma is based on the powerful concept of closed-loop business system models:

- Any change in process Output (O) will be related to one or more changes in supplier, inputs or process actions (SIPs).
- If all SIPs are stable, the Output (O) will be stable.
- A change in O means one or more of the SIPs must have changed.
- Apparent violations of this rule indicate that the process model is incomplete.
- If one or more of the SIPs change significantly, the Os may or may not change.
- Closed-loop relationships between SIPs and Os provide a method to define process correlations and possible cause-effect relationships.

Six Sigma relies on the SIPOC model to create, monitor and improve closed-loop business systems for process management, process improvement, and process design/redesign.
III. BUSINESS PROCESS MANAGEMENT
   A. PROCESS VS FUNCTION
      1. PROCESS ELEMENTS

Process Elements (Continued)

It is often convenient to think of at least three levels of the overall process because Six Sigma methods and procedures change somewhat from level to level. The three main levels may be described as Business, Operations, and Process.

The Business Level. The primary objective of Six Sigma at the Business Level is to identify the Xs or Key Process Input Variables (KPIVs) from component subsystems at the Operations Level that relate to changes in the Ys or Key Process Output Variables at the Business Level.

The Operations Level. The key to improvement at the Operations Level often lies in identifying the Xs or Key Process Input Variables (KPIVs) from component subsystems at the Process Level that relate to changes in the Ys or Key Process Output Variables at the Operations Level.

The Process Level. The key to improvement at this level often lies in identifying the Xs or Key Process Input Variables (KPIVs) from suppliers, procedures, people, machines, and the environment that relate to changes in the Ys or Key Process Output Variables at the Process Level.
Owners and Stakeholders

Businesses have many stakeholders including stockholders, customers, suppliers, company management, employees and their families, and the community and society. Each stakeholder has unique relationships with the business. Figure 3.3 illustrates some typical Business – Stakeholder relationships.

Figure 3.3 Illustration of Company Stakeholder Interactivity
Owners and Stakeholders (Continued)

Figure 3.4. Stakeholder Relationships
Owners and Stakeholders (Continued)

Organizational performance and the related strategic goals and objectives may be determined for:

- Short term or long term emphasis
- Profit
- Cycle times
- Marketplace response
- Resources

Goals may be set for either short term or long term results. The profit margin required to operate a business should be optimized for all stakeholder requirements. Projects and programs initiated by the company usually require a return on investment (ROI).

The marketplace response is an organizational performance measure. The ability to respond quickly to competitor quality, technology, product designs, safety features, or field service are collectively very important. As a performance measure, proper resource utilization will result in reduced waste, reduced costs, and a more effective organization.
Project Management and Benefits

The successful Black Belt candidate should have the “ability to manage projects and reach closure: a persistent drive toward meaningful bottom-line results and timely completion of projects.”

Breyfogle defines the roles and responsibilities of Six Sigma Black Belts under the heading, Black Belt (Project Manager/Facilitator). Project Management related roles in this list include:

- Lead the (cross function) team
- Possess excellent interpersonal and meeting facilitation skills
- Develop and manage a detailed project plan
- Schedule and lead team meetings
- Sustain team motivation and stability
- Communicate the benefit of the project to all associated with the process
- Track and report milestones and tasks
- Interface between financial and information management
Project Measures

Project Measures provide the data and information needed to analyze, evaluate and improve the business process as well as manage and evaluate the impact of the Six Sigma project.

The project budget must be reasonable, attainable, and based on estimates of the tasks to be accomplished.

Revenue Factors included in the budget and analyses are:

- Income from additional sales
- Reduced losses for scrap, customer returns, warranty claims, Cost of Poor Quality (COPQ)

Cost factors included in the budget are:

- Manpower and labor costs
- Materials
- Equipment costs, rentals, leases, etc.
- Subcontracted work or fees
- Overhead or consulting charges
- Reserve or contingency funds
III. BUSINESS PROCESS MANAGEMENT
   A. PROCESS VS FUNCTION
      4. PROJECT MEASURES

Project Measures (Continued)

The budget becomes the measurement standard for project costs.

Estimates of project revenues and costs are described by four types of measurements: budget, forecast, actual, and variance.

- **Budget**: The plan of the total costs and cash inflows, expressed in dollar amounts, and includes timing of the revenue and costs, and a benefit-cost analysis.

- **Forecast**: The predicted total revenues and costs, adjusting the budget to include actual information at that point in the completion of the project.

- **Actual**: Revenues and costs that have occurred, and for which the amounts are known instead of estimated.

- **Variance**: The difference between the budget and actual revenues and costs. A positive variance denotes a favorable deviation and a negative variance denotes an unfavorable deviation.
III. BUSINESS PROCESS MANAGEMENT
   A. PROCESS VS FUNCTION
      4. PROJECT MEASURES

Project Reviews

Project reviews are formal and documented critiques conducted by a committee of qualified company personnel, such as the executive steering committee.

A project review considers all of the important project factors such as:

- The adequacy of personnel, time, equipment and money
- The effectiveness of the entire project
- The effectiveness of corrective actions
- The true quality level of the delivered product and/or service
III. BUSINESS PROCESS MANAGEMENT
B. VOICE OF THE CUSTOMER
   1. IDENTIFY CUSTOMER

Voice of the customer is presented in the following topic areas:

- Identify customer
- Collect customer data
- Analyze customer data
- Determine critical customer requirements
III. BUSINESS PROCESS MANAGEMENT
B. VOICE OF THE CUSTOMER
   1. IDENTIFY CUSTOMER

Identify the Customer

Customers are the most important part of any business. If we can identify them and understand their requirements, we can design products (goods and services) that they will want to buy.

Businesses compete for customers and must excel in at least one category in order to succeed. They can do this best by identifying their customers and determining their requirements.

There are two main types of customers:

- Internal customers
- External customers
  - intermediate
  - end user
Internal Customers

An internal customer can be defined as anyone in the company who is affected by the product or service as it is being generated.

The internal customer is sometimes forgotten in the effort to produce an item or service for the external customer. The immediate goal should be to produce the product or service in a simple and convenient manner for internal consumption.

Internal customers are often employees of the company. Kaoru Ishikawa coined “The next operation as customer” in order to remove the sectionalism of departments toward each other. The essential idea is to enable employees of all departments to come together to solve problems.

Staff members must consider themselves as service providers. Within a company, the staff should consider what kind of work it can perform for the line departments.
III. BUSINESS PROCESS MANAGEMENT
B. VOICE OF THE CUSTOMER
1. IDENTIFY CUSTOMER

External Customers

External customers are not part of the organization but are impacted by it. End Users, Intermediate Customers, and Impacted Parties are described in more detail below.

Generally, External Customers play a critical role by providing the major portion of company revenues.

External customers include three types of customers:

- End users
- Intermediate customers
- Those impacted but do not purchase or use the product
III. BUSINESS PROCESS MANAGEMENT
B. VOICE OF THE CUSTOMER
  1. IDENTIFY CUSTOMER

External Customers (Continued)

• End Users

  The category of external customer includes those that purchase a product or service for their own use. In this case, they would be the “end user” of the product.

• Intermediate Customers

  Intermediate customers purchase the product or service and then resell, repackaging, modify, or assemble the product for sale to and end user.

• Impacted Parties

  Those who did not purchase or use the product, but would be impacted by it.

Meeting external customer’s needs can become a complex process.
External Customer Identification

External Customers may be sorted in many ways in an attempt to better understand their requirements and identify possible market niches.

Business customers can include for-profit and not-for-profit enterprises.

The consumer customer market differs from the business market as follows:

- The consumer market has a large number of customers
- The majority of consumer purchases are small in actual dollar amounts
- The transaction is usually a simple purchase
- Most consumers are not very knowledgeable about the product
- The supplier does not share proprietary information with the consumer
External Customer Identification (Cont.)

In contrast, the business customer acts in the following manner:

- There are a very small number of business customers; maybe only one
- The amount purchased per transaction is quite large
- The purchase is handled through specialized personnel
- The customer may know more about the requirements than the producer
- The supplier may allow the customer access to all sorts of information

It is also important to look at the market for the next two to five years and estimate how it will change and grow. This requires a look at all potential customers and their requirements.
External Market Segmentation

Market segmentation starts by distinguishing customer needs and wants and divides the market into subsets of customers.

Typical segmentation examples include:

- **Geography**: region, county size, city
- **Demographic**: age, sex, family size, income, occupation, race
- **Psychographic**: compulsive, extrovert, introvert, conservative, leader, etc.
- **Buyer behavior**: heavy user, aware of need, status, loyalty
- **Volume**: grouping based on usage of the product (heavy, medium, light)
- **Marketing-factor**: brand loyal customers
- **Product space**: customer perception comparison, brand A versus brand B
Customer Driven Service

The customer driven company is beginning to emerge in America. The public demands and expects better quality products and service.

- Listen to the customer
- Define a service strategy
- Set standards of performance
- Select and train employees
- Recognize and reward accomplishment

There is the need to listen to the customer, provide a vision, provide training, improve the process, find or develop response metrics, and measure the results.

Ways for a company to become an outstanding service company:

1. Select the best service people
2. Give employees the right training
3. Provide service leadership
4. Create a spirit of service
5. Weed out the bad apples
6. Empower employees at all levels
7. Promote the message
8. Ask for continuous improvement
9. Get constant feedback from customers
10. Be ready to make changes and improvements to the service firm
Customer Retention

Once a customer purchases a service or a product from the company, the work should start to retain them for further purchases. Most organizations spend the bulk of their resources on attaining new customers and smaller amounts on retaining customers.

The life cycle of a customer is defined by 5 stages:

- **Acquisition**: Converting a prospect to a customer, high costs
- **Retention**: Keeping the customer, 1/4 of the cost to acquire them
- **Attrition**: Customer enthusiasm fades, as dissatisfaction creeps in
- **Defection**: Losing the customer
- **Reacquisition**: Regaining the customer, but at a high cost
Customer Loyalty

The value of a loyal customer is not measured on the basis of one gigantic purchase, but rather on his/her lifetime worth. Loyal customers account for a high proportion of sales and profit growth. Customer retention generates repeat sales. It is cheaper to retain customers.

Customer loyalty is something that must be demonstrated through an act of execution, trust, or delightful service. They become your partners.
Collecting Customer Data

Collecting data to gain “the voice of the customer” is a multi-level task. When collecting data from customers, it helps to consider the levels where these customers impact the business.

- Business Level
- Operations Level
- Process Level
III. BUSINESS PROCESS MANAGEMENT
   B. VOICE OF THE CUSTOMER
      2. COLLECT CUSTOMER DATA

Voice of the Internal Customer

Surveys can establish a communication process serving as a tool for overall improvement.

Voice of the External Customer

The voice of the customer is an expression for listening to the external customer. It is necessary to have constant contact with the customer. To some companies, complaints are the only way that they listen to their customers.
III. BUSINESS PROCESS MANAGEMENT  
B. VOICE OF THE CUSTOMER  
2. COLLECT CUSTOMER DATA

Customer Surveys

Research on customer satisfaction can be worthwhile in helping the company efforts. The objectives of customer research vary, but a few major themes are noted below:

- To determine what quality is  
- Find out what competitors are doing  
- Define quality performance measures for use  
- Identify factors to give a competitive edge  
- Identify urgent problems

The use of multiple instruments to collect customer satisfaction data is recommended. The opportunity to collect misleading or useless information is possible with just one instrument.

Surveys can be developed in questionnaire form. An adequate number would range from 25 to 30 questions.
III. BUSINESS PROCESS MANAGEMENT
   B. VOICE OF THE CUSTOMER
      2. COLLECT CUSTOMER DATA

Survey Pitfalls

Surveys are a method to gather data, but care should be taken with that data. A well designed and properly executed survey can be a help to the company. The survey can show what resources do not satisfy customers, identify opportunities for growth or correction, and focus on customer issues. There can be problems in the use of surveys:

- Improper survey form design
- Poorly defined survey issues
- Sampling errors or poor sampling techniques
- Ignoring nonresponses
- Treating customer perceptions as objective measures
- Using incorrect analysis methods
- Treating surveys as an event, not a process
- Asking nonspecific questions
- Failing to ask the right questions
- Ignoring the results or using them incorrectly
- Failing to provide feedback when necessary
- Using too many questions (25-30 questions are typical)
- Using a temporary employee to conduct interviews
III. BUSINESS PROCESS MANAGEMENT
B. VOICE OF THE CUSTOMER
  2. COLLECT CUSTOMER DATA

Instruments to Gather Data

There are instruments or tools available to everyone for the purposes of collecting customer information. Some of the common instruments are described below:

- Surveys
- Focus groups
- Face-to-face interviews
- Satisfaction/complaint cards
- Dissatisfaction sources
- Competitive shopper
Customer Service Measurement

Customer service measurements can be obtained through the various instruments mentioned above. Some of the more common techniques include:

- Customer surveys measuring quality, service, performance, etc.
- Customer visits
- Customer service engineer feedback
- Complaint analysis: rejects, Pareto analysis
Customer Data Analysis

The CSSBB analyzes customer data in order to determine when and where customer attitudes are different or are changing.

Comparing customer attitudes over time or between groupings can provide insights into market niches and changes. The results of customer feedback data collection can be analyzed using a variety of tools:

- Statistical tests
- Line graphs
- Control charts
- Matrix diagrams
- Pareto analysis
- Other comparative analyses
Determine Critical Customer Requirements

Customers ultimately determine the value of any product with their decision to buy or not buy. In order to manage any business process we must be able to determine the critical customer requirements that influence these decisions.

Customer Expectations

The customer’s expectations of the product can be described through an analogy similar to Maslow’s hierarchy of human needs:

- **Basic**: The bare essential attributes of the product or service should be present.
- **Expected**: Some attributes will be provided as a part of the product.
- **Desired**: These are attributes that are worthwhile to have, but not necessarily provided as part of the package.
- **Unanticipated**: These are surprise attributes that go beyond what the customer expects from a purchase.
Customer Needs

Customer needs are not stable, but continuing to change. A product or service that satisfied a certain need may generate new needs for the customer. As the customer obtains a suitable product or service (the basic needs are fulfilled), they will look for new attributes.

Juran lists customer needs as follows:

- Stated needs: What the customers say they want
- Real needs: What the customer really wants
- Perceived needs: What the customer thinks is desired
- Cultural needs: Status of the product
- Unintended needs: The customer uses the product in an unintended manner.

There are customer needs related to the use of a product:

- Convenience
- Safety needs
- Product simplification features
- Communications
- Service for product failures
- Customer service
Customer Priorities

The customer will have priorities as to which of their many expectations and needs will be met.

Companies can make use of customer interviews, surveys, focus groups, phone surveys, mail surveys, audits, sales reports, or other data gathering tools to identify customer needs and expectations. The tools do not have to be complicated but should ask the right questions:

- What attributes are of value?
- How desirable is each attribute
- How do we compare with competitor’s products?
- What other features or services would be of value?

The information could be gathered and summarized for management use. For example, an L-Type matrix could be used to display the collected information.
Quality Function Deployment

Quality Function Deployment (QFD) is a tool that is sometimes referred to as the “voice of the customer,” or as the “house of quality.” Quality Function Deployment has been described as a process to ensure that customers’ wants and needs are heard and translated into technical characteristics.

QFD provides a graphic method of expressing relationships between customer wants and design features. It is a matrix that lists the attributes a customer wants and compares it to the design features (services that satisfy customer wants).

The primary matrix is the relationship matrix between the customer needs or wants and the design features and requirements.
III. BUSINESS PROCESS MANAGEMENT
   B. VOICE OF THE CUSTOMER
      4. DETERMINE CRITICAL REQUIREMENTS

Quality Function Deployment (Cont.)

- The left side of the house has the customer needs.
- The ceiling has the design features and technical requirements.
- The right side contains the customer priorities.
- The foundation contains the benchmarking, target values.
- The roof of the house contains a matrix describing the relationship between design features.

Figure 3.7 Basic House of Quality Description
Quality Function Deployment (Cont.)

The possible benefits for using the QFD process are:

- Creates a customer driven environment
- Reduces the cycle time for new products
- Uses concurrent engineering methods
- Reduces design to manufacture costs
- Increases communications through cross functional teams
- Creates data for proper documentation of engineering knowledge
- Establishes priority requirements and improves quality
III. BUSINESS PROCESS MANAGEMENT
B. VOICE OF THE CUSTOMER
4. DETERMINE CRITICAL REQUIREMENTS

Quality Function Deployment (Cont.)

Figure 3.8 A Hypothetical CSSBB Primer
House of Quality Example
Simplified Approaches
Cause-and-Effect Matrix

A cause-and-effect matrix can help prioritize the importance of key process input variables (KPIVs). To construct the cause-and-effect matrix:

- List the key process output variables (KPOVs) for the process.

- Assign a priority number for customer importance to each KPOV from 1 (low) to 10 (high) and place this number in the cells across the top of the matrix.

- List the KPIVs that may cause variability or non-conformance in the process in the cells down the column on the left side of the matrix.

- Assign a number from 1 (low) to 10 (high) for the effect each KPIV has on each KPOV in the appropriate cells in the matrix.

- For each KPIV column in the matrix, multiply the KPOV value by the KPIV effect value in each cell and sum across the row to compute a total for the KPIV and reach consensus on which KPIVs should receive priority attention.
III. BUSINESS PROCESS MANAGEMENT
B. VOICE OF THE CUSTOMER
   4. DETERMINE CRITICAL REQUIREMENTS

Simplified Approaches (Continued)

Perceptual Maps

Appropriate questions to help quantify and prioritize the needs of the customer.

- Conduct brainstorming sessions to identify a wish list of features and/or problem resolutions.

- Rank the brainstorming session items and consider the highest ranking items for possible customer survey questions.

- Construct the set of questions, being careful not to bias responses on customer satisfaction or customer importance with the wording.

- Collect a numerical ranking (e.g. 1-5 on both satisfaction and importance) for each item and plot them on a perceptual map as shown in Figure 3.9.
Simplified Approaches (Continued)

Perceptual Maps (Continued)

In this perceptual map example, items 3 and 7 are rated as very important but satisfaction is low. These items clearly need attention. Item 2 is not important, so the high satisfaction levels will not be likely to leverage customer decisions to buy. Items 5, 6 and 9 appear to be relatively strong points that may influence buy decisions.

Figure 3.9 A Perceptual Map Example
III. BUSINESS PROCESS MANAGEMENT
C. BUSINESS RESULTS
1. PROCESS PERFORMANCE RESULTS

Business Results are presented in the following topic areas:

- Process performance metrics
- Benchmarking
- Financial Benefits
Effective Business Process Management (BPM) requires an integrated system of metrics in order to achieve the desired Six Sigma business improvements. This system of metrics links all three levels of the enterprise, with the KPOVs of each level of the process becoming the KPIVs of the next:

![Six Sigma System of Metrics](image)

**Figure 3.10 A System of Business Process Performance Metrics**
III. BUSINESS PROCESS MANAGEMENT  
C. BUSINESS RESULTS  
1. PROCESS PERFORMANCE RESULTS

Business Level Metrics

Business level metrics are typically financial and operational summaries for shareholders and management. Kaplan and Norton introduced the Balanced Scorecard for business level management metrics in the following areas:

- Financial
- Customer Perception
- Internal-Business-Process (Operations)
- Company Learning and Growth
- Employee satisfaction (sometimes added as a fifth category)

Operations Level Metrics

Business effectiveness measures track how well products are meeting customer needs and they should have a longer-term perspective and reflect the total variation that the customer sees.

Operational efficiency measures relate to the cost and time required to produce the products. They provide key linkages between detailed process measures and summary business results, and help identify important relationships and root causes.
III. BUSINESS PROCESS MANAGEMENT
   C. BUSINESS RESULTS
      1. PROCESS PERFORMANCE RESULTS

Process Metrics

Detailed process-level metrics include the data from production people and machinery. This is the information that operators and supervisors need to run normal operations.

This information is also the subject of much of the measure, analyze, improve and control phases (MAIC) of Six Sigma once the improvement project has been selected and defined.
III. BUSINESS PROCESS MANAGEMENT
C. BUSINESS RESULTS
1. PROCESS PERFORMANCE RESULTS

Six Sigma Metrics

Harry introduced a significant new group of metrics for Six Sigma that serve to:

- Measure customer opinions
- Determine customer Critical to Quality (CTQ) factors
- Measure Product Outcomes (Throughput Yield, Rolled Throughput Yield, Normalized Yield)
- Correlate process outcomes to CTQs (measure processes with metrics that correlate to the company’s fundamental economics)

Breyfogle defines a large number of Six Sigma Measurements with the suggestion that some are controversial and an organization need not use them all.

Widely Used Symbols

- Defects = D
- Units = U
- Opportunities (for a defect) = O
- Yield = Y
III. BUSINESS PROCESS MANAGEMENT
C. BUSINESS RESULTS
  1. PROCESS PERFORMANCE RESULTS

Six Sigma Metrics (Continued)

Defect Relationships

- Total opportunities: \( TO = TOP = U \times O \)

- Defects per unit: \( DPU = \frac{D}{U} \) also \( = -\ln (Y) \)

- Defects per normalized unit: \( = -\ln (Y_{\text{norm}}) \)

- Defects per unit opportunity: \( DPO = \frac{DPU}{O} = \frac{D}{U \times O} \)

- Defects per million opportunities:
  \[ DPMO = DPO \times 10^6 \]
Six Sigma Metrics (Continued)

Defect Relationships (Continued)

Example 3.1 A matrix chart indicates the following information for 100 production units. Determine DPU:

<table>
<thead>
<tr>
<th>Defects</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>70</td>
<td>20</td>
<td>5</td>
<td>4</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

\[
DPU = \frac{D}{U} = \frac{1(20) + 2(5) + 3(4) + 5(1)}{100}
\]

\[
DPU = \frac{20 + 10 + 12 + 5}{100} = \frac{47}{100} = 0.47
\]

We expect to find 0.47 defects per unit.

Example 3.2 Assume that each unit in Example 3.1 had 6 opportunities for a defect (i.e. characteristics A, B, C, D, E, and F). Determine DPO and DPMO.

\[
DPO = \frac{DPU}{0} = \frac{0.47}{6} = 0.078333
\]

\[
DPMO = DPO \times 10^6 = 78,333
\]
III. BUSINESS PROCESS MANAGEMENT
C. BUSINESS RESULTS
   1. PROCESS PERFORMANCE RESULTS

Six Sigma Metrics (Continued)

Yield Relationships

Note that the Poisson equation is normally used to model defect occurrences. If there is a historic defect per unit (DPU) level for a process, the probability that an item contains $X$ flaws ($P_x$) is described mathematically by the equation:

$$P_x = \frac{e^{-DPU} DPU^X}{X!}$$

Where: $X$ is an integer greater or equal to 0  
DPU is greater than 0

If we are interested in the probability of having a defect free unit (as most of us are), then $X = 0$ in the Poisson formula and the math is simplified:

$$P(0) = e^{-DPU}$$
III. BUSINESS PROCESS MANAGEMENT  
C. BUSINESS RESULTS  
1. PROCESS PERFORMANCE RESULTS

Six Sigma Metrics (Continued)

Yield Relationships (Continued)

Assuming X = 0, the following common yield formulas follow:

Yield or first pass yield: \( Y = \text{FPY} = e^{-\text{DPU}} \)

Defects per unit: \( \text{DPU} = -\ln(Y) \)

Rolled throughput yield: \( Y_{\text{rt}} = \text{RTY} = \prod_{i=1}^{n} Y_i \)

Normalized yield: \( Y_{\text{norm}} = \sqrt[n]{\text{RTY}} \) (Where \( n \) = # steps)

Total defects per unit: \( \text{TDPY} = -\ln(Y_{\text{rt}}) \)

Example 3.5 A process consists of 4 sequential steps: 1, 2, 3, and 4. The yield of each step is as follows: \( Y_1 = 99\% \), \( Y_2 = 98\% \), \( Y_3 = 97\% \), \( Y_4 = 96\% \). Determine the rolled throughput yield and the total defects per unit.

\[
Y_{\text{rt}} = \prod_{i=1}^{4} Y_i = (0.99)(0.98)(0.97)(0.96) = 0.90345 = 90.345\%
\]

\[
\text{TDPY} = -\ln(\text{RTY}) = -\ln 0.90345 = 0.1015
\]
III. BUSINESS PROCESS MANAGEMENT
C. BUSINESS RESULTS
   1. PROCESS PERFORMANCE RESULTS

Six Sigma Metrics (Continued)

Sigma Relationships

Probability of a defect = \( P(d) = 1 - Y \) or \( 1 - \text{FPY} \)

also \( P(d) = 1 - Y_{RT} \) (for a series of operations)

\( P(d) \) can be looked up in a Z table (using the table in reverse to determine Z).

Example 3.6   The first pass yield for a single operation is 95%. What is the probability of a defect and what is the Z value?

\[
P(d) = 1 - 0.95 = 0.05
\]

Using the Z table for 0.05 approximates 1.645 sigma.

The Z value determined in Example 3.6 is called Z long term or Z equivalent.

\( Z_{ST} = Z_{LT} + 1.5 \) shift
III. BUSINESS PROCESS MANAGEMENT
C. BUSINESS RESULTS
1. PROCESS PERFORMANCE RESULTS

Six Sigma Metrics (Continued)

Sigma Relationships (Continued)

Schmidt and Launsby report that the 6 sigma quality level (with the 1.5 sigma shift) can be approximated by:

\[
6 \text{Sigma Quality Level} = 0.8406 + \sqrt{29.37 - 2.221 \times \ln(\text{ppm})}
\]

Example 3.8 If a process were producing 80 defectives/million, what would be the 6 sigma quality level?

\[
6\sigma = 0.8406 + \sqrt{29.37 - 2.221 \times \ln(80)}
\]

\[
= 0.8406 + \sqrt{29.37 - 2.221 \times 4.3820}
\]

\[
= 0.8406 + 4.4314 = 5.272 \quad \text{(about 5.3)}
\]

This answer can be also looked up in Appendix Table II, which (by interpolation) appears to be about 5.3.
III. BUSINESS PROCESS MANAGEMENT
   C. BUSINESS RESULTS
      2. BENCHMARKING

Benchmarking

Companies should always know their strongest competitors on a process by process basis. Benchmarking provides measurements of a company’s performance compared to the competition.

One important note in this regard is that benchmarking results should be treated like any other measure. A single value should not receive too much value, especially when the normal range of values for that measure are not well known.

Benchmarking Sequences

Benchmarking activities often follow the following sequence:

- Determine Current Practices
- Identify Best Practices
- Analyze Best Practices
- Model Best Practices
- Repeat the cycle
Benchmarking Sequences (Continued)

Juran presents the following examples of benchmarks in an advancing order of attainment:

- The customer specification
- The actual customer desire
- The current competition
- The best in related industries
- The best in the world
Benchmarking Sequences (Continued)

Omdahl defines benchmarking as continuous improvement process in which a company:

- Measures the most relevant specific attributes of its own products, services and practices
- Compares its own performance against best in class company performance and industry leaders
- Determines how those companies achieved their significantly superior performance level
- Uses that information to improve its own performance
- Ultimately achieves a level of performance achieved by the benchmarked process
- Continually repeats the process in an iterative fashion
Benchmarking Sequences (Continued)

Some companies attempt to achieve a higher performance level than their benchmark partner. Shown below is a comparison between a typical and a breakthrough benchmark approach.

![Benchmarking Comparison Diagram]

**Figure 3.11 Benchmarking Comparison**

In some cases, a benchmarking against the best-in-class is not possible because:

- The best in world is not known (should be rare)
- There is no related process available (rare)
- The best-in-class is not willing to partner
- The best-in-class is inaccessible due to geography or expense
Organizational Benchmarking

Benchmarking is the process of comparing the current project, methods, or processes with the best practices and using this information to drive improvement of overall company performance. The standard for comparison may be competitors within the industry, but is often found in unrelated business segments.

Benchmarking applications can be grouped into distinctive types. Examples are explained below:

• Process Benchmarking focuses on discrete work processes and operating systems.

• Performance benchmarking enables managers to assess their competitive positions through product and service comparisons.

• Project benchmarking areas such as new product introduction, construction, or new services which are activities common to many types of organizations.

• Strategic benchmarking examines how companies compete.
Harry states simply that Six Sigma is about making money. It is about profitability, although improved quality and efficiency are immediate byproducts. Financial benefits and associated risks are the factors used to evaluate, prioritize, select, and track all Six Sigma projects.

**Benefit - Cost Analysis**

Project benefit-cost analysis is a comparison to determine if a project will be (or was) worthwhile. The sequence for performing a benefit-cost analysis is:

1. Identify the project benefits.
2. Express the benefits in dollar amounts, timing, and duration.
3. Identify the project cost factors including materials, labor, resources.
4. Estimate the cost factors in terms of dollar amounts and expenditure period.
5. Calculate the net project gain (loss).
6. Decide if the project should be implemented, or if the project was beneficial.
7. If the project is not beneficial using this analysis, what changes in benefits and costs are possible to improve the benefit-cost calculation?
III. BUSINESS PROCESS MANAGEMENT  
C. BUSINESS RESULTS  
3. FINANCIAL BENEFITS

Return on Assets (ROA)

\[ \text{ROA} = \frac{\text{Net Income}}{\text{Total Assets}} \]

Where: net income for a project is the expected earnings and total assets is the value of the assets applied to the project.

Return on Investment (ROI)

\[ \text{ROI} = \frac{\text{Net Income}}{\text{Investment}} \]

Where: net income for a project is the expected earnings and investment is the value of the investment in the project.

Three common methods used for evaluating a project based on the dollar or cash amounts and time periods are the Net Present Value (NPV), the Internal Rate of Return (IRR), and the Payback Period methods. Project risk or likelihood of success can be incorporated into the various benefit-cost analyses as well.
III. BUSINESS PROCESS MANAGEMENT  
C. BUSINESS RESULTS  
3. FINANCIAL BENEFITS

Net Present Value (NPV) Method

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1 + r)^t}$$

Where: $n$ is the number of periods, $t$ is the time period, $r$ is the per period cost of capital for the organization (also denoted as $i$ if annual interest rate is used) and $CF_t$ is the cash flow in time period $t$. Note that $CF_0$ cash flow in period zero is also denoted as the initial investment.

The cash flow for a given period, $CF_t$ is calculated as:

$$CF_t = CF_{B,t} - CF_{C,t}$$

Where $CF_{B,t}$ is the cash flow from project benefits in time period $t$ and $CF_{C,t}$ are the project costs in the same time period. The standard convention for cash flow is positive (+) for inflows and negative (−) for outflows.

The conversion from an annual percentage rate (APR) equal to $i$, to a rate $r$ for a shorter time period, with $m$ periods per year is:

$$r = \left( 1 + \frac{i}{m} \right)^{m} - 1$$

If the project NPV is positive, for a given cost of capital, $r$, the project is normally approved.
Internal Rate of Return (IRR) Method

The internal rate of return (IRR) is the interest or discount rate, \( i \) or \( r \), that results in a zero net present value, \( NPV = 0 \), for the project. This is equivalent to stating that time weighted inflows equal the time weighted outflows.

\[
NPV = 0 = \sum_{t=0}^{n} \frac{CF_t}{(1 + r)^t}
\]

The IRR is that value of \( r \) which results in \( NPV \) being equal to 0, and is calculated by an iterative process. The projects with the highest IRR are approved, until the available investment capital is allocated.

Payback Period Method

The payback period is the length of time necessary for the net cash benefits or inflows to equal the net costs or outflows and ignores the time value of money.

\[
\text{Payback Period} = \frac{\text{Initial (\& Incremental) Investment}}{\text{Annual (or Monthly) Cash Inflow}}
\]
Project Decision Analysis

In addition to the benefit-cost analysis for a project, the decision to proceed must also include an evaluation of the risks associated with the project. To manage project risks, first identify and assess all potential risk areas.

After the risk areas are identified, each is assigned a probability of occurrence and the consequence of risk. The project risk factor is then the sum of the products of the probability of occurrence and the consequence of risk.

\[
\text{Project Risk Factor} = \sum \{(\text{probability of occurrence}) \times \text{(consequence of risk)}\}
\]

Risk factors for several projects can be compared, if alternative projects are being considered. Projects with lower risk factors are chosen in preference to projects with higher risk factors.
Project Portfolio Analysis

When there is a portfolio of project opportunities and limited resources, as in the real world, management must make decisions to approve, postpone, or reject project proposals. These decisions are based on the project benefit-cost analysis, and the evaluation of the risks.

Typically the project with the highest financial benefit, shortest payback period, or lowest risk factor is chosen for implementation first.
Traditional Cost Concept

Most companies utilize financial reports which compare actual with budgeted costs. The difference is called a variance and may prompt management action.

Origin of Quality Cost Measurements

In the 1950’s and 1960’s, some enlightened companies began to evaluate and report quality costs. What resulted was a method of defining and measuring quality costs and reporting them on a regular basis (monthly or quarterly). The quality cost reports became a vehicle to:

- Determine the status of cost control efforts, and
- Identify opportunities for reducing costs by systematic improvements

Since the costs of quality are high (15-25% of total costs), the opportunity for improvement should easily capture the attention of management.
III. BUSINESS PROCESS MANAGEMENT  
C. BUSINESS RESULTS  
3. FINANCIAL BENEFITS

Quality Cost Categories

Quality costs consist of all those costs associated with company efforts devoted to planning the quality system, efforts to verify that quality is being obtained, and those associated with failures resulting from inadequate systems. Quality cost categories are:

**Prevention costs:** The costs of activities specifically designed to prevent poor quality in products or services.

**Appraisal costs:** The costs associated with measuring, evaluating, or auditing products or services to assure conformance to quality standards and performance requirements.

**Failure costs:** The costs resulting from products or services not conforming to requirements or the costs resulting from poor quality.

  **Internal failure costs:** Failure costs which occur prior to delivery or shipment of the product, or the furnishing of a service, to the customer.

  **External failure costs:** Failure costs which occur after shipment of the product, or during or after furnishing a service, to the customer.
Quality Cost Categories (Continued)

The relationship of the three levels of product costs are shown in Figure 3.12.

Figure 3.12 The Three Levels of Product Costs

Items included in each cost category are shown in Primer pages III - 60/61.
Optimum Quality Costs

The total quality curve is depicted in the theoretical model in Figure 3.13. The lowest total cost point is ideal. The location of this point can be shifted, based on competitive market conditions and technological advances.

Figure 3.13 Optimum Quality Cost Model
Optimum Quality Costs (Continued)

Figure 3.14 Hypothetical Quality Costs Trends Over Time
Quality Cost Improvement Sequence

- Define the company quality goals and objectives
- Translate the quality goals into quality requirements
- Estimate capabilities of current processes, machines, systems, etc.
- Develop realistic programs and projects consistent with the company goals
- Determine the resource requirements for approved programs and projects
- Set up quality cost categories of prevention, appraisal, and failure to accumulate costs
- Arrange for accounting to collect and present quality costs
- Insure accurate figures or estimates by category
- Analyze the cost data for improvement candidates
- Utilize the Pareto principle to isolate specific vital areas for investigation
Quality Cost Comparison Bases

Quality costs should be related to as many different volume bases as practical. Two or three comparisons are normal. Some examples are:

Labor bases:

- Total direct labor (worked)
- Standard labor (planned)

Manufacturing cost bases:

- Shop cost of output
- Manufacturing cost of output

Sales bases:

- Net sales billed
- Contributed value

Unit bases:

- Quality costs, dollars per unit of production
- Quality costs related to production
## Typical Quality Cost Report

<table>
<thead>
<tr>
<th>Quality Cost Report for December, 2001</th>
<th>Dollars ($)</th>
<th>Percent of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Prevention Costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quality Control Administration</td>
<td>5250</td>
<td>2.1</td>
</tr>
<tr>
<td>Quality Control Engineering</td>
<td>14600</td>
<td>5.9</td>
</tr>
<tr>
<td>Other Quality Planning</td>
<td>1250</td>
<td>0.5</td>
</tr>
<tr>
<td>Training</td>
<td>2875</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Total Prevention</strong></td>
<td>23975</td>
<td>9.7</td>
</tr>
<tr>
<td><strong>Appraisal Costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inspection</td>
<td>55300</td>
<td>22.3</td>
</tr>
<tr>
<td>Test</td>
<td>23800</td>
<td>9.6</td>
</tr>
<tr>
<td>Vendor Control</td>
<td>1700</td>
<td>0.7</td>
</tr>
<tr>
<td>Measurement Control</td>
<td>1950</td>
<td>0.8</td>
</tr>
<tr>
<td>Materials Consumed</td>
<td>375</td>
<td>0.2</td>
</tr>
<tr>
<td>Product Quality Audits</td>
<td>800</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Total Appraisal</strong></td>
<td>83925</td>
<td>33.8</td>
</tr>
<tr>
<td><strong>Internal Failure Costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scrap</td>
<td>66500</td>
<td>26.8</td>
</tr>
<tr>
<td>Repair, Rework</td>
<td>1900</td>
<td>0.8</td>
</tr>
<tr>
<td>Vendor Losses</td>
<td>2500</td>
<td>1.0</td>
</tr>
<tr>
<td>Failure Analysis</td>
<td>4000</td>
<td>1.6</td>
</tr>
<tr>
<td><strong>Total Internal</strong></td>
<td>74900</td>
<td>30.1</td>
</tr>
<tr>
<td><strong>External Failure Costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failures - Manufacturing</td>
<td>14500</td>
<td>5.8</td>
</tr>
<tr>
<td>Failures - Engineering</td>
<td>7350</td>
<td>3.0</td>
</tr>
<tr>
<td>Failures - Sales</td>
<td>4430</td>
<td>1.8</td>
</tr>
<tr>
<td>Warranty Charges</td>
<td>31750</td>
<td>12.8</td>
</tr>
<tr>
<td>Failure Analysis</td>
<td>7600</td>
<td>3.1</td>
</tr>
<tr>
<td><strong>Total External</strong></td>
<td>65630</td>
<td>26.4</td>
</tr>
<tr>
<td><strong>Total Quality Costs</strong></td>
<td>248430</td>
<td>100.0</td>
</tr>
<tr>
<td><strong>Bases</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Labor</td>
<td>94900</td>
<td>8.1</td>
</tr>
<tr>
<td>Conversion Cost</td>
<td>476700</td>
<td>40.8</td>
</tr>
<tr>
<td>Sales</td>
<td>1169082</td>
<td>100.0</td>
</tr>
<tr>
<td><strong>Ratios</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal Failure Costs to Direct Labor</td>
<td></td>
<td>78.9</td>
</tr>
<tr>
<td>Internal Failure Costs to Conversion</td>
<td></td>
<td>15.7</td>
</tr>
<tr>
<td>Total Quality Costs to Sales</td>
<td></td>
<td>21.3</td>
</tr>
</tbody>
</table>
Advantages of a Quality Cost System

- Provides a single overview of quality and aligns quality and company goals
- Provides a prioritization system and a means for measuring change

Limitations of a Quality Cost System

- Quality cost measurement does not solve quality problems and does not suggest specific actions
- Important costs may be omitted, inappropriate costs may be included and costs are susceptible to measurement errors

Other Quality Cost Pitfalls

- Perfectionism in the numbers
- Presentation discussion on the merits of improvement proposals and not on data validity
- Inclusion of non-quality costs
- Implications of reducing quality costs to zero
- Reducing quality costs but increasing total company costs
- Understatement of quality costs
III. BUSINESS PROCESS MANAGEMENT QUESTIONS

3.1. The SIPOC business model helps everyone in the company see the business from an overall processes perspective by:
   I. Providing a framework applicable to processes of all sizes
   II. Identifying the few key business customers
   III. Displaying cross-function activities in simple terms
   IV. Helping maintain the big business picture
   a. I, II and III only  c. I, III and IV only
   b. I, II and IV only  d. II, III and IV only

3.3. If one chose to look at any business enterprise on a three main level basis: process, operations and business, which of these categories would have both KPIV (key process input variables) and KPOV (key process output variables)?
   I. Process      II. Operations      III. Business
   a. I only       c. II and III only
   b. I and II only d. I, II and III

3.7. Variances from budget for a project:
   I. Are used to focus corrective action efforts
   II. Are the difference between planned and actual
   III. Indicate the project manager did a poor job of controlling costs
   IV. Are usually expressed in standard deviation units from the norm
   a. I and II only  c. III and IV only
   b. II, III and IV only d. I, II, III and IV

Answers  3.1 c, 3.3 d, 3.7 a
III. BUSINESS PROCESS MANAGEMENT QUESTIONS

3.15. A process consists of three sequential steps with the following yields: \( Y_1 = 99.8 \), \( Y_2 = 97.4 \), \( Y_3 = 96.4 \). Determine the total defects per unit.

a. 0.063  c. 0.067  
b. 0.065  d. 0.069

3.16. One thousand units of product were examined for the possibility of 5 different undesirable characteristics. A total of 80 defects were found. How many defects would be expected in a million opportunities?

a. 16,000  c. 61,458  
b. 26,666  d. 80,000

3.17. The DPMO for a process is 860. What is the approximate 6 sigma level of the process?

a. 4.2  c. 4.6  
b. 4.4  d. 4.8

Answers 3.15 b, 3.16 a, 3.17 c
OUR PLANS MISCARRY BECAUSE THEY HAVE NO AIM. WHEN A MAN DOES NOT KNOW WHAT HARBOR HE IS MAKING FOR, NO WIND IS THE RIGHT WIND.

 SENECU (4BC - AD65)
IV. PROJECT MANAGEMENT
A. PROJECT CHARTER AND PLAN
1. CHARTER/PLAN ELEMENTS

Project Management

Project management is reviewed in the following topic areas:

- Project charter and plan
- Team leadership
- Team dynamics and performance
- Change agent
- Management and planning tools

Project Charter and Plan

Project charter and plan includes the following topic areas:

- Charter/plan elements
- Planning tools
- Project documentation
- Charter negotiation
A critical element in the establishment of an improvement team is the development and acceptance of a charter. A charter is a written document that defines the team’s mission, scope of operation, objectives, time frame, and consequences.

Charters can be developed by top management and presented to teams, or teams can create their own charters and present them to top management. Top management’s endorsement of a team’s charter project is a critical factor in giving the team the direction and support it needs to succeed.

The charter includes:

- Purpose Statement, a one or two line statement explaining why the team is being formed.
- Objectives the team is expected to achieve, stated in measurable terms.
- Operating scope, defining operational boundaries within which the team operates.
- Top management’s support and commitment.
IV. PROJECT MANAGEMENT
A. PROJECT CHARTER AND PLAN
1. CHARTER/PLAN ELEMENTS

Project Charter

A charter provides the following advantages:

- Eliminates any confusion
- Defines the subject boundaries
- Identifies areas which should not be addressed
- Identifies the deliverable product
- Provides a basis for team goal setting
- Authorizes the team to collect relevant data
- Provides access to necessary resources
- Approves time for team members to address problems
Project Plan Elements

A project is a series of activities and tasks with a specified objective, starting and ending dates and resources. Resources consumed by the project include time, money, people, and equipment. Project management includes project planning and implementation to achieve:

- The specified goals and objectives,
- At the desired performance or technology level,
- Within the time and cost constraints,
- While utilizing the allocated resources.

The stages of project management are:

- Planning - deciding what to do
- Scheduling - deciding when to do it
- Controlling - assuring that desired results are obtained
Work Breakdown Structure

The work breakdown structure (WBS) is a detailed plan which expands the project (statement of work) into a detailed listing of activities required to complete the project.

The project team leader is usually responsible for completion of the work breakdown structure, including an assignment of responsibilities for each task to individuals or team groups.
Planning Tools

Project planning tools include developing and analyzing the project timeline, required resources, and estimating of costs. Common techniques for evaluating project timelines include PERT charts, Gantt charts, and critical path method (CPM). The work breakdown structure (WBS) helps identify detailed activities for the plan and enables estimation of project costs.

Network Planning Rules

- Before an activity may begin, all activities preceding it must be completed.

- Arrows imply logical precedence only. The length and compass direction of the arrows have no meaning.

- Any two events may be directly connected by only one activity.

- Event numbers must be unique.

- The network must start at a single event, and end at a single event.
IV. PROJECT MANAGEMENT
A. PROJECT CHARTER AND PLAN
   2. PLANNING TOOLS

Program Evaluation and Review Technique (PERT)

- All project individual tasks must be included in the network.
- Events and activities must be sequenced in the network to allow determination of the critical path.
- Time estimates must be made for each activity in the network, and stated as three values: optimistic, most likely, and pessimistic elapsed times.
- The critical path and slack times for the project are calculated. The critical path is the sequence of tasks which requires the greatest expected time.

The slack time, $S$, for an event is the latest date an event can occur or can be finished without extending the project, $(T_L)$, minus the earliest date an event can occur $(T_E)$. For events on the critical path, $T_L = T_E$, and $S = 0$.

$$S = T_L - T_E$$
IV. PROJECT MANAGEMENT
A. PROJECT CHARTER AND PLAN
2. PLANNING TOOLS

PERT (Continued)

Each starting or ending point for a group of activities on a PERT chart is an event, also called a node, and is denoted as a circle with an event number inside. Events are connected by arrows with a number indicating the time duration required to go between events.

An event at the start of an arrow must be completed before the event at the end of the arrow may begin. The expected time between events, \( t_e \), is given by:

\[
    t_e = \frac{t_o + 4t_m + t_p}{6}
\]

Where: \( t_o \) is optimistic time, \( t_m \) is most likely time, and \( t_p \) is pessimistic time.
An example of a PERT chart for a company seeking ISO 9001 Certification is shown below. Circles represent the start and end of each task. The numbers within the circles identify the events. The arrows represent tasks and the numbers along the arrows are the task durations in weeks.

Figure 4.1 PERT Chart Example
IV. PROJECT MANAGEMENT
   A. PROJECT CHARTER AND PLAN
      2. PLANNING TOOLS

PERT Chart Example (Continued)

Event 1 on the chart is called a burst point because more than one task (1-2, 1-3, and 1-4) start at that event. Event 5 is also a burst point. Points 6, 7, and 8 are sink points because more than one task ends at that event.

To calculate the critical path, add the durations for each possible path through the network. Which path is the critical path, and how long is it? The possible paths and total times are:

<table>
<thead>
<tr>
<th>PATH</th>
<th>TOTAL TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1-2-6-8-9-10</td>
<td>22 weeks</td>
</tr>
<tr>
<td>0-1-3-5-6-8-9-10</td>
<td>25 weeks</td>
</tr>
<tr>
<td>0-1-3-5-7-8-9-10</td>
<td>28 weeks</td>
</tr>
<tr>
<td>0-1-4-7-8-9-10</td>
<td>25 weeks</td>
</tr>
</tbody>
</table>

Table 4.3 Comparison of Possible Event Paths

The critical path is 0-1-3-5-7-8-9-10.

What is the slack time for event 6?

\[ S = T_L - T_E = 20 - 17 = 3 \text{ weeks for event 6.} \]
Critical Path Method (CPM)

The critical path method (CPM) is very similar to PERT, except PERT is event oriented, while CPM is activity oriented. Unique features of CPM include:

- The emphasis is on activities
- The time and cost factors for each activity are considered
- Only activities on the critical path are contemplated
- Activities with the lowest crash cost (per incremental time savings) are selected first
- As an activity is crashed, it is possible for a new critical path to develop

For each activity, there is a normal cost and time required for completion. To crash an activity, the duration is reduced, while costs increase. Crash means to apply more resources to complete the activity in a shorter time. The activity with the lowest incremental cost per time saved is crashed first.
IV. PROJECT MANAGEMENT
   A. PROJECT CHARTER AND PLAN
      2. PLANNING TOOLS

CPM Example

Using information from the PERT chart example, and adding crash times and costs, we have:

![CPM Example Diagram]

Figure 4.4 CPM Example

Note that each activity arrow on the PERT chart example becomes a circle on the CPM example. The letter indicates the activity and a number. The number, in this example is, the normal activity duration in weeks.

The critical path is indicated by the thicker arrows, along path A-C-F-I-K-L-M.
CPM Example (Continued)

The normal time is 28 weeks. The total normal cost is the sum of the normal costs for each activity, or $48,400.

If we wish to complete the project in 27 weeks, we must crash an activity on the critical path. It does no good to crash activities off of the critical path, because the total project duration would not be reduced.
The CPM time-cost trade-off for this example can be represented graphically as shown below:

Figure 4.7 CPM Time-Cost Trade-off Example
### Gantt Charts (Bar Charts)

Gantt Charts (bar charts), named after Henry Gantt, display activities or events as a function of time. Each activity is shown as a horizontal bar with ends positioned at the starting and ending dates for the activity. See the Gantt Chart Example on Primer page IV-15.

**Advantages of Gantt Charts include:**

- The charts are easy to understand and simple to change.
- Each bar represents a single activity.
- The chart can be constructed with minimal data.
- Program task progress versus date is shown.

**Disadvantages of Gantt Charts include:**

- They do not show interdependencies of activities.
- The effects of early or late start of an activity are not shown and details of an activity are not indicated.
- There is little predictive value.
IV. PROJECT MANAGEMENT
   A. PROJECT CHARTER AND PLAN
      3. PROJECT DOCUMENTATION

Project Documentation

Project documentation includes the following:

- Project proposal: includes the objectives, project plan, and budget.

- Project review: formal and documented critique which extends over all phases from inception to completion. It includes adequacy of personnel, time and money, project effectiveness, and the quality level of the delivered product and/or service.

- Measurement of project activity: scheduled briefing sessions during the project ranging from an overview of the project milestones to comprehensive reports.

- Project monitoring plan: what is being monitored, purpose, timing or frequency of reporting, method of reporting, criteria for reporting of unusual events, assignment of feedback loop responsibilities, and action to be taken when performance differs from requirements.
IV. PROJECT MANAGEMENT
   A. PROJECT CHARTER AND PLAN
      3. PROJECT DOCUMENTATION

Project Documentation (Continued)

The success or failure of a project is measured in the following dimensions:

- Were the specified goals and objectives achieved?
- Within the time deadlines?
- At or below cost constraints?
- Utilizing the allocated resources?

Well executed project plans meet all of the above criteria. As project complexity, project duration, or innovative technology increase, the more likely the project will not meet the desired time target. Crash programs, to return a project to the desired time schedule, are done at the expense of higher costs and resource usage.

Nearly every project encounters unanticipated events or problems, but this is not an acceptable excuse for failure to meet the performance standards. The skillful project leader will manage the resources to resolve the issues and maintain the project schedule and budgets. Performance is measured on results, not effort.
Project Documentation (Continued)

The project time line is the most visible yardstick for measurement of project activities. The overall project has definite starting and ending dates, both planned and attained. Both early and late projects have the opportunity for poor quality compared to the project on schedule.

- Milestones Reporting: significant points in the project which are planned to be completed at specific points in time. Milestones typically occur at points where they act as a gate for a go/no go decision to continue the project.

- Project Report: the report card on project performance for completion of objectives. The intent is to avoid making the same mistakes, and to benefit from effective processes.

- Document Archiving: documents need to be complete, organized and stored to provide protection from damage, security of access and retrievability within a reasonable period.
Charter Negotiation

Charter negotiation may be required. Consider the following examples:

1. **Objectives:** The final customer product or internal process may require a substantial redesign that was not envisioned.

2. **Scope:** The boundaries of the project could require expansion. The project may be sufficiently large to require break-up into more manageable pieces.

3. **Boundaries:** The project team may discover that additional areas should be included in the solution.

4. **Resources:** An oversight of some key component may be encountered which requires additional resources.

5. **Project transition:** The transition to normal company controls may necessitate a time extension or additional monitoring.

6. **Project closure:** Discovery that related processes or products need the same type of effort as that undertaken for the initial project.
Team Leadership

Team leadership is presented in the following topic areas:

- Initiating teams
- Selecting team members
- Team stages

Team Introduction

A participative style of management is the best approach to insure employee involvement in the improvement process. There is no better way of motivating employees than to provide them with challenging jobs which make use of their talents and abilities.

In spite of all the obvious advantages, team participation is one of the key areas where most American companies fail.
Company Team Benefits

The benefits of a team approach to issues are numerous. Team members may represent the role of supplier, processor and customer. On a team, each member often brings different experiences, skills, know-how, and perspectives to the issues.

Such diversity is important for most improvement teams. The most significant gains are usually achieved by teams – groups of individuals pooling their talents and expertise.

Improvement teams:

- Can tackle larger issues than individuals
- Can build a fuller understanding of the process needing improvement
- Can have immediate access to the technical skills and knowledge of all team members
- Can rely on the mutual support and cooperation that arises among team members as they work on a common project
Team Member Benefits

Teamwork offers some obvious benefits to team members, including:

- An opportunity for greater understanding of the issues affecting their work
- A chance to be creative and share ideas
- The opportunity to forge stronger working relationships with colleagues
- The opportunity to learn new skills and enhance existing ones
- A chance to work on a project with the full support and interest of upper management
- The satisfaction of solving a chronic problem, which may attract and/or retain more customers, increase revenues, and reduce costs
IV. PROJECT MANAGEMENT
B. TEAM LEADERSHIP
1. INITIATING TEAMS

Team Empowerment

Most power is derived from the organization’s management authority. A team is empowered by virtue of that power that is granted to it by management. A team charter is a very useful tool for helping a team and management understand just exactly what the team is empowered to do.

- Control is one source of power.
- Information is another source of power. Teams should be aware of financial conditions, organizational changes, market conditions, etc.
- Access to resources is a third source of power.

Management Support

Management must be educated and enthusiastic about the team concept.

(1) Does the company have the proper environment in which teams can survive and thrive?
(2) Does management fully comprehend the value of teams, to make them work?
IV. PROJECT MANAGEMENT
B. TEAM LEADERSHIP
   1. INITIATING TEAMS

Types of Teams

- Six Sigma Teams
- Improvement Teams
- Process Improvement Team
- Project Teams/Task Forces/Ad Hoc Teams
- Self Directed Teams
- Cross Functional Teams
- Quality Circles
- Quality Teams
- Natural Work Team Organization
Synopsis of Team Applications

<table>
<thead>
<tr>
<th>Team Type</th>
<th>Best Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improvement Teams</td>
<td>Work on quality or productivity issues, process flow and product issues.</td>
</tr>
<tr>
<td>Quality Teams</td>
<td>Work on quality topics or overall department performance.</td>
</tr>
<tr>
<td>Project Teams</td>
<td>Work on specific projects, material related items.</td>
</tr>
<tr>
<td>Six Sigma Teams</td>
<td>Work on specific process or customer based projects of importance. Usually disbands upon project completion.</td>
</tr>
<tr>
<td>Cross Functional Teams</td>
<td>Tend to deal more with policies, practices and operations.</td>
</tr>
<tr>
<td>Self Directed Teams</td>
<td>Requires training and exposure. Can be given objectives or develop their own.</td>
</tr>
</tbody>
</table>

Table 4.9 Synopsis of Team Types, Structure and Applications
Steering Committee Role

Various companies call this committee the Six Sigma Steering Committee, the Quality Council, or the Executive Steering Committee.

Establishing a Steering Committee is a logical first step when an organization launches a Six Sigma improvement program. The Steering Committee is usually composed of upper management. In some companies, middle management and hourly employees are also represented.

Some of the Steering Committee key roles include:

- Setting goals
- Identifying projects
- Selecting teams
- Supporting project teams
- Monitoring progress
IV. PROJECT MANAGEMENT
B. TEAM LEADERSHIP
1. INITIATING TEAMS

The Process Owner Role

The process owner is called the Six Sigma sponsor or champion in some organizations. This upper level manager should:

- Support team members with resources
- Share information with the team
- Understand the team’s mission
- Participate in project reviews
- Be knowledgeable of Six Sigma core elements

The Leader Role

Some teams have both leaders and facilitators. The leader focuses on the results and the facilitator is concerned with the team process. The leader will:

- Provide direction and suggest assignments
- Act as a liaison with management
- Consider individual needs and expectations
- Assess group progress
- Take the steps necessary to ensure success
- Encourage participation and be supportive
- Work with, not over participants
- Stick to the task at hand and be a good listener
The Team Member Role

- Participating in training to become an effective team member
- Attending team meetings, as required
- Completing assignments between meetings
- Participating actively during meetings
- Encouraging participation by other team members
- Benefitting from the experience, expertise and perspectives of others
- Applying the steps of the improvement process

The Recorder Role

- Maintains the team’s minutes and agendas
- May or may not participate as a member
- Takes clear notes including project responsibilities
- May ask for clarification of issues (for the record)

The Timekeeper Role

- Advises team of the remaining time to review a project or activity
- Enforces any time “norms” of the team
IV. PROJECT MANAGEMENT
B. TEAM LEADERSHIP
  1. INITIATING TEAMS

Typical Team Operating Guidelines

- Team agenda
- Attendance
- Meetings
- Decision process
- Minutes and reports
- Leader role
- Behavioral norms
- Confidentiality
- Guests
- Meeting audits
- Facilitator
- Conflict
- Recommendations
- Commitments
Team Meeting Structure

1. Develop an agenda: define goals, identify items, who should attend, set time and place
2. Distribute the agenda in advance
3. Start on time
4. Appoint a recorder to record minutes
5. Use visual aids liberally (flip chart, chalkboard)
6. Reinforce: participation, consensus building, conflict resolution, problem solving process
7. Summarize and repeat key points throughout
8. Put unfinished items on next agenda
9. Review assignments and completion dates
10. Finish on time
11. Distribute minutes promptly
12. Critique meeting effectiveness periodically
Sample Meeting Forms

Shown in Figure 4.10 are some very basic sample meeting forms, including:

- Agenda/Minutes
- Meeting Attendance Log
- Group Accomplishments
- Facilitator’s Log
Selecting Team Members

When selecting a team, upper management identifies those parts of the organization that are associated most closely with the problem.

- Where the problem is observed or the pain is felt
- Where causes of the problem might be found
- Among those with special knowledge or skill
- Areas that can be helpful in developing the remedy

Adding New Team Members

Care must be taken when adding new people to existing teams. Involve the entire team in the selection process. When the team has a significant role in deciding on any new team member, the team will be more committed to making sure the decision was the right decision.

Removing Team Members

Despite everyone’s best efforts, a team member may need to be taken off the team. The team and the manager should have discussions with the individual and explain what needs to happen. If the situation doesn’t improve, the team member must be removed.
Team Size

Conventional wisdom is that teams over 15 or 20 people lose the active participation of team members. Teams of 4 people or less may not generate enough ideas.

That people will more readily accept and support a change, if they are included in the development of the solution. This presents a major dilemma for teams: How can the team be kept small enough to effectively work together and at the same time involve everyone?

Team Diversity

To achieve optimum performance a team often needs diversity in the orientation of its individual team members.

Some team members are needed who are primarily oriented towards task and target date accomplishment. Other team members will be needed who hold process, planning, organization and methods in the highest regard. Teams also need members who nurture, encourage and communicate well. Teams need some members who are creative and innovative.
IV. PROJECT MANAGEMENT
B. TEAM LEADERSHIP
3. TEAM STAGES

Team Stages

Most teams go through four development stages before they become productive: forming, storming, norming, and performing. Bruce W. Tuckman first identified the four development stages.

- **Forming**: Expectations are unclear. When a team forms, its members typically start out by exploring the boundaries of acceptable group behavior.

- **Storming**: Consists of conflict and resistance to the group’s task and structure. Conflict often occurs. However, if dealt with appropriately, these stumbling blocks can be turned into performance later. This is the most difficult stage for any team to work through.

- **Norming**: A sense of group cohesion develops. Team members use more energy on data collection and analysis as they begin to test theories and identify root causes. The team develops a routine.

- **Performing**: The team begins to work effectively and cohesively.
IV. PROJECT MANAGEMENT
B. TEAM LEADERSHIP
3. TEAM STAGES

Team Stages (Continued)

- **Forming**
  - Members are:
  - inexperienced
  - excited
  - anxious
  - proud

- **Storming**
  - Members:
  - have confrontation
  - think individually
  - are learning roles
  - have divided loyalties

- **Norming**
  - Members:
  - cooperate
  - talk things out
  - focus on objectives
  - have fewer conflicts

- **Performing**
  - Members:
  - show maturity
  - focus on the process
  - achieve goals
  - operate smoothly

Figure 4.11 Schematic of Team Development Phases
IV. PROJECT MANAGEMENT
B. TEAM LEADERSHIP
3. TEAM STAGES

Team Life Cycle Characteristics

![Diagram showing team life cycle characteristics: Build Phase (Forming/Storming), Develop Phase (Norming), Optimize Phase (Performing)]

Figure 4.12 Team Life Cycle Characteristics

- Build Phase (Forming/Storming)
- Develop Phase (Norming)
- Optimize Phase (Performing)
Adjourning

At the end of most Six Sigma projects the team disbands. Adjourning is also a very common practice for non Six Sigma companies in regards to project teams, task forces and ad hoc teams.

Recognition and Reward

The ultimate reason that rewards and recognition are given is to provide positive reinforcement for good performance or correct behavior, with the expectation that this performance will be repeated in the future.

The effect of the reward will depend on the perception of the person receiving the reward. Recognition and rewards for teams and team members can be grouped into the following types:

- Material items of significant value or equivalent
- Material incidental value or equivalent
- Intangible Items

Probably one of the best rewards is “Thank you” when it is sincerely meant.
Team Dynamics and Performance

Team dynamics and performance includes the following sections:

- Team-building techniques
- Team facilitation techniques
- Team performance evaluation
- Team tools
Team Objectives

The fundamental purpose of establishing teams is to improve the internal and external efficiencies of the company. This is done through the efforts of the team members to improve quality, methods, and/or productivity.

If teams are properly functioning, they will:

- Improve employee morale
- Remove areas of conflict
- Develop creative skills of members
- Improve communication and leadership skills of members
- Develop problem solving techniques
- Improve attitudes of both management and team members
- Indicate to team members that management will listen
- Demonstrate that employees have good ideas
- Improve management/employee relationships
Team Objectives (Continued)

Listed below are some of the reasons that teams have been successful in many companies:

- Management will be more apt to listen to employees and believe they have ideas worthy of implementation.

- The team procedure allows all team members to communicate and exercise creative expression.

- The concept of teams is supported by modern motivational theory.

Team members must have a reason to work together, accept an interdependent relationship, and commit to team values.

Management supports the team process by:

- Ensuring a constancy of purpose
- Reinforcing positive results,
- Sharing business results
- Giving people a sense of mission
- Developing a realistic and integrated plan
- Providing direction and support
IV. PROJECT MANAGEMENT
   C. TEAM DYNAMICS AND PERFORMANCE
      1. TEAM-BUILDING TECHNIQUES

Team Building Activities

Three key characteristics of effective team building are mutual trust, respect, and support. The facilitator is responsible for teaching team building behavior. Team leaders, facilitators, or coaches are also helpful in making certain that the team receives guidance and training as needs arise.

Activities that improvement teams may undertake include:

- Awareness and education
- Data collection and presentation
- Problem solving and decision making
- Organizing breakthroughs

The initial project selection must have broad appeal to team members, co-workers and management and be fairly simple - but not trivial. Initially select an item to show some quick benefit that is within the group’s control.
IV. PROJECT MANAGEMENT
C. TEAM DYNAMICS AND PERFORMANCE
   1. TEAM-BUILDING TECHNIQUES

DMAIC Process

Each step in the cyclical DMAIC Process is required to ensure the best possible results from Six Sigma team projects. The process steps are detailed below:

**Define** the Customer, their Critical to Quality (CTQ) issues, and the Core Business Process involved.

**Measure** the performance of the Core Business Process involved.

**Analyze** the data collected and process map to determine root causes of defects and opportunities for improvement.

**Improve** the target process by designing creative solutions to fix and prevent problems.

**Control** the improvements to keep the process on the new course.
IV. PROJECT MANAGEMENT
C. TEAM DYNAMICS AND PERFORMANCE
1. TEAM-BUILDING TECHNIQUES

The Six Classic Team Problem Solving Steps

1. Identify business or customer problems; select one to work on.
2. Define the problem; if it is large, break it down to smaller ones and solve these one at a time.
3. Investigate the problem. Collect data and facts.
4. Analyze the problem. Find all the possible causes; decide which are major ones.
5. Solve the problem. Choose from available solutions. Select the one that has the greatest organizational benefit. Obtain management approval and support. Implement the solution.
6. Confirm the results. Collect more data and keep records on the implemented solution. Was the problem fixed? Make sure it stays fixed.
IV. PROJECT MANAGEMENT
  C. TEAM DYNAMICS AND PERFORMANCE
     2. TEAM FACILITATION TECHNIQUES

Team Facilitation

The team leader and/or facilitator must understand group dynamics. Facilitators are useful in assisting a group in the following ways:

- Identifying members of the group that need training or skill building
- Avoiding team impasses
- Providing feedback on group effectiveness
- Summarizing points made by the group
- Balancing group member activity
- Helping to secure resources that the team needs
- Providing an outside neutral perspective
- Clarifying points of view on issues
- Keeping the team on track with the process
- Helping with interpersonal difficulties that may arise
- Focusing on progress
- Assessing the change process
- Assessing cultural barriers (attitudes, personalities)
- Assessing how well groups are accomplishing their purpose
- Asking for feelings on sensitive issues
- Helping the leader to do his/her job more easily
- Coaching the leader and participants
IV. PROJECT MANAGEMENT
C. TEAM DYNAMICS AND PERFORMANCE
2. TEAM FACILITATION TECHNIQUES

Team Facilitation (Continued)

The facilitator must avoid:

- Being judgmental of team members or their ideas, comments, opinions
- Taking sides or becoming caught-up in the subject matter
- Dominating the group discussions
- Solving a problem or giving an answer
- Making suggestions on the task instead of on the process
Facilitation and leadership requirements often diminish as leadership capability is developed within the team. Refer to the diagram below:

Figure 4.13 Plot of Team Roles over Time
Common Team Problems

- Floundering
- Dominant Participants
- Overbearing Participants
- Negative Nellies
- Opinions as Facts
- Shy Members
- Jump to Solutions
- Attributions
- Put-downs (Discounts & Plops)
- Wanderlust (Tangents & Digressions)
- Feuding
- Risky-Shift
Groupthink

One aspect of group cohesiveness can work to a team’s disadvantage. Strong feelings of group loyalty can make it hard for members to criticize and evaluate others’ ideas and suggestions. Desiring to hold the group together and avoid disagreements may lead to poor decision making.

Irving Janis describes groupthink as: “A mode of thinking that people engage in when they are deeply involved in a cohesive in-group, when the members’ strivings for unanimity override their motivation to realistically appraise alternative courses of action.”

Eight “Symptoms” of Groupthink

1. Illusion of Invulnerability
2. Belief in Inherent Morality of Group
3. Collective Rationalization
4. Out-Group Stereotypes
5. Self-Censorship
6. Illusion of Unanimity
7. Direct Pressure on Dissenters
8. Self-Appointed Mindguards
Risky - Shift

Many people think that the proposed solutions to team projects would be fairly conservative. However, those experienced with team mechanics and dynamics have found the opposite to be the case. Teams often get swept up into expansive and expensive remedies.

There are ways to combat this tendency. One way is to ask the question, “If this were our personal money would we still risk it on the proposed solution.”
Additional Team Problem Areas

- Waning management support
- Inadequate documentation of meeting results
- Inadequate time or training given to team members
- Teams expose problems that may be viewed as a threat by mid-management
- Controversies developing between facilitators and leaders
- Good facilitators may be hard to find
- How should suggestion programs function with teams?
- Labor unions may resist team involvement
- Problems outside the realm of team responsibility
- Crisis management creates team scheduling problems
- Measurement and reward systems may be inconsistent
- Unproductive competition and conflict may occur among team members
- Idea generation and evaluation are not kept separate
- Facts and opinions are not distinguished
- There is a failure to assign team members specific responsibilities
Team Performance Evaluation

Management Presentations

Management presentations are opportunities for Six Sigma and other improvement teams to:

- Display skills
- Show accomplishments
- Summarize the project
- Gain any necessary management approvals
- Keep lines of communication open to upper management
- Demonstrate an understanding of the customer’s true needs
Team Performance Checklist

- Establish Agenda: Clarity about goals and content
- Stick to Subject: Always to the point
- Only One Person Talks: No interruptions
- Build on Positive: Comments are additive
- Active Listening: No misunderstandings
- Participation: Active participation
- Consensus: Buy-in on all issues
Team Performance Factors

Well functioning teams have the following factors:

- **Relationship Factors**
  - There is a firm team identity
  - Conflict is openly discussed
  - Team members support each other

- **Process Factors**
  - Decisions are made by consensus
  - There is growth and learning
  - There is ongoing performance feedback

- **Goal Factors**
  - Team members help set objectives
  - Objectives are understood by all members
  - Objectives are realistically set and met

- **Environmental Factors**
  - Team members are in close physical proximity
  - There are adequate skills and resources
  - There is management and member support

- **Role Factors**
  - There is strong effective leadership
  - Clear responsibilities are defined and supported
  - Members work as a team
IV. PROJECT MANAGEMENT
C. TEAM DYNAMICS AND PERFORMANCE
4. TEAM TOOLS

Nominal Group Technique

The nominal group technique (NGT) brings people together to solve problems but prevents peer pressures from influencing the generation of ideas. To conduct a NGT problem solving meeting:

- A facilitator or moderator leads the discussion
- A group of five to nine individuals are assembled for idea generation
- A problem is presented
- Before any discussion is held, all members create ideas silently and individually onto a sheet of paper
- The facilitator then requests and records an idea from each member in sequence until ideas are exhausted
- No discussion is allowed at this point
- After the exhaustion of ideas, evaluation of ideas is permitted. Hitchhiking on the ideas of others is encouraged.
- Voting for the best solution idea is then conducted
Multivoting

Multivoting is a popular way to select the most popular or potentially most important items from a previously generated list.

Often there are too many items for a team to work on at a single time. Multivoting is useful to narrow the field to a few items worthy of immediate attention and consists of the following steps:

1. Generate and number a list of items
2. Combine similar items if the group agrees
3. If necessary, renumber the list
4. Allow members to choose several items that they feel are most important
5. Members may make their initial choices silently and then the votes are then tallied
6. To reduce the list, eliminate those items with the fewest votes
Another tool often used for problem identification and resolution is Force Field Analysis. Eitington provides a description of the process used to perform a force field analysis:

1. A desire to understand the forces acting on a problem to be resolved

2. Determine the forces favoring the desired goal (driving forces)

3. Determine the opposing forces to the desired goal (restraining forces)

4. Determine how to add to the driving forces to overwhelm the restraining forces, or

5. Remove or weaken the restraining forces, or

6. Do both (strengthen driving forces and weaken restraining forces)
Change Agent Introduction

The change agent segment is presented in the following topic areas:

- Managing change
- Organizational roadblocks
- Negotiation and conflict resolutions techniques
- Motivation techniques
- Communication
Managing Change

What was delightful to the customer yesterday, is now deemed to be expected. The company must improve its products to meet the customer’s new expectations.

In times of change, everyone is involved in the change effort. Key managers are expected to be change agents. The change agent role is not limited to the top leaders of the corporation. Organizations generally undergo change in four major areas: strategy, technology, structure and personnel.

- Strategic change occurs when the company shifts its direction and resources toward new businesses or markets.

- Technological change occurs when the company decides that automation or modernization of key processes are essential for overall competitiveness.

- Structural changes occur when the company undergoes a management delayering process or goes from a functional structure to a product structure.

- Changing the attitudes and behaviors of company personnel are often undertaken through organizational development techniques.
The Change Process

There is a classical model for the change process. It has three phases to it: unfreezing, movement, and refreezing.

- **Unfreezing**: To the change agent, the first phase, means unfreezing the existing behavior patterns and practices of the work group.

- **Movement**: The next step would be to move the people or practices to a new arrangement.

- **Refreezing**: At the proper moment in time (with the skills, technology, or practices in place), the process, including the people, are refrozen.

With the acceleration of change in the world, our change effort is never complete.
Resistance to Change

People often resist change because they will be asked to do something that they may be unfamiliar with. They could also be asked to accept a change which could cause them a personal loss.

The change agent must anticipate resistance to change and find ways to overcome the resistance. Kotter lists a strategy for dealing with resistance to change:

- Educate and communicate the change
- Enlist employee participation in the project
- Have support efforts such as training or counseling
- Have negotiated arrangements for change
- Use manipulation to obtain support
- Use threats or direct force
Change Agent

The change agent is the person or group that acts as the catalyst and assumes the responsibility for managing the change process. Key managers usually act as sponsors or patrons of the change process. The sponsor is a key political supporter and may provide the change effort with funds, staff, and resources. The process, to be changed, is defined as the target.

Managers or other employees of the organization are termed internal change agents. External change agents are outside individuals who are free from the political restraints of the organization.

Some of the characteristics of good change agents include: being empathetic, sensitive, open, tolerant, flexible, patient, friendly, cooperative, imaginative, confident, self-reliant, and risk taking.
Large Scale Change

Generally most change agents enacting revolutionary organizational changes can be advised to allow 3 to 5 years for change to take effect. The Chief Executive Officer is anxious for results to appear much quicker than that.

A new movement coming from the organizational development area is the concept of very large groups coming together to work on a change.

The idea is to involve people at the start and to have them enrolled in the cause. Teams of large size definitely will shorten the time to transmit the vision and mission and to enroll people in the change effort.

A very key element is that everyone who can make a decision is in the room.

A large scale change effort of this type generally lasts three days, but organizations can see immediate results, not a year down the road.
Organizational Roadblocks

- Structural Roadblocks
  - Flat Organizations
  - Tall (Vertical) Organizations
  - Functional Organizations
  - Product Organizations
  - Geographic Organizations
  - Matrix Organizations
  - Team Based Organizations
- Cultural Roadblocks
  - Subcultures Concerns
  - National Culture Concerns
Organizational Culture Diagnosis

A process for management to diagnose and align the organizational culture with strategic objectives for competitive advantage is:

1. Provide clarity on the business goals
2. Ensure that the top (5-6) strategic elements are appropriately clarified
3. Decide on the 3 or 4 norms that are critical to the business goals
4. Diagnose the current culture
5. Identify the cultural gaps
6. Design a method to close the gaps
Conflict Resolution

Conflict is the result of mutually exclusive objectives or views, manifested by emotional responses such as anger, fear, frustration and elation.

The results of conflicts may be positive in some instances, negative in some, and irrelevant in others. Irrelevant conflicts occur when the outcome has neither positive nor negative effects for either party.

Positive conflicts result in:

- Win - win situations
- Creative ideas brought forth
- Better understanding of tasks, problems, views
- Wider selection of alternatives
- Increased employee interest and participation
- Increased motivation and energy

Negative conflicts result in:

- Hostile, impulsive drives to destroy
- Win - lose situations
- Lose - lose situations
- Undesirable consequences
- Isolation
- Loss of productivity
Conflict Resolution (Continued)

The ways of dealing with conflicts can be depicted in a two dimensional model for conflict handling behavior, adapted from Thomas-Kilmann Conflict Mode Instrument:

![Conflict Resolution Matrix](image)

Figure 4.19 Conflict Resolution Matrix
Conflict Resolution (Continued)

- Avoiding is unassertive and uncooperative - the individual withdraws from the situation.

- Accommodating is unassertive but cooperative - the individual yields to the wishes of others.

- Competing is assertive and uncooperative - the individual tries to win, even at the expense of others.

- Collaborating is assertive but cooperative - the individual wants things done their way, but is willing to satisfy the other person’s needs.

- Compromising is intermediate in both assertiveness and cooperativeness - the individual is willing to give in to reach a middle position and partially satisfy both parties.
Handling Conflict

There is no specific right or wrong method for handling conflicts. The method that works best depends upon the situation.

Effort/Impact

One of the most viable methods of deciding on an acceptable course of action is by determining and comparing the impact of that action with the effort to accomplish it. Some form of a matrix or modified Johari window may be used as shown in Figure 4.20.

<table>
<thead>
<tr>
<th>Impact</th>
<th>Little</th>
<th>Great</th>
</tr>
</thead>
<tbody>
<tr>
<td>Little</td>
<td>This is low hanging fruit. It should be done when convenient</td>
<td>A low priority. Shelve it until all other options are completed</td>
</tr>
<tr>
<td>Great</td>
<td>A top priority. It should be given immediate attention</td>
<td>An important long term objective. Needs a champion to keep it active</td>
</tr>
</tbody>
</table>

Figure 4.20 An Illustrative Effort/Impact Matrix
Brainstorming

Brainstorming is an intentionally uninhibited technique for generating creative ideas when the best solution is not obvious. The brainstorming technique is widely used to generate ideas when using the fishbone (cause and effect) diagram.

- Generate a large number of ideas, don’t inhibit anyone, just let the ideas out
- Free-wheeling is encouraged
- Don’t criticize
- Encourage everyone to participate
- Record all the ideas
- Let ideas incubate
- Select an appropriate meeting place
- Group size, the ideal group size is 4-10 people
Negotiation Techniques

Negotiating concentrates on developing agreements among individuals or groups. Nierenberg states that negotiating is the act of exchanging ideas or changing relationships to meet a need.

Negotiating should not be a process of using overwhelming and irresistible force on the other party. Some degree of cooperation must be employed in the negotiating process.

Interest - Based Bargaining

Interest based bargaining can be considered, for all intents and purposes, to be the same as win-win negotiations. This contrasts with traditional collective bargaining, based largely on the premise that the outcome of negotiations creates only winners and losers.
Win-Win Negotiations

In a business context, the best approach is to think win-win. The concept of win-win negotiating is for both sides to emerge with a successful deal.

There are 4 steps to the win-win negotiations philosophy:

- Establish Win-Win Plans
- Develop Win-Win Relationships
- Form Win-Win Agreements
- Perform Win-Win Maintenance
Motivation Techniques

Probably the most important part of management is the manager’s responsibility for motivating the people for whom he or she is responsible. Certainly the most challenging management responsibility is how to both sustain and increase internal motivation in the work group.

Effective managers have confidence in their subordinates and trust them to a greater degree than do less effective leaders.

Frederick Taylor

Frederick Taylor produced a systematic organization of the shop work, broken down by task and instruction, to improve efficiency of the work. This significantly raised productivity. Piecework incentives rewarded the productive and punished the slackers.

Maximum efficiency became the driving force of the time. Time and motion studies revealed where to cut down on wasted steps in the process. The workers were encouraged to do more by providing incentives.
The Hawthorne Studies

The Hawthorne Studies were the major starting project in the movement of the behavioral approach. Western Electric Company in 1924 started research on individual productivity at its Chicago facility. They eventually allowed Elton Mayo of Harvard to conduct studies on the effects of worker fatigue and output. Two important points were revealed in this study:

1. Group behavior has a powerful influence upon individual members. The work group is a significant factor, either for or against productivity, being largely influenced by the management’s ability to effectively lead the work force.

2. The work group is a social group which fulfills certain human needs. Up to this time, these needs were considered to be fulfilled in the home, church, and organizations away from the working environment.

The study actually revealed so long as people are treated as human beings they tend to cooperate in increasing productivity. The “Hawthorne effect” suggested that people who are singled out for special attention tend to perform as anticipated.
Abraham Maslow

Maslow’s theory is that individuals are motivated to lower-order needs until these are relatively satisfied, and then higher-order needs must be met to sustain satisfaction.

- Self-actualization needs: Maximum achievement for self-fulfillment
- Esteem needs: Respect, prestige, recognition, personal mastery
- Social needs: Love, affection, relationships
- Safety needs: Security, protection, and stability
- Physiological needs: Basic human needs; food, water, housing
IV. PROJECT MANAGEMENT  
D. CHANGE AGENT  
4. MOTIVATION TECHNIQUES

Douglas McGregor

Douglas McGregor introduced new theories, Theory X and Theory Y. McGregor contended that traditional management practices were rooted in certain basic negative assumptions about people (Theory X):

- Are fundamentally lazy, work as little as possible
- Avoid responsibility, lack integrity
- Are not very bright, are indifferent to organizational needs
- Prefer to be directed by others
- Avoid making decisions, are not interested in achievement

Theory Y contains the following important points:

- Physical effort in work is as natural as play.
- The threat of punishment is not the only means to achieve objectives.
- Man can exercise self-direction and self-control.
- Commitment is a function of the rewards.
- Humans can accept and seek responsibility.
- Imagination, ingenuity, and creativity are widely, not narrowly, distributed.
- Only a fraction of the intellectual potential of workers is utilized.
Douglas McGregor (Continued)

McGregor listed the following forms of motivation that would be effective for various basic human needs.

<table>
<thead>
<tr>
<th>Human Needs</th>
<th>Forms of Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical needs. (food, shelter, clothing, etc.) This translates into a job paying minimum wages.</td>
<td>Provide an opportunity to increase wages through good work.</td>
</tr>
<tr>
<td>Safety needs. A need to maintain employment even at a subsistence level.</td>
<td>Appeal to job security. Quality products satisfies the customer’s needs making jobs secure.</td>
</tr>
<tr>
<td>Social needs. The desire to be accepted as a member of a group.</td>
<td>Appeal to employees to not let members of their work group down.</td>
</tr>
<tr>
<td>Ego needs. The need for respect both internal and external.</td>
<td>Appeal to an employee’s pride through awards and recognition.</td>
</tr>
<tr>
<td>Self-fulfillment. Self actualization through expression and creativity.</td>
<td>Give the employees the training and encouragement to propose creative ideas and implement them.</td>
</tr>
</tbody>
</table>
Frederick W. Herzberg

Herzberg proposed that motivation can be divided into two factors, which have been referred to by a variety of names:

- Dissatisfiers and Satisfiers, or
- Maintenance factors and Motivators, or
- Hygiene factors and Motivators, or
- Extrinsic factors and Intrinsic factors

The dissatisfiers or hygiene factors do not provide strong motivation, but do cause dissatisfaction if they are not present. On the other hand, satisfiers, motivators, or intrinsic factors do provide strong motivation and satisfaction when they are present.
Employee Empowerment

Organizations have been searching for higher performance for many years. Organizations find that with empowerment, solutions are better, decisions have better acceptance, and performance is increased. French provides the following definition of empowerment:

“To empower is to give someone power, which is done by giving individuals the authority to make decisions, to contribute their ideas, to exert influence, and to be responsible.”

Goetsch points out that “empowerment is employee involvement that matters.” The employees have authority and responsibility to make things happen.

Barriers To Empowerment

It appears that empowerment might be a good idea, but there are self-made barriers in many companies. These barriers can stop the empowerment movement in its tracks.

Barriers can be created by employees, management, and unions.
Organizational Empowerment

Management has the responsibility of setting the tone for organizational empowerment. The purpose of this action is to engage the entire workforce in the activity of making things better.

Organizational empowerment generally consists of steps or stages. Very few companies would attempt to advance from employee awareness directly to employee ownership.

Figure 4.25 Organizational Empowerment Steps
IV. PROJECT MANAGEMENT
D. CHANGE AGENT
4. MOTIVATION TECHNIQUES

What Employees Want

Often management thinks that they know what employees want. Surprisingly most employees actually follow the theories of Maslow and Herzberg and management thinks otherwise. Consider the following job factor survey from Kinni and contrast the employee and manager rankings:

<table>
<thead>
<tr>
<th>Factor</th>
<th>Employee Rating</th>
<th>Manager Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interesting Work</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Appreciation</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Involvement</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Job Security</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Good Pay</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Promotion/growth</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Good working Conditions</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Loyalty to employees</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Help with personal problems</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Tactful discipline</td>
<td>10</td>
<td>6</td>
</tr>
</tbody>
</table>

Contrast of Ranking of Work Factors
Motivating the Work Force

Kinni suggests that managers, at all levels cannot directly cause an employee to become motivated. The best that they can do is follow the following concepts to create an environment for individuals to motivate themselves:

1. Know thyself
2. Know your employees
3. Establish a positive attitude
4. Share the goals
5. Monitor progress
6. Develop interesting work
   • Job rotation, Job enlargement, Job enrichment
7. Communicate effectively
8. Celebrate success
Communication Techniques

For any organization to survive, information must continually flow vertically and horizontally across the company. A good manager must be able to understand the process flow and how to use it.

- Downward Flow of Communication
- Upward Flow of Communications
- Misleading Information
- Horizontal Communications
- Formal and Informal Communications
- Special Roles
- Appropriate Vehicles for Different Situations
- Other Communication Forms
- Questioning Techniques
- Listening Strategies
Management and Planning Tools

Management and planning tools include:

- Affinity Diagrams
- Interrelationship Digraphs
- Tree Diagrams
- Prioritization Matrices
- Matrix Diagrams
- Process Decision Program Charts
- Activity Network Diagrams
Management and Planning Tools (Cont.)

The 7 new tools as written by Japanese authors Mizuno Shigeru; and Asaka Tetsuichi and Ozeki Kazuo are:

1. Relations diagram
2. Affinity diagram (KJ method ... registered trademark)
3. Systematic diagram
4. Matrix diagram
5. Matrix data analysis
6. Process decision program chart (PDPC)
7. Arrow diagram

The 7 modified tools are identified by the corresponding Japanese sequence number and are listed below:

2. Affinity diagram (KJ method ... registered trademark)
3. Tree diagram
6. Process decision program chart (PDPC)
5. Matrix diagram
1. Interrelationship digraph (I.D.)
4. Prioritization matrices
7. Activity network diagram
Affinity Diagrams

The affinity diagram is beneficial for unfamiliar new, or complex problems. It can be widely used in the planning stages of a problem to organize the ideas and information. The affinity diagram can also be referred to as the KJ method. It was developed by Dr. Kawakita Jiro. The steps can be organized as follows:

- Define the problem under consideration.
- Have 3" x 5" cards or Post-it® notes for use.
- Enter ideas, data, facts, opinions, etc. on the cards or notes.
- Place the cards or notes on a conference table or on a wall.
- Arrange the groups into similar thought patterns or categories.
- Develop a main category or idea for each group. That main category idea becomes the affinity card.
- Once all the cards have been placed under a proper affinity card, the diagram can be drawn up. Borders can be drawn around the affinity groups for clarity.
IV. PROJECT MANAGEMENT
E. MANAGEMENT AND PLANNING TOOLS
1. AFFINITY DIAGRAMS

Example Affinity Diagram

HOW TO PREPARE FOR THE CSSBB EXAM

RESOURCES
GET CSSBB PRIMER
REVIEW OTHER BOOKS
GET OTHER SIX SIGMA TEXTBOOKS
CALL ASQ TO OBTAIN BODY OF KNOWLEDGE

PREPARATION
TEACH CSSBB SUBJECTS
DEVELOP PRACTICAL EXPERIENCE
STUDY INTENSIVELY
START EARLY 1-2 YEARS
STUDY 1 SUBJECT AT A TIME FOR 3 - 4 WEEKS
STUDY CSSBB TESTS
MAKE YOUR OWN CSSBB EXAMS

OBTAIN KNOWLEDGE
WATCH VIDEO PRESENTATION
TAKE SIX SIGMA SEMINARS
ATTEND CSSBB REFRESHER
STUDY IN GROUPS
HAVE A TUTOR
CONSIDER A SIX SIGMA 4 WEEK TRAINING COURSES
HAVE A Q & A SOURCE

MOTIVATION
MOTIVATE SELF
GET BONUS
LISTEN TO SUCCESSFUL PASSED CSSBBS
DEVELOP PRIDE
BE AROUND OTHERS WHO ARE POSITIVE
PUMP YOURSELF UP

REVIEW OTHER BOOKS
GET OTHER SIX SIGMA TEXTBOOKS
CALL ASQ TO OBTAIN BODY OF KNOWLEDGE

STUDY IN GROUPS
HAVE A TUTOR
CONSIDER A SIX SIGMA 4 WEEK TRAINING COURSES
HAVE A Q & A SOURCE

MOTIVATION
MOTIVATE SELF
GET BONUS
LISTEN TO SUCCESSFUL PASSED CSSBBS
DEVELOP PRIDE
BE AROUND OTHERS WHO ARE POSITIVE
PUMP YOURSELF UP
IV. PROJECT MANAGEMENT
E. MANAGEMENT AND PLANNING TOOLS
2. INTERRELATIONSHIP DIGRAPHS

Interrelationship Digraphs (I.D.)

For complex problems the idea is to have a process of creative problem solving that will eventually indicate some key causes. In fact, the final “solution” to the problem will be determined when the team has analyzed the graph for the key causes. To create an interrelationship digraph:

- Develop about 50 items that pertain to the basic problem on I.D. cards.
- Use a pattern of placing closely related items together or shuffle the cards for a random display on a table.
- Draw in relationship arrows from the cause item to the effect item for every card.
- The digraph can be distributed to team members for study, and several revisions can be made.
- With a final draft of the digraph, an analysis can be attempted. The drawing of arrows leading away or to certain (I.D.) cards lead to inferences for the team.
- The team will select a few key items for project work, possibly be the ones with the most arrows.
Example Interrelationship Digraph

- BONUS for CSSBB
- GET CSSBB PRIMER
- HAVE A TUTOR
- TAKE ASQ CSSBB WORKSHOP
- STUDY IN GROUPS
- CALL ASQ
- HAVE A CALL-IN SOURCE
- STUDY CSSBB TESTS
- STUDY INTENSIVELY
- TAKE UNIVERSITY COURSES
- PROMOTION REQUIRES CSSBB
- MOTIVATION OF SELF
- ATTEND CSSBB REFRESHER
- PEERS HAVE CSSBB
- JOB EVALUATION NEEDS CSSBB

Figure 4.28 ID Example for CSSBB Exam
Tree Diagrams

The tree diagram, also be referred to as a systematic diagram, is a systematic method to outline all the details needed to complete a given objective. The organization is by levels of importance. The tree diagram can be used to:

- Develop the elements for a new product
- Show the relationships of a production process
- Create new ideas in problem solving
- Outline project implement steps

One way to organize a tree diagram is as follows:

- Determine the overall objective, goal, basic function of the tree diagram.

- Next determine the second level of means that would achieve the goal.

- For each level of the tree, the same line of questioning is used, until you have determined that all details necessary to solve the overall objective.

- Go back over the diagram to confirm that each means will lead to a successful objective.
Example Tree Diagram

- Pass the CSSBB Exam
  - Need resources
    - Get CSSBB Primer
    - Call ASQ for B.O.K.
    - Get other textbooks
  - Obtain videos
    - Obtain seminars
    - Restudy seminar
    - Take CSSBB seminars
    - Attend CSSBB refresher
    - Study at home
    - Study in group
    - Study via tutor
    - Have a source as a call-in for Q/A
    - Take university level courses in quality
  - Obtain others knowledge
    - Obtain own CSSBB exams
    - Motivate yourself for each step
    - Reward yourself for each step
    - Listen to successful CSSBB
    - Ask for helpful tips
    - Be around others who are positive
    - Ask for bonus
  - Examine motivation
    - Need to prepare
    - Use practical experience
    - Teach CSSBB subjects
    - Study B.O.K.
    - Start early 1-2 years

Figure 4.29 A Tree Diagram Example
Prioritization Matrices

To use the prioritization matrices, the key issues and concerns have been identified and alternatives have been generated. The need is to determine the option to use. The prioritization matrix is a system for decision making such that computer usage is not a requirement.

M. Brassard in *The Memory Jogger Plus+* provides a description of 3 types of prioritization matrices that can be developed for use:

- The full analytical criteria method
- The consensus criteria method
- The combination I.D./matrix method

The criteria get prioritized, weighted, and applied against the options generated. A decision based on numerical values generally can be obtained.
### Prioritization Matrices (Continued)

#### The Criteria Composite Ranking (4 People)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Factors</th>
<th>0.45 Work Experience</th>
<th>0.70 Have Tutor</th>
<th>0.50 Study Group</th>
<th>0.95 Attend Refresher</th>
<th>0.65 Study Tests</th>
<th>0.75 High Motivation</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Work Experience</td>
<td></td>
<td>0.05</td>
<td>0.10</td>
<td>0.10</td>
<td>0.20</td>
<td></td>
<td></td>
<td>0.45</td>
</tr>
<tr>
<td>B. Have Tutor</td>
<td></td>
<td>0.10</td>
<td>0.20</td>
<td>0.30</td>
<td>0.10</td>
<td></td>
<td></td>
<td>0.70</td>
</tr>
<tr>
<td>C. Study In Group</td>
<td></td>
<td>0.15</td>
<td>0.10</td>
<td>0.05</td>
<td>0.20</td>
<td></td>
<td></td>
<td>0.50</td>
</tr>
<tr>
<td>D. Attend Refresher</td>
<td></td>
<td>0.25</td>
<td>0.20</td>
<td>0.20</td>
<td>0.30</td>
<td></td>
<td></td>
<td>0.95</td>
</tr>
<tr>
<td>E. Study Tests</td>
<td></td>
<td>0.15</td>
<td>0.15</td>
<td>0.25</td>
<td>0.10</td>
<td></td>
<td></td>
<td>0.65</td>
</tr>
<tr>
<td>F. High Motivation</td>
<td></td>
<td>0.30</td>
<td>0.25</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
<td>4.00</td>
</tr>
</tbody>
</table>

#### Completed Rank Order Scores

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Factors</th>
<th>0.45 Work Experience</th>
<th>0.70 Have Tutor</th>
<th>0.50 Study Group</th>
<th>0.95 Attend Refresher</th>
<th>0.65 Study Tests</th>
<th>0.75 High Motivation</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deployment</td>
<td></td>
<td>2(0.45)</td>
<td>1(0.70)</td>
<td>2(0.50)</td>
<td>1(0.95)</td>
<td>2(0.65)</td>
<td>1(0.75)</td>
<td>5.6</td>
</tr>
<tr>
<td>Business Management</td>
<td></td>
<td>4(0.45)</td>
<td>2(0.70)</td>
<td>1(0.50)</td>
<td>3(0.95)</td>
<td>3(0.65)</td>
<td>2(0.75)</td>
<td>10</td>
</tr>
<tr>
<td>Project Management</td>
<td></td>
<td>6(0.45)</td>
<td>4(0.70)</td>
<td>6(0.50)</td>
<td>5(0.95)</td>
<td>5(0.65)</td>
<td>6(0.75)</td>
<td>21</td>
</tr>
<tr>
<td>Define Six Sigma</td>
<td></td>
<td>5(0.45)</td>
<td>3(0.70)</td>
<td>3(0.50)</td>
<td>2(0.95)</td>
<td>1(0.65)</td>
<td>3(0.75)</td>
<td>10.65</td>
</tr>
<tr>
<td>*Measure Six Sigma</td>
<td></td>
<td>10(0.45)</td>
<td>9(0.70)</td>
<td>9(0.50)</td>
<td>7(0.95)</td>
<td>9(0.65)</td>
<td>8(0.75)</td>
<td>33.8</td>
</tr>
<tr>
<td>*Analyze Six Sigma</td>
<td></td>
<td>7(0.45)</td>
<td>8(0.70)</td>
<td>8(0.50)</td>
<td>10(0.95)</td>
<td>10(0.65)</td>
<td>9(0.75)</td>
<td>35.5</td>
</tr>
<tr>
<td>*Improve Six Sigma</td>
<td></td>
<td>9(0.45)</td>
<td>10(0.70)</td>
<td>10(0.50)</td>
<td>9(0.95)</td>
<td>8(0.65)</td>
<td>7(0.75)</td>
<td>35.05</td>
</tr>
<tr>
<td>Control Six Sigma</td>
<td></td>
<td>1(0.45)</td>
<td>5(0.70)</td>
<td>4(0.50)</td>
<td>4(0.95)</td>
<td>4(0.65)</td>
<td>4(0.75)</td>
<td>15.35</td>
</tr>
<tr>
<td>Lean Enterprise</td>
<td></td>
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<td>6(0.70)</td>
<td>5(0.50)</td>
<td>6(0.95)</td>
<td>7(0.65)</td>
<td>5(0.75)</td>
<td>22.05</td>
</tr>
<tr>
<td>*DFSS</td>
<td></td>
<td>8(0.45)</td>
<td>7(0.70)</td>
<td>7(0.50)</td>
<td>8(0.95)</td>
<td>6(0.65)</td>
<td>10(0.75)</td>
<td>31</td>
</tr>
</tbody>
</table>

*Within table columns, first number is rank order and the second is criteria total from top table.*

**Figure 4.30 Prioritization Matrix Example**
Matrix Diagrams

Matrix diagrams show the relationship between objectives and methods, results and causes, tasks and people, etc. The objective is to determine the strength of relationships between a grid of rows and columns. The intersection of the grid will clarify the problem strength. There are several basic types of matrices:

- **L-type**...elements on the Y-axis and X-axis
- **T-type**...2 sets of elements on the Y-axis, split by a set of elements on the X-axis.
- **X-type**...2 sets of elements on both the Y-axis and X-axis
- **Y-type**...2 L-type matrices joined at the Y axis to produce a matrix design in 3 planes
- **C-type (3-d matrix)**...2 L-type matrices joined at the Y-axis, but with only 1 set of relationships indicated in 3 dimensional space (better use computer software)
### X-Type Matrix

<table>
<thead>
<tr>
<th></th>
<th>Cause 1</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cause 2</td>
<td>△</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cause 3</td>
<td></td>
<td>△</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cause 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Mach 1</th>
<th>Mach 2</th>
<th>Mach 3</th>
<th>Dept 1</th>
<th>Dept 2</th>
<th>Dept 3</th>
<th>Dept 4</th>
<th>Dept 5</th>
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<tbody>
<tr>
<td>Problem</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Problem</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Problem 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>△</td>
<td>△</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Problem 4</td>
<td></td>
<td>△</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Problem 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Problem 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **◎** Strong Relationship (3)
- **○** Relationship (2)
- **△** Possible (1)

**Figure 4.31 X Type Matrix Example**
IV. PROJECT MANAGEMENT
E. MANAGEMENT AND PLANNING TOOLS
6. PROCESS DECISION PROGRAM CHARTS

Process Decision Program Charts (PDPC)

The process decision program chart (PDPC) method is used to chart the course of events that will take us from a start point to our final complex goal. As with many complex goals, an uncertainty of attaining intermediate events is possible. The various events are charted and contingencies are planned for.

Of course, some contingencies can not be planned for. There may be insufficient knowledge or unexpected changes in events may occur. This method is similar to contingency planning.

Some uses for the process decision program chart (PDPC) include:

- The problem is new, unique, or complex in nature and may involve a sequence that can have very difficult and challenging steps.

- The opportunity to create contingencies and to counter problems are available to the team.
PDPC (Continued)

Major Categories 2nd Level Last Level Last Level "What-ifs" Solutions to "What-ifs"

A1 A3 A5 RA5 CONTINGENCY

A2 A4 RESULT RA4 CONTINGENCY

B1 B2 B4 RB4 CONTINGENCY

B3 B5 RB5 CONTINGENCY

ENROLL IN CSSBB REFRESHER

STUDY WITH CLASS

LOSS OF MOTIVATION

GET PUMPED UP

GET TUTOR

STUDY VIA TUTOR

PASS THE TEST

NEED FOR THE CSSBB

OBtain RESOURCES

NO CSSBB CLASSES

FIND OTHERS

STUDY IN A GROUP

CALL EXPERT

STUDY ALONE

FIND A CSSBB
Activity Network Diagrams

The arrow diagram or activity network diagram describes a methodology that includes program evaluation and review techniques (PERT), critical path method (CPM), node/activity on node diagrams (AON), precedence diagrams (PDM), and other network diagrams.

The activities, milestones, and critical times must be developed and then drawn onto a chart. The chart will then provide a tool to help monitor, schedule, modify, and review the project.

Some definitions for use with the activity network diagram:

Event, node: The junction point of an activity
Job, activity: The activity or task
Dummy node: A note inserted to combine the relative timing of parallel operations
Critical path: The path with the longest time
Slack time (SL): The difference between the latest time and the earliest finish time
IV. PROJECT MANAGEMENT QUESTIONS

4.5. The critical path in a project means that:

I. The project is important to the profits of the organization
II. Slack times can be used to delay the ending date of the project
III. Events on this path have no slack time
IV. Delays of events on this path delay the ending date of the project

a. I and IV only  c. III and IV only
b. II and IV only  d. II, III and IV only

4.9. Which of the following places should be considered when selecting improvement team members?

I. Where the problem is observed
II. Where the sources or causes may be found
III. Among those with special knowledge, information or skills
IV. In areas that can be helpful in developing remedies

a. I, II and III only
b. II, III and IV only
c. I, III and IV only
d. I, II, III and IV

4.10. Which of the following is NOT a team leader role?

a. Conducts meetings
b. Schedules the next meeting
c. Acts as a liaison with management
d. Distributes meeting minutes

Answers 4.5 c, 4.9 d, 4.10 d
IV. PROJECT MANAGEMENT

QUESTIONS

4.16. Place the four team development stages in order of occurrence:

a. Forming, storming, performing, norming
b. Forming, storming, norming, performing
c. Norming, storming, forming, performing
d. Norming, forming, storming, performing

4.18. Excessive conflict within a work team:

I. Has a negative effect on team members and should be avoided
II. Has a positive effect on creating alternate solutions
III. Most often results in lose-lose situations

a. I only
b. I and III only
c. II and III only
d. III only

4.19. A skilled facilitator will:

I. Intervene when progress ceases
II. Correct the group when their ideas are wrong
III. Take sides when one side is correct
IV. Make sure all opinions are heard

a. I and III only
b. II and IV only
c. I and IV only
d. I, II, III and IV

Answers 4.16 b, 4.18 b, 4.19 c
IV. PROJECT MANAGEMENT QUESTIONS

4.25. What roles are needed for a change process to be successful?

I. A catalyst
II. A sponsor
III. A CEO
IV. An accountant

a. I only c. I and II only
b. II and III only d. I, III and IV only

4.28. Modern managers recognize, in order to be either good leaders or good managers, one must know the difference between the two concepts. Which of the following is most clearly a leader role?

a. The ability to plan and budget complex projects
b. The ability to create and align people toward a vision
c. The capacity to organize and staff properly
d. The ability to accomplish detailed plans

4.29. An accommodating approach to conflict resolution is most appropriate when:

I. One party is wrong
II. The issue is much more important to one party
III. Both views are seen as important
IV. An integrated solution is desired

a. I and II only c. I and IV only
b. II and III only d. II and IV only

Answers 4.25 c, 4.28 b, 4.29 a
IV. PROJECT MANAGEMENT QUESTIONS

4.31. When giving instructions to those who will perform a task, the communication process is completed:
   
a. When the worker goes to his work station to do the task
b. When the person giving the instruction has finished talking
c. When the worker acknowledges these instructions by describing how he/she will perform the task
d. When the worker says that he/she understands the instructions

4.35. New quality management tools are being used to help the problem solving process. Which tool provides a ranking of options for review?
   
a. Interrelationship digraph
b. Affinity diagram
c. Activity network diagram
d. Prioritization matrices

4.40. In order to select a problem to work on from a list of contenders, which of the following team tools would a facilitator be LEAST likely to employ?
   
a. Nominal group technique
b. Groupthink
c. Multivoting
d. Force field analysis

Answers 4.31 c, 4.35 d, 4.40 b
THE STARTING POINT FOR IMPROVEMENT IS TO RECOGNIZE THE NEED.

IMAI
Six Sigma Methodology - Define

The Define portion of Six Sigma Improvement Methodology is presented in the following topic areas:

- Project Scope
- Metrics
- Problem Statement
Project Scope

The initial step of the Six Sigma problem solving methodology is the define step. As the adage goes, properly defining the problem is the most important part of solving the problem. The following tools and techniques are useful in the definition step:

- Project Charter (boundaries)
- Stakeholder Analysis
- Defining the Customer
- Pareto Diagrams
- SIPOC
- Rolled Throughput Yield (RTY)
- Voice of the Customer
- Affinity Diagrams
- Kano Model

Most of the above tools and techniques are explained as part of this BOK element. A few of the techniques are presented in other portions of this Primer because they are also very applicable to other Six Sigma areas.
V. SIX SIGMA METHODOLOGY - DEFINE
A. PROJECT SCOPE

Project Charter

Upper management may or may not provide a team with a mission (or purpose) statement. If a mission statement is not provided it should be developed by the team. The improvement team is generally given the task of developing the project charter. This charter is developed with the assistance of the team leader or facilitator.

The project charter is very useful for several reasons:

- The team is aware of the project goals and boundaries
- The team can remain focused on the goals
- The team will work on projects that align with the organization’s goals
- The team champion will support the team and their goals
Project Charter (Continued)

A team project charter should contain the following key points:

- **Business case** - a short summary of the strategic reasons for the project.

- **Problem statement** - will detail the issue that the team wants to improve.

- **Project scope** - The project scope refers to the boundaries of the project.

- **Goal statement** - created and agreed to by the team and team champion and achievable within a 120 to 160 day period.

- **Role of team members** - composed of qualified people with sufficient training and expertise to carry out the team’s charter.

- **Milestones/deliverables** - used to keep the project on track and to help bring a project to completion.

- **Resources required** - detailed including qualified people, equipment, machinery, work space, computers, etc.
Stakeholders can be identified as:

- Managers of the process
- People in the process
- Upstream people in the process
- Downstream people in the process
- Customers
- Suppliers
- Finance

Rath & Strong propose developing a communication plan involving the stakeholders and identifying the level of commitment or resistance that the stakeholder is perceived to have.
Stakeholder Analysis (Continued)

Beckhard & Harris describe a responsibility chart that identifies the stakeholder and the behavior that would be required for a change. The responsibility communications chart will help to clarify the needed improvement in commitment.

<table>
<thead>
<tr>
<th>Level of Commitment</th>
<th>Sales</th>
<th>Management</th>
<th>Employees</th>
<th>Customer A</th>
<th>Supplier A</th>
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</thead>
<tbody>
<tr>
<td>Supporter</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>O</td>
</tr>
<tr>
<td>Compliant</td>
<td>O</td>
<td>O</td>
<td></td>
<td>O</td>
<td></td>
</tr>
<tr>
<td>Indifferent</td>
<td></td>
<td></td>
<td></td>
<td>X O</td>
<td></td>
</tr>
<tr>
<td>Uncooperative</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Opposed</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hostile</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Not needed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Legend: X = present level of commitment
         O = required commitment level

The table indicates where the various players in the project are currently positioned and a projection of where they must be in order to have a successful project.
Defining the Customer

At times, the customer of the project may not be as evident as initially thought. The receiver of the next operation could be thought of as a customer or the external customer of a process could be the purchaser.

Pande states that the primary customer of the process will or should have the highest impact on the process.

Customers can constitute:

- Current, happy customers
- Current, unhappy customers
- Lost customers
- Competitor’s customers
- Prospective customers

Customer satisfaction surveys may result in survey information that reflect the thoughts of a market segment for which the product was not intended.
V. SIX SIGMA METHODOLOGY - DEFINE
A. PROJECT SCOPE

Pareto Diagrams

Pareto diagrams are very specialized forms of column graphs which are used to prioritize problems so that the major problems can be identified.

Vilfredo Pareto (1848-1923) was an economist that made extensive studies about the unequal distribution of wealth and formulated mathematical models to quantify this maldistribution.

Dr. Joe M. Juran needed a name to apply to the phenomenon of the “vital few” and the “trivial many.” He depicted some cumulative curves in his manuscript and put a caption under them, “Pareto’s principle of unequal distribution...” Dr. Juran applied this principle as a “universal.” Thus, the diagram could be named a “Juran diagram.”

To complicate matters more, the cumulative curve diagram itself was first used by M. O. Lorenz in 1904.

The principle suggests that a few problem categories (approximately 20%) will present the most opportunity for improvement (approximately 80%).
V. SIX SIGMA METHODOLOGY - DEFINE
A. PROJECT SCOPE

Typical Pareto Diagram

Note that the “all others” category is placed last.

“First things first” is the thought behind the Pareto diagram. Our attention is focused on problems in priority order.

Pareto diagrams are used to:

- Analyze a problem from a new perspective
- Focus attention on problems in priority order
- Compare data changes during different time periods
- Provide for the construction of a cumulative line
Weighted Pareto Analysis

In many cases, the Pareto chart is constructed based upon the number of event occurrences. However, criticality (or potential safety or economic loss) factors might result in a different Pareto alignment.

Criticality of deficiencies or dollar costs associated with deficiencies can be used to yield a weighted Pareto analysis.

An example of a weighted Pareto analysis is show in the Primer.
V. SIX SIGMA METHODOLOGY - DEFINE
A. PROJECT SCOPE

Suppliers, Inputs, Process, Outputs, Customers (SIPOC)

SIPOC is a high level process view with 4 - 7 steps displayed. This approach enables all team members to view the process in the same light. Simon suggests the following steps for developing a SIPOC diagram:

1. Have the team create the process map.

2. How is the raw material or product transformed?

3. List the outputs of the process. What is the end result, product/service of this process?

4. List the customers of the output of the process.

5. List the inputs of the process.

6. List the suppliers of the process.

7. As an optional step, identify some preliminary requirements of the customers.

8. Involve the team leader, champion, and other stakeholders for verification of the project.
SIPOC (Continued)

An example of a SIPOC diagram:

<table>
<thead>
<tr>
<th>Suppliers</th>
<th>Inputs</th>
<th>Process</th>
<th>Outputs</th>
<th>Customers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper Suppliers</td>
<td>BOK from ASQ</td>
<td>See below</td>
<td>Primers</td>
<td>ASQ members</td>
</tr>
<tr>
<td>Binder Suppliers</td>
<td>Written and Electronic Text</td>
<td></td>
<td>Solution</td>
<td>Quality Professionals</td>
</tr>
<tr>
<td>Tab Suppliers</td>
<td>Charts and Graphics</td>
<td></td>
<td>Question CDs</td>
<td>Test Takers</td>
</tr>
<tr>
<td>Reproduction</td>
<td>Reviews</td>
<td></td>
<td>Instructor</td>
<td>Education Chairs</td>
</tr>
<tr>
<td>Services</td>
<td></td>
<td></td>
<td>PDF CDs</td>
<td></td>
</tr>
<tr>
<td>Authors</td>
<td>Reference Materials</td>
<td></td>
<td></td>
<td>Company Trainers</td>
</tr>
<tr>
<td>Reviewers</td>
<td></td>
<td></td>
<td></td>
<td>Libraries</td>
</tr>
</tbody>
</table>

Process

Authors submit materials → Publisher edits materials → Materials assemble into book → Orders processed for materials → Send materials to customer
Rolled Throughput Yield (RTY)

Rolled throughput yield can be defined as the cumulative calculation of yield or defects through multiple process steps.

The determination of the rolled throughput yield (RTY) can help a team focus on the problem. An example of RTY calculation and analysis:

<table>
<thead>
<tr>
<th>Process</th>
<th>Weld 1</th>
<th>Weld 2</th>
<th>Fab 1</th>
<th>Fab 2</th>
<th>Assy</th>
</tr>
</thead>
<tbody>
<tr>
<td>yield:</td>
<td>90%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>yield:</td>
<td>yield:</td>
<td>yield:</td>
<td>yield:</td>
</tr>
<tr>
<td></td>
<td>86%</td>
<td>92%</td>
<td>87%</td>
<td>65%</td>
<td></td>
</tr>
</tbody>
</table>

RTY = 1 x 0.90 x 0.86 x 0.92 x 0.87 x 0.65 = 0.403

The process RTY is only 40.3%. A very significant drop in yield occurs in the Assembly process with only 65% yield. This indicates that the Assembly process could warrant an initial improvement project.
Voice of the Customer (VOC)

An understanding of the needs of the customer is critical to the survival of most companies. A detailed plan to gather and collect customer needs and customer perceptions can be described as listening to the voice of the customer (VOC).

This enables the organization to:

- Make decisions on products and services
- Identify product features and specifications
- Focus on improvement plans
- Develop baseline metrics on customer satisfaction
- Identify customer satisfaction drivers
The Kano Model is also referred to as Kano Analysis. It is used to analyze customer requirements. Noriaki Kano is a Japanese engineer and consultant, whose work is being used by a growing number of Japanese and American companies. The model is based on 3 categories of customer needs:

1. Dissatisfiers, (basic requirements, or “must be’s”)
2. Satisfiers, (variable requirements, or “more is better”)
3. Delighters, (latent requirements):
Critical to Quality (CTQ) Tree

The construction of a critical to quality tree focuses on the key metrics of customer satisfaction.

A CTQ tree translates initial customer requirements to numerical or quantified requirements for the product or service. These can be regarded as key results, or the “Ys” of the process.

<table>
<thead>
<tr>
<th>General</th>
<th>Specific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Need</td>
<td>Drivers</td>
</tr>
</tbody>
</table>

The creation of the CTQ tree steps:

1. Identify the customer.
2. Identify the customer’s need.
3. Identify the basic requirements of the customer.
4. Progress further with more levels as needed.
5. Validate the requirements with the customer.
Critical to Quality Tree (Continued)

Order Meal → Price → Taste → Delivery → Speed → Cheap → Good

Figure 5.8 Sample CTQ for Meal Performance
Metrics Selection

As indicated in the Critical to Quality Tree (CTQ tree) the primary and more detailed metrics are developed but are not finalized in the definition step. That is left to the Measure step. On a general basis, the primary metrics for consideration in a project would be from several sources:

- Suppliers
- Internal process
- Customers

The basic metrics that will affect those projects involving suppliers, internal process, and customers would be: quality, cycle time, cost, value, labor.

9 dimensions of quality to consider:

- Performance
- Features
- Conformance
- Reliability
- Durability
- Service
- Response
- Aesthetics
- Reputation
V. SIX SIGMA METHODOLOGY - DEFINE
B. METRICS

Metrics Selection (Continued)

The secondary or consequential metrics would be derived from the primary metrics. That is, if cycle time is determined to be a key metric, the next level down would be to establish the numerical measurement.

Examples include:

- Defects per Unit (DPU)
- Defect per Million Opportunities (DPMO)
- Average Age of Receivables
- Lines of Error Free Software Code
- Reduction in Scrap
Problem Statement

A problem statement will detail the issue that the team wants to improve. The problem statement should include a reference to a baseline measure. A baseline measure can be defined as data on the level of performance of the particular metric at the initial start of a project.

The collection of good data and process performance measures will provide a picture of the areas in the company that are in greatest need of improvement. The measurement system will also provide a foundation for other teams to use to become a more responsive company.

The problem statement may include the goals of the project.
Summary

The Six Sigma Define phase should result in the following information for the team champion, team leader, and team members:

1. Importance of the project
2. Goals of the project
3. Knowledge of the team champion, leader and members
4. Scope of the project in terms of time and budget resources
5. The key process involved
6. Current baseline metrics
7. What the customer requirements are
V. SIX SIGMA METHODOLOGY - DEFINE QUESTIONS

5.2. A project charter is essential for the team to develop because:

I. The team will be focused on the appropriate problem
II. The solution will be aligned towards the organization’s goals
III. The team champion will be supportive
IV. The charter provides a complete history of the project

a. I and II only  c. I, II and III only
b. I and III only  d. I, II, III and IV

5.7. The composition of a team for a typical Six Sigma project should:

a. Be composed of interested floor operators and area staff
b. Consist of qualified people with the expertise needed
c. Consist of a cross-functional blend of people from various departments
d. Consist of Green belts, at the very least

5.8. In the preparation of a project, efforts should be made to identify and involve various parties affected by the planned changes. These other parties are known as:

a. Process owners
b. Champions
c. Team leaders
d. Stakeholders

Answers: 5.2 c, 5.7 b, 5.8 d
V. SIX SIGMA METHODOLOGY - DEFINE QUESTIONS

5.15. The process map known as SIPOC provides team members an understanding of the process. It is a view of the process taken at:

a. Floor level
b. A very high level
c. The customer’s perspective
d. A very detailed level

5.17. The purpose of “rolled throughput yield” in the Six Sigma define step would NOT be to:

a. Spot significant differences in yield
b. Provide a baseline metric
c. Use the calculation for customer analysis
d. Analyze a process flow for improvement ideas

5.23. In the Six Sigma define step, The critical to quality tree is used by the project team. The various levels of the tree are determined EXCEPT for:

a. The exact metrics for the customer
b. The needs of the customer
c. The basic drivers for the customer
d. The potential third level CTQ metrics

Answers: 5.15 b, 5.17 c, 5.23 a
DO NOT PUT YOUR FAITH IN WHAT STATISTICS SAY UNTIL YOU HAVE CAREFULLY CONSIDERED WHAT THEY DO NOT SAY.

WILLIAM W. WATT
VI. SIX SIGMA METHODOLOGY - MEASURE

Six Sigma Methodology - Measure

Six Sigma Improvement Methodology and Tools - Measure is presented in the following topic areas:

- Process analysis and documentation
- Probability and statistics
- Collecting and summarizing data
- Properties and applications of probability distributions
- Measurement systems
- Analyzing process capability
VI. SIX SIGMA METHODOLOGY - MEASURE  
A. PROCESS ANALYSIS AND DOCUMENTATION  
1. TOOLS

**Process Analysis and Documentation**

A process is a set of interrelated resources and activities which transform inputs into outputs with the objective of adding value. The activities relative to any process of importance, should be documented and controlled.

Process analysis and documentation is described in the following topics:

- Tools
- Process inputs and outputs

**Tools**

Flow charts, process maps, written procedures and work instructions are tools used for process analysis and documentation.
Flow Charts

A flow chart or process map is useful to both people familiar with a process and to those people that have a need to understand a process, such as an auditor. A flow chart can depict the sequence of product, containers, paperwork, operator actions or administrative procedures.

A flow chart is often the starting point for process improvement. A plot of the steps in the process can generate numerous improvement ideas.
VI. SIX SIGMA METHODOLOGY - MEASURE
A. PROCESS ANALYSIS AND DOCUMENTATION
   1. TOOLS

Flow Charts to Identify Improvements

- Organize a team for the purpose of examining the process.
- Construct a flow chart to represent each process step.
- Discuss and analyze each step in detail.
- Ask the key question, “Why do we do it this way?”
- Compare the actual process to an imagined “perfect” process.
- Is there unnecessary complexity?
- Does duplication or redundancy exist?
- Are there control points to prevent errors or rejects? Should there be?
- Is this process being run the way it should?
- Can this process be run differently?
- Improvement ideas may come from substantially different processes.
VI. SIX SIGMA METHODOLOGY - MEASURE
A. PROCESS ANALYSIS AND DOCUMENTATION
1. TOOLS

Common Flow Chart Symbols

- Process
- Alternate Process
- Decision
- Data
- Preparation
- Document
- Terminator
- Display
- Manual
- Predefined Process
- Operation
- Connector
- Merge
- Extract
- Off Page
- Connector
- Magnetic Disk or Storage
- Delay
VI. SIX SIGMA METHODOLOGY - MEASURE
A. PROCESS ANALYSIS AND DOCUMENTATION
1. TOOLS

Flow Chart Example

- Beginning
- 2-Way: Yes → Process or Task; No → Process or Task
- Multiple Decisions
  - Choice1 → Process or Task 1
  - Choice2 → Process or Task 2
  - Choice3 → Process or Task 3
- Loop: Yes → Activity or Task; No → End
VI. SIX SIGMA METHODOLOGY - MEASURE
A. PROCESS ANALYSIS AND DOCUMENTATION
1. TOOLS

Process Mapping

There are advantages in depicting a process in schematic format. The major advantage is the ability to visualize the process being described.

Process mapping or flow charting has the benefit of describing a process with symbols, arrows and words without the clutter of sentences. Many companies use process maps to outline new procedures and review old procedures for viability and thoroughness.

Most flow charting uses certain standardized symbols (ANSI Y15.3). Computer flow charting software may contain 15 to 185 shapes with customized variations extending to the 500 range. Many software programs have the ability to create flow charts or process maps, although the information must come from someone knowledgeable about the process.
VI. SIX SIGMA METHODOLOGY - MEASURE
A. PROCESS ANALYSIS AND DOCUMENTATION
   1. TOOLS

Written Procedures

Obviously, for most operations a procedure can be created in advance by the appropriate individual(s). Consider the situation where a process exists, but has not been documented. The procedure should be developed by those having responsibility for the process of interest.

Documenting the process in the form of a procedure facilitates consistency in the process. The use of a flow chart helps to visualize the sequence of actions. Most critical procedures should have corresponding flow charts.

Work Instructions

Procedures describe the process at a general level, while work instructions provide details and a step-by-step sequence of activities.

Flow charts may also be used with work instructions to show relationships of process steps. Controlled copies of work instructions are kept in the area where the activities are performed.
VI. SIX SIGMA METHODOLOGY - MEASURE  
A. PROCESS ANALYSIS AND DOCUMENTATION  
2. PROCESS INPUTS AND OUTPUTS

Process Inputs and Outputs

Before a process can be improved, it must first be measured. This is accomplished by identifying process input variables and process output variables, and documenting their relationships through cause and effect diagrams, relational matrices, flowcharts and other similar tools.

<table>
<thead>
<tr>
<th>Prioritization number</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>Results</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Output Variables</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td></td>
<td>84</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>63</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5</td>
<td>1</td>
<td></td>
<td></td>
<td>25</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>6</td>
<td></td>
<td>4</td>
<td>22</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td></td>
<td>2</td>
<td>3</td>
<td>42</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Totals</td>
<td>236</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Cause and Effect Matrix Example
VI. SIX SIGMA METHODOLOGY - MEASURE
   A. PROCESS ANALYSIS AND DOCUMENTATION
      2. PROCESS INPUTS AND OUTPUTS

Cause and Effect (Fishbone) Diagrams

A cause and effect (fishbone) diagram:

- Breaks problems down into bite-size pieces.
- Displays possible causes in a graphic manner.
- Also called a cause & effect, 4-M or Ishikawa diagram.
- Shows how various causes interact.
- Follows brainstorming rules when generating ideas.

A fishbone session is divided into three parts:

- Brainstorming
- Prioritizing
- Development of an action plan
VI. SIX SIGMA METHODOLOGY - MEASURE
A. PROCESS ANALYSIS AND DOCUMENTATION
2. PROCESS INPUTS AND OUTPUTS

Cause and Effect Diagrams (Continued)

M A C H I N E  M A T E R I A L  M E A S U R E M E N T

M E T H O D  M A N P O W E R  E N V I R O N M E N T

P R O B L E M  S T A T E M E N T

Basic Fishbone 5 - M and E Example
**Probability and Statistics**

Probability and statistics is described in the following topic areas:

- Drawing valid statistical conclusions
- Central limit theorem and sampling distribution of the mean
- Basic probability concepts
VI. SIX SIGMA METHODOLOGY - MEASURE
B. PROBABILITY AND STATISTICS
   1. DRAWING VALID STATISTICAL CONCLUSIONS

Drawing Valid Statistical Conclusions

Analytical (Inferential) Studies

The objective of statistical inference is to draw conclusions about population characteristics based on the information contained in a sample. Statistical inference in a practical situation contains two elements: (1) the inference and (2) a measure of its validity. The steps involved in statistical inference are:

- Define the problem objective precisely
- Decide if it will be evaluated by a one or two tail test
- Formulate a null and an alternate hypothesis
- Select a test distribution and critical value of the test statistic reflecting the degree of uncertainty that can be tolerated (the alpha, $\alpha$, risk)
- Calculate a test statistic value from the sample
- Comparing the calculated value to the critical value and determine if the null hypothesis is to be accepted or rejected. If the null is rejected, the alternate must be accepted.
VI. SIX SIGMA METHODOLOGY - MEASURE
B. PROBABILITY AND STATISTICS
1. DRAWING VALID STATISTICAL CONCLUSIONS

Drawing Valid Conclusions (Continued)

Null Hypothesis and Alternate Hypothesis

The null hypothesis is the hypothesis to be tested. The null hypothesis directly stems from the problem statement and is denoted as $H_0$. Examples:

- If we are investigating whether a modified seed will result in a different yield/acre, the null hypothesis (2 - tail) would assume the yields to be the same.
  - Null hypothesis: $H_0: Y_a = Y_b$
  - Alternate hypothesis: $H_1: Y_a \neq Y_b$

- If a strong claim is made that process A is greater than process B, the null hypothesis (1 - tail) would state that process A ≤ process B.
  - Null hypothesis: $H_0: A \leq B$
  - Alternate hypothesis: $H_1: A > B$

A null hypothesis can only be rejected, or fail to be rejected, it cannot be accepted because of a lack of evidence to reject it.

The alternate hypothesis must include all possibilities which are not included in the null hypothesis and is designated $H_1$. 
VI. SIX SIGMA METHODOLOGY - MEASURE
B. PROBABILITY AND STATISTICS
   1. DRAWING VALID STATISTICAL CONCLUSIONS

Drawing Valid Conclusions (Continued)

Test Statistic

In order to test a null hypothesis, a test calculation must be made from sample information. This calculated value is called a test statistic and is compared to an appropriate critical value. A decision can then be made to reject or not reject the null hypothesis.

A sample statistic is used to make inferences or draw conclusions about population parameters. For example, the sample average is used to make inferences about the population mean.
Types of Errors

When formulating a conclusion regarding a population based on observations from a small sample, two types of errors are possible:

1. **Type I error:** This error results when the null hypothesis is rejected when it is, in fact, true. The probability of making a type I error is called $\alpha$ (alpha) and is commonly referred to as the producer's risk.
2. **Type II error:** This error results when the null hypothesis is not rejected when it should be rejected. This error is called the consumer's risk and is denoted by the symbol $\beta$ (beta).

The degree of risk ($\alpha$) is normally chosen by the concerned parties ($\alpha$ is normally taken as 5%) in arriving at the critical value of the test statistic, the assumption is that a small value for $\alpha$ is desirable. Unfortunately, a small $\alpha$ risk increases the $\beta$ risk. For a fixed sample size, $\alpha$ and $\beta$ are inversely related. Increasing the sample size can reduce both the $\alpha$ and $\beta$ risks.
VI. SIX SIGMA METHODOLOGY - MEASURE
B. PROBABILITY AND STATISTICS
1. DRAWING VALID STATISTICAL CONCLUSIONS

Drawing Valid Conclusions (Continued)

Enumeration (Descriptive) Studies

Enumerative data is data that can be counted. Deming defined a contrast between enumeration and analysis:

Enumerative study  A study in which action will be taken on the universe.

Analytic study  A study in which action will be taken on a process to improve performance in the future.

Descriptive Statistics

Numerical descriptive measures calculated from a sample are called statistics. When these measures describe a population, they are called parameters.

<table>
<thead>
<tr>
<th>Measures</th>
<th>Statistics</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>$\bar{X}$</td>
<td>$\mu$</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>$s$</td>
<td>$\sigma$</td>
</tr>
</tbody>
</table>
Central Limit Theorem

If a random variable $X$ has mean $\mu$ and finite variance $\sigma_x^2$, as $n$ increases, $\bar{X}$ approaches a normal distribution with mean $\mu$ and variance $\sigma_{\bar{X}}^2$.

Where, $\sigma_{\bar{X}}^2 = \frac{\sigma_x^2}{n}$ and $n$ is the number of observations on which each mean is based. The significance of the central limit theorem on control charts is the distribution of sample means approaches a normal distribution, regardless of the shape of the parent population.

Sampling Distribution of the Mean

![Sampling Distribution of the Mean Diagram]

- Normal Distribution of Sample Means
- Distribution of Individuals
Central Limit Theorem (Continued)

The Central Limit Theorem States:

- The sample means (\( \bar{X} \)'s) will be more normally distributed around \( \mu \) than individual readings (\( X \)'s). The distribution of sample means approaches normal regardless of the shape of the parent population. This is the underlying reason that \( \bar{X} \) - R control charts work.

- For normal distributions, the spread in sample means (\( \bar{X} \)'s) is less than \( X \)'s with the standard deviation of \( X \)'s equal to the standard deviation of the population (individuals) divided by the square root of the sample size and is referred to as the standard error of the mean, \( S_{\bar{X}} \):

\[
S_{\bar{X}} = \frac{\sigma_X}{\sqrt{n}}
\]
VI. SIX SIGMA METHODOLOGY - MEASURE
B. PROBABILITY AND STATISTICS
2. CENTRAL LIMIT THEORY

Confidence Interval for the Mean

For continuous data and a large sample, use the normal distribution to calculate the confidence interval for the mean.

\[
\bar{X} \pm Z_{\alpha} \frac{\sigma}{\sqrt{n}}
\]

If \( \sigma \) is unknown and a relatively small sample is used (<30) then the \( t \) distribution must be used with \( (n - 1) \) degrees of freedom.

\[
\bar{X} \pm t_{\alpha} \frac{S}{\sqrt{n}}
\]

Confidence Interval for Proportion

For large sample sizes, with \( n(p) \) and \( n(1-p) \) equal to 4 or 5 or greater, the normal distribution can be used to calculate a confidence interval for proportion. The following formula is used:

\[
p \pm Z_{\alpha} \sqrt{\frac{p(1-p)}{n}}
\]
Confidence Interval for Variance

The confidence intervals for the mean were symmetrical about the average. This is not true for the variance, since it is based on the Chi-Square distribution. The formula for \((n - 1)\) degrees of freedom is:

\[
\frac{(n - 1) S^2}{\chi^2_{\alpha/2, n - 1}} \leq \sigma^2 \leq \frac{(n - 1) S^2}{\chi^2_{1 - \alpha/2, n - 1}}
\]

Confidence Interval for Standard Deviation

The confidence interval for the population standard deviation is found by taking the square root of each term in the preceding inequality. The formula for \((n - 1)\) degrees of freedom is:

\[
\sqrt{\frac{(n - 1) S^2}{\chi^2_{\alpha/2, n - 1}}} \leq \sigma \leq \sqrt{\frac{(n - 1) S^2}{\chi^2_{1 - \alpha/2, n - 1}}}
\]
Basic Probability Concepts

The probability of any event (E) varies between 0 (no probability) and 1 (perfect probability). The sum of the probabilities of all possible events (multiple E’s) in total sample space (S) is equal to 1.

Definition of Probability

The ratio of the chances favoring an event to the total number of chances for and against the event. Probability (P) is always a ratio.

\[
P(E) = \frac{\text{Chances Favoring}}{\text{Chances Favoring Plus Chances not Favoring}}
\]

Number of Points in Sample Space Participating in the Event of Interest

\[
P(\text{Event}) = \frac{\text{Total Points in Sample Space}}{\text{Number of Points in Sample Space}}
\]

We can state that if an experiment is repeated a large number of times, (N), and the event (E) is observed \( n_E \) times, the probability of E is approximately:

\[
P(E) \approx \frac{n_E}{N}
\]
Simple Events

An event that cannot be decomposed is a simple event (E). The set of all sample points for an experiment is called the sample space (S).

Compound Events

Compound events are formed by a composition of two or more events. The two most important probability theorems are the additive and multiplicative. For the following discussion, $E_A = A$ and $E_B = B$.

I. Composition. Consists of two possibilities -- a union or intersection.

A. Union of A and B. ($A \cup B$).

If $A$ and $B$ are two events in a sample space (S), the union of $A$ and $B$ ($A \cup B$) contains all sample points in event $A$ or $B$ or both.

B. Intersection of A and B. ($A \cap B$).

If $A$ and $B$ are two events in a sample space (S), the intersection of $A$ and $B$ ($A \cap B$) is composed of all sample points that are in both $A$ and $B$. 
Compound Events (Continued)

II. Event Relationships. There are three relationships in finding the probability of an event: complementary, conditional and mutually exclusive.

A. Complement of an Event

The complement of an event A is all sample points in the sample space (S), but not in A. The complement of A is $1 - P_A$.

B. Conditional Probabilities

The conditional probability of event A given that B has occurred is:

$$P(A|B) = \frac{P(A \cap B)}{P(B)} \quad \text{IF } P(B) \neq 0$$

Two events A and B are said to be independent if either:

$$P(A|B) = P(A) \quad \text{or} \quad P(B|A) = P(B)$$

Otherwise, the events are said to be dependent.
Compound Events (Continued)

C: Mutually Exclusive Events

If event A contains no sample points in common with event B, then they are said to be mutually exclusive.

D. Testing for Event Relationships

Are events A and B, mutually exclusive, complementary, independent or dependent? If events A and B contain two or more sample points in common, then they are not mutually exclusive. If event B does not contain all points in S that are not in A, then they are not complementary.
The Additive Law

If the two events are not mutually exclusive:

1. \( P(A \cup B) = P(A) + P(B) - P(A \cap B) \)

Note that \( P(A \cup B) \) is shown in many texts as \( P(A + B) \) and is read as the probability of A or B. If the two events are mutually exclusive, the law reduces to:

2. \( P(A \cup B) = P(A) + P(B) \) also \( P(A + B) = P(A) + P(B) \)

The Multiplicative Law

If events A and B are dependent, the probability of A influences the probability of B. This is known as conditional probability and the sample space is reduced.

1. \( P(A \cap B) = P(A) \times P(B|A) \)
   also \( P(A \cap B) = P(B) \times P(A|B) \)

Note in some texts \( P(A \cap B) \) is shown as \( P(A \cdot B) \) and is read as the probability of A and B. \( P(B|A) \) is read as the probability of B given that A has occurred.

If events A and B are independent:

2. \( P(A \cap B) = P(A) \times P(B) \)
VI. SIX SIGMA METHODOLOGY - MEASURE
B. PROBABILITY AND STATISTICS
3. BASIC PROBABILITY CONCEPTS

Expected Value

Daniel Bernoulli stated that “expected value equals the sum of the values of each of a number of outcomes multiplied by the probability of each outcome relative to all the other possibilities.” If \( E \) represents the expected value operator and \( V \) represents the variance operator, such that:

\[
V(x) = E[(x - \mu)^2] = \sigma^2
\]

If \( x \) is a random variable and \( c \) is a constant, then:

1. \( E(c) = c \)
2. \( E(x) = \mu \)
3. \( E(cx) = cE(x) = c\mu \)
4. \( V(c) = 0 \)
5. \( V(x) = \sigma^2 \)
6. \( V(cx) = c^2V(x) = c^2\sigma^2 \)
VI. SIX SIGMA METHODOLOGY - MEASURE
   B. PROBABILITY AND STATISTICS
      3. BASIC PROBABILITY CONCEPTS

Permutations

An ordered arrangement of n distinct objects is called a permutation. The number of ways of ordering n distinct objects taken r at a time is designated by the symbol \( P_r^n \). (Various texts use \( P(n,r) \) and \( _nP_r \)).

Counting Rule for Permutations
The number of ways that n distinct objects can be arranged taking them r at a time is:

\[
P_r^n = n(n-1)(n-2)\ldots(n-r+1) = \frac{n!}{(n-r)!}
\]

Note: \( 0! = 1 \), \( P_n^n = n! \), \( P_0^n = \frac{n!}{n!} = 1 \)

Combinations

The number of distinct combinations of n distinct objects taken r at a time is denoted by the symbol \( C_r^n \). (Various texts use \( _nC_r \), \( C(n,r) \) and \( (^n)_r \)).

Counting Rule for Combinations
The number of different combinations that can be formed from n distinct objects taken r at a time is:

\[
C_r^n = \frac{n!}{r!(n-r)!}
\]

Note: \( 0! = 1 \), \( C_n^n = 1 \), \( C_0^n = 1 \)
Collecting and Summarizing Data

Collecting and summarizing data is described in the following topics:

- Types of data
- Measurement scales
- Methods for collecting data
- Techniques for assuring data accuracy and integrity
- Descriptive statistics
- Graphical methods
VI. SIX SIGMA METHODOLOGY - MEASURE  
C. COLLECTING AND SUMMARIZING DATA  
1. TYPES OF DATA

Types of Data

The three types of data are attribute data, variables data and locational data. Of these three, attribute and variables data are more widely used.

Attribute Data

Attribute data is discrete. This means that the data values can only be integers, for example, 3, 48, 1029. Counted data or attribute data are answers to questions like “how many”, “how often” or “what kind.”

Variables Data

Variables data is continuous. This means that the data values can be any real number, for example, 1.037, -4.69, 84.35. Measured data (variables data) are answers to questions like “how long,” “what volume,” “how much time” and “how far.” This data is generally measured with some instrument or device.
VI. SIX SIGMA METHODOLOGY - MEASURE
C. COLLECTING AND SUMMARIZING DATA
1. TYPES OF DATA

Variables Data (Continued)

Measured data is regarded as being better than counted data. It is more precise and contains more information. In some situations, data will only occur as counted data.

For information which can be obtained as either attribute or variables data, it is generally preferable to collect variables data.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Variables</th>
<th>Attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>measurable</td>
<td>countable</td>
</tr>
<tr>
<td></td>
<td>continuous</td>
<td>discrete units or occurrences</td>
</tr>
<tr>
<td></td>
<td>may derive from counting</td>
<td>good/bad</td>
</tr>
<tr>
<td>Types of Data</td>
<td>length</td>
<td>no. of defects</td>
</tr>
<tr>
<td></td>
<td>volume</td>
<td>no. of defectives</td>
</tr>
<tr>
<td></td>
<td>time</td>
<td>no. of scrap items</td>
</tr>
<tr>
<td>Examples</td>
<td>width of door gap</td>
<td>audit points lost</td>
</tr>
<tr>
<td></td>
<td>lug nut torque</td>
<td>paint chips per unit</td>
</tr>
<tr>
<td></td>
<td>fan belt tension</td>
<td>defective lamps</td>
</tr>
<tr>
<td>Data Examples</td>
<td>1.7 inches</td>
<td>10 scratches</td>
</tr>
<tr>
<td></td>
<td>32.06 psi</td>
<td>6 rejected parts</td>
</tr>
<tr>
<td></td>
<td>10.542 seconds</td>
<td>25 paint runs</td>
</tr>
</tbody>
</table>
VI. SIX SIGMA METHODOLOGY - MEASURE  
C. COLLECTING AND SUMMARIZING DATA  
1. TYPES OF DATA

Locational Data

Locational data answers the question “where.” Charts that utilize locational data are often called “measles charts” or concentration charts. Examples are a drawing showing locations of paint blemishes on an automobile or a map with sales and distribution offices indicated.

Conversion of Attributes Data to Variables Measures

When collecting data, there are opportunities for some types of data to be either attributes or variables. Instead of a good or bad part, the data can be stated as to how far out of tolerance or within tolerance.

Two attribute data examples that could easily be presented as variables data: 10 scratches could be reported as total scratch length of 8.37 inches, and 25 paint runs as 3.2 sq. in. surface area of paint runs. Part failures can be reported as failure after 2,133 hours of operation, instead of 10 failures.

The ultimate purpose for the data collection and the type of data are the most significant factors in the decision to collect attribute or variables data.
Measurement Scales

Four measurement scales in increasing order of statistical desirability are shown in the Table below.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>Data consists of names or categories only. No ordering scheme is possible.</td>
<td>A bag of candy contained the following colors: Yellow 15, Red 10, Orange 9, Green 7</td>
</tr>
<tr>
<td>Ordinal</td>
<td>Data is arranged in some order but differences between values cannot be determined or are meaningless.</td>
<td>Product defects, where A type defects are more critical than D defects are tabulated as follows: A 16, B 32, C 42, D 30</td>
</tr>
<tr>
<td>Interval</td>
<td>Data is arranged in order and differences can be found. However, there is no inherent starting point and ratios are meaningless.</td>
<td>The temperatures of three ingots were 200°F, 400°F and 600°F. Note, that three times 200°F is not the same as 600°F as a temperature measurement.</td>
</tr>
<tr>
<td>Ratio</td>
<td>An extension of the interval level that includes an inherent zero starting point. Both differences and ratios are meaningful.</td>
<td>Product A costs $300 and product B costs $600. Note, that $600 is twice as much as $300.</td>
</tr>
</tbody>
</table>
### Measurement Scales (Continued)

**Statistical Measures for Measurement Scales**

<table>
<thead>
<tr>
<th>Scale</th>
<th>Central Location</th>
<th>Dispersion</th>
<th>Significance Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>Mode</td>
<td>Information Only</td>
<td>Chi-square</td>
</tr>
<tr>
<td>Ordinal</td>
<td>Median</td>
<td>Percentages</td>
<td>Sign or Run Test</td>
</tr>
</tbody>
</table>
| Interval| Arithmetic Mean | Standard or Average Deviation | t test  
|        |                  |                                    | F test  
|        |                  |                                    | Correlation Analysis |
| Ratio  | Geometric or Harmonic Mean | Percent Variation | *                                    |

*Note: Many of the interval measures may be useful for ratio data as well.*
VI. SIX SIGMA METHODOLOGY - MEASURE
C. COLLECTING AND SUMMARIZING DATA
3. METHODS FOR COLLECTING DATA

Methods for Collecting Data

Data collection includes both manual and automatic methods. Some guidelines are:

- Formulate a clear statement of the problem
- Define precisely what is to be measured
- List all the important characteristics to be measured
- Carefully select the right measurement technique
- Construct an uncomplicated data form
- Decide who will collect the data
- Arrange for an appropriate sampling method
- Decide who will analyze and interpret the results
- Decide who will report the results
VI. SIX SIGMA METHODOLOGY - MEASURE
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3. METHODS FOR COLLECTING DATA

Data Coding

The efficiency of data entry and analysis is frequently improved by data coding.

Coding by adding or subtracting a constant or by multiplying or dividing by a factor:

- Code: \( X_c = X + C \)  
  Decode: \( \bar{X} = \bar{X}_c - C, \quad \sigma = \sigma_c \)

- Code: \( X_c = X - C \)  
  Decode: \( \bar{X} = \bar{X}_c + C, \quad \sigma = \sigma_c \)

- Code: \( X_c = fX \)  
  Decode: \( \bar{X} = \bar{X}_c / f, \quad \sigma = \sigma_c / f \)

- Code: \( X_c = X / f \)  
  Decode: \( \bar{X} = \bar{X}_c f, \quad \sigma = \sigma_c f \)

Coding by substitution:

For an observation of 32-3/8 inches, the data can be coded as integers expressing the number of 1/8 inch increments deviating from nominal.

Coding by truncation of repetitive place values:

Measurements such as 0.55303, 0.55310, 0.55308 can be recorded as the last two digits expressed as integers, 3, 10, 8.
Techniques for Assuring Data Accuracy and Integrity

Bad data is not only costly to capture, but corrupts the decision-making process.

- Avoid emotional bias relative to tolerances
- Avoid unnecessary rounding
- With time sequence data, record in time order
- If a characteristic changes over time, record the initial measurements and after stabilization
- If statistics assume a normal population, determine if dispersion of data can be represented by at least 8 to 10 resolution increments. If not, the default statistic may be the count of observations.
- Screen data to detect and remove data entry errors
- Use objective statistical tests to identify outliers
- Each important classification identification should be recorded along with the data
Random Sampling

The use of a sampling plan requires randomness in sample selection and requires giving every part an equal chance of being selected for the sample. Sampling without randomness ruins the effectiveness of any plan. The sampling sequence must be based on an independent random plan.

Sequential Sampling

Sequential sampling can theoretically continue indefinitely. Usually, these plans are ended after the number inspected has exceeded three times the sample size of a corresponding single sampling plan. Sequential testing is used for costly or destructive testing with sample sizes of one and are based on a probability ratio test developed by Wald.

Stratified Sampling

The concept behind stratified sampling is to select random samples from each group or process that is different. The resulting mix of samples can be biased if the proportion of the samples does not reflect the relative frequency of the groups.
Descriptive Statistics

Descriptive statistics includes measures of central tendency, measures of dispersion, probability density function, frequency distributions and cumulative distribution functions.

Measures of Central Tendency

Measures of central tendency represent different ways of characterizing the central value of a collection of data.

The Mean (\( \bar{X} \))

The mean is the sum total of all data values divided by the number of data points. The arithmetic mean is the most widely used measure of central tendency.

\[
\bar{X} = \frac{\sum X}{n}
\]
Measures of Central Tendency (Cont.)

The Mode

The mode is the most frequently occurring number in a data set. Note: It is possible for groups of data to have more than one mode.

The Median (Midpoint)

The median is the middle value when the data is arranged in ascending or descending order. For an even set of data, the median is the average of the middle two values.
VI. SIX SIGMA METHODOLOGY - MEASURE
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Measures of Central Tendency (Cont.)

For a Normal Distribution

Mean = Median = Mode

For a Skewed Distribution

Mode
Median
Mean
VI. SIX SIGMA METHODOLOGY - MEASURE  
C. COLLECTING AND SUMMARIZING DATA  
5. DESCRIPTIVE STATISTICS 

Measures of Dispersion 

Range (R) 

The range of a set of data is the difference between the largest and smallest values.

Variance ($\sigma^2$, $S^2$) 

Population, $\sigma^2 = \frac{\sum(X - \mu)^2}{N}$ 

Sample, $S^2 = \frac{\sum(X - \bar{X})^2}{n - 1}$

Standard Deviation ($\sigma$, $s$) 

Population, $\sigma = \sqrt{\frac{\sum(X - \mu)^2}{N}}$ 

Sample, $S = \sqrt{\frac{\sum(X - \bar{X})^2}{n - 1}}$

Note: N is used for a population, and n - 1 for a sample (to remove potential bias in relatively small samples - less than 30)
Measures of Dispersion (Continued)

Coefficient of Variation (COV)

The coefficient of variation equals the standard deviation divided by the mean and is expressed as a percentage.

\[
\text{COV} = \frac{S}{X} \cdot 100 \quad \text{or} \quad \frac{\sigma}{\mu} \cdot 100
\]
VI. SIX SIGMA METHODOLOGY - MEASURE  
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5. DESCRIPTIVE STATISTICS  

Probability Density Function  

The probability density function, $f(x)$, describes the behavior of a random variable. Typically, the probability density function is viewed as the “shape” of the distribution. It is normally a grouped frequency distribution.

A histogram is an approximation of the distribution’s shape. When using statistics, the “smooth curve” represents the population, and the differences between the sample data represented by the histogram and the population data represented by the smooth curve is assumed to be due to sampling error.

Example Histogram with Overlaid Model
The area below the probability density function to the left of a given value, $x$, is equal to the probability of the random variable represented on the x-axis being less than the given value $x$.

Since the probability density function represents the entire sample space, the area under the probability density function must equal one. Since negative probabilities are impossible, the probability density function, $f(x)$, must be positive for all values of $x$.

Stating these two requirements mathematically for continuous distributions with $f(x) \geq 0$:

$$\int_{-\infty}^{\infty} f(x)dx = 1$$

For discrete distributions for all values of $n$ with $f(x) \geq 0$:

$$\sum_{0}^{n} f(x) = 1$$
Cumulative Distribution Function

The cumulative distribution function, \( F(x) \), denotes the area beneath the probability density function to the left of \( x \).

The area of the shaded region of the probability density function in is 0.2525 which corresponds to the cumulative distribution function at \( x = 190 \).

\[
F(x) = \int_{-\infty}^{x} f(t) \, dt
\]
Graphical Methods

Graphical methods includes boxplots, stem and leaf plots, scatter diagrams, pattern and trend analysis, histograms, normal probability distributions and Weibull distributions.

Boxplots

The boxplot is a number summary of the data. The data median is a line dividing the box. The upper and lower quartiles of the data define the ends of the box. The minimum and maximum data points are drawn as points at the end of lines (whiskers) extending from the box. Notches indicate variability of the median, and widths are proportional to the log of the sample size.
VI. SIX SIGMA METHODOLOGY - MEASURE
C. COLLECTING AND SUMMARIZING DATA
6. GRAPHICAL METHODS

Stem and Leaf Plots

The stem-and-leaf diagram is a convenient, manual method for plotting data sets. The diagram consists of grouping the data by class intervals, as stems, and the smaller data increments as leaves.

![Shear Strength Histogram](image)

<table>
<thead>
<tr>
<th>Strength</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>41#</td>
<td>4</td>
</tr>
<tr>
<td>43#</td>
<td>3</td>
</tr>
<tr>
<td>45#</td>
<td>5</td>
</tr>
<tr>
<td>47#</td>
<td>8</td>
</tr>
<tr>
<td>49#</td>
<td>5</td>
</tr>
<tr>
<td>51#</td>
<td>2</td>
</tr>
<tr>
<td>53#</td>
<td>1</td>
</tr>
</tbody>
</table>

Stem and Leaf:

<table>
<thead>
<tr>
<th>Stem</th>
<th>Leaf</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1</td>
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<tr>
<td>4</td>
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<td>1</td>
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<td>4</td>
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<td>4</td>
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<td>1</td>
</tr>
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<td>4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

5
2
5 3 8
6 9 8 7 0 9
1 6 8 8 5 9 1
5 1 4 6 4 4 9 6 6
8 6 2 1 2 4 0 8 6 4 4

Leaf: 2 4 8 2 4 5 0 6 8 3 0 2
Stem: 0 1 2 3 4 5 6 7 8 9 0 1 2
4 4 4 4 4 4 4 4 4 4 4 5 5 5
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Scatter Diagrams

A scatter diagram is a graphic display of many XY coordinate data points which represent the relationship between two different variables. It is also referred to as a correlation chart. Scatter diagrams can help determine if a relationship exists and how to control the effect of the relationship on the process.

In most cases, there is an independent variable and a dependent variable. By tradition, the dependent variable is represented by the vertical axis and the independent variable is represented by the horizontal axis.

The dependent variable can be controlled if the relationship is understood. Correlation originates from the following:

- A cause-effect relationship
- A relationship between one cause and another cause
- A relationship between one cause and two or more other causes
Scatter Diagrams (Continued)

Not all scatter diagrams reveal a linear relationship. The examples below definitely portray a relationship between the two variables, even though they do not necessarily produce a straight line. To use scatter diagrams, you must be able to decide what factors will best control the process within the specifications.

- Low-positive
- High-positive
- No-correlation
- High-negative
- Non-linear Relationships
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Scatter Diagrams (Continued)

Sample Correlation Coefficient

A sample correlation coefficient “r” can be calculated to determine the degree of association between two variables.

\[
r = \frac{\sum_{i=1}^{n} (X_i - \bar{X}) (Y_i - \bar{Y})}{\sqrt{\left(\sum_{i=1}^{n} (X_i - \bar{X})^2\right)\left(\sum_{i=1}^{n} (Y_i - \bar{Y})^2\right)}}
\]

- \(r = -1.0\) strong negative when X increases, Y decreases
- \(r = -0.5\) slight negative when X increases, Y generally decreases
- \(r = 0\) no correlation the two variables are independent
- \(r = +0.5\) slight positive when X increases, Y generally increases
- \(r = +1.0\) strong positive when X increases, Y increases
Concluding Comments

- A correlation analysis seeks to uncover relationships. Common-sense must be liberally applied.

- The line of “best fit” can be obtained by calculating a “regression line.” However, to make a decision whether or not there exists a relationship, the line can be fitted by “eyeball.”

- Scatter diagrams should always be analyzed prior to making decisions in correlation statistics.
Pattern and Trend Analysis

Data can be presented in either summary (static) or time sequence (dynamic) fashion. Important elements of most processes can change over time. For many business activities, trend charts will show patterns that indicate if a process is running normally or whether desirable or undesirable changes are occurring.

It should be noted that normal convention has time increasing across the page (from left to right) and the measurement value increasing up the page.
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Trend Examples

SALES AND COMPLAINTS - ALL PRODUCTS

- UNITS SOLD
- TOTAL COMPLAINTS

YEAR:
- 1995
- 1996
- 1997
- 1998
- 1999
- 2000
- 2001

NUMBER OF UNITS SOLD:
- 0
- 5000
- 10000
- 15000
- 20000

% COMPLAINTS:
- 30
- 40
- 50
- 60
VI. SIX SIGMA METHODOLOGY - MEASURE
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Histograms

Histograms have the following characteristics:

- Frequency column graphs that display a static picture of process behavior and require a minimum of 50-100 data points.

- A histogram is characterized by the number of data points that fall within a given bar or interval. This is commonly referred to as “frequency.”

- A stable process is frequently characterized by a histogram exhibiting unimodal or bell-shaped curves. A stable process is predictable.

- An unstable process is often characterized by a histogram that does not exhibit a bell-shaped curve. Obviously distribution shapes like exponential, lognormal, gamma, beta, Weibull, Poisson, binomial, hypergeometric, geometric, etc. exist as a stable process.

- When the bell curve is the approximate distribution shape, variation around the bell curve is chance or natural variation. Other variation is due to special or assignable causes.
Histogram Construction

FREQUENCY TALLY  SPECIFICATION LIMITS 0.50 - 0.60

Histogram Construction Example
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6. GRAPHICAL METHODS

Histogram Examples

- Column Graph
- Bar Graph
- Normal Histogram
- Histogram with Special Causes
- Bimodal Histogram (May Also Be Polymodal)
- Negatively Skewed
- Truncated Histogram
How Are Normal Distributions Predictable?

When all special causes of variation are eliminated, the process will produce a product that when sampled and plotted, has a bell-shaped distribution. If the base of the histogram is divided into six (6) equal lengths (three on each side of the average), the amount of data in each interval exhibits the following percentages:

- $\mu - 3\sigma$: 0.135% (99.87%)
- $\mu - 2\sigma$: 2.28% (97.72%)
- $\mu - \sigma$: 13.51% (86.49%)
- $\mu$: 50.00% (50.00%)
- $\mu + \sigma$: 34.13% (65.87%)
- $\mu + 2\sigma$: 2.28% (97.72%)
- $\mu + 3\sigma$: 0.135% (99.87%)
By changing the value of the shape parameter, the Weibull distribution can model a wide variety of data. If $\beta = 1$ the Weibull distribution is identical to the exponential distribution, if $\beta = 2$, the Weibull distribution is identical to the Rayleigh distribution; if $\beta$ is between 3 and 4 the Weibull distribution approximates the normal distribution. The Weibull distribution approximates the lognormal distribution for several values of $\beta$.
Properties and Applications of Probability Distributions

Properties and applications of probability distributions is described in the following topic areas:

- Distributions commonly used by Black Belts
- Other distributions

Distributions Commonly Used by Black Belts

Distributions commonly used by Black Belts include the following:

- Binomial
- Poisson
- Normal
- Chi-square
- Student’s t
- F distribution
**Binominal Distribution**

The binominal distribution is used to model discrete data and applies when the population is large (N > 50) and the sample size is small compared to the population (n < 0.1N). Binomial sampling is with replacement. It is appropriate to use when proportion defective is equal to or greater than (0.1). The binominal is an approximation to the hypergeometric. The normal distribution approximates the binominal when np ≥ 5.

\[
P(r) = C_r^n \ p^r (1-p)^{n-r} = \frac{n!}{r!(n-r)!} \ p^r (1 - p)^{n-r}
\]

The binominal mean = \( \mu = np \)

The binominal sigma = \( \sigma = \sqrt{np(1-p)} \)
Poisson Distribution

The Poisson distribution can be used to model discrete data. The Poisson distribution can be an approximation to the binomial when \( p \) is equal to or less than 0.1, and the sample size \( n \) is fairly large (generally, \( n \geq 16 \)) by using \( np \) as the mean of the Poisson distribution.

\[
P(r) = \frac{\mu^r e^{-\mu}}{r!} = \frac{(np)^r e^{-np}}{r!}
\]

\( \mu = np = \text{average} = \text{the population mean} \)

The Poisson average = \( \mu = np = \bar{c} \)

The Poisson sigma = \( \sqrt{\mu} = \sqrt{np} = \sqrt{\bar{c}} \)
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Normal Distribution

When a sample of several random measurements are averaged, distribution of such repeated sample averages tends to be normally distributed regardless of the distribution of the measurements being averaged. Mathematically, if

$$\bar{X} = \frac{x_1 + x_2 + x_3 + \ldots + x_n}{n}$$

the distribution of $\bar{X}$s becomes normal as $n$ increases. If the set of samples being averaged have the same mean and variance then the mean of the $\bar{X}$s is equal to the mean ($\mu$) of the individual measurements, and the variance of $\bar{X}$s is:

$$\sigma_{\bar{X}}^2 = \frac{\sigma^2}{n}$$

Where $\sigma^2$ is the variance of the individual variables being averaged.

The tendency of sums and averages to become normally distributed as the number of variables being summed or averaged becomes large is known as the Central Limit Theorem or the Theory of Large Numbers.
Normal Distribution (Continued)

The normal probability density function is:

\[ f(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{x - \mu}{\sigma} \right)^2}, \quad -\infty < x < \infty \]

Where \( \mu \) is the mean and \( \sigma \) is the standard deviation.

Z transformations include:

\[ Z = \frac{X - \mu}{\sigma} = \frac{X - \bar{X}}{\sigma_{\bar{X}}} = \frac{\bar{X} - \mu}{\sigma} = \frac{X - \text{Std}}{\sigma_{\text{Std}}} = \frac{X - \text{Std}}{\sigma_{\text{Std}}} \]
Normal Distribution (Continued)

Example 6.4: A battery is produced with an average voltage of 60 and a standard deviation of 4 volts. If 9 batteries are selected at random, what is the probability that the total voltage of the 9 batteries is greater than 530? The expected total voltage for nine batteries is 540. The expected standard deviation of the voltage of the total of nine batteries is:

\[ S_{\text{TOTAL}}^2 = 9 \times (4)^2 = 144 \quad S_{\text{TOTAL}} = 12 \]

Transforming to standard normal:

\[ z = \frac{530 - 540}{12} = -0.833 \]

From the standard normal table, the area to the right of z is 0.7976.

What is the probability that the average voltage of the 9 batteries is less than 62? The expected value is 60. The standard deviation is:

\[ S_{x} = \frac{\sigma}{\sqrt{n}} = \frac{4}{\sqrt{9}} = 1.333 \quad \text{Thus,} \quad z = \frac{62 - 60}{1.333} = 1.5 \]

The area to the left of z is 1 - 0.0668 = 0.9332
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Chi-Square Distribution

The chi-square distribution is formed by summing the squares of standard normal random variables. For example, if $z$ is a standard normal random variable, then the following is a chi-square random variable (statistic) with $n$ degrees of freedom:

$$y = z_1^2 + z_2^2 + z_3^2 + \ldots + z_n^2$$

The chi-square probability density function where $\nu$ is the degrees of freedom, and $\Gamma(x)$ is the gamma function is:

$$f(x) = \frac{x^{(\nu/2)-1}e^{-x/2}}{2^{\nu/2}\Gamma(\nu/2)}, x > 0$$
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Student’s t Distribution

If \( z \) is a standard normal random variable, and \( \chi^2 \) is a chi-square random variable with \( \nu \) degrees of freedom, then a random variable with a t-distribution is:

\[
t = \frac{z}{\sqrt{\frac{\chi^2}{\nu}}}
\]

The t probability density function where \( \nu \) is the degrees of freedom is:

\[
f(x) = \frac{\tau(\nu + 1)/2}{\tau(\nu/2)\sqrt{\pi\nu}} \left(1 + \frac{x^2}{\nu}\right)^{-\frac{(\nu + 1)/2}{2}}, \quad -\infty < x < \infty
\]
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Student’s t-Distribution (Continued)

The mean and variance of the t-distribution are:

$$\mu = 0 \quad \sigma^2 = \frac{v}{v - 2}, \quad v \geq 3$$

From a random sample of $n$ items, the probability that

$$t = \frac{\bar{x} - \mu}{s / \sqrt{n}}$$

falls between any two specified values is equal to the area under the t-probability density function between the corresponding values on the x-axis with $n-1$ degrees of freedom.

The burst strength of 15 randomly selected seals is:

480 489 491 508 501 500 486 499 479 496 499 504 501 496 498

What is the probability that the burst strength of the population is greater than 500? The mean is 495.13. The sample standard deviation is 8.467.

$$t = \frac{495.13 - 500}{8.467 / \sqrt{15}} = -2.227$$

With 14 degrees of freedom, the area under the t-probability density function, to the left of -2.227 is 0.0214.
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F Distribution

If X is a chi-square random variable with \( \nu_1 \) degrees of freedom and Y is a chi-square random variable with \( \nu_2 \) degrees of freedom and if X and Y are independent, then is an F distribution with \( \nu_1 \) and \( \nu_2 \) degrees of freedom.

\[
F = \frac{X / \nu_1}{Y / \nu_2}
\]

The F distribution is used extensively to test for equality of variances from two normal populations. If \( U \) and \( V \) are the variances of independent random samples of size \( n \) and \( m \) taken from normally distributed populations with variances of \( w \) and \( z \), then

\[
F = \frac{U/w}{V/z}
\]

is a random variable with an F distribution with \( \nu_1 = n - 1 \) and \( \nu_2 = m - 1 \).

The F probability density function is:

\[
f(x) = \frac{1}{\Gamma(\frac{\nu_1}{2})\Gamma(\frac{\nu_2}{2})} \left( \frac{\nu_1 \nu_2}{\nu_1 + \nu_2} \right)^{\frac{\nu_1 + \nu_2}{2}} \frac{x^{\nu_1/2 - 1}}{(1 + \frac{\nu_1 x}{\nu_2})^{(\nu_1 + \nu_2)/2}}, x > 0
\]
The F distribution function is given in the Appendix. Most texts only give one tail, and require the other tail to be computed using the expression:

\[ F_{\alpha, n_1, n_2} = \frac{1}{F_{1-\alpha, n_2, n_1}} \]

Given that with \( \nu_1 = 8 \) and \( \nu_2 = 10 \), \( F_{0.05} \) is 3.07, find the value of \( F_{0.95} \) with \( \nu_1 = 10 \) and \( \nu_2 = 8 \).

\[ F_{0.95, 10, 8} = \frac{1}{F_{0.05, 8, 10}} = \frac{1}{3.07} = 0.326 \]
Other Distributions

Other distributions less commonly used by Black Belts include the following:

- Hypergeometric
- Bivariate
- Exponential
- Lognormal
- Weibull
Hypergeometric Distribution

The hypergeometric distribution applies when the sample \( n \) is a relatively large proportion of the population \( n > 0.1N \). Sampling is done without replacement.

\[
P(r) = \frac{C_d^r C_{n-r}^{N-d}}{C_n^N}
\]

From a group of 20 products, 10 are selected at random for testing. What is the probability that the 10 selected contain the 5 best units?

\[N = 20, \ n = 10, \ d = 5, \ (N-d) = 15 \text{ and } r = 5\]

\[
P(r) = \frac{\binom{5}{5} \binom{15}{5}}{\binom{20}{10}} \quad \text{recall that } \binom{n}{r} = \frac{n!}{r!(n-r)!}
\]

\[
P(r) = \frac{\left( \frac{5!}{5!0!} \right) \left( \frac{15!}{5!10!} \right)}{\frac{20!}{10!10!}} = \left( \frac{15!}{5!10!} \right) \left( \frac{10!10!}{20!} \right)
\]

Answer \( P(r) = 0.0163 = 1.63\% \)
Hypergeometric Distribution (Continued)

\[ P(r) = \binom{d}{r} \frac{\binom{N-d}{n-r}}{\binom{N}{n}} \]

The hypergeometric distribution is referred to as the distribution that models sampling without replacement. Where \( p(x,N,n,m) \) is the probability of exactly \( x \) successes in a sample of \( n \) drawn from a population of \( N \) containing \( m \) successes. The hypergeometric probability density function is:

\[ p(x, N, n, m) = \frac{\left( \begin{array}{c} m \\ x \end{array} \right) \left( \begin{array}{c} N-m \\ n-x \end{array} \right) \left( \begin{array}{c} N \\ n \end{array} \right)}{\left( \begin{array}{c} N \\ n \end{array} \right)} \]

The mean and the variance of the hypergeometric distribution are:

\[ \mu = \frac{nm}{N} \quad \sigma^2 = \left( \frac{nm}{N} \right) \left( 1 - \frac{m}{N} \right) \left( \frac{N-n}{N-1} \right) \]
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Choosing the Correct Discrete Distribution

Figure 6.37 Discrete Distribution Flow Chart
Bivariate Distribution

The joint distribution of two variables is called a bivariate distribution. Bivariate distributions may be discrete or continuous. There may be total independence of the two independent variables, or there may be a covariance between them.

The bivariate normal density with the correlation coefficient, \( \rho \), is:

\[
f(x, y) = \frac{e^{-\frac{1}{2} \left(1 - \rho^2\right)}}{2 \pi \sigma_1 \sigma_2 \sqrt{1 - \rho^2}} \left[ \left( \frac{x - \mu_1}{\sigma_1} \right)^2 - 2 \rho \left( \frac{x - \mu_1}{\sigma_1} \right) \left( \frac{y - \mu_2}{\sigma_2} \right) + \left( \frac{y - \mu_2}{\sigma_2} \right)^2 \right]
\]

Figure 6.38 Bivariate Normal Distribution Surface
Exponential Distribution

The exponential distribution is used to model items with a constant failure rate, and is closely related to the Poisson distribution. If a random variable, x, is exponentially distributed, then the reciprocal of x, y = 1/x follows a Poisson distribution. Likewise, if x is Poisson distributed, then y = 1/x is exponentially distributed.

The exponential probability density function is:

$$f(x) = \frac{1}{\theta} e^{-\frac{x}{\theta}} = \lambda e^{-\lambda x}, \ x \geq 0$$

Where: \( \lambda \) is the failure rate and \( \theta \) is the mean.

From the equations above, it can be seen that \( \lambda = 1/\theta \).

Figure 6.39 Exponential Probability Density Function
Exponential Distribution (Continued)

\[ P(x) = \frac{1}{\mu} e^{-\frac{x}{\mu}} = \lambda e^{-\lambda x} \]

\( \mu = \theta = \text{mean} \)
\( \lambda = \text{failure rate} \)
\( x = \text{x axis value} \)

Exponential Distribution Example

The variance of the exponential distribution is equal to the mean squared.

\[ \sigma^2 = \theta^2 = \frac{1}{\lambda^2} \]

hence \( \sigma = \theta = \frac{1}{\lambda} \)

The exponential distribution is characterized by its hazard function which is constant.

That is, the probability of survival for a time interval, given survival to the beginning of the interval, is dependent ONLY on the length of the interval, and not on the time of the start of the interval.
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Lognormal Distribution

The most common transformation is made by taking the natural logarithm, but any base logarithm, such as base 10 or base 2 may be used.

\[ y = x_1 \times x_2 \times x_3 \]
\[ \ln y = \ln x_1 + \ln x_2 + \ln x_3 \]

The lognormal probability density function is:

\[ f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{\ln x - \mu}{\sigma} \right)^2}, \quad x > 0 \]

\( \mu \) is the location parameter or log mean
\( \sigma \) is the scale (or shape) parameter or standard deviation of natural logarithms of the individual values.

Lognormal Probability Density Function

The lognormal distribution mean and variance are:

\[ \text{mean} = e^{(\mu + \sigma^2 / 2)} \]
\[ \text{variance} = (e^{(2\mu + \sigma^2)}) (e^{\sigma^2} - 1) \]
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Weibull Distribution

The Weibull distribution is one of the most widely used distributions in reliability and statistical applications. The two and three parameter Weibull common versions. The difference is the three parameter Weibull distribution has a location parameter when there is some non-zero time to first failure.

The three parameter Weibull probability density function is:
\[
f(x) = \frac{\beta}{\theta} \left( \frac{x-\delta}{\theta} \right)^{\beta-1} \exp\left( -\left( \frac{x-\delta}{\theta} \right)^\beta \right), \text{ for } x \geq \delta
\]

- \(\beta\) is the shape parameter,
- \(\theta\) is the scale parameter,
- \(\delta\) is the location parameter.

The three parameter Weibull distribution can also be expressed as:
\[
f(t) = \frac{\beta}{\eta} \left( \frac{t-\gamma}{\eta} \right)^{\beta-1} \exp\left( -\left( \frac{t-\gamma}{\eta} \right)^\beta \right), \text{ for } t \geq 0
\]

- \(\beta\) is the shape parameter,
- \(\eta\) is the scale parameter,
- \(\gamma\) is the non-zero location parameter.

The scale parameter is also known as the characteristic life if the location parameter is equal to zero. If \(\delta\) does not equal zero, the characteristic life is equal to \(\theta + \delta\).
Weibull Distribution (Continued)

Effect of Shape Parameter, $\beta$
with $\theta = 100$ and $\delta = 0$

Effect of Scale Parameter
Weibull Distribution (Continued)

Effect of Location Parameter

The mean of the Weibull distribution is:

\[ \mu = \theta \Gamma \left( 1 + \frac{1}{\beta} \right) \]

The variance of the Weibull distribution is:

\[ \sigma^2 = \theta^2 \left[ \Gamma \left( 1 + \frac{2}{\beta} \right) - \Gamma^2 \left( 1 + \frac{1}{\beta} \right) \right] \]

The variance of the Weibull distribution decreases as the value of the shape parameter increases.
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Measurement Systems

Measurement systems is described in the following sections:

- Measurement methods
- Measurement system analysis
- Metrology
Measurement Methods

Overview

The terms measuring tool and measuring instrument are used interchangeably in this text.

Tool Care

Measuring instruments are typically expensive and should be treated with care. Measuring tools must be calibrated on a scheduled basis as well as after any suspected damage.

Reference/Measuring Surfaces

A reference surface is the surface of a measuring tool that is fixed. The measuring surface is movable.

Transfer Tools

Transfer tools have no reading scale, an example, is spring calipers. The measurement is transferred to another measurement scale for direct reading.
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Measurement Methods (Continued)

Attribute Gages

Attribute gages are fixed gages which typically are used to make a go, no-go decision. Examples of attribute instruments are master gages, plug gages, contour gages, thread gages, limit length gages, assembly gages, etc. Attribute data indicates only whether a product is good or bad.

Variable Gages

Variable measuring instruments provide a physical measured dimension. Examples of variable instruments are line rules, vernier calipers, micrometers, depth indicators, runout indicators, etc.

Variable information provides a measure of the extent that a product is good or bad, relative to specifications. Variable data is often useful for process capability determination and may be monitored via control charts.
Attribute Screens

Attribute screens are screening tests performed on a sample with the results falling into one of two categories, such as acceptable or not acceptable.

Because the screen tests are conducted on either the entire population of items or on a significantly large proportion of the population, the screen test must be of a nondestructive nature. Screening programs should have the following characteristics:

- A clearly defined purpose
- High sensitivity to the attribute being measured. This equates to a low false negative rate
- High specificity to the attribute being measured. This equates to a low false positive rate
- Benefits of the program outweigh the costs
- Measured attributes identify major problems (serious and common)
- Results lead to useful actions
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Gage (Gauge) Blocks  

Carl Johansson developed steel blocks to establish a measurement standard to duplicate national standards and that could be used in any shop and had an accuracy within a few millionths of an inch.  

Generally, gage blocks or “Jo” blocks are made from high carbon or chromium alloyed steel, tungsten carbide, chromium carbide or fused quartz. They are used to set a length dimension for a transfer measurement, and for calibration of a number of other tools.  

<table>
<thead>
<tr>
<th>FEDERAL ACCURACY GRADES</th>
<th>ACCURACY IN LENGTH*</th>
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<tr>
<td>NEW DESIGNATION</td>
<td>OLD DESIGNATION</td>
</tr>
<tr>
<td>0.5</td>
<td>AAA</td>
</tr>
<tr>
<td>1</td>
<td>AA</td>
</tr>
<tr>
<td>2</td>
<td>A+</td>
</tr>
<tr>
<td>3</td>
<td>A &amp; B</td>
</tr>
</tbody>
</table>

Standard Gage Block Grades
Gage Blocks (Continued)

Block stacks are assembled by a wringing process which attaches the blocks by a combination of molecular attraction and the adhesive effect of a very thin oil film. Air between the block boundaries is squeezed out. The sequential steps for the wringing of rectangular blocks is shown below. Light pressure is used throughout the process.

Illustration of the Wringing of Gage Blocks

Gage Block Sets

The contents of a typical 81 piece set are:
- Ten-thousandth blocks (9): 0.1001, 0.1002, ..., 0.1009
- One-thousandth blocks (49): 0.101, 0.102, ..., 0.149
- Fifty-thousandth blocks (19): 0.050, 0.100, ..., 0.950
- One inch blocks (4): 1.000, 2.000, 3.000, 4.000
Calipers

Calipers are used to measure length. The length can be an inside dimension, outside dimension, height, or depth. Calipers are generally one of four types:

- Spring calipers
- Dial calipers
- Vernier calipers
- Digital calipers

Spring Calipers

Spring calipers provide a measurement accuracy of approximately 1/16 inch by transfer to a steel rule.
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Vernier Calipers

Vernier calipers use a vernier scale to indicate the measurement of length. Vernier calipers have been replaced with dial or digital calipers in many applications.

The Vernier Scale

Vernier scales are used on a variety of measuring instruments such as height gages, depth gages, inside or outside vernier calipers and gear tooth verniers.

Zero on the vernier plate exceeds 1.050" on the beam.
Record ..................................1.050"
The marks on the plate and beam align at 0.019". Add ..................0 . 019"
Final reading ........................ 1.069"
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Dial Calipers

Dial caliper measurement is indicated by a scale reading to the nearest 0.1 inch and a dial indicating the resolution to 0.001 inch. Errors include misreading the scale by 0.1 inch or using the calipers in applications which require an accuracy of 0.001 inch.

Digital Calipers

Digital calipers use a digital display and may be read in either inches or millimeters, and the zero point can be set for any point along the travel. Display resolutions of 0.0005 inch are common. Digital calipers are often used in applications which require a different device to attain the required accuracy.

Optical Comparators

Comparators use a beam of light directed upon the part to be inspected, and the resulting shadow is magnified and projected upon a viewing screen. The image can then be measured by comparing it with a master chart or outline on the viewing screen or measurements taken. To pass inspection, the shadow outline of the object must fall within predetermined tolerance limits.
Micrometers

Micrometers, or “mics,” are may be purchased with frame sizes from 0.5 inches to 48 inches. A 2" micrometer readings are from 1-2". Most “mics” have an accuracy of 0.001" and using a vernier scale, an accuracy of 0.0001" can be obtained. Supermicrometers when used in temperature and humidity controlled rooms, are able to make linear measurements to millionths of an inch.

Micrometers may make inside, outside, depth or thread measurements based upon the customization desired. The two primary scales for reading a micrometer are the sleeve scale and the thimble scale. Shown below, are simplified examples of typical micrometer readings.
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<tr>
<td><strong>1. MEASUREMENT METHODS</strong></td>
</tr>
</tbody>
</table>

## Tensile Strength Measurement

Tensile strength is the ability of a metal to withstand pulling apart. A uniaxial load is applied to a test bar and is gradually increased load until the bar breaks. The tensile data may be analyzed using a stress-strain curve which shows load versus elongation.

## Shear Test

Shear strength is the ability to resist a “sliding past” type of action when parallel but slightly off-axis forces are applied.

## Compression Test

Compression is the result of forces pushing toward each other. A load is applied and the deformation is recorded. A compressive stress-strain curve can be drawn from the data.

## Fatigue Test

Fatigue strength is the ability of material to take repeated loading. At various stress levels, the number of cycles are counted until failure occurs.
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Titration

A titration is a method of analysis that allows determination of the precise quantity of reactant in the titration flask. The solution to be analyzed is prepared by placing it in a Erlenmeyer flask or beaker. An indicator, such as phenolphthalein, is added to the solution. A buret is used to deliver the second reactant to the flask and an indicator or pH Meter is used to detect the endpoint of the reaction. The indicator changes color when the endpoint is reached.

Hardness Measurement

Hardness testing is performed by creating an indentation on the surface of a material with a hard ball or a diamond pyramid and then measuring the depth of penetration.
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### Hardness Testing Methods

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<th>PENETRATOR</th>
<th>LOADING</th>
<th>SCALE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brinell</td>
<td>Area of Penetration</td>
<td>10 mm Ball</td>
<td>500, 1500 or 3000 kg</td>
<td>HBW or HBS</td>
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<tr>
<td>File</td>
<td>Appearance of Scratch</td>
<td>File</td>
<td>Manual</td>
<td>None</td>
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<tr>
<td>Knoop</td>
<td>Area of Penetration</td>
<td>Pyramidal Diamond</td>
<td>25 to 3600 g</td>
<td>HK</td>
</tr>
<tr>
<td>Mohs</td>
<td>Presence of Scratch</td>
<td>10 Stones</td>
<td>Manual</td>
<td>Units Mohs</td>
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<tr>
<td>Rockwell</td>
<td>Depth of Penetration</td>
<td>Diamond Point or 1/16-1/8 Ball</td>
<td>60-100-150 kg</td>
<td>HRB, HRC, and many others</td>
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<tr>
<td>Rockwell Superficial</td>
<td>Depth of Penetration</td>
<td>Diamond Point or 1/16-1/8 Ball</td>
<td>15, 30 or 45 kg</td>
<td>15N, 30T, 45X, etc.</td>
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<td>Shore</td>
<td>Height of Bounce</td>
<td>40 Grain Weight</td>
<td>Gravity</td>
<td>Units Shore</td>
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<td>Vibration Frequency</td>
<td>Vibrating Rod</td>
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<td>BHN</td>
</tr>
<tr>
<td>Vickers</td>
<td>Area of Penetration</td>
<td>Pyramidal Diamond</td>
<td>25 g to 120 kg</td>
<td>HV</td>
</tr>
</tbody>
</table>
Torque Measurement

Torque measurement is required when the product is held together by nuts and bolts. Torque is described as a force producing rotation about an axis. The formula for torque is:

\[ \text{Torque} = \text{Force} \times \text{Distance} \]

Impact Test

Impact strength is a material's ability to withstand shock. Tests such as Charpy and Izod use notched samples which are struck with a blow from a calibrated pendulum.

The Steel Rule

The steel rule is used for direct length measurement. The fine divisions on a steel rule establish its discrimination which are typically 1/32, 1/64, or 1/100 of an inch.
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Surface Plates

Surface plates are a reference plane for dimensional measurements. They are customarily used with a toolmaker's flat, angles, parallels, V blocks and cylindrical gage block stacks.

Dial Indicators

Dial indicators are mechanical instruments for measuring distance variations. Most dial indicators amplify a contact point reading by use of an internal gear train mechanism.

Continuous Dial with 0.001" Graduations

Indicators have discriminations from 0.00002" to 0.001" with a wide assortment of measuring ranges.
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E. MEASUREMENT SYSTEMS
1. MEASUREMENT METHODS

Ring Gages

Ring gages are used to check external cylindrical dimensions and are often in “go, no-go” sets. A thread ring gage is used to check male threads.

Plug Gages

Plug gages are generally “go, no-go” gages, and are used to check internal dimensions. The thread plug gage is designed exactly as the plug gage but instead of a smooth cylinder at each end, the ends are threaded.
Pneumatic Gages

Pneumatic amplification gages types include one actuated by varying air pressure and the other by varying air velocity at constant pressure. Measurements can be read to millionths of an inch.

Interferometry

Interference occurs when two or more beams of monochromatic light of the same wave length are 180° out of phase traveling paths of different lengths. Irregularities are evidenced by alternate dark and light bands.

Laser Designed Gaging

The laser beam is transmitted to a receiver on the opposite side of the gage. Measurement takes place when the beam is broken by an object and the receiver denotes the dimension.

Coordinate Measuring Machine (CMM)

Workpieces are placed on a surface plate and a probe is maneuvered to various contact points using computer controlled measurements taken on three mutually perpendicular axes.
Non-Destructive Testing (NDT) and Non-Destructive Evaluation (NDE)

NDT and NDE techniques evaluate material properties without impairing the future usefulness of the items being tested. The advantages of NDT techniques include the use of automation, 100% product testing and the guarantee of internal soundness. Some NDT results are open to interpretation and demand considerable skill on the part of the examiner.

Visual Inspection

Visual examination of product color, texture, and appearance gives valuable information. The human eye is frequently aided by magnifying lenses or other instrumentation. This technique is sometimes called scanning inspection.
Ultrasonic Testing

Ultrasonic waves are generated in a transducer and transmitted through a material which may contain a defect. A portion of the waves will strike any defect present and be reflected or “echoed” back to a receiving unit, which converts them into a “spike” or “blip” on a screen. For non-destructive testing purposes, the vibration range is from 200,000 to 25,000,000 Hertz.

Schematic of a Typical Ultrasonic Test Unit
Magnetic Particle Testing

Magnetic particle inspection is a non-destructive method of detecting the presence of defects or voids in ferromagnetic metals or alloys. This technique can be used to detect both surface and subsurface defects in any material capable of being magnetized.

The part is magnetized, then fine steel particles are applied to the surface of the test part. These particles will align themselves with the magnetic field and concentrate at places where magnetic flux lines enter or leave the part. The test part is examined for concentrations of magnetic particles which indicate that discontinuities are present.

Alternating current (AC) is used to discover surface discontinuities while direct current (DC) provides greater sensitivity for the location of subsurface defects. Magnetic particle general categories are wet or dry.
VI. SIX SIGMA METHODOLOGY - MEASURE
E. MEASUREMENT SYSTEMS

1. MEASUREMENT METHODS

Liquid Penetrant Testing

Liquid penetrant inspection is a rapid method for detecting open surface defects in both ferrous and nonferrous materials. A penetrant carries a dye into a surface defect and a developer contrasts that defect by capillary attraction. False positive results may confuse an inspector.

Eddy Current Testing

Eddy currents are induced in a test object by passing an alternating current through a coil placed near the surface of the test object. A secondary electromagnetic field is produced in the test piece which can be compared with that of a standard.
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1. MEASUREMENT METHODS

Radiography

Either X-rays or gamma rays can be directed through a test object onto a photographic film and the internal characteristics of the part can be reproduced and analyzed.

For proper X-ray examination, adequate standards must be established for evaluating the results. A radiograph can show voids, porosity, inclusions, and cracks if they lie in the proper plane and are sufficiently large.

Neutron Radiography

Neutrons are uncharged atomic particles which move through materials unaffected by density. They are scattered or absorbed by particles in the atomic nuclei rather than by electrons. The object is placed in a neutron beam in front of an image detector.

Related Techniques

Several recent applications include fluoroscopy, gamma radiography, televised x-ray (TVX), microwave testing and holographic inspection.
Measurement Summary

Listed in the CSSBB Primer is a summary of the accuracy and application of various gages and measuring instruments.
VI. SIX SIGMA METHODOLOGY - MEASURE
E. MEASUREMENT SYSTEMS
2. MEASUREMENT SYSTEM ANALYSIS

Measurement System Analysis

Sensitivity
The gage should be sensitive enough to detect differences in measurement as slight as one-tenth of the total tolerance specification or process spread.

Reproducibility
The reproducibility of a single gage is customarily checked by comparing the results of different operators taken at different times.

Accuracy
Accuracy is an unbiased true value and is normally reported as the difference between the average of a number of measurements and the true value.

Precision
Precision or “repeatability” is the ability to repeat the same measurement by the same operator at or near the same time.

Precise, but not accurate
Accurate, but not precise
Accurate and precise
Repeatability and Reproducibility

There are three widely used methods to quantify measurement error: the range method, the average and range method, and the ANOVA method. A brief description of each follows:

**Range Method**

The range method is a simple way to quantify the combined repeatability and reproducibility of a measurement system.

**Average and Range Method**

The average and range method computes the total measurement system variability, and allows the total measurement system variability to be separated into repeatability, reproducibility, and part variation.

**Analysis of Variance Method**

ANOVA is the most accurate method for quantifying repeatability and reproducibility and allows the variability of the interaction between the appraisers and the parts to be determined.
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Analysis of Variance Method (Continued)

The example in the Primer is for five parts, three technicians and two replications.

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>DF</th>
<th>MS</th>
<th>F_cal</th>
<th>F(α)</th>
<th>Var</th>
<th>Adj Var</th>
<th>%</th>
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</thead>
<tbody>
<tr>
<td>Technician</td>
<td>0.6167</td>
<td>2</td>
<td>0.3083</td>
<td>1.28</td>
<td>3.68</td>
<td>0.0111</td>
<td>0.0111</td>
<td>2.34</td>
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<tr>
<td>Part No.</td>
<td>9.867</td>
<td>4</td>
<td>2.467</td>
<td>10.21</td>
<td>3.06</td>
<td>0.2225</td>
<td>0.2225</td>
<td>46.81</td>
</tr>
<tr>
<td>Interaction</td>
<td>1.633</td>
<td>8</td>
<td>0.2041</td>
<td>0.84</td>
<td>2.64</td>
<td>-0.019</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Error</td>
<td>3.625</td>
<td>15</td>
<td>0.2417</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total DF 29
SIGe = 0.4916
Totals 0.4753 100
SIGtot = 0.7368

For this example, repeatability is the error variance and contributes 50.85% of the total variation in the data.

Reproducibility is the variation among technicians which contributes 2.34% of the variation in the data.

Process variation accounts for 46.81% of the total variation in the data.

Hypothesis tests based on the F distribution are used to determine if there are differences between technicians or between processes.
VI. SIX SIGMA METHODOLOGY - MEASURE
E. MEASUREMENT SYSTEMS
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Measurement Correlation

The term *measurement correlation* means the correlation or comparison of the measurement values from one measurement system with the corresponding values reported by one or more different measurement systems.

A measurement system or device can be used to compare values against a known standard. The measurement system or device may also be compared against the mean and standard deviation of multiple other similar devices, all reporting measurements of the same or similar artifacts, often referred to as proficiency testing or round robin testing.

Measurement correlation can also mean comparison of values obtained using different measurement methods used to measure different properties. Examples are correlation of hardness and strength of a metal, temperature and linear expansion of an item being heated, and weight and piece count of small parts.

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Bias

Bias is the difference between the output of the measurement system and the true value. It is often referred to as accuracy.

\[
\text{Bias} = \frac{1}{n} \sum_{i=1}^{n} X_i - \tau
\]

Where \( n \) is the number of times the standard is measured, \( X_i \) is the \( i \)th measurement, and \( \tau \) is the value of the standard. Bias is usually reported as a percent of process variation or as a percent of tolerance.

Linearity

Plot the bias versus reference part measurement values throughout the operating range of the instrument. The percent linearity is equal to the slope, \( b \), of the best-fit straight line through the data points, and the linearity is equal to the slope multiplied by the process variation:

\[
L = b V_p
\]

The bias at any point can be estimated from the slope and the \( y \)-intercept, \( (y_0) \) of the best-fit line:

\[
B = y_0 + bx
\]
Percent Agreement

Percent agreement between the measurement system and either reference values or the true value of a variable being measured, can be estimated using a correlation coefficient, “r”. If \( r = \pm 1.0 \), then there is 100 percent agreement and if \( r = 0 \), then there is 0 percent agreement between the measurement system variables and the reference or true values.

Precision/Tolerance (P/T)

The precision/tolerance ratio (P/T) is the ratio between the estimated measurement error (precision) and the tolerance of the characteristic being measured.

\[
P/T \text{ Ratio} = \frac{6 \sigma_E}{\text{Total Tolerance}}
\]

Where \( 6\sigma_E \) is the standard deviation due to measurement variability. The assumptions are:

- Measurement errors are independent
- Measurement errors are normally distributed
- Measurement error is independent of the magnitude of the measurement
VI. SIX SIGMA METHODOLOGY - MEASURE
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Precision/Total Variation (P/TV)

The precision/total variation (P/TV) is given by:

\[
P/TV \text{ Ratio} = \frac{6 \sigma_E}{\text{Total Variation}}
\]

\[
= \frac{\text{Measurement Variation}}{\text{Product Variation} + \text{Measurement Variation}}
\]

It is desirable to minimize the P/TV ratio to reduce the effect of measurement variation on assessments of process variation.

As P/T or P/TV increases, the ability to discriminate a change in the process diminishes. When the measurement process is inadequate to detect part-to-part variations, then the measurement system is inadequate and a system with a smaller measurement variation must be used.
VI. SIX SIGMA METHODOLOGY - MEASURE
E. MEASUREMENT SYSTEMS
2. MEASUREMENT SYSTEM ANALYSIS

ANOVA

The observed value using an ANOVA study is given by:

\[
\text{Observed Value} = \text{Part Mean} + \text{Bias} + \text{Part Effect} + \text{Appraiser Effect} + \text{Replication Error}
\]

or: \( \text{Observed Value} = \text{Reference Value} + \text{Deviation} \)

in equation format: \( Y_{ijm} = x_i + c_{ijm} \)

Where \( y_{ijm} \) is the \( m \)th measurement taken by appraiser \( j \) on the \( i \)th part. Assuming that the \( x_i \)'s are independent and normally distributed with mean \( \mu \) and variance \( \sigma^2 \), the total variance is given by:

\[
\text{VAR}(y_{ijm}) = \sigma^2 + \omega^2 + \alpha^2 + \tau^2
\]

Where \( \omega^2 \), \( \alpha^2 \) and \( \tau^2 \) are the variances due to the part effect, the appraiser effect, and the replication error.

Control Chart Methods

A mathematical model for the variables study using average and range with \( r \) replications, by \( k \) appraisers, on \( n \) parts, the average range is found from:

\[
\overline{R} = \frac{1}{nk} \sum_{i=1}^{n} \sum_{j=1}^{k} R_{ij}
\]
VI. SIX SIGMA METHODOLOGY - MEASURE
E. MEASUREMENT SYSTEMS
3. METROLOGY

Metrology

Metrology is the science of measurement. The word metrology derives from two Greek words: matron (meaning measure) and logos (meaning logic). Metrology encompasses the following key elements:

- The establishment of measurement standards that are both internationally accepted and definable
- The use of measuring equipment to correlate the extent that product and process data conforms to specification
- The regular calibration of measuring equipment, traceable to established international standards
Units of Measurement

The SI system classifies measurements into seven distinct categories:

1. Length (meter)
2. Time (second)
3. Mass (kilogram)
4. Electric current (ampere)
5. Temperature (Kelvin)
   \[ \text{Temp F} = 1.8 \times (\text{Temp C}) + 32 \]
   \[ \text{Temp C} = \frac{(\text{Temp F} - 32)}{1.8} \]
   \[ \text{Temp K} = \text{Temp C} + 273.15 \]
6. Light (candela)
7. Amount of substance (mole)
Calibration

Calibration is the comparison of a measurement standard or instrument of known accuracy with another standard or instrument to detect, correlate, report or eliminate by adjustment, any variation in the accuracy of the item being compared. The elimination of measurement error is the primary goal of calibration systems.

Total Product Variability

The total variability in a product includes the variability of the measurement process:

$$\sigma^2_{\text{Total}} = \sigma^2_{\text{Process}} + \sigma^2_{\text{Measurement}}$$

Measurement Error

The error of a measuring instrument is the indication of a measuring instrument minus the true value.

$$\sigma^2_{\text{Error}} = \sigma^2_{\text{Measurement}} - \sigma^2_{\text{True}}$$

or

$$\sigma^2_{\text{Measurement}} = \sigma^2_{\text{True}} + \sigma^2_{\text{Error}}$$
Measurement Error (Continued)

The confidence interval for the mean of measurements is reduced by obtaining multiple readings according to the central limit theorem using the following relationship.

$$\sigma_{\text{Measure}} = \frac{\sigma_{\text{Readings}}}{\sqrt{n}},$$

There are many reasons that a measuring instrument may yield erroneous variation, including the following categories:

- Operator Variation
- Operator to Operator Variation
- Equipment Variation
- Material Variation
- Procedural Variation
- Software Variation
- Laboratory to Laboratory Variation
VI. SIX SIGMA METHODOLOGY - MEASURE
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Calibration Interval

It is generally accepted that the interval of calibration of measuring equipment be based on stability, purpose and degree of usage.

1. The stability of a measurement instrument refers to the ability of a measuring instrument to consistently maintain its metrological characteristics over time.

2. The purpose is important, in general, the critical applications will increase frequency and minor applications would decrease frequency.

3. The degree of usage refers to how often an instrument is utilized and to what environmental conditions an instrument is exposed.

Measuring and test equipment should be traceable to records that indicate the date of the last calibration, by whom it was calibrated and when the next calibration is due. Coding is sometimes used.
Calibration Standards

In the SI system, most of the fundamental units are defined in terms of natural phenomena that are unchangeable. This recognized true value is called the standard.

Primary reference standards consist of copies of the international kilogram plus measuring systems which are responsive to the definitions of the fundamental units and to the derived units of the SI table.

National standards are taken as the central authority for measurement accuracy, and all levels of working standards are traceable to this “grand” standard. The downward direction of this traceability is shown as follows:

1. National Institute of Standards and Technology
2. Standards Laboratory
3. Metrology Laboratory
4. Quality Control System
5. Work Center
ISO 10012 Synopsis

ISO 10012-1:1992. *Quality assurance requirements for measuring equipment - Part 1: Metrological confirmation system for measuring equipment* contains quality assurance requirements to ensure that measurements are made with intended accuracy. Key elements:

- All measuring equipment must be identified, controlled, and calibrated and records of the calibration and traceability to national standards must be kept.
- The uncertainty of measurement must be determined.
- Suitable procedures must be in place to assure that nonconforming measuring equipment is not used.
- A labeling system must be in place that shows the unique identification and its status.
- The frequency of recalibration must be established.
- Calibrations must be traceable to national standards.
- Documented procedures are required for the qualifications and training of personnel.
VI. SIX SIGMA METHODOLOGY - MEASURE
F. ANALYZING PROCESS CAPABILITY
1. PROCESS CAPABILITY STUDIES

Analyzing Process Capability

Analyzing process capability is described in the following sections:

- Designing and conducting process capability studies
- Calculating process performance vs. specification
- Process capability indices
- Process performance indices
- Short-term vs. long-term capability
- Non-normal data transformations
- Process capability for attributes data
VI. SIX SIGMA METHODOLOGY - MEASURE
F. ANALYZING PROCESS CAPABILITY
1. PROCESS CAPABILITY STUDIES

Designing and Conducting Process Capability Studies

Process capability is a predictable pattern of statistically stable behavior where the chance causes of variation are compared to the engineering specifications. A capable process is a process whose spread on the bell-shaped curve is narrower than the tolerance range.

Comparison of Process Spread to Tolerance Range

Where USL and LSL are defined as upper specification and lower specification limits, respectively.

It is often necessary to compare the process variation with the engineering or specification tolerances to judge the suitability of the process. Process capability analysis addresses this issue.
Process Capability Study Objectives

The objective of a process capability study is to establish a state of control over the manufacturing process and then maintaining that state of control through time.

When the natural process limits are compared with the specification range, any of the following possible courses of action may result:

- Do Nothing
- Change the Specifications
- Center the Process
- Reduce Variability
- Accept the Losses
VI. SIX SIGMA METHODOLOGY - MEASURE
F. ANALYZING PROCESS CAPABILITY
   1. PROCESS CAPABILITY STUDIES

Identifying Characteristics

The identification of characteristics to be measured in a process capability study should meet the following requirements:

- The characteristic should be indicative of a key factor in the quality of the product or process
- It should be possible to adjust the value of the characteristic
- The operating conditions that affect the measured characteristic should be defined and controlled

The *Production Part Approval Process (PPAP)* states “An acceptable level of preliminary process capability must be determined prior to submission for all characteristics designated by the customer or supplier as Safety, Key, Critical, or Significant, that can be evaluated using variables (measured) data.”

Identifying Specifications/Tolerances

The process specifications or tolerances are determined either by customer requirements, industry standards, or the organization’s engineering department.
VI. SIX SIGMA METHODOLOGY - MEASURE
F. ANALYZING PROCESS CAPABILITY
1. PROCESS CAPABILITY STUDIES

Developing Sampling Plans

If the process fits a normal distribution and is in statistical control, then the standard deviation can be estimated from:

$$\sigma_R \approx \frac{\bar{R}}{d_2}$$

For new processes, for example for a project proposal, a pilot run may be used to estimate the process capability.
VI. SIX SIGMA METHODOLOGY - MEASURE
F. ANALYZING PROCESS CAPABILITY
1. PROCESS CAPABILITY STUDIES

Verifying Stability and Normality

If only common causes of variation are present in a process, then the output of the process forms a distribution that is stable over time and is predictable. If special causes of variation are present, the process output is not stable over time.

Unstable Process with Average and Variation Out-of-control
Verifying Stability and Normality (Cont.)

The validity of the normality assumption may be tested using the chi-square hypothesis test. The chi-squared hypothesis test is:

\[ H_0: \text{The data follow a specified distribution} \]
\[ H_1: \text{The data do not follow a specified distribution} \]

and is tested using the following test statistic:

\[ \chi^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \]

Continuous data may be tested using the Kolmogorov-Smirnov goodness-of-fit test. It has the same hypothesis test as the chi-squared test and the test statistic is given by:

\[ D = \max_{1 \leq i \leq N} \left| F(Y_i) - \frac{i}{N} \right| \]

Where \( D \) is the test statistic and \( F \) is the theoretical cumulative distribution of the continuous distribution being tested. An attractive feature of this test is that the distribution of the test statistic does not depend on the underlying cumulative distribution function being tested.
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   F. ANALYZING PROCESS CAPABILITY
      2. CALCULATING PROCESS PERFORMANCE

Calculating Process Performance vs. Specification

Process Variations

Rejected Material

Specification

Rejected Material

Aim
VI. SIX SIGMA METHODOLOGY - MEASURE
F. ANALYZING PROCESS CAPABILITY
   2. CALCULATING PROCESS PERFORMANCE

### Capability Index Failure Rates

<table>
<thead>
<tr>
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<th>ppm</th>
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<tr>
<td>0.33</td>
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</tr>
<tr>
<td>0.67</td>
<td>45,500</td>
</tr>
<tr>
<td>1.00</td>
<td>2,700</td>
</tr>
<tr>
<td>1.10</td>
<td>967</td>
</tr>
<tr>
<td>1.20</td>
<td>318</td>
</tr>
<tr>
<td>1.30</td>
<td>96</td>
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<td>1.60</td>
<td>1.6</td>
</tr>
<tr>
<td>1.67</td>
<td>0.6</td>
</tr>
</tbody>
</table>

ppm: Parts per million of nonconformance

- For a two-tailed specification
- Normally distributed, continuous variable
- Assuming $\bar{X}$ is centered on the nominal specification
- With no process shifts (Most Black Belt analyses include a $\pm 1.5 \sigma$ process shift, see the table in the Appendix)

Note that there is a direct link between these failure rates and the standard normal (Z value) chart. A $C_p$ of 1.0 is the loss suffered at a Z value of 3.0 (doubled, since the table is one sided).
The Z Value

The area outside of specification can be determined by a “Z value.”

\[
Z_{\text{UPPER}} = \frac{\text{USL} - \bar{X}}{\sigma} \quad \text{and} \quad Z_{\text{LOWER}} = \frac{\bar{X} - \text{LSL}}{\sigma}
\]

Looking up the value of Z in a Standard Normal Table gives the area outside of specification. In the example above, Z upper = 1.0. Thus, 15.9% is above the USL.

The Z transformation formula is:

\[
Z = \frac{X - \mu}{\sigma}
\]

Where: \( x = \text{Data value}, \ \mu = \text{Mean}, \ \sigma = \text{Standard deviation} \)
VI. SIX SIGMA METHODOLOGY - MEASURE
F. ANALYZING PROCESS CAPABILITY
2. CALCULATING PROCESS PERFORMANCE

Z Value (Continued)

1. Up to the z value with $P(z = 1) = 0.8413$.

2. Beyond the z value with $P(z=1) = 0.1587$.

3. As a number under the curve and at a distance from the mean with $P(z=1) = 0.3413$. 
VI. SIX SIGMA METHODOLOGY - MEASURE
F. ANALYZING PROCESS CAPABILITY
3. PROCESS CAPABILITY INDICES

Process Capability Indices

\[ \sigma_R = \frac{\bar{R}}{d_2} \quad \text{or} \quad \sigma_i = \sqrt{\frac{\Sigma(X - \bar{X})^2}{(n - 1)}} \]

\( \sigma_R \) is an estimate of process capability sigma. \( \sigma_i \) is a measure of total data sigma.

Capability ratio:

\[ C_R = \frac{6 \sigma_R}{(USL - LSL)} \]

Performance ratio:

\[ P_R = \frac{6 \sigma_i}{(USL - LSL)} \]

Capability index:

\[ C_P = \frac{(USL - LSL)}{6 \sigma_R} \]

Performance index:

\[ P_P = \frac{(USL - LSL)}{6 \sigma_i} \]

\( C_R < 0.75, \text{ or } C_P > 1.33, \text{ Capable} \)

\( C_R = 0.75 \text{ to } 1.00, \text{ or } C_P = 1.00 \text{ to } 1.33, \text{ Capable with tight control} \)

\( C_R > 1.00, \text{ or } C_P < 1.00, \text{ Incapable} \)
VI. SIX SIGMA METHODOLOGY - MEASURE
F. ANALYZING PROCESS CAPABILITY
4. PROCESS PERFORMANCE INDICES

Process Performance Indices

Customers frequently require $C_{pk}$, where $C_{pk}$ is the ratio giving the smallest answer between:

$$C_{pk} = \frac{USL - \bar{X}}{3 \sigma_R} \quad \text{or} \quad \frac{\bar{X} - LSL}{3 \sigma_R}$$

Customers may also request $P_{pk}$, where $P_{pk}$ is the ratio giving the smallest answer between:

$$P_{pk} = \frac{(USL - \bar{X})}{3 \sigma_i} \quad \text{or} \quad \frac{(\bar{X} - LSL)}{3 \sigma_i}$$

There is a difficulty in selecting critical values for $C_{pk}$. The sigma of this capability statistic varies widely for different values of $N$. 
VI. SIX SIGMA METHODOLOGY - MEASURE
F. ANALYZING PROCESS CAPABILITY
4. PROCESS PERFORMANCE INDICES

Process Performance Indices (Cont.)

The sigma and confidence interval are respectively:

\[ \sigma_{C_{pk}} = \sqrt{\frac{1}{9N} + \frac{(C_{pk})^2}{2N - 2}} \]

\[ CI_{C_{pk}} = C_{pk} \pm Z_{\alpha/2} \sqrt{\frac{1}{9N} + \frac{(C_{pk})^2}{2N - 2}} \]

Depending on the choice of \( N \) and \( \alpha \) the minimum value of \( C_{pk} \) is:

\[ 1.00 + Z_{\alpha/2} \left( \sqrt{\frac{1}{9N} + \frac{(C_{pk})^2}{2N - 2}} \right) \]

Another capability index is called \( C_{pm} \) which considers the target value of a process when it is not the mean of the tolerance range. This capability index attempts to capture real performance not potential performance:

\[ C_{pm} = \frac{C_p}{\sqrt{1 + \frac{(\text{mean} - \text{target})^2}{\sigma_i^2}}} \]
VI. SIX SIGMA METHODOLOGY - MEASURE
F. ANALYZING PROCESS CAPABILITY
   5. SHORT-TERM VS. LONG-TERM CAPABILITY

Short-Term vs. Long-Term Capability

When a process capability is determined using one operator on one shift, with one piece of equipment, the process variation is relatively small. Control limits based on a short-term process evaluation are closer together than control limits based on the long-term process.

A modified $\overline{X}$ and R chart can be used for short runs, based on an initial 3 to 10 pieces, using a calculated value compared with a critical value. Inflated $D_4$ and $A_2$ values are used to establish control limits. Control limits are recalculated after additional groups are run.

The $X$ and MR chart can also be used for small runs, with a limited amount of data. The $X$ represents individual data values, and the MR is the moving range, a measure of piece to piece variability.

Process capability or $C_{pk}$ values determined from either of these methods must be considered preliminary information. As the number of data points increases, the calculated process capability will approach the true capability.
Non-Normal Data Transformations

Process Capability for Non-Normal Data

Data does not always fit a normal distribution. One strategy is to make non-normal data resemble normal data by using a transformation.

A family of power transformations for positive data values are attributed to G.E.P Box and D.R. Cox. The Box-Cox power transformations are given by:

\[ x(\lambda) = \frac{(x^\lambda - 1)}{\lambda} \quad \text{for } \lambda \neq 0 \]

\[ x(\lambda) = \ln(x) \quad \text{for } \lambda = 0 \]

Given data observations \( x_1, x_2, ... x_n \), select the power \( \lambda \) that maximizes the logarithm of the likelihood function:

\[
f(x) = -\frac{n}{2} \ln \left[ \sum_{i=1}^{n} \frac{(x_i(\lambda) - \bar{x}(\lambda))^2}{n} \right] + (\lambda - 1) \sum_{i=1}^{n} \ln(x_i)\]

Where the arithmetic mean of the transformed data is:

\[
\bar{x}(\lambda) = \frac{1}{n} \sum_{i=1}^{n} x_i(\lambda)
\]
Process Capability for Attribute Data

The control chart represents the process capability, once special causes have been identified and removed from the process. For attribute charts, capability is defined as the average proportion or rate of nonconforming product.

- For p charts, the process capability is the process average nonconforming, $\bar{p}$. The proportion conforming to specification, $1 - \bar{p}$, may be used.
- For np charts, the process capability is the process average nonconforming, $\bar{p}$.
- For c charts, the process capability is the average number of nonconformities, $\bar{c}$, in a sample of fixed size $n$.
- For u charts, the process capability is the average number of nonconformities per reporting unit, $\bar{u}$.

The average proportion of nonconforming may be reported on a defects per million opportunities scale by multiplying $\bar{p}$ times 1,000,000.
VI. SIX SIGMA METHODOLOGY - MEASURE QUESTIONS

6.4. Which of the following are principle reasons for utilizing process mapping?

I. To identify where unnecessary complexity exists
II. To visualize the process quickly
III. To eliminate the total planning process
IV. To assist in work simplification

a. I and II only  c. I, II and IV only
b. I, II and III only  d. I, II, III and IV

6.8. An Ishikawa diagram is also known as a:

I. Cause and effect diagram
II. Process flow diagram
III. Scatter diagram
IV. Fishbone diagram

a. I only  c. I and IV only
b. I, III and IV only  d. I, II, III and IV only

6.10. In statistical quality control, a parameter is:

a. A random variable
b. A sample value
c. A population value
d. The solution to a statistical problem

Answers 6.4 c, 6.8 c, 6.10 c
VI. SIX SIGMA METHODOLOGY - MEASURE QUESTIONS

6.12. Let $X$ be any random variable with mean $\mu$ and standard deviation $\sigma$. Take a random sample of size $n$. As $n$ increases and as a result of the central limit theorem:

a. The distribution of the sum $S_n = X_1 + X_2 + \ldots + X_n$ approaches a normal distribution with mean $\mu$ and standard deviation $\sigma/\sqrt{n}$

b. The distribution of $S_n = X_1 + X_2 + \ldots + X_n$ approaches a normal distribution with mean $\mu$ and standard deviation $\sigma/\sqrt{n}$

c. The distribution of $X$ approaches a normal distribution with mean $\mu$ and standard deviation $\sigma/\sqrt{n}$

d. The distribution of $\bar{X}$ approaches a normal distribution with mean $\mu$ and standard deviation $\sigma/\sqrt{n}$

6.15. Which table should be used to determine a confidence interval on the mean when $\sigma$ is not known and the sample size is 10?

a. $z$   b. $t$   c. $F$   d. $X^2$

6.20. For two events, $A$ and $B$, which one of the following is a true probability statement?

a. $P(A \text{ or } B) = P(A) + P(B)$ if $A$ and $B$ are independent

b. $P(A \text{ or } B) = P(A) + P(B)$ if $A$ and $B$ are mutually exclusive

c. $P(A \text{ and } B) = P(A) \times P(B)$ if $A$ and $B$ are mutually exclusive

d. $P(A \text{ or } B) = P(A) \times P(B)$ if $A$ and $B$ are independent

Answers 6.12 d, 6.15 b, 6.20 b
VI. SIX SIGMA METHODOLOGY - MEASURE QUESTIONS

6.21. One would normally describe recorded values reflecting length, volume and time as:

I. Measurable   III. Continuous
II. Discrete     IV. Variable

a. I and III only  c. I, III and IV
b. II and IV only  d. I, II, III and IV

6.27. When performing calculations on sample data:

a. The continuous relative frequency graph called a histogram, results
b. Rounding the data has no effect on the mean and standard deviation

6.28. Random selection of a sample:

a. Theoretically means that each item in the lot had an equal chance to be selected
b. Assures that the sample average will equal the population average

Answers 6.21 c, 6.27 d, 6.28 a
VI. SIX SIGMA METHODOLOGY - MEASURE QUESTIONS

6.34. Determine the coefficient of variation for the last 500 pilot plant test runs of high temperature film having a mean of 900° Kelvin with a standard deviation of 54°.

a. 6%  c. 0.6%
b. 16.7%  d. 31%

6.38. Which three of the following four techniques could easily be used to display the same data?

I. Stem and leaf plots
II. Boxplots
III. Scatter Diagrams
IV. Histograms

a. I, II and III only  c. I, III and IV only
b. I, II and IV only  d. II, III and IV only

6.39. The histogram below displays what type of distribution?

a. Bimodal
b. Polymodal
c. Negative skewed
d. Truncated

Answers 6.34 a, 6.38 b, 6.39 a
VI. SIX SIGMA METHODOLOGY - MEASURE QUESTIONS

6.43. What is the most widespread use of the F distribution?

a. To model discrete data when the population size is small compared to the sample size
b. To test for equality of variances from two normal populations
c. To compensate for error in the estimated standard deviation for small sample size
d. To make decisions and construct confidence intervals by summing the square of normal random variables

6.47. There are several forms of the exponential distribution used to model reliability. Using the formula below, what does $\theta$ represent?

$$P(x) = \frac{e^{-\frac{x}{\theta}}}{\theta}$$

a. The mean c. The variance
b. The x axis value d. The failure rate

6.51. Identify the testing methods below which would be considered destructive:

1. Acid etch 4. Liquid penetrant 7. Eddy current
3. Spectroscopic 6. Ultrasonic

a. 1, 3 and 5 only c. 1, 4, 6 and 8 only
b. 2, 3 and 8 only d. 3, 5 and 6 only

Answers 6.43 b, 6.47 a, 6.51 a
VI. SIX SIGMA METHODOLOGY - MEASURE QUESTIONS

6.55. When making measurements with test instruments, precision and accuracy mean:

a. The same  
b. The opposite  
c. Consistency and correctness, respectively  
d. Exactness and traceability, respectively

6.59. The standard deviation of measurements of dimension A on a group of randomly chosen parts is $\sigma_1$, and the standard deviation of the series of measurements of dimension A on one part is $\sigma_2$. What is the standard deviation $\sigma$ of the true values of dimension A in the population from which the parts were taken?

a. $\sigma = \sqrt{\sigma_1^2 - \sigma_2^2}$  
b. $\sigma = \sigma_1 - \sigma_2$  
c. $\sigma = \frac{\sigma_1 - \sigma_2}{2}$  
d. $\sigma = \frac{\sqrt{\sigma_1^2 - \sigma_2^2}}{2}$

6.60. Which of the following is most important when calibrating a piece of equipment?

a. The calibration sticker  
b. The maintenance history card  
c. The standard used  
d. The calibration interval

Answers 6.55 c, 6.59 a, 6.60 c
6.66. Control limits are set at the three-sigma level because:

a. This level makes it difficult for the output to get out of control
b. This level establishes tight limits for the production process
c. This level reduces the probability of looking for trouble in the production process when none exists
d. This level assures a very small type II error

6.68. Which one of the following best describes machine capability?

a. The total variation of all cavities of a mold, cavities of a die cast machine or spindles of an automatic assembly line
b. The inherent variation of the machine
c. The total variation over a shift
d. The variation in a short run of consecutively produced parts

6.69. In a normal distribution, what is the area under the curve between +0.7 and +1.3 standard deviation units?

a. 0.2903
b. 0.7580
c. 0.2580
d. 0.1452

Answers 6.66 c,  6.68 b,  6.69 d
VI. SIX SIGMA METHODOLOGY - MEASURE QUESTIONS

6.74. If $C_{pk}(\text{upper})$ were determined to be 2.0 and $C_{pk}(\text{lower})$ were determined to be 1.0, what factual statements can be made about the process?

I. The process is shifted to the left
II. A calculation error has been made
III. The process is not stable
IV. $C_{pk}$ must be reported as 1.0

a. IV only  
   b. I and IV only
   c. II and III only  
   d. I, III and IV only

6.76. When selecting an audit sample size, which of the following rules should govern your choice?

a. Since quality may change over time, we should look at a fixed quantity each time period for audit purposes
b. We need only a very small sample for audit purposes, as long as it is chosen at random
   c. Any size sample if randomly selected can be suitable for audit purposes, since we are not directly performing lot acceptance or rejection
   d. ANSI/ASQ Z1.4 is a scientific sampling procedure and we need scientific sampling for audit purposes

6.79. When attempting to determine process capability for non-normal data, which of the following alternatives can be appropriate?

I. Plot a histogram and determine if the data values are well within specifications
II. Transform the data using the Box-Cox technique
III. If the data can be represented by a probability plot, make predictions using this technique

a. I only  
   b. II only  
   c. II and III only  
   d. I, II and III

Answers 6.74 b, 6.76 c, 6.79 d
THE ENGINEER WHO IS SUCCESSFUL IN DIVIDING HIS (HER) DATA INITIALLY INTO RATIONAL SUBGROUPS... IS INHERENTLY BETTER OFF IN THE LONG RUN THAN THE ONE WHO IS NOT THUS SUCCESSFUL.

W. A. SHEWHART
Six Sigma Methodology - Analyze

Six Sigma Methodology - Analyze is presented in the following topic areas:

- Exploratory data analysis
- Hypothesis testing

Exploratory data analysis is reviewed in the topic areas of:

- Multi-vari studies
- Modeling relationships between variables
Multi-Vari Analysis

Often the variation is within piece and the source of this variation is different from piece-to-piece and time-to-time variation. The multi-vari chart is a very useful tool for analyzing all three types of variation.

Multi-vari charts are used to investigate the stability or consistency of a process. The chart consists of a series of vertical lines, or other appropriate schematics, along a time scale. The length of each line or schematic shape represents the range of values found in each sample set.

In Figure 7.1 variation within samples (five locations across the width) is shown by the line length. Variation from sample to sample is shown by the vertical positions of the lines.

![Figure 7.1 An illustrative Multi-Vari Line Chart](image)
VII. SIX SIGMA METHODOLOGY - ANALYZE
   A. EXPLORATORY DATA ANALYSIS
      1. MULTI-VARI ANALYSIS

Multi-Vari Analysis (Continued)

Figure 7.2 shows an injection molded plastic part. The thickness is measured at four points across the width as indicated by arrows.

\[ \text{USL} = 0.110\" \]
\[ \text{LSL} = 0.100\" \]

Figure 7.2 Multi-Vari Measurements on a Plastic Piece

Figure 7.4 Less Variability Within Piece (center is thicker)

Excessive variability may also be within piece (part is tapered) or shift over time (part is getting larger).
Multi-Vari Analysis (Continued)

Interpretation of the chart is apparent once the values are plotted. The advantages of multi-vari charts are:

1. It can dramatize the variation within the piece (positional).

2. It can dramatize the variation from piece to piece (cyclical).

3. It helps to track any time related changes (temporal).

4. It helps minimize variation by identifying areas to look for excessive variation. It also identifies areas not to look for excessive variation.
Multi-Vari Case Study

Flat sheets of aluminum produced on a hot rolling mill have a thickness specification of 0.245" ±0.005". A process capability study indicated that the process spread was 0.0125" (a $C_p$ of 0.8) versus the requirement of 0.010".

Four positional measurements were made at the corners of each flat sheet, three flat sheets were measured in consecutive order, and samples were collected each hour and plotted on a multi-vari chart.

The results were that 50% of the variation was due to time-to-time, 30% was due to within piece from non-parallel settings, 10-15% due to within piece from inadequate roll cooling, and 5-10% due to piece-to-piece. After making all of the modifications, the resulting measurement spread was ± 0.002" or 0.004" total.
A Simple Linear Model

An initial analysis of the data is to plot the points on a graph known as a scatter diagram.

![Plot of Study Time Versus CSSBB Test Results](image)

The mathematical equation of a straight line is:

\[ y = \beta_0 + \beta_1 X \]

Where \( \beta_0 \) is the Y intercept when \( X = 0 \) and \( \beta_1 \) is the slope of the line.
A Simple Linear Model (Continued)

We assume that for any given value of \( X \) the observed value of \( Y \) varies in a random manner and possesses a normal probability distribution.

Variation in \( Y \) as a Function of \( X \)

The probabilistic model for any particular observed value of \( Y \) is:

\[
y = \left( \text{Mean value of } y \text{ for a given value of } X \right) + (\text{random error})
\]

\[
y = \beta_0 + \beta_1 X + \epsilon
\]
The Method of Least Squares

The statistical procedure of finding the “best-fitting” straight line is found when we minimize the deviations of the points from the prospective line. If we denote the predicted value of $Y$ obtained from the fitted line as $\hat{y}$, the prediction equation is:

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x$$

$\hat{\beta}_0$ and $\hat{\beta}_1$ represent estimates of the true $\beta_0$ and $\beta_1$.

Plot of Study Time Versus CSSBB Test Results
Method of Least Squares (Continued)

The best fit criterion of goodness known as the principle of least squares is employed:

Choose, as the best fitting line, the line that minimizes the sum of squares of the deviations of the observed values of Y from those predicted.

Expressed mathematically, we wish to minimize the sum of squared errors given by:

\[
SSE = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2
\]

Substituting for \( \hat{y}_i \) we obtain the following expression:

\[
\text{Sum of squared errors} = SSE = \sum_{i=1}^{n} [y_i - (\hat{\beta}_0 + \hat{\beta}_1 x_i)]^2
\]
Method of Least Squares (Continued)

The least square estimator of $\beta_0$ and $\beta_1$ equals:

$$\hat{\beta}_1 = \frac{S_{xy}}{S_{x^2}} \quad \text{and} \quad \hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x}$$

where:

$$S_{x^2} = \sum_{i=1}^{n} x_i^2 - \frac{(\sum x_i)^2}{n}$$

$$S_{xy} = \sum_{i=1}^{n} x_i y_i - \frac{(\sum x_i)(\sum y_i)}{n}$$
Once $\hat{\beta}_0$ and $\hat{\beta}_1$ have been computed, we substitute their values into the equation of a line to obtain the least squares prediction equation, or regression line.

Example 7.1 in the Primer shows how to obtain the least squares prediction line for the example data.

**Hints on Regression Analysis**

- Be careful of rounding errors. The calculating device should carry a minimum of six significant figures in computing sums of squares of deviations.

- Always plot the data points and graph the least squares line. If the line does not provide a reasonable fit to the data points, there may be a calculation error.

- Projecting a regression line outside of the test area can be risky.
Calculating $S^2$, an Estimator of $\sigma^2$

Recall, the model for $y$ assumes that $y$ is related to $x$ by the equation:

$$y = \beta_0 + \beta_1x + \epsilon$$

If the least squares line is used:

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1x$$

A random error $\epsilon$ enters into the calculations of $\beta_0$ and $\beta_1$. The random errors affect the error of prediction.

We estimate $\sigma^2$ from SSE (sum of squares for error) based on $(n-2)$ degrees of freedom.

An Estimator for $\sigma^2$:

$$\hat{\sigma}^2 = S^2 = \frac{SSE}{n-2}$$

Formula for Calculating SSE:

$$SSE = S_y^2 - \hat{\beta}_1S_{xy} = S_y^2 - \frac{(S_{xy})^2}{S_{x^2}}$$

where

$$S_y^2 = \sum_{i=1}^{n}(y_i - \overline{y})^2 = \sum_{i=1}^{n}y_i^2 - \frac{n(\sum y_i)^2}{n}$$

$S_{xy}$ and $S_{x^2}$ have been previously defined.
Inferences Concerning the Slope $\beta_1$ of a Line

The following test statistic is used:

$$ t = \frac{\hat{\beta}_1 - \beta_1}{S/\sqrt{S_{\chi^2}}} $$

where $\frac{S}{\sqrt{S_{\chi^2}}}$ is the standard deviation of the slope.

Use a t test to test the null hypothesis:

$$ H_0 : \beta_1 = 0 $$

If $t_{\text{calc}}$ exceeds $t_{\text{critical}}$, we will reject the null hypothesis and conclude $\beta_1 \neq 0$ or that there is a slope.

To establish a $(1-\alpha)$ confidence Interval for $\beta_1$ use the formula:

$$ \hat{\beta}_1 \pm t_{0.025} \frac{S}{\sqrt{S_{\chi^2}}} $$
Correlation Coefficient

An indicator of the strength of the linear relationship between two variables \( y \) and \( x \) is called the Pearson product-moment coefficient of correlation, where:

\[
r = \frac{S_{xy}}{\sqrt{S_x^2 S_y^2}} \quad \text{or} \quad r = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{[\sum (x - \bar{x})^2 \sum (y - \bar{y})^2]}}
\]

Example 7.5: Using the study time and test score data reviewed earlier determine the correlation coefficient.

Given: \( S_{xy} = 772 \quad S_x^2 = 1110 \quad S_y^2 = 696.9 \)

Solution: \( r = \frac{772}{\sqrt{1110(696.9)}} = 0.878 \)

The coefficient of correlation \( r \) will assume exactly the same sign as \( \beta_1 \) and will equal zero when \( \beta_1 = 0 \).

Note that \( r = 0 \) implies no linear correlation, not simply “no correlation.” A pronounced curvilinear pattern may exist.
Correlation Coefficient (Continued)

If $X$ is of any value in predicting $Y$, then $SSE$, can never be larger than:

$$S_{y^2} = \sum_{i=1}^{n} (y_i - \bar{y})^2$$

Because:

$$SSE = S_{y^2} - \beta_1 S_{xy} = S_{y^2} - \left( \frac{S_{xy}}{S_{x^2}} \right) S_{xy}$$

$$SSE = S_{y^2} - \frac{(S_{xy})^2}{S_{x^2}}$$

Coefficient of Determination ($r^2$)

The coefficient of determination* ($R^2 = r^2$) equals:

$$r^2 = \frac{S_{y^2} - SSE}{S_{y^2}} = 1 - \frac{SSE}{S_{y^2}}$$

The coefficient of determination is also called the square of the linear correlation coefficient.
VII. SIX SIGMA METHODOLOGY - ANALYZE
A. EXPLORATORY DATA ANALYSIS
2. MODELING RELATIONSHIPS - VARIABLES

Correlation Example

Figure 7.15 Correlation Plot of Car Weight and MPG

\[
\text{SST} = \sum D_1^2 + D_2^2 \ldots D_9^2
\]

\[
\text{SSE} = \sum d_1^2 + d_2^2 \ldots d_9^2
\]

\[
r^2 = 1 - \frac{\text{SSE}}{\text{SST}} \quad \text{or} \quad \frac{\text{SST} - \text{SSE}}{\text{SST}}
\]
Multiple Linear Regression

Multiple linear regression is an extension of linear regression to more than one independent variable so a higher proportion of the variation in Y may be explained.

First-Order Linear Model

\[ y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \epsilon \]

Second-Order Linear Model

\[ y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 + \beta_4 x_1^2 + \beta_5 x_2^2 + \epsilon \]

\[ s^2 = \frac{\text{SSE}}{n - (k+1)} \]

\( R^2 \) (the multiple coefficient of determination) has values in the interval:

\[ 0 \leq R^2 \leq 1 \]

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<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>k</td>
<td>SSR</td>
<td>MSR=SSR/k</td>
</tr>
<tr>
<td>Error</td>
<td>n-(k+1)</td>
<td>SSE</td>
<td>MSE=SSE[n-(k+1)]</td>
</tr>
<tr>
<td>Total</td>
<td>n-1</td>
<td>Total SS</td>
<td></td>
</tr>
</tbody>
</table>

\( k = \) the number of predictor variables
Hypothesis testing is reviewed in the following topic areas:

- Fundamental concepts
- Point and interval estimation
- Tests for means, variances and proportions
- Paired comparison tests
- Goodness of fit tests
- Analysis of variance
- Contingency tables
- Nonparametric tests
Fundamental Concepts

We will first review a number of hypothesis test terms.

Null Hypothesis

This is the hypothesis to be tested. The null hypothesis directly stems from the problem statement and is denoted as $H_0$. Examples:

- If we are investigating whether a modified seed will result in a different yield/acre, the null hypothesis (2-tail) would assume the yields to be the same $H_0: \ Y_a = Y_b$.

- If a strong claim is made that the average of process A is greater than the average of process B, the null hypothesis (1-tail) would state that process A $\leq$ process B. This is written as $H_0: A \leq B$.

A null hypothesis can only be rejected, or fail to be rejected, it cannot be accepted because of a lack of evidence to reject it. When rejecting the null hypothesis, the alternate hypothesis must be accepted.
Test Statistic

In order to test a null hypothesis, a test calculation must be made from sample information. This calculated value is called a test statistic and is compared to an appropriate critical value. A decision can then be made to reject or not reject the null hypothesis.

Types of Errors

When formulating a conclusion regarding a population based on observations from a small sample, two types of errors are possible:

- **Type I error**: This error results when the null hypothesis is rejected when it is, in fact, true. The probability of making a type I error is called $\alpha$ (alpha) and is commonly referred to as the producer’s risk (in sampling).

- **Type II error**: This error results when the null hypothesis is not rejected when it should be rejected. This error is called the consumer’s risk (in sampling) and is denoted by the symbol $\beta$ (beta).
The assumption is that a small value for $\alpha$ is desirable, unfortunately, a small $\alpha$ risk increases the $\beta$ risk. For a fixed sample size, $\alpha$ and $\beta$ are inversely related. Increasing the sample size can reduce both the $\alpha$ and $\beta$ risks.

Types of Errors (Continued)

Null Hypothesis

<table>
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<th>The Decision Made</th>
<th>True</th>
<th>False</th>
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</thead>
<tbody>
<tr>
<td>Fail to Reject $H_0$</td>
<td>$p = 1 - \alpha$ Correct Decision</td>
<td>$p = \beta$ Type II Error</td>
</tr>
<tr>
<td>Reject $H_0$</td>
<td>$p = \alpha$ Type I Error</td>
<td>$p = 1 - \beta$ Correct Decision</td>
</tr>
</tbody>
</table>

Types of Errors Matrix
One Tail Test

A study was conducted to determine if the mean battery life produced by a new method is greater than the present battery life of 35 hours. In this case, the entire $\alpha$ risk will be placed on the right tail of the existing life distribution curve.

$H_0$: new $\leq$ present  \hspace{2cm} $H_1$: new $>$ present

Determine if the true mean is within the $\alpha$ critical region.
Two Tail Test

If a null hypothesis is established to test whether a population shift has occurred, in either direction, then a two tail test is required. The allowable $\alpha$ error is generally divided into two equal parts.

- A study is made to determine if the salary levels of company A differ significantly from those of company B.

\[ H_0: \text{levels are} = \quad H_1: \text{levels are} \neq \]

Determine if the true mean is within either the upper or lower $\alpha$ critical regions.
In the statistical inference discussion thus far, it has been assumed that the sample size \( (n) \) for hypothesis testing has been given and that the critical value of the test statistic will be determined based on the \( \alpha \) error that can be tolerated.

The ideal procedure, however, is to determine the \( \alpha \) and \( \beta \) error desired and then to calculate the sample size necessary to obtain the desired decision confidence.

The sample size \( (n) \) needed for hypothesis testing depends on:

- The desired type I \( (\alpha) \) and type II \( (\beta) \) risk
- The minimum value to be detected between the population means \( (\mu - \mu_0) \)
- The variation in the characteristic being measured \( (S \text{ or } \sigma) \)
Required Sample Size (Continued)

Example 7.7: What is the minimum sample size which, at the 95% confidence level (Z=1.96), would confirm the significance of a mean shift greater than 4 tons per hour, if the standard deviation of the hourly output is 20 tons?

The sample size equation for variable data (normal distribution) is:

\[ n = \frac{Z^2 \sigma^2}{E^2} = \frac{(1.96)^2 (20)^2}{(4)^2} = 96 \]

Obtain 96 pilot hourly yield values and determine the hourly average. If this mean deviates by more than 4 tons from the previous hourly average, a significant change at the 95% confidence level has occurred.

The above formula works for Poisson data using \( \bar{c} \) for \( \sigma \).

For binomial data, use the following formula:

\[ n = \frac{Z^2 (\bar{p})(1 - \bar{p})}{(\Delta p)^2} \]

\( Z = \) The appropriate Z value \quad \bar{p} = \) Proportion rate \quad \Delta p = \) The desired proportion interval \quad n = \) Sample size
Hypotheses Tests

- **Large samples**
  - Means
    - $\bar{X} \text{ vs } \mu$
    - $Z = \frac{\bar{X} - \mu}{\sigma/\sqrt{n}}$
  - Variances
    - $S_1^2 \text{ vs } \sigma^2$
    - $S_1^2 \text{ vs } S_2^2$
    - $F = \frac{S_1^2}{S_2^2}$
  - $X^2 = \frac{(n - 1)s^2}{\sigma^2}$

- **Small samples**
  - Means
    - $t = \frac{\bar{X} - \mu}{s/\sqrt{n}}$
  - $\bar{X}_1 \text{ vs } \bar{X}_2$
    - $S^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}$
    - $S_{\bar{X}_1, \bar{X}_2} = S \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}$
    - $df = n_1 + n_2 - 2$
    - $t = \frac{\bar{X}_1 - \bar{X}_2}{S_{\bar{X}_1, \bar{X}_2}}$
  - $\sigma_1^2 \neq \sigma_2^2$
    - $A = S_1^2 / n_1$
    - $B = S_2^2 / n_2$
    - $S_{\bar{X}_1, \bar{X}_2} = \sqrt{A + B}$
    - $df = \frac{(A + B)^2}{A^2/n_1 - 1} + \frac{B^2/n_2 - 1}$
VII. SIX SIGMA METHODOLOGY - ANALYZE
B. HYPOTHESIS TESTING
   1. FUNDAMENTAL CONCEPTS

Extreme Value Test

Normal ➔ Single samples ➔ Outlier test ➔ Outlier ratio table

Attribute Distribution Hypotheses

- **Binomial**
  - $p$ vs $\mu$
  - $p_1$ vs $p_2$
  - $\bar{p} = \frac{n_1p_1 + n_2p_2}{n_1 + n_2}$
  - $\sigma_{p_1-p_2} = \sqrt{\frac{p(1-p)}{n_1} + \frac{1}{n_2}}$
  - $Z = \frac{p_1 - p_2}{\sigma_{p_1-p_2}}$

- **Poisson**
  - $c$ vs $\mu$
  - $\sigma = \sqrt{c}$
  - $Z = \frac{c - \bar{c}}{\sqrt{\frac{c}{\bar{c}}}}$

- $c$ vs $c$
  - $c =$ no. of defects
  - $k =$ no. samples

- $X^2 = \left(\frac{c_1^2}{k_1} + \frac{c_2^2}{k_2}\right) \left(\frac{k_1 + k_2}{c_1 + c_2}\right) - (c_1 + c_2)$
Estimators

Example 7.8 Given tensile strength readings from 4 piano wire segments: 28.7, 27.9, 29.2 and 26.5 psi.

- **Point estimation**: represented by $\bar{X}$ is:

$$\bar{X} = \frac{\sum X_i}{n} = \frac{28.7 + 27.9 + 29.2 + 26.5}{4} = 28.08 \text{ and } (S = 1.1786)$$

The point estimate for the population mean is 28.08 psi.

- **Interval Estimate or CI (Confidence Interval)**: The critical value from the t distribution for 95% confidence, $t = 3.182$ for $n-1$ degrees of freedom.

$$\bar{X} \pm 3.182 \frac{S}{\sqrt{n}} = 28.08 \pm 3.182 \left( \frac{1.1786}{2} \right) = 26.205 \text{ and } 29.955$$

Had we known the population sigma (say $\sigma = 2$ psi), we could have used the Z distribution. The critical Z value for 95% confidence is 1.96.

$$\bar{X} \pm 1.96 \frac{\sigma}{\sqrt{n}} = 28.08 \pm 1.96 \left( \frac{2}{2} \right) = 26.12 \text{ and } 30.04$$
VII. SIX SIGMA METHODOLOGY - ANALYZE
B. HYPOTHESIS TESTING
  2. POINT AND INTERVAL ESTIMATION

Confidence Intervals for the Mean

Continuous Data - Large Samples

The confidence interval for the mean:

\[ \bar{X} \pm Z_\alpha \frac{\sigma}{\sqrt{n}} \]

\[ Z_\alpha = \text{the normal distribution value for a desired confidence level} \]

Continuous Data - Small Samples

If a relatively small sample is used (<30) then the t distribution must be used.

\[ \bar{X} \pm t_\frac{\alpha}{2} \frac{S}{\sqrt{n}} \]

The \[ t_\frac{\alpha}{2} \] distribution value for a desired confidence level, \( \alpha \), uses \( (n - 1) \) degrees of freedom.
Confidence Intervals for Variation

The confidence intervals for variance is based on the Chi-Square distribution. The formula is:

\[
\frac{(n - 1) S^2}{X^2_{\alpha/2, n - 1}} \leq \sigma^2 \leq \frac{(n - 1) S^2}{X^2_{1 - \alpha/2, n - 1}}
\]

\(S^2 = \text{point estimate of variance}\)

\(X^2_{\alpha/2}\) and \(X^2_{1 - \alpha/2}\) = are the chi-square table values for \((n - 1)\) degrees of freedom

Confidence Intervals for Proportion

For large sample sizes, with \(n(p)\) and \(n(1-p)\) greater than or equal to 4 or 5, the normal distribution can be used to calculate a confidence interval for proportion. The following formula is used:

\[
p \pm Z_{\alpha/2} \sqrt{\frac{p(1-p)}{n}}
\]

\(Z_{\alpha/2}\) = the appropriate confidence level from a Z table
VII. SIX SIGMA METHODOLOGY - ANALYZE
B. HYPOTHESIS TESTING
3. MEANS, VARIANCES AND PROPORTIONS

Hypothesis Tests for Means

Z Test

When the population follows a normal distribution and the population standard deviation, \( \sigma_x \), is known, then the hypothesis tests for comparing a population mean, \( \mu \), with a fixed value, \( \mu_0 \), are given by the following:

\[
\begin{align*}
H_0 & : \mu = \mu_0 \\
H_1 & : \mu \neq \mu_0
\end{align*}
\]

\[
\begin{align*}
H_0 & : \mu \leq \mu_0 \\
H_1 & : \mu > \mu_0
\end{align*}
\]

\[
\begin{align*}
H_0 & : \mu \geq \mu_0 \\
H_1 & : \mu < \mu_0
\end{align*}
\]

The null hypothesis is denoted by \( H_0 \) and the alternative hypothesis is denoted by \( H_1 \). The test statistic is given by:

\[
Z = \frac{\bar{X} - \mu_0}{\sigma_x} = \frac{\bar{X} - \mu_0}{\sigma_x / \sqrt{n}}
\]

The test statistic, \( Z \), is compared with a critical value \( Z_\alpha \) or \( Z_{\alpha/2} \) which is based on a significance level, \( \alpha \), for a one tailed test or \( \alpha/2 \) for a two tailed test. If the \( H_1 \) sign is \( \neq \), it is a two tailed test. If the \( H_1 \) sign is \( > \), it is a right one tailed test, and if the \( H_1 \) sign is \( < \), it is a left one tailed test.
Hypothesis Tests for Means (Continued)

Z Test (Continued)

**Example 7.13:** The average vial height from an injection molding process has been 5.00 inches with a standard deviation of 0.12". New material yielded: 5.10, 4.90, 4.92, 4.87, 5.09, 4.89, 4.95, and 4.88 inches. Can we state with 95% confidence that the new material is producing shorter vials with the existing molding machine set-up?

\[ H_0: \mu \geq \mu_0 \quad H_1: \mu < \mu_0 \]
\[ H_0: \mu \geq 5.00" \quad H_1: \mu < 5.00" \]

\[ \bar{X} = 4.95", \ n = 8, \ \text{and} \ \sigma_X = 0.12". \] The test statistic is:

\[ Z = \frac{\bar{X} - \mu_0}{\sigma_X / \sqrt{n}} = \frac{4.95 - 5.00}{0.12 / \sqrt{8}} = \frac{-0.05}{0.042} = -1.18 \]

Since the \( H_1 \) sign is \(<\), it is a left one tailed test. The level of significance, \( \alpha = 0.05 \). \( Z_{0.05} = -1.645 \). Since the test statistic, -1.18, does not fall in the reject (or critical) region, the null hypothesis cannot be rejected. There is insufficient evidence to conclude that the vials made with the new material are shorter.
Hypothesis Tests for Means (Continued)

Student’s t Test

The student’s t distribution applies to samples drawn from a normally distributed population. It is used for making inferences about a population mean when the population variance $\sigma^2$ is unknown and the sample size $n$ is small, usually $n < 30$. The test statistic formula is:

$$t = \frac{\bar{X} - \mu_0}{s / \sqrt{n}}$$

The null and alternative hypotheses are the same as were given for the Z test.

The test statistic, $t$, is compared with a critical value $t_\alpha$ or $t_{\alpha/2}$ which is based on a significance level, $\alpha$, for a one tailed test or $\alpha/2$ for a two tailed test, and the number of degrees of freedom, d.f. The degrees of freedom is determined by the number of samples, $n$, and is simply:

$$d.f. = n - 1$$
Hypothesis Tests for Means (Continued)

Student’s t Test (Continued)

Example 7.14: A chemical process has $\mu = 880$ tons. A new process has been evaluated for 25 days with a yield of 900 tons ($\bar{X}$) and $s = 20$ tons. Can we say with 95% confidence that the process has changed?

$H_0: \mu = \mu_0$ \hspace{1cm} $H_1: \mu \neq \mu_0$

$H_0: \mu = 880$ tons \hspace{1cm} $H_1: \mu \neq 880$ tons

The test statistic calculation is:

$$t = \frac{\bar{X} - \mu_0}{s / \sqrt{n}} = \frac{900 - 880}{20/\sqrt{25}} = \frac{20}{4} = 5$$

Since the $H_1$ sign is $\neq$, it is a two tailed test and with a 95% confidence, the level of significance, $\alpha = 0.05$. Since it is a two tail test, $\alpha/2$ is used to determine the critical values. The degrees of freedom, d.f. = $n - 1 = 24$. $t_{0.025} = -2.064$ and $t_{0.975} = 2.064$. Since the test statistic, 5, falls in the right-hand reject (or critical) region, the null hypothesis is rejected. We conclude with 95% confidence that the process has changed.
Hypothesis Tests for Variance

Chi-Square ($X^2$) Test

Population variances are distributed according to the chi-square distribution. Therefore, inferences about a single population variance will be based on chi-square.

The chi-square test is widely used in two applications.

Case I. Comparing variances when the variance of the population is known.

Case II. Comparing observed and expected frequencies of test outcomes when there is no defined population variance (attribute data).
When the population follows a normal distribution, the hypothesis tests for comparing a population variance, \( \sigma_x^2 \), with a fixed value, \( \sigma_0^2 \), are given by the following:

\[
\begin{align*}
H_0: \ \sigma_x^2 &= \sigma_0^2 \\
H_1: \ \sigma_x^2 &\neq \sigma_0^2
\end{align*}
\]

\[
\begin{align*}
H_0: \ \sigma_x^2 &\leq \sigma_0^2 \\
H_1: \ \sigma_x^2 &> \sigma_0^2
\end{align*}
\]

\[
\begin{align*}
H_0: \ \sigma_x^2 &\geq \sigma_0^2 \\
H_1: \ \sigma_x^2 &< \sigma_0^2
\end{align*}
\]

The test statistic is given by:

\[
\chi^2 = \frac{(n - 1)s^2}{\sigma_x^2}
\]

The test statistic, \( \chi^2 \), is compared with a critical value \( \chi^2_{\alpha} \) or \( \chi^2_{\alpha/2} \) which is based on a significance level, \( \alpha \), for a one tailed test or \( \alpha/2 \) for a two tailed test. The degrees of freedom is:

\[
d.f. = n - 1
\]

If the \( H_1 \) sign is \( \neq \), it is a two tailed test. If the \( H_1 \) sign is \( > \), it is a right one tailed test, and if the \( H_1 \) sign is \( < \), it is a left one tailed test.
Example 7.16: Case I, Population Variance Is Known. Will new material show a four sigma tensile variation less than or equal to 60 psi with 95% confidence? This translates to a population sigma of 15 psi. An eight sample test yielded a standard deviation of 8 psi.

\[ H_0: \sigma_1^2 \geq (15)^2 \quad \text{H}_1: \sigma_1^2 < (15)^2 \]

This is a left tail test with \( n - 1 = 7 \). The critical value for 95% confidence is 2.17. The calculated statistic is:

\[ \chi^2 = \frac{(n - 1)s^2}{\sigma_1^2} = \frac{(7)(8)^2}{(15)^2} = 1.99 \]

Since 1.99 is less than 2.17, the null hypothesis must be rejected. There is decreased variation in the new steel alloy tensile strength.
Chi-Square ($X^2$) Test (Continued)

Chi-Square Case II. Comparing Observed and Expected Frequencies of Test Outcomes. (Attribute Data). This application of chi-square is called the contingency table or row and column analysis.

The chi-square statistic using observed frequencies (O), expected frequencies (E) and degrees of freedom (R-1)(C-1) with the entire level of significance, $\alpha$, in the one-tail, right side, of the distribution.

$$X^2 = \sum \frac{(O - E)^2}{E}$$

Example 7.17: An airport authority wanted to evaluate the ability of three X-ray inspectors to detect transistor radios in luggage.

<table>
<thead>
<tr>
<th>Inspectors</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Treatment Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radios detected</td>
<td>27</td>
<td>25</td>
<td>22</td>
<td>74</td>
</tr>
<tr>
<td>Radios undetected</td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Sample total</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>90</td>
</tr>
</tbody>
</table>

Is there any significant difference in the abilities of the inspectors at a 95% confidence?
VII. SIX SIGMA METHODOLOGY - ANALYZE
B. HYPOTHESIS TESTING
3. MEANS, VARIANCES AND PROPORTIONS

Chi-Square ($X^2$) Test (Continued)

Example 7.18 continued:
H$_0$: $p_1 = p_2 = p_3$ (no difference among the inspectors)
H$_1$: $p_1 \neq p_2 \neq p_3$ (at least one proportion is different)

DF = (rows - 1)(columns - 1) = (2-1)(3-1) = 2

The critical value of $X^2$ for DF = 2 and $\alpha = 0.05$ in the one-tail, right side of the distribution is 5.99

The expected values for the test are:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Treatment Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radios detected</td>
<td>24.67</td>
<td>24.67</td>
<td>24.67</td>
<td>74</td>
</tr>
<tr>
<td>Radios undetected</td>
<td>5.33</td>
<td>5.33</td>
<td>5.33</td>
<td>16</td>
</tr>
<tr>
<td>Sample total</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>90</td>
</tr>
</tbody>
</table>

$$X^2 = \sum \frac{(O - E)^2}{E}$$

$$X^2 = \frac{(2.33)^2}{24.67} + \frac{(0.33)^2}{24.67} + \frac{(2.67)^2}{24.67} + \frac{(2.33)^2}{5.33} + \frac{(0.33)^2}{5.33} + \frac{(2.67)^2}{5.33}$$

$$X^2 = 0.220 + 0.004 + 0.289 + 1.019 + 0.020 + 1.338$$

$$X^2 = 2.89$$

Since the calculated value of $X^2$ is less than 5.99 and this is a right tail test, the null hypothesis cannot be rejected. There is insufficient evidence to say with 95% confidence that the abilities of the inspectors differ.
Hypothesis Tests for Proportions

p Test

When testing a claim about a population proportion and we have a fixed number of independent trials having constant probabilities, and each trial has two outcome possibilities (a binomial experiment), we may use a $p$ test. When $np < 5$ or $n(1-p) < 5$, the binomial distribution is used to test hypotheses relating to proportion.

If conditions that $np \geq 5$ and $n(1-p) \geq 5$ are met, then the binomial distribution of sample proportions can be approximated by a normal distribution. The hypothesis tests for comparing a sample proportion, $p$, with a fixed value, $p_0$, are given by the following:

- $H_0: p = p_0$
- $H_0: p \leq p_0$
- $H_0: p \geq p_0$
- $H_1: p \neq p_0$
- $H_1: p > p_0$
- $H_1: p < p_0$

The test statistic is given by:

$$Z = \frac{x - np_0}{\sqrt{np_0(1-p_0)}}$$
Paired-Comparison Hypothesis Tests

2 Mean, Equal Variance, t Test

Tests the difference between 2 sample means ($\bar{X}_1$ vs $\bar{X}_2$) when $\sigma_1$ and $\sigma_2$ are unknown but considered equal.

$$H_0: \mu_1 = \mu_2 \quad H_1: \mu_1 \neq \mu_2$$

$$t = \frac{\bar{X}_1 - \bar{X}_2}{s_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

$$s_p = \text{Pooled standard deviation}$$

$$s_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}$$

$$DF = n_1 + n_2 - 2$$
Paired-Comparison Hypothesis (Cont.)

2 Mean, Unequal Variance, t Test

Tests the difference between 2 sample means ($\bar{X}_1$ vs $\bar{X}_2$) when $\sigma_1$ and $\sigma_2$ are unknown, but are not considered equal.

$$H_0: \mu_1 = \mu_2 \quad H_1: \mu_1 \neq \mu_2$$

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

$$DF = \frac{1}{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2 \left(\frac{n_1 - 1}{n_1} + \frac{n_2 - 1}{n_2}\right)}$$
Paired-Comparison Hypothesis (Cont.)

Paired t Test

Tests the difference between 2 sample means. Data is taken in pairs with the difference calculated for each pair.

\[ H_0: \mu_1 = \mu_2 \quad H_1: \mu_1 \neq \mu_2 \]

\[ t = \frac{\bar{d}}{s_d / \sqrt{n}} \]

DF = n - 1. A paired t test is always a two tail test.

\( \bar{d} \) = average of differences of pairs of data.

The paired method (dependent samples), compared to treating the data as two independent samples, will often show a more significant difference because the standard deviation of the d’s (\( S_d \)) includes no sample to sample variation. This comparatively more frequent significance occurs despite the fact that “n - 1” represents fewer degrees of freedom than “\( n_1 + n_2 -2 \).”

In general, the paired t test is a more sensitive test than the comparison of two independent samples.
Paired-Comparison Hypothesis (Cont.)

**F Test**

If independent random samples are drawn from two normal populations with equal variances, the ratio of \((s_1)^2/(s_2)^2\) creates a sampling distribution known as the F distribution. The hypothesis tests for comparing a population variance, \(\sigma_1^2\), with another population variance, \(\sigma_2^2\), are given by the following:

\[
\begin{align*}
H_0: \sigma_1^2 &= \sigma_2^2 \\
H_1: \sigma_1^2 &\neq \sigma_2^2 \\
H_0: \sigma_1^2 &\leq \sigma_2^2 \\
H_1: \sigma_1^2 >& \sigma_2^2 \\
H_0: \sigma_1^2 &> \sigma_2^2 \\
H_1: \sigma_1^2 < \sigma_2^2
\end{align*}
\]

The number of degrees of freedom associated with \(s_1^2\) and \(s_2^2\) are represented by \(v_1\) and \(v_2\) respectively. \(v_1\) is the DF in the numerator.

The F statistic is the ratio of two sample variances (two chi-square distributions) and is given by the formula:

\[
F = \frac{(s_1)^2}{(s_2)^2}
\]

Where \(s_1^2\) and \(s_2^2\) are sample variances. It is customary to designate the larger sample variance as \(s_1^2\) and place it in the numerator.
Paired-Comparison Hypothesis (Cont.)

F Test (Continued)

F Distribution for Two Normal Samples

Example 7.22:  $s_1 = 900$ psi, $n_1 = 9$, $s_2 = 300$ psi, $n_2 = 7$. At a 95% confidence level, can we conclude there is now less variation?

$H_0$: $\sigma_1^2 \leq \sigma_2^2$  
$H_1$: $\sigma_1^2 > \sigma_2^2$ and $DF_1 = 8$  $DF_2 = 6$

Use a one tail test with the entire $\alpha$ risk in the right tail. The critical value of F is 4.15. Since the calculated F value is in the critical region, the null hypothesis is rejected. There is sufficient evidence to indicate a reduced variance.
Robustness

Statistical procedures are based on assumptions about their theoretical behavior. When obtained statistics are not affected by moderate deviations from theoretical expectation, they are said to be robust.
### VII. SIX SIGMA METHODOLOGY - ANALYZE

#### B. HYPOTHESIS TESTING

#### 4. PAIRED-COMPARISON TESTS

#### Summary of Inference Tests

<table>
<thead>
<tr>
<th>TYPE</th>
<th>TEST STATISTIC</th>
<th>DF</th>
<th>APPLICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>$\frac{\bar{X} - \mu}{\frac{\sigma}{\sqrt{n}}}$</td>
<td>N.A.</td>
<td>Single sample mean. Standard deviation of population is known.</td>
</tr>
<tr>
<td>t Test</td>
<td>$t = \frac{\bar{X} - \mu}{\frac{S}{\sqrt{n}}}$</td>
<td>n - 1</td>
<td>Single sample mean. Standard deviation of population unknown.</td>
</tr>
<tr>
<td>2 Mean Equal Variance t Test</td>
<td>$t = \frac{\bar{X}_1 - \bar{X}_2}{s_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$</td>
<td>$n_1+n_2-2$</td>
<td>2 sample means. Variances are unknown, but considered equal. * $s_p$ must be calculated.</td>
</tr>
<tr>
<td>2 Mean Unequal Variance t Test</td>
<td>$t = \frac{X_1 - X_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}}$</td>
<td>*</td>
<td>2 sample means. Variances are unknown, but considered unequal. * A special DF calculation is required.</td>
</tr>
<tr>
<td>Paired t Test</td>
<td>$t = \frac{\bar{d}}{s_d / \sqrt{n}}$</td>
<td>n - 1</td>
<td>2 sample means. Data is taken in pairs. A different $d$ is calculated for each pair.</td>
</tr>
<tr>
<td>$\chi^2$ $\sigma^2$ Known</td>
<td>$\chi^2 = \frac{(n - 1)S^2}{\sigma^2}$</td>
<td>n - 1</td>
<td>Tests sample variance against known variance.</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>$\chi^2 = \sum \frac{(O - E)^2}{E}$</td>
<td>(r-1)(c-1)</td>
<td>Compares observed and expected frequencies of test outcomes.</td>
</tr>
<tr>
<td>F</td>
<td>$F = \frac{(S_1)^2}{(S_2)^2}$</td>
<td>$\frac{n_1 - 1}{n_2 - 1}$</td>
<td>Tests if two sample variances are equal.</td>
</tr>
</tbody>
</table>
Goodness of Fit

GOF (Goodness of Fit) tests are part of a class of procedures that are structured in cells. In each cell there is an observed frequency, \( F_0 \). We can calculate the expected or theoretical frequency, \( F_e \). Chi Square (\( \chi^2 \)) is then summed across all cells according to the formula:

\[
\chi^2 = \sum \frac{(F_0 - F_e)^2}{F_e}
\]

The calculated chi square is then compared to the chi square critical value for the following appropriate degrees of freedom:

<table>
<thead>
<tr>
<th>Goodness of Fit Distribution</th>
<th>Degrees of Freedom (DF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>No. of cells - 3</td>
</tr>
<tr>
<td>Poisson</td>
<td>No. of cells - 2</td>
</tr>
<tr>
<td>Binomial</td>
<td>No. of cells - 2</td>
</tr>
<tr>
<td>Uniform</td>
<td>No. of cells - 1</td>
</tr>
</tbody>
</table>

The Primer provides examples for the following:
- Uniform Distribution (GOF)
- Normal Distribution (GOF)
- Poisson Distribution (GOF)
- Binomial Distribution (GOF)
Analysis of Variance Introduction

In many investigations, it is necessary to compare three or more population means simultaneously. There are underlying assumptions in this analysis of variance of means: the variance is the same for all factor treatments or levels, the individual measurements within each treatment are normally distributed and the error term is considered a normally and independently distributed random effect.

With analysis of variance, the variations in response measurement are partitioned into components that reflect the effects of one or more independent variables. The variability of a set of measurements is proportional to the sum of squares of deviations used to calculate the variance:

\[ \sum (X - \bar{X})^2 \]

Analysis of variance partitions the sum of squares of deviations of individual measurements from the grand mean (called the total sum of squares) into parts: the sum of squares of treatment means plus a remainder which is termed the experimental or random error.
A Comparison of Three or More Means

An analysis of variance to detect a difference in three or more population means first requires obtaining some summary statistics for calculating variance of a set of data as shown below:

Where:

\[ \sum X^2 \] is called the crude sum of squares

\[ \frac{(\sum X)^2}{N} \] is the CM (Correction for the Mean),
or CF (Correction Factor)

\[ \sum X^2 - \frac{(\sum X)^2}{N} \] is termed SS (total Sum of Squares, or corrected SS).

\[
\frac{\sum X^2 - \frac{(\sum X)^2}{N}}{N - 1} = \sigma^2 \text{ (variance)}
\]

\[
= \frac{\text{Total Sum of Squares}}{\text{Total DF (degrees of freedom)}}
\]
One-Way ANOVA

In the 1-Way ANOVA, the total variation in the data has two parts: the variation among treatment means and the variation within treatments. The equations are given in the Primer.

To test the null hypothesis:

\[ H_0: \mu_1 = \mu_2 = \ldots = \mu_t \quad H_1: \text{At least one mean different} \]

\[ F = \frac{\text{MST}}{\text{MSE}} \quad \text{When } F > F_{\alpha}, \text{ reject } H_0 \]

Example 7.28: As an example of a comparison of three means consider a single factor experiment: The following coded results were obtained from a single factor randomized experiment, in which the outputs of three machines were compared. Determine if there is a significant difference in the results (\(\alpha=0.05\)).

<table>
<thead>
<tr>
<th>Machines</th>
<th>Data</th>
<th>Sum</th>
<th>n</th>
<th>Avg</th>
<th>TCM = (Sum)^2/n</th>
<th>(\sum \chi^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5, 7, 6, 7, 6</td>
<td>31</td>
<td>5</td>
<td>6.2</td>
<td>192.2</td>
<td>195</td>
</tr>
<tr>
<td>B</td>
<td>2, 0, 1, -2, 2</td>
<td>3</td>
<td>5</td>
<td>0.6</td>
<td>1.8</td>
<td>13</td>
</tr>
<tr>
<td>C</td>
<td>1, 0, -2, -3, 0</td>
<td>-4</td>
<td>5</td>
<td>-0.8</td>
<td>3.2</td>
<td>14</td>
</tr>
<tr>
<td>Total</td>
<td>30</td>
<td>15</td>
<td></td>
<td></td>
<td>197.2</td>
<td>222</td>
</tr>
</tbody>
</table>
One-Way ANOVA (Continued)

\[\Sigma X = 30 \quad N = 15 \quad \text{Total DF} = N - 1 = 15 - 1 = 14\]

\[GM = \frac{\Sigma X}{N} = \frac{30}{15} = 2.0 \quad \Sigma X^2 = 222\]

\[CM = \frac{(\Sigma X)^2}{N} = \frac{(30)^2}{15} = 60\]

Total SS = \Sigma X^2 - CM = 222 - 60 = 162

\[\Sigma(TCM) = 197.2\]

SST = \Sigma(TCM) - CM = 197.2 - 60 = 137.2

SSE = Total SS - SST = 162 - 137.2 = 24.8

The completed ANOVA table is:

<table>
<thead>
<tr>
<th>Source (of variation)</th>
<th>SS</th>
<th>DF</th>
<th>Mean Square</th>
<th>F</th>
<th>(F_{\alpha,v_1,v_2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machines</td>
<td>137.2</td>
<td>2</td>
<td>68.6</td>
<td>33.2</td>
<td>(F_{0.05,2,12} = 3.89)</td>
</tr>
<tr>
<td>Error</td>
<td>24.8</td>
<td>12</td>
<td>2.067</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>162</td>
<td>14</td>
<td></td>
<td></td>
<td>(\sigma_e = \sqrt{2.07} = 1.44)</td>
</tr>
</tbody>
</table>

Since the computed value of F (33.2) exceeds the critical value of F, the null hypothesis is rejected.
Two-Way ANOVA

It will be seen that the 2-Way analysis procedure is an extension of the patterns described in the 1-Way analysis. Recall that a 1-Way ANOVA has two components of variance: Treatments and experimental error (may be referred to as columns and error or rows and error).

In the 2-Way ANOVA there are three components of variance: Factor A treatments, Factor B treatments, and experimental error (may be referred to as columns, rows and error).

An example of a 2 Factor 2 Way ANOVA with two instructors and three materials is given in the Primer. The experiment may also have interaction between the factors, and an example is shown as well.
Components of Variance

The Analysis of Variance can be extended with a determination of the COV (Components of Variance). The COV table uses the MS (Mean Square), F, and F(alpha) columns from the previous ANOVA TABLE and adds columns for EMS (Expected Mean Square), Variance, Adjusted Variance and Percent Contribution to design data variation. The model for the ANOVA is:

\[ X_{ijk} = \mu + M_i + I_j + MI_{ij} + \varepsilon_{klj} \]

The model states that any measurement \( X \) represents the combined effect of the population mean \( \mu \), the different materials \( M \), the different instructors \( I \), the materials/instructor interaction \( MI \), and the experimental error \( \varepsilon \).

Where: \( i \) represents materials at 3 levels, \( j \) represents instructors at 2 levels, \( k \) represents cells with 3 replications.
ANOVA for A x B Factorial Experiment

In a factorial experiment involving factor A at a levels and factor B at b levels, total sum of squares can be partitioned into:

\[
\text{Total SS} = \text{SS}(A) + \text{SS}(B) + \text{SS}(AB) + \text{SSE}
\]

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor A</td>
<td>(a-1)</td>
<td>SS(A)</td>
<td>SS(A)/(a-1)</td>
</tr>
<tr>
<td>Factor B</td>
<td>(b-1)</td>
<td>SS(B)</td>
<td>SS(B)/(b-1)</td>
</tr>
<tr>
<td>Interaction AB</td>
<td>(a-1)(b-1)</td>
<td>SS(AB)</td>
<td>SS(AB)/(a-1)(b-1)</td>
</tr>
<tr>
<td>Error</td>
<td>(N-ab)</td>
<td>SSE</td>
<td>SSE/(N-ab)</td>
</tr>
<tr>
<td>Total</td>
<td>(N-1)</td>
<td>Total SS</td>
<td></td>
</tr>
</tbody>
</table>
ANNOVA for Randomized Block Design

The randomized block design implies the presence of two independent variables, “blocks” and “treatments.”

The total sum of squares of the response measurements can be partitioned into three parts; the sum of the squares for the blocks, treatments, and error. The analysis of a randomized block design is of less complexity than an A x B factorial experiment.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blocks</td>
<td>b-1</td>
<td>SSB</td>
<td>MSB = SSB/(b-1)</td>
</tr>
<tr>
<td>Treatments</td>
<td>t-1</td>
<td>SST</td>
<td>MST = SST/(t-1)</td>
</tr>
<tr>
<td>Error</td>
<td>(b-1)(t-1)</td>
<td>SSE</td>
<td>MSE = SSE/(b-1)(t-1)</td>
</tr>
<tr>
<td>Total</td>
<td>bt-1</td>
<td>Total SS</td>
<td></td>
</tr>
</tbody>
</table>
Contingency Tables

A two-way classification table (rows and columns) containing original frequencies can be analyzed to determine whether the two variables (classifications) are independent or have significant association. The Chi Square will test whether there is dependency between the two classifications. In addition, a contingency coefficient (correlation) can be calculated. If the Chi Square test shows a significant dependency, the contingency coefficient shows the strength of the correlation.

A measure of the difference found between observed and expected frequencies is supplied by the statistic chi-square, $\chi^2$, where:

$$\chi^2 = \sum_{n=1}^{k} \frac{(O_n-E_n)^2}{E_n} = \frac{(O_1-E_1)^2}{E_1} + \frac{(O_2-E_2)^2}{E_2} + \ldots + \frac{(O_k-E_k)^2}{E_k}$$

If $\chi^2=0$ observed and theoretical frequencies agree exactly. If $\chi^2>0$ they do not agree exactly. The larger the value of $\chi^2$ the greater the discrepancy between observed and theoretical frequencies. Contingency tables are very similar to goodness-of-fit tests.
Contingency Tables (Continued)

Example 7.30 (Continued): Each of these 15 cells makes a contribution to Chi Square ($X^2$). For an illustrative cell the contribution is:

$$\frac{(O - E)^2}{E} = \frac{(\text{Observed frequency} - \text{Expected frequency})^2}{\text{Expected frequency}} = \frac{(15 - 12.5)^2}{12.5} = 0.48$$

Chi Square = $\sum \frac{(O - E)^2}{E}$ over all cells.

<table>
<thead>
<tr>
<th></th>
<th>0.48</th>
<th>0.74</th>
<th>7.30</th>
<th>4.61</th>
<th>30.21</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.14</td>
<td>0.95</td>
<td>0.50</td>
<td>0.50</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>0.03</td>
<td>3.08</td>
<td>2.10</td>
<td>0.99</td>
<td>14.12</td>
</tr>
</tbody>
</table>

Chi Sq = 66.22

Assume alpha to be 0.01.
d.f. = (rows - 1) x (columns - 1) = (5 - 1) x (3 - 1) = 8

The critical chi-square: $\chi^2 = \chi^2_{(0.01, 8)} = 20.09$

The calculated chi square is larger than critical chi square, therefore, we reject the null hypothesis of hospital equality of results.
VII. SIX SIGMA METHODOLOGY - ANALYZE
   B. HYPOTHESIS TESTING
      7. CONTINGENCY TABLES

Coefficient of Contingency (C)

The degree of relationship, association or dependence of the classifications in a contingency table is given by:

\[ C = \sqrt{\frac{X^2}{X^2 + N}} \]

Where \( N \) equals the grand frequency total.

Example 7.30 (Continued): The contingency coefficient is:

\[ C = \sqrt{\frac{66.22}{66.22 + 393}} = \frac{66.22}{66.22 + 393} = 0.38 \]

For the example data, the maximum coefficient of contingency is:

\[ \text{Max } C = \sqrt{\frac{k-2}{k}} = \sqrt{\frac{8-2}{8}} = \sqrt{\frac{6}{8}} = 0.866 \]

Correlation of Attributes

For \( (k = r = c) \) tables, the correlation coefficient, \( \phi \), is defined as:

\[ \phi = \sqrt{\frac{X^2}{N(k - 1)}} \]

Where \( 0 \leq \phi \leq 1 \)
Parametric vs. Nonparametric Tests

Parametric implies that a distribution is assumed for the population, commonly the normal distribution. Nonparametric implies that there is no assumption of a specific distribution for the population.

An advantage of a parametric test is that if the assumptions hold, the power, or the probability of rejecting $H_0$ when it is false, is higher than is the power of a corresponding nonparametric test with equal sample sizes.

An advantage of nonparametric tests is that the test results are more robust against violation of the assumptions.
Nonparametric Techniques

Three powerful nonparametric techniques will be described with examples: Kendall Coefficient of Concordance, Spearman Rank Correlation Coefficient ($r_s$), and Kruskal-Wallis One-way Analysis of Variance.

Kendall Coefficient of Concordance

Example 7.31:  $K =$ Judges $=$ 4   $N =$ Samples $=$ 10
$R = \frac{220}{10} = 22$   $s = 1066$
$v =$ degrees of freedom $=$ $N - 1 = 9$
Critical chi square $= X^2_{0.01,9} = 21.67$

\[
X^2 = \frac{s}{\frac{1}{12}KN(N + 1)} = \frac{1066}{\left(\frac{1}{12}\right)(4)(10)(11)} = 29.07
\]

The null hypothesis is rejected. Calculated chi square is larger than critical chi square. The four judges are significantly associated. They constitute a homogeneous panel. This is not to say that they are correct; only that they respond in a uniform way to this form of sensory input.
The Spearman Rank Correlation Coefficient ($r_s$)

The Spearman correlation coefficient is a measure of association which requires that both variables be measured in at least an ordinal scale so that the samples or individuals to be analyzed may be ranked in two ordered series.

Example 7.32: The ten rank sums from the Kendall Coefficient example are ranked from largest to smallest. The rank numbers from 1 through 10 are then assigned to the ranked panel sums.

For the same samples, the handleometer values are ranked and then assigned the integer values from 1 through 10. The differences between paired ranks are squared and summed.

$N = 10$. If $N$ is equal to or greater than 10, the following correlation equation can be used.

$$r_s = 1 - \frac{6 \sum d^2}{N^3 - N} = 1 - \frac{6(5.5)}{990} = 1 - 0.03 = 0.97$$
Kruskal-Wallis One-Way Analysis of Variance by Ranks

This is a test of independent samples. The measurements may be continuous data but the underlying distribution is either unknown or known to be non-normal.

Example 7.33:

<table>
<thead>
<tr>
<th>Rank Sum</th>
<th>Plant A</th>
<th>Plant B</th>
<th>Plant C</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>8</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>(RankSum)^2/n</td>
<td>693.781</td>
<td>495.042</td>
<td>1486.286</td>
</tr>
</tbody>
</table>

\[
G = \frac{(\text{RankSum})^2}{n} = 693.781 + 495.042 + 1486.286 \\
= 2675.109 \\
N = 8 + 6 + 7 = 21
\]

The significance statistic is H. H is distributed as chi square. Tie values are included in the calculation of chi square. Let t = number of tied values in each tied set. Then \[T = t^3 - t\] for that set.
Kruskal-Wallis (Continued)

\[
H = \left( \frac{12}{N(N+1)} G - 3(N+1) \right) = \left( \frac{12}{(21)(22)} \frac{(2675.109) - 3(21+1)}{1 - \frac{690}{(21^3 - 21)}} \right) = 3.76
\]

Let \( k \) = number of sample sets. \( \text{DF} = k - 1 = 3 - 1 = 2. \)
Let \( \alpha = 0.05. \) Critical chi square = \( \chi^2_{0.05,2} = 5.99 \)

\( H \) is less than critical chi square. Therefore, the null hypothesis of equality of sample means cannot be rejected.
Mann-Whitney U Test

When there are ordinal measurements, the Mann-Whitney U test may be used to test whether two independent groups have been drawn from the same population. This is a powerful nonparametric test and is an alternative to the t test when the normality of the population is either unknown or believed to be non normal.

Consider two populations, A and B. The null hypothesis, $H_0$, is that A and B have the same frequency distribution with the same shape and spread (the same median). An alternative hypothesis, $H_1$, is that A is larger than B, a directional hypothesis. We may accept $H_1$ if the probability is greater than 0.5 that a score from A is larger than a score from B. That is, if $a$ is one observation from population A, and $b$ is one observation from population B, then $H_1$ is that $P(a > b) > 0.5$.

If the evidence from the data supports $H_1$, this implies that the bulk of population A is higher than the bulk of population B. If we wished instead to test if B is statistically larger than A, then $H_1$ is that $P(a > b) < 0.5$. For a 2-tailed test, that is, for a prediction of differences which does not state direction, $H_1$ would be that $P(a > b) \neq 0.5$ (the medians are not the same).
Mann-Whitney U Test (Continued)

If there are \( n_1 \) observations from population A, and \( n_2 \) observations from population B, rank all \((n_1 + n_2)\) observations in ascending order. Ties receive the average of their rank number. The data sets should be selected so that \( n_1 \leq n_2 \). Calculate the sum of observation ranks for population A, and designate the total as \( R_a \), and the sum of observation ranks for population B, and designate the total as \( R_b \).

\[
U_a = n_1 n_2 + 0.5 n_1 (n_1 + 1) - R_a \\
U_b = n_1 n_2 + 0.5 n_2 (n_2 + 1) - R_b \\
\text{Where } U_a + U_b = n_1 n_2
\]

Calculate the U statistic as the smaller of \( U_a \) and \( U_b \). For \( n_2 \leq 20 \), Mann-Whitney tables are used to determine the probability, based on the \( U \), \( n_1 \), and \( n_2 \) values.

If \( n_2 > 20 \), the distribution of \( U \) rapidly approaches the normal distribution and the following apply:

\[
\mu_U = 0.5 n_1 n_2 \\
\sigma_U = \sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}} \\
Z = \frac{U - \mu_U}{\sigma_U} = \frac{U - 0.5 n_1 n_2}{\sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}}}
\]
VII. SIX SIGMA METHODOLOGY - ANALYZE
B. HYPOTHESIS TESTING
8. NONPARAMETRIC TESTS

Wilcoxon-Mann-Whitney Rank Sum Test

The Wilcoxon-Mann-Whitney rank sum test is similar in application to the Mann-Whitney Test.

Determine if two random samples could have come from two populations with the same mean. The null hypothesis is that both populations have frequency distributions with the same range and shape.

The observations or scores of the two samples (a and b) are combined in order of increasing rank and given a rank number. Tied values are assigned tied rank values. In cases where equal results occur, the mean of the available rank numbers is assigned. Next find the rank sum R of the smaller sample. Let N equal the size of the combined samples and n equal the size of the smaller sample. Then calculate:

$$R' = n(N+1) - R$$

The values R and R' are compared with critical values. If either R or R' is less than the critical value, the null hypothesis of equal means is rejected. If the two samples are of equal size, the rank sum R is taken as the smaller of the two rank sums.
Levene’s Test

Levene’s test is used to test the null hypothesis that multiple population variances are equal. Levene’s test determines whether a set of k samples have equal variances. Equal variances across samples is called homogeneity of variances.

The Levene test is less sensitive than the Bartlett test to departures from normality. If there is strong evidence that the data do in fact come from a normal, or approximately normal, distribution, then Barlett’s test has better performance.

Levene’s variance test is more robust against departures from normality than the F test. When there are just two sets of data, the Levene procedure is to:

1. Determine the mean.
2. Calculate the deviation of each observation from the mean.
3. Let Z equal the square of the deviation from the mean.
4. Apply the t test of two means to the Z data.
Mood’s Median Test

Mood’s Median Test performs a hypothesis test of the equality of population medians in a one-way design. The test is robust against outliers and errors in data, and is particularly appropriate in the preliminary stages of analysis. The median test determines whether k independent groups have either been drawn from the same population or from populations with equal medians.

Find the combined median for all scores in the k groups. Replace each score by a plus if the score is larger than the combined median and by a minus if it is smaller than the combined median. If any scores fall at the combined median, the scores may be assigned to the plus and minus groups by designating a plus to those scores which exceed the combined median and a minus to those which fall at the combined median or below. Next set up a Chi Square “k x 2” table with the frequencies of pluses and minuses in each of the k groups.
Mood’s Median Test (Continued)

The null hypothesis $H_0$: states that all style medians are equal. The alternative hypothesis $H_1$: states that at least one style median is different. The Chi Square calculation over all ten cells is represented by:

$$
X^2 = \sum \frac{(O - E)^2}{E} = \frac{(5 - 6.5)^2}{6.5} + \frac{(7 - 4.5)^2}{4.5} + \frac{(9 - 7)^2}{7} + \frac{(2 - 4)^2}{4} + \frac{(3 - 4)^2}{4} + \frac{(8 - 6.5)^2}{6.5} + \frac{(2 - 4.5)^2}{4.5} + \frac{(5 - 7)^2}{7} + \frac{(6 - 4)^2}{4} + \frac{(5 - 4)^2}{4} = 7.11
$$

The degrees of freedom for contingency tables is:

$$
df = (\text{rows} - 1) \times (\text{columns} - 1) = (2 - 1) \times (5 - 1) = 4
$$

Assume we want a level of significance (alpha) of 0.05. The critical chi-square:

$$
X^2 = X^2_{(0.05, 4)} = 9.49
$$

Since the calculated $X^2$ is less than the critical $X^2$, the null hypothesis cannot be rejected, at a 0.05 level of significance (or a 95% confidence level).
Nonparametric Test Summary

- **1-Sample Sign** performs a one-sample sign test of the median and calculates the corresponding point estimate and confidence interval.

- **1-Sample Wilcoxon** performs a one-sample Wilcoxon signed rank test of the median and calculates the corresponding point estimate and confidence interval.

- **Mann-Whitney** performs a hypothesis test of the equality of two population medians and calculates the corresponding point estimate and confidence interval.

- **Kruskal-Wallis** performs a hypothesis test of the equality of population medians for a one-way design.

- **Mood’s Median Test** performs a hypothesis test of the equality of population medians in a one-way design.
### Nonparametric Test Summary (Cont.)

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Data Type</th>
<th>Test</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kruskal-Wallis Test</td>
<td>Measurement or Count</td>
<td>$X^2$</td>
<td>Data is ranked or converted to ranks for a 1-way analysis of variance.</td>
</tr>
<tr>
<td>Kendall Coefficient of Concordance</td>
<td>Ranked Data</td>
<td>$X^2$</td>
<td>Determines degree of association among classifications based on ranked scores.</td>
</tr>
<tr>
<td>Spearman Rank Correlation Coefficient</td>
<td>Ranked Data</td>
<td>Formula</td>
<td>A measure of association ($r_s$) which requires both variables be measured in at least an ordinal scale.</td>
</tr>
<tr>
<td>Kendall Rank Correlation Coefficient</td>
<td>Ranked Data</td>
<td>Formula</td>
<td>Same as Spearman except calculates, $r$, which also permits determining partial correlation coefficient.</td>
</tr>
<tr>
<td>Contingency Coefficient</td>
<td>Count Data</td>
<td>$X^2$</td>
<td>A measure of association between two classifications.</td>
</tr>
<tr>
<td>Mann-Whitney U Test</td>
<td>Ranked Data</td>
<td>Tables</td>
<td>Determines if two independent groups are from same population. An alternative if $t$ test assumptions cannot be met.</td>
</tr>
<tr>
<td>Wilcoxon-Mann Whitney Rank Sum Test</td>
<td>Ranked Data</td>
<td>Tables</td>
<td>Same as above. Slightly simpler to use. An alternative if $Z$ and $t$ test assumptions cannot be met.</td>
</tr>
<tr>
<td>Levene's Test</td>
<td>Converting Data to Squares of Deviations</td>
<td>$t$</td>
<td>Verifies homogeneity of variances across $k$ samples. An alternative procedure if $F$ and $t$ assumptions are not met.</td>
</tr>
<tr>
<td>Mood's Median Test</td>
<td>Sample Medians</td>
<td>$X^2$</td>
<td>Determines equality of sample medians by scoring sample medians relative to population median.</td>
</tr>
<tr>
<td>Kolmogorov-Smirnov 1-sample</td>
<td>Sample Values</td>
<td>Table</td>
<td>Goodness of fit between observed scores and specified theoretical distribution.</td>
</tr>
<tr>
<td>Kolmogorov-Smirnov 2-sample</td>
<td>Sample Values</td>
<td>Table</td>
<td>Determines whether two independent samples come from same distribution.</td>
</tr>
<tr>
<td>McNemar Test</td>
<td>Classification or Ranks</td>
<td>$X^2$</td>
<td>Determines significance of change in “before and after” designs.</td>
</tr>
<tr>
<td>Walsh Test</td>
<td>Response Scores</td>
<td>$\alpha %$ of $2^n$</td>
<td>Randomization test for matched pairs.</td>
</tr>
<tr>
<td>Fisher Exact Probability</td>
<td>Classification or Ranks</td>
<td>Table or $\alpha$</td>
<td>Determines whether two groups differ in the proportions within two classifications.</td>
</tr>
<tr>
<td>Cochran Q Test</td>
<td>Classification or Ranks</td>
<td>$X^2$</td>
<td>Determines whether 3 or more matched set of proportions differ significantly.</td>
</tr>
<tr>
<td>Friedman Test</td>
<td>Ranks</td>
<td>$X^2$</td>
<td>2-Way analysis of variance for $k$ matched samples.</td>
</tr>
<tr>
<td>Runs Test</td>
<td>Symbol Sequence</td>
<td>Table</td>
<td>Determines whether a sequence of samples are randomly distributed.</td>
</tr>
</tbody>
</table>
VII. SIX SIGMA METHODOLOGY - ANALYZE QUESTIONS

7.4. In the broadest sense, how many of the following areas of variation in multi-vari analysis can include process time related elements?

I. Positional
II. Cyclical
III. Temporal

a. I and II only  c. II and III only
b. I and III only  d. I, II and III

7.7. In a simple two variable linear regression study, what does the term $\beta_1$ represent?

a. The slope of the line
b. The measurement of interaction
c. The x axis intercept
d. The y axis intercept

7.8. A study was conducted on the relationship between the speed of different cars and their gasoline mileage. The correlation coefficient was found to be 0.35. Later, it was discovered that there was a defect in the speedometers and they had all been set 5 miles per hour too fast. The correlation coefficient was computed using the corrected scores. Its new value will be:

a. 0.30  c. 0.40
b. 0.35  d. -0.35

Answers  7.4 d, 7.7 a, 7.8 b
VII. SIX SIGMA METHODOLOGY - ANALYZE QUESTIONS

7.15. The equation below is:
\[ \frac{S_{xy}}{\sqrt{S_{xx} S_{yy}}} \]

    a. The covariance of X and Y
    b. The correlation coefficient of X and Y
    c. The coefficient of determination of X and Y
    d. The variance of the product of X and Y

7.16. Referring to the figure below, which of the statements is obviously FALSE?

    I. The correlation coefficient is negative
    II. The coefficient of determination is positive
    III. The coefficient of determination is less than the correlation coefficient

    a. I only  c. III only
    b. II only  d. II and III only

7.20. A correlation problem:

    a. Is solved by estimating the value of the dependent variable for various values of the independent variable
    b. Considers the joint variation of two measurements, neither of which is restricted by the experimenter
    c. Is the one case where the underlying distributions must be geometric
    d. Is solved by assuming that the variables are normally and independently distributed with mean = 0 and variance = s²

Answers 7.15 b, 7.16 c, 7.20 b
VII. SIX SIGMA METHODOLOGY - ANALYZE QUESTIONS

7.21. A random sample size \( n \) is to be taken from a large population having a standard deviation of 1 inch. The sample size is to be determined so that there will be a 0.05 risk probability of exceeding a 0.1 inch tolerance error in using the sample mean to estimate \( \mu \). Which of the following values is nearest the required sample size?

a. 385  
   b. 40  
   c. 200  
   d. 100

7.26. The difference between setting alpha equal to 0.05 and alpha equal to 0.01 in hypothesis testing is:

a. With alpha equal to 0.05, we are more willing to risk a type I error
b. With alpha equal to 0.05, we are more willing to risk a type II error
   c. Alpha equal to 0.05 is a more "conservative" test of the null hypothesis (H_0)
   d. With alpha equal to 0.05, we are less willing to risk a type I error

7.28. If a sample size of 16 yields an average of 12 and standard deviation of 3, estimate the 95% confidence interval for the population (assume a normal distribution).

a. \( 10.40 \leq \mu \leq 13.60 \)  
   b. \( 10.45 \leq \mu \leq 13.55 \)  
   c. \( 10.53 \leq \mu \leq 13.47 \)  
   d. \( 10.77 \leq \mu \leq 13.23 \)

Answers 7.21 a, 7.26 a, 7.28 a
VII. SIX SIGMA METHODOLOGY - ANALYZE QUESTIONS

7.31. In a random sample of 900 vehicles, 80% had anti-lock brakes. What is the 95% confidence interval for the percent of vehicles with anti-lock brakes?

   a. 0.778-0.821  c. 0.639-0.954
   b. 0.771-0.829  d. 0.774-0.826

7.33. Determine whether the following two types of rockets have significantly different variances at the 5% level.

<table>
<thead>
<tr>
<th>Rocket A</th>
<th>Rocket B</th>
</tr>
</thead>
<tbody>
<tr>
<td>61 readings</td>
<td>31 readings</td>
</tr>
<tr>
<td>1,347 miles$^2$</td>
<td>2,237 miles$^2$</td>
</tr>
</tbody>
</table>

   a. Significant difference because $F_{\text{calc}} < F_{\text{table}}$
   b. No significant difference because $F_{\text{calc}} < F_{\text{table}}$
   c. Significant difference because $F_{\text{calc}} > F_{\text{table}}$
   d. No significant difference because $F_{\text{calc}} > F_{\text{table}}$

7.36. The critical value for $t$, when making a two-tailed paired $t$ test, with samples of 13 and alpha = 0.05, is:

   a. 1.782  c. 2.064
   b. 2.179  d. 1.711

Answers 7.31 d, 7.33 b, 7.36 b
VII. SIX SIGMA METHODOLOGY - ANALYZE QUESTIONS

7.43. Three trainees were given the same lot of 50 pieces and asked to classify them as defective or non-defective, with the following results:

<table>
<thead>
<tr>
<th>Trainee #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defective</td>
<td>17</td>
<td>30</td>
<td>25</td>
<td>72</td>
</tr>
<tr>
<td>Non-defective</td>
<td>33</td>
<td>20</td>
<td>25</td>
<td>78</td>
</tr>
<tr>
<td>Total</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>150</td>
</tr>
</tbody>
</table>

In determining whether or not there is a difference in the ability of the three trainees to properly classify the parts. Which of the following statements is (are) true?

I. The chi-square calculated value is 6.9
II. Using a level of significance of 0.050, the critical value of the chi-square is 5.99
III. Since the obtained chi-square is greater than 5.99, we reject the null hypothesis

a. I only  
b. I and II only  
c. II only  
d. I, II and III

7.47. A two-way analysis of variance has r levels for one variable and c levels for the second variable with 2 observations per cell. The degree of freedom for interaction is:

a. 2(r)(c)  
b. (r - 1)(c - 1)  
c. rc -1  
d. 2(r -1)(c - 1)

Answers  7.43 d,  7.47 b
VII. SIX SIGMA METHODOLOGY - ANALYZE QUESTIONS

7.49. Basic assumptions underlying the analysis of variance include:
   I. Observations are from normally distributed populations
   II. Observations are from populations with equal variances
   III. Observations are from populations with equal means
   a. I and II only  c. II and III only
   b. I and III only  d. I, II, and III

7.55. The expected (theoretical) value for a cell in a contingency table is calculated as:
   a. \( \frac{\text{row total} \times \text{column total}}{\text{grand total}} \)
   b. \( \frac{\text{row total} \times \text{column total}}{\text{column total}} \)
   c. \( \left( \frac{O - E}{E} \right)^2 \)
   d. (Rows - 1)(Columns - 1)

7.58. Which of the following statements are true regarding nonparametric tests?
   I. They have a greater efficiency than comparable parametric tests
   II. They can be applied to correlation studies
   III. They require assumptions about the shape or nature of the populations involved
   IV. They require computations that are more difficult than corresponding parametric methods
   a. II only  c. II and IV only
   b. I and III only  d. I, II and III only

Answers 7.49 a, 7.55 a, 7.58 a
MOST PEOPLE WOULD RATHER LIVE WITH A PROBLEM THEY CAN'T SOLVE, THAN ACCEPT A SOLUTION THEY CAN'T UNDERSTAND.

LLOYD S. NELSON
Six Sigma - Improve

Six Sigma Methodology - Improve is presented in the following topic areas:

- Design of Experiments
  - Introduction
  - Terminology
  - Planning and Organizing Experiments
  - Randomized and Randomized Block Designs
  - Full Factorial Experiments
  - Fractional Factorial Experiments
  - Taguchi Robustness Concepts
  - Mixture Experiments

- Response Surface Methodology
  - Steepest Ascent/Descent Experiments
  - Higher Order Experiments

- Evolutionary Operations (EVOP)
Introduction

Design of experiments is a methodology of varying a number of input factors simultaneously in a carefully planned manner, such that their individual and combined effects on the output can be identified. Advantages of DOE include:

- Many factors can be evaluated simultaneously.
- Some input factors can be controlled to make the output insensitive to noise factors.
- Statistical knowledge is not always necessary.
- Experiments can distinguish important factors.
- There is confidence in the conclusions drawn. The factors can easily be set at the optimum levels.
- Results indicate if important factors are overlooked.
- Precise statistical analysis can be run using standard computer programs.
- Quality and reliability can be improved without cost increase or cost savings can be achieved.
VIII. SIX SIGMA METHODOLOGY - IMPROVE
A. DESIGN OF EXPERIMENTS
2. TERMINOLOGY

DOE Terms

Blocking When structuring fractional factorial experimental test trials, blocking is used to account for variables that the experimenter wishes to avoid. A block may be a dummy factor which doesn’t interact with the real factors.

Box-Behnken When full second-order polynomial models are to be used in response surface studies of three or more factors, Box-Behnken designs are often very efficient. They are highly fractional, three-level factorial designs.

Confounded When the effects of two factors are not separable.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>AB</th>
<th>AC</th>
<th>BC</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

A is confounded with BC, B with AC, and C with AB
DOE Terms (Continued)

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation Coefficient (r)</td>
<td>A number between -1 and 1 that indicates the degree of linear relationship between two sets of numbers. Zero (0) indicates no linear relationship.</td>
</tr>
<tr>
<td>Covariates</td>
<td>Things which change during an experiment which had not been planned to change, such as temperature or humidity. Randomize the test order to alleviate this problem. Record the value of the covariate for possible use in regression analysis.</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>The term used is DOF, DF, df or ν. The number of measurements that are independently available for estimating a population parameter.</td>
</tr>
<tr>
<td>EVOP</td>
<td>Stands for evolutionary operation, a term that describes the way sequential experimental designs can be made to adapt to system behavior by learning from present results and predicting future treatments for better response.</td>
</tr>
</tbody>
</table>
### DOE Terms (Continued)

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental Error</td>
<td>Variation in response or outcome of virtually identical test conditions. This is also called residual error.</td>
</tr>
<tr>
<td>First-order</td>
<td>Refers to the power to which a factor appears in a model. If “$X_1$” represents a factor and “$B$” is its factor effect, then the model: $Y = B_0 + B_1X_1 + B_2X_2 + \epsilon$ is first-order in both $X_1$ and $X_2$.</td>
</tr>
<tr>
<td>Fractional</td>
<td>An adjective that means fewer experiments than the full design calls for. Three-factor two-level, half-fractional designs are shown in the Primer</td>
</tr>
<tr>
<td>Full Factorial</td>
<td>Describes experimental designs which contain all combinations of all levels of all factors. No possible treatment combinations are omitted. A two-level, three factor full factorial design is shown in the Primer</td>
</tr>
</tbody>
</table>
VIII. SIX SIGMA METHODOLOGY - IMPROVE
A. DESIGN OF EXPERIMENTS
2. TERMINOLOGY

DOE Terms (Continued)

Interaction Occurs when the effect of one input factor on the output depends upon the level of another input factor.

Level A given factor or a specific setting of an input factor. Four levels of a heat treatment may be 100°F, 120°F, 140°F and 160°F.

Main Effect An estimate of the effect of a factor independent of any other factors.

Mixture Experiments Experiments in which the variables are expressed as proportions of the whole and sum to 1.0.
VIII. SIX SIGMA METHODOLOGY - IMPROVE
A. DESIGN OF EXPERIMENTS
  2. TERMINOLOGY

DOE Terms (Continued)

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nested Experiments</td>
<td>An experimental design in which all trials are not fully randomized. (i.e. In an experiment technicians might be nested within labs.)</td>
</tr>
<tr>
<td>Optimization</td>
<td>Involves finding the treatment combinations that gives the most desired response. Optimization can be “maximization” or “minimization”</td>
</tr>
<tr>
<td>Orthogonal</td>
<td>A design is orthogonal if the main and interaction effects in a given design can be estimated without confounding the other main effects or interactions.</td>
</tr>
<tr>
<td>Paired Comparison</td>
<td>The basis of a technique for treating data so as to ignore sample-to-sample variability and focus more clearly on variability caused by a specific factor effect. Only differences in response for each sample are tested because sample-to-sample differences are irrelevant.</td>
</tr>
</tbody>
</table>
### VIII. SIX SIGMA METHODOLOGY - IMPROVE
**A. DESIGN OF EXPERIMENTS**

<table>
<thead>
<tr>
<th>Terminology</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Repeated Trials</strong></td>
<td>Trials that are conducted to estimate the pure trial-to-trial experimental error so that lack of fit may be judged. Also called replications.</td>
</tr>
<tr>
<td><strong>Residual Error</strong></td>
<td>The difference between the observed and the predicted value for that result, based on an empirically determined model. It can be variation in outcomes of virtually identical test conditions.</td>
</tr>
<tr>
<td><strong>Residuals</strong></td>
<td>The difference between experimental responses and predicted model values.</td>
</tr>
<tr>
<td><strong>Resolution III</strong></td>
<td>A fractional factorial design in which no main effects are confounded with each other but the main effects and two factor interaction effects are confounded.</td>
</tr>
<tr>
<td><strong>Response Surface Methodology (RSM)</strong></td>
<td>The graph of a system response plotted against system factors. RSM employs experimental design to discover the “shape” of the response surface and uses geometric concepts to take advantage of the relationships.</td>
</tr>
</tbody>
</table>
## DOE Terms (Continued)

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robust Design</td>
<td>A term associated with the application of Taguchi experimentation in which a response variable is considered robust or immune to input variables that may be difficult or impossible to control.</td>
</tr>
<tr>
<td>Screening Experiment</td>
<td>A technique to discover the most (probable) important factors in an experimental system. Most screening experiments employ two-level designs. A word of caution about the results of screening experiments: if a factor is not highly significant, it does not necessarily mean that it is insignificant.</td>
</tr>
<tr>
<td>Simplex Design</td>
<td>A spatial design used to determine the most desirable variable combination (proportions) in a mixture.</td>
</tr>
<tr>
<td>Treatments</td>
<td>In an experiment, the various factor levels that describe how an experiment is to be carried out.</td>
</tr>
</tbody>
</table>
Applications of DOE

Experimental design can be effectively used:

- Choosing between alternatives
- Selecting the key factors affecting a response
- Response surface modeling

DOE Steps

- Set objectives
- Select process variables
- Select an experimental design
- Execute the design
- Check that the data are consistent with the experimental assumptions
- Analyze and interpret the results
- Use/present the results
Experimental Objectives

Choosing an experimental design depends on the objectives of the experiment and the number of factors to be investigated.

1. Comparative objective
2. Screening objective
3. Response surface (method) objective
4. Optimizing responses when factors are proportions of a mixture objective
5. Optimal fitting of a regression model objective
Select and Scale the Process Variables

Process variables include both inputs and outputs - i.e. factors and responses. The selection of these variables should:

- Include all important factors
- Be bold, not foolish, in choosing the low and high factor levels
- Avoid factor settings for impractical or impossible combinations
- Include all relevant responses
- Avoid using responses that combine two or more process measurements

When choosing the range of settings for input factors, it is wise to avoid extreme values.

The most popular experimental designs are called two-level designs.
### Design Guidelines

<table>
<thead>
<tr>
<th>Number of Factors</th>
<th>Comparative Objective</th>
<th>Screening Objective</th>
<th>Response Surface Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-factor completely randomized design</td>
<td>____</td>
<td>____</td>
</tr>
<tr>
<td>2 - 4</td>
<td>Randomized block design</td>
<td>Full or fractional factorial</td>
<td>Central composite or Box-Behnken</td>
</tr>
<tr>
<td>5 or more</td>
<td>Randomized block design</td>
<td>Fractional factorial or Plackett-Burman</td>
<td>Screen first to reduce number of factors</td>
</tr>
</tbody>
</table>
A Typical DOE Checklist

- Define the objective of the experiment.
- Learn about the process prior to brainstorming.
- Brainstorm a list of the key independent and dependent variables.
- Run “dabbling experiments” to debug equipment and get preliminary results.
- Assign levels to each independent variable in the light of all available knowledge.
- Select a standard DOE plan or develop one.
- Run the experiments in random order and analyze results periodically.
- Draw conclusions.
The Iterative Approach to DOE

While one experiment might give a useful result, it is more common to perform two or three, or perhaps more, experiments before a complete answer is attained. In other words, an iterative approach is best and, in the end, is the most economical.

Experimental Assumptions

- Are the measurement systems capable for all responses?
- Is the process stable?
- Are the residuals well behaved?

The $X_1$ model is properly specified

The variance increases with $X_2$

Need for a quadratic term added to $X_3$
An interaction occurs when the effect of one input factor on the output depends upon the level of another input factor.

Interactions can be readily examined with full factorial experiments. Often, interactions are lost with fractional factorial experiments.
VIII. SIX SIGMA METHODOLOGY - IMPROVE
A. DESIGN OF EXPERIMENTS
3. PLANNING AND ORGANIZING EXPERIMENTS

Full Versus Fractional Factorial

A full factorial is an experimental design which contains all levels of all factors. No possible treatments are omitted. A fractional factorial is a balanced experimental design which contains fewer than all combinations of all levels of all factors. Listed below are full and half fractional factorial designs for 3 factors at two levels:

<table>
<thead>
<tr>
<th>EXP .</th>
<th>T</th>
<th>P</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>8</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EXP .</th>
<th>T</th>
<th>P</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

The half fractional factorial also requires an equal number of plus and minus signs in each column.
Design Catalogue

A condensed version of a design catalogue compiled by G. J. Hahn and S. S. Shapiro of General Electric is provided in the Primer on pages VIII-19/25. The design catalogue index and detailed master plans should be sufficient for most industrial experiments.

A Three Factor, Three Level Experiment

Often a three factor experiment is required after screening a larger number of variables. These experiments may be full or fractional factorial. Shown below is a 1/3 fractional factorial design. Generally the (-) and (+) levels in two level designs are expressed as 0 and 1 in most design catalogues. Three level designs are often represented as 0, 1 and 2.
Randomized Block Plans

When each homogeneous group in the experiment contains exactly one measurement on every treatment, the experimental plan is called a randomized block plan.

For example, an experimental scheme may take several days to complete. If we expect some biasing differences among days, we might plan to measure each item on each day, or to conduct one test per day on each item. A day would then represent a block. A randomized Incomplete block (tension response) design is shown below.

<table>
<thead>
<tr>
<th>Block (Days)</th>
<th>Treatment</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-5</td>
<td>Omitted</td>
<td>-18</td>
<td>-10</td>
</tr>
<tr>
<td>2</td>
<td>Omitted</td>
<td>-27</td>
<td>-14</td>
<td>-5</td>
</tr>
<tr>
<td>3</td>
<td>-4</td>
<td>-14</td>
<td>-23</td>
<td>Omitted</td>
</tr>
<tr>
<td>4</td>
<td>-1</td>
<td>-22</td>
<td>Omitted</td>
<td>-12</td>
</tr>
</tbody>
</table>
Latin Square Designs

A Latin square plan is useful to allow for two sources of non-homogeneity in the conditions affecting test results. A third variable, the experimental treatment, is then applied to the source variables in a balanced fashion. A Latin square design is essentially a fractional factorial experiment, restricted by two conditions:

- The number of rows, columns and treatments must be the same.
- There should be no expected interactions between row and column factors.

5 automobiles, 5 carburetors are used to evaluate gas mileage by five drivers in the 5 x 5 Latin square:

<table>
<thead>
<tr>
<th>Car</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>D</td>
<td>E</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>E</td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>5</td>
<td>E</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>
VIII. SIX SIGMA METHODOLOGY - IMPROVE
A. DESIGN OF EXPERIMENTS
4. RANDOMIZED BLOCK DESIGNS

Graeco-Latin Designs

A Graeco-Latin Design is an extension of the Latin square design but one extra blocking variable is added for a total of three blocking variables. The response variable is gas mileage by 4 drivers.

<table>
<thead>
<tr>
<th>Car</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aα</td>
<td>Bβ</td>
<td>Cγ</td>
<td>Dδ</td>
</tr>
<tr>
<td>2</td>
<td>Bδ</td>
<td>Aγ</td>
<td>Dβ</td>
<td>Cα</td>
</tr>
<tr>
<td>3</td>
<td>Cβ</td>
<td>Dα</td>
<td>Aδ</td>
<td>Bγ</td>
</tr>
<tr>
<td>4</td>
<td>Dγ</td>
<td>Cδ</td>
<td>Bα</td>
<td>Aβ</td>
</tr>
</tbody>
</table>

Drivers: A,B,C,D
Days: α,β,γ,δ

Hyper-Graeco-Latin Designs

A Hyper-Graeco-Latin square design permits the study of treatments with more than three blocking variables.

<table>
<thead>
<tr>
<th>Car</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>Drivers</th>
<th>Tires</th>
<th>Days</th>
<th>Speeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AαMφ</td>
<td>BβNX</td>
<td>CγOψ</td>
<td>DδΡΩ</td>
<td>A,B,C,D</td>
<td>M,N,O,P</td>
<td>α,β,γ,δ</td>
<td>φXψΩ</td>
</tr>
<tr>
<td>2</td>
<td>BδNΩ</td>
<td>AγMψ</td>
<td>DβΡΧ</td>
<td>CαΟφ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>CβΟΧ</td>
<td>DαΡφ</td>
<td>AδМΩ</td>
<td>BγΝΨ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>DγΡΨ</td>
<td>CδΟΩ</td>
<td>BαΝφ</td>
<td>AβΜΧ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A Full Factorial Example

Suppose that pressure, temperature and concentration are three suspected key variables affecting the yield of a chemical process which is currently running at 64%. We wish to fix these variables at two levels (high and low) to see how they influence yield. In order to find out the effect of all three factors and their interactions, we need to conduct $2 \times 2 \times 2 = 2^3 = 8$ experiments. This is called a full factorial experiment. The low and high levels of input factors are noted below by (-) and (+).

Temperature:  
(-) = 120°C  
(+) = 150°C  
Pressure:  
(-) = 10 psi  
(+) = 14 psi  
Concentration:  
(-) = 10N  
(+) = 12N

The temperature effect:

$$\frac{(77 + 73 + 80 + 73) - (55 + 47 + 56 + 51)}{4} = 23.5$$

The pressure effect:

$$\frac{(47 + 73 + 51 + 73) - (55 + 77 + 56 + 80)}{4} = -6$$

The concentration effect:

$$\frac{(56 + 80 + 51 + 73) - (55 + 77 + 47 + 73)}{4} = 2$$
A Full Factorial Example (Continued)

Following the same principles used for the main effects:

\[ T \times P \text{ interaction: } \frac{(55 + 73 + 56 + 73) - (77 + 47 + 80 + 51)}{4} = 0.5 \]

\[ P \times C \text{ interaction: } \frac{(55 + 77 + 51 + 73) - (47 + 73 + 56 + 80)}{4} = 0 \]

\[ T \times C \text{ interaction: } \frac{(55 + 47 + 80 + 73) - (77 + 73 + 56 + 51)}{4} = -0.5 \]

\[ T \times P \times C \text{ interaction: } \frac{(77 + 47 + 56 + 73) - (55 + 73 + 80 + 51)}{4} = -1.5 \]

In this example, the interactions have either zero or minimal negative yield effects. If the interactions are significant compared to the main effects, they must be considered before choosing the final level combinations.

The best combination of factors here is: high temperature, low pressure and high concentration.
Two Level Fractional Factorial Example

The following seven step procedure will be followed:

1. Select a process
2. Identify the output factors of concern
3. Identify the input factors and levels to be investigated
4. Select a design
5. Conduct the experiment under the predetermined conditions
6. Collect the data (relative to the identified outputs)
7. Analyze the data and draw conclusions

CSSBB Test Success

Step 7  The optimum performance would be obtained by running the following trial:

\[
\begin{array}{cccccccc}
A & B & C & D & E & F & G \\
+ & 0 & + & + & 0 & 0 & + \\
\end{array}
\]
One can further examine the significance of the CSSBB design results using the sum of squares and a scree plot.

Note that

\[ SS = \frac{(\Delta \text{ value})^2}{8} \]

The scree plot indicates that factors D, B, E and F are noise.
CSSBB Test Success (Continued)

The SS (Sum of Squares) for the error term is 3.1 (3.1 + 0 + 0 + 0).

\[ \text{MSE (Mean Square Error)} = \frac{3.1}{4} = 0.775 \]

The maximum F ratio for factor G is 85.29. The critical maximum F value from the F Table for k-1=7, p=4 and \( \alpha = 0.05 \) is 73. Thus, factor G is important at the 95% confidence level.

The maximum F ratio for Factor C is 65.42. The critical maximum F value for k-1=7, p=4 and \( \alpha = 0.10 \) is 49. Thus, factor C is important at the 90% Confidence Level.

The maximum F ratio for factor A is 27.22. The critical maximum F values for both alpha values are larger than 27.22. Therefore, factor A is not considered important.

Table 8.10 in the Primer shows Percentiles of the Max-F Distribution for Screening Designs.
Plackett-Burman Designs

Plackett-Burman designs are used for screening experiments and are very economical. The run number is a multiple of four rather than a power of 2.

PB geometric designs are two-level designs with 4, 8, 16, 32, 64 and 128 runs and work best as screening designs. Each interaction effect is confounded with exactly one main effect.

All other two-level PB designs (12, 20, 24, 28, etc.) are non-geometric designs. In these designs a two-factor interaction will be partially confounded with each of the other main effects in the study. A PB design in 12 runs, for example, may be used to conduct an experiment containing up to 11 factors.
Taguchi Designs

The Taguchi philosophy emphasizes two tenets:

1. Reduce the variation of a product or process which reduces the loss to society,

2. Use a proper development strategy to intentionally reduce variation.

Orthogonal Arrays Degrees of Freedom

Let df = Degrees of Freedom
Let k = number of factor levels

For factor A, \( df_A = k_A - 1 \)
For factor B, \( df_B = k_B - 1 \)
For A x B interaction, \( df_{AB} = df_A \times df_B \)

\( df_{min} = \sum df \text{ all factors} + \sum df \text{ all interactions of interest} \)
Taguchi Designs (Continued)

Two - Level OAs

The simplest orthogonal array (OA) is an L4 (four trial runs). Factors A and B can be assigned to any two of the three columns. The remaining column is the interaction column.

The effects of factors A, B, AxB are determined for each column. Then calculate SS_T, SS_A, SS_B, SS_AxB and SS_e. A standard ANOVA table can now be set up to determine factor significance at a selected alpha value.
Taguchi Designs (Continued)

Linear Graphs & Triangular Tables

If the two factors are assigned to columns 1 and 2, the interaction will be in column 3. The L4 triangular Table shows that if the two factors are put in columns 1 and 3, the other point of the triangle for the interaction is in column 2.
Taguchi Designs (Continued)

Linear Graphs & Triangular Tables (Cont.)

The linear graphs indicate that several factors can be assigned to different columns and several different interactions may be evaluated in different columns. If three factors (A, B and C) are assigned, the L8 linear graph indicates the assignment to columns 1, 2 and 4 located at the vertices in the type A triangle.

Let us add another factor, D, to the experiment. The resolution power of the experiment is reduced because of the greater amount of confounding in the columns.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>AxB</td>
<td>C</td>
<td>AxC</td>
<td>BxC</td>
<td>AxBxC</td>
<td></td>
</tr>
<tr>
<td>BxCxD</td>
<td>AxCxD</td>
<td>CxD</td>
<td>AxBxD</td>
<td>BxD</td>
<td>AxD</td>
<td>D</td>
<td></td>
</tr>
</tbody>
</table>

Resolution III Experiment
Taguchi Designs (Continued)

Linear Graphs & Triangular Tables (Cont.)

Design resolution is the degree of confounding in two-level fractional screening designs. That is, the degree to which factors are entangled so that one cannot separate their effects.

Resolution II designs will have some main effects confounded with some other main effects.

Resolution III designs do not confound main effects with each other, but do confound main effects with two-factor interactions.

Resolution IV designs do not confound main effects and two-factor interactions, but do confound two-factor interactions with other two-factor interactions.

Resolution V designs do not confound main effects and three-factor interactions, but do confound two-factor interactions with higher-order interactions.
Conducting the Taguchi Experiment

Randomization

The order of running the various trials should include some form of randomization. The pattern of any unknown or uncontrollable effects will be evenly spread across the experiment. This will prevent bias of the factors and interactions assigned to the experimental columns. The three most common forms of randomization are:

1. Complete Randomization or ideal randomization means that any trial has an equal chance of being selected for the first test run.

2. Simple Repetition means that each trial has an equal random chance of being selected for the first test run, but once selected, all repetitions are run before the next trial is randomly selected.

3. Complete Randomization Within Blocks is used when changing the setup for say, factor C, may be expensive but changing all other factors is relatively easy. All $C_1$ trials could be randomly selected and run and then all $C_2$ trials could be randomly selected.
Taguchi Robust Concepts

Dr. Genichi Taguchi’s basic message is that the consistency of the product is very important. However, it is futile to try to achieve consistent output characteristics by controlling the variation in every variable. There are a few key variables (signal or noise factors) and their interaction in any process. When these factors are fixed at the right levels, the process will be insensitive to variations in other input factors or “robust.”

Achieving Design Robustness

Three types of design considerations are involved for any product or process:

1. **System design:** includes the selection of parts, methods, and tentative product parameter values.

2. **Parameter design:** is the selection of nominal product and process operating levels, to determine the optimum combinations.

3. **Tolerance design:** is the establishment of the permissible variation in the product and process to achieve a consistent output.
Taguchi Robust Concepts (Continued)

Signal Factors

Signal factors are the factors that strongly influence the mean response. Signal factors normally have minimal influence in varying the output response and are controllable. We should vary their level to adjust the mean.

Noise Factors

Noise factors are those factors that influence the variation in the output. The controllable ones are varied during the experimentation to see which combination gives the highest (or lowest as desired) signal to noise ratio (S/N). This is the key to achieving design “robustness.”

S/N Ratios

The S/N ratio is a calculation to quantify the effects (in dB) of variation in the controllable factors resulting in the variation of output.
Taguchi Robustness Concepts (Cont.)

S/N Ratios (Continued)

When higher results are desired:

$$S/N \text{ (in dB)} = -10 \log \frac{1}{n} \left( \frac{1}{(Y_1)^2} + \frac{1}{(Y_2)^2} + \ldots + \frac{1}{(Y_n)^2} \right)$$

When lower results are desired:

$$S/N \text{ (in dB)} = -10 \log \frac{1}{n} \left( (Y_1)^2 + (Y_2)^2 + \ldots + (Y_n)^2 \right)$$

$n =$ number of observations of controllable factors

$Y =$ output response for each experiment conducted

One of the factors in a three level experiment S/N ratio:

Levels of the controllable factor

Chose the input factor between the medium and high levels so input variation causes little output variation.
Mixture Designs

In a mixture experiment, the independent factors are proportions of different components of a blend and must sum to 100%. There are standard mixture designs such as Simplex-Lattice designs and Simple-Centroid designs. When there are additional constraints, such as a maximum and/or minimum value, constrained mixture designs or Extreme-Vertices designs, are appropriate.

The measured response is assumed to depend only on the relative proportions of the components and not on the amount of the mixture. The purpose of the experiment is to model the blending surface with some form of mathematical equation so that:

- Predictions of the response for any mixture can be made empirically.
- The influence on the response of each component can be obtained.

It is assumed that the errors are independent and identically distributed with zero mean and common variance. Another assumption is that the true underlying response surface is continuous over the region being studied.
Simplex-Lattice Designs

A \( \{q, m\} \) simplex lattice design for \( q \) components consists of points defined by the following coordinate settings: the proportions assumed by each component take the \( m+1 \) equally spaced values from 0 to 1,

\[
X_i = 0, \frac{1}{m}, \frac{2}{m}, \ldots, 1 \quad \text{for} \quad i = 1, 2, \ldots, q
\]

and all possible combinations (mixtures) of the proportions from this equation are used.

Note that the standard Simplex-Lattice are boundary point designs. When one is interested in prediction in the interior, it is highly desirable to augment the simplex type designs with interior design points.

There are a total of 10 design runs for the \( \{3, 3\} \) simplex lattice design.
VIII. SIX SIGMA METHODOLOGY - IMPROVE
A. DESIGN OF EXPERIMENTS
7. TAGUCHI ROBUST CONCEPTS

Simplex-Lattice Designs (Continued)

The number of design points in the simplex-lattice is
\((q+m-1)!/(m!(q-1)!).\)

Now consider the form of the polynomial model that one
might fit to the data from a mixture experiment. Due to
the restriction \(X_1 + X_2 + ... + X_q = 1\), the form of the
regression function is referred to as the canonical
polynomial.

The canonical polynomial is derived using the general
form of the regression function that can be fit to data
collected at the points of a \(\{q, m\}\) simplex-lattice design
and substituting into this the dependence relationship
among the \(X_i\) terms.

The number of terms in the \(\{q, m\}\) polynomial is
\((q+m-1)!/m!(q-1)!\). This number is equal to the number of
points that make up the associated \(\{q, m\}\) simplex-
lattice design.
Simplex-Lattice Designs (Continued)

In general, the canonical forms of the mixture models are as follows:

**Linear**

\[ E(Y) = \sum_{i=1}^{q} \beta_i X_i \]

**Quadratic**

\[ E(Y) = \sum_{i=1}^{q} \beta_i X_i + \sum_{i<j} \beta_{ij} X_i X_j \]

**Cubic**

\[ E(Y) = \sum_{i=1}^{q} \beta_i X_i + \sum_{i<j} \beta_{ij} X_i X_j + \sum_{i<j<k} \delta_{ijk} X_i X_j (X_i - X_j) \]

\[ + \sum_{i<j<k} \sum_{q} \beta_{ijk} X_i X_j X_k \]

The terms in the canonical mixture polynomials have simple interpretations. Geometrically, the parameter \( \beta_i \) in the above equations represent the expected response to the pure mixture \( X_i =1, X_j = 0, ij \), and is the height of the mixture surface at the vertex \( X_i =1 \). The portion of each of the above polynomials given by

\[ \sum_{i=1}^{q} \beta_i X_i \]

is called the linear blending portion. When blending is strictly additive, then the linear model form above is an appropriate model.
Simplex-Lattice Design Example

The example consists of a three component mixture problem. The three components are polyethylene (X1), polystyrene (X2), and polypropylene (X3) which are blended together to form fiber that will be spun into yarn. The product developers are only interested in the pure and binary blends of these three materials.

The response variable of interest is yarn elongation in kilograms of force applied. A \{3,2\} simplex-lattice design is used to study the blending process. There were two replicate observations run at each of the pure blends. There were three replicate observations run at the binary blends. There are a total of 15 observations with six unique design runs.

<table>
<thead>
<tr>
<th>X1</th>
<th>X2</th>
<th>X3</th>
<th>Observed Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>16.8, 16.0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>10.0, 9.7, 11.8</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>8.8, 10.0</td>
</tr>
<tr>
<td>0.5</td>
<td>0</td>
<td>0.5</td>
<td>17.7, 16.4, 16.6</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>15.0, 14.8, 16.1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>11.0, 12.4</td>
</tr>
</tbody>
</table>
Simplex-Lattice Designs (Continued)

\{3,2\} Simplex-Lattice Design Parameter Estimates

<table>
<thead>
<tr>
<th>Term</th>
<th>Estimate</th>
<th>Std Error</th>
<th>t Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>X₁</td>
<td>11.7</td>
<td>0.603692</td>
<td>19.38</td>
</tr>
<tr>
<td>X₂</td>
<td>9.4</td>
<td>0.603692</td>
<td>15.57</td>
</tr>
<tr>
<td>X₃</td>
<td>16.4</td>
<td>0.603692</td>
<td>27.17</td>
</tr>
<tr>
<td>(X₂ \cdot X₁)</td>
<td>19.0</td>
<td>2.608249</td>
<td>7.28</td>
</tr>
<tr>
<td>(X₃ \cdot X₁)</td>
<td>11.4</td>
<td>2.608249</td>
<td>4.37</td>
</tr>
<tr>
<td>(X₃ \cdot X₂)</td>
<td>-9.6</td>
<td>2.608249</td>
<td>-3.68</td>
</tr>
</tbody>
</table>

Under the parameter estimates section of the output are the individual t-tests for each of the parameters in the model. The three cross product terms are \((X₁ \cdot X₂)(X₃ \cdot X₁)(X₃ \cdot X₂)\) indicating a significant quadratic fit. The fitted quadratic mixture model is:

\[ y = 11.7X₁ + 9.4X₂ + 16.4X₃ + 19.0X₁X₂ + 11.4X₁X₃ - 9.6X₂X₃ \]

Since \(b₃ > b₁ > b₂\), one can conclude that component 3 (polypropylene) produces yarn with the highest elongation. Since \(b_{12}\) and \(b_{13}\) are positive, blending components 1 and 2 or components 1 and 3 produce higher elongation values than would be expected by averaging the elongations of the pure blends. This is an example of “synergistic” blending effects. Components 2 and 3 have antagonistic blending effects because \(b_{23}\) is negative.
Steepest Ascent/Descent

In an experimental problem the contours are usually not known. The object is to move from some initial point P in the $(X_1, X_2)$ space within the contour system.

Consider the directional line arrow obtained by joining the center of the circle (point P) to the point on the circumference of the circle where it just touches one of the response contours. As the diameter of the circle is decreased, the directional line is said to point in the direction of steepest ascent on the surface at point P. This direction achieves the greatest rate of increase per unit of distance traveled in contour space.

The path of steepest ascent is perpendicular to the contour lines if the space is measured in the same relative units chosen to scale the design.
Simplex Approaches to Steepest Ascent

1. Requires one more point than the number of independent variables.

2. Move away from lowest response point through the mid-point of the other two points to an equal distance on the other side.

3. Repeat this cycle dropping the lowest point at each step.

Note: this can be expanded to any number of variables, projecting away from the lowest, through the centroid of the remaining points.
VIII. SIX SIGMA METHODOLOGY - IMPROVE
B. RESPONSE SURFACE METHODOLOGY
1. STEEPEST ASCENT/DESCENT EXPERIMENTS

Response Surfaces

3D Response Surface  Matching Dome Contour

Rising Ridge  Stationary Ridge  Saddle Minimax

Various Contour Examples
Experimental Equations are Pictures

The equation represents a response line, plane or surface of the factors being evaluated.

\[
Y = B_0 + S_1 X_1 + C_1 X_1^2 + S_2 X_2 + C_2 X_2^2 + T_{1,2} X_1 X_2 + S_3 X_3 + C_3 X_3^2 + T_{1,3} X_1 X_3 + \cdots
\]

Description of Equation Components

The S, C, and T values depend on the size of slopes, curves and twists, respectively.
Central Composite Designs

A Box-Wilson central composite design contains an imbedded factorial or fractional factorial matrix with center points augmented with a group of “star points” that allow estimation of curvature. If the distance from the center of the design space to a factorial point is ±1 unit for each factor, the distance from the center of the design space to a star point is ±\( \alpha \), where \(|\alpha| > 1\).

Central Composite Design for Two Factors

A central composite design always contains twice as many star points as there are factors in the design. The star points represent new extreme values for each design factor.

Three Types of Central Composite Designs
Central Composite Designs (Continued)

<table>
<thead>
<tr>
<th>Design Type</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumscribed CCC</td>
<td>The star points are at some distance $\alpha$ from the center based on the properties desired and the number of factors in the design. The star points establish new extremes for the low and high settings for all factors. These designs have circular, spherical, or hyperspherical symmetry and require 5 levels for each factor.</td>
</tr>
<tr>
<td>Inscribed CCI</td>
<td>The CCI design uses the factor settings as the star points and creates a factorial or fractional factorial matrix within those limits. This design also requires 5 levels of each factor.</td>
</tr>
<tr>
<td>Face Centered CCF</td>
<td>The star points are at the center of each face of the factorial space, so $\alpha = \pm 1$. This design requires 3 levels of each factor.</td>
</tr>
</tbody>
</table>
Central Composite Designs (Continued)

CCC Design for Three Factors (15 runs shown)
Determining $\alpha$ in Central Composite Designs

To maintain rotatability, the value of $\alpha$ depends on the number of experimental runs in the factorial portion of the central composite design:

$$\alpha = \left[ \text{number of factorial runs} \right]^{1/4}$$

If the factorial is a full factorial, then:

$$\alpha = \left[2^k\right]^{1/4}$$

Where $K = \text{the number of factors.}$
Box-Behnken Designs

The Box-Behnken design is an independent quadratic design in that it does not contain an embedded factorial or fractional factorial matrix. In this design the treatment combinations are at the mid-points of edges of the process space and at the center. These designs are rotatable (or near rotatable) and require 3 levels of each factor. These designs have limited capability for orthogonal blocking compared to the central composite designs.

Box-Behnken Design for Three Factors (13 runs)
VIII. SIX SIGMA METHODOLOGY - IMPROVE  
B. RESPONSE SURFACE METHODOLOGY  
2. HIGHER-ORDER EXPERIMENTS

Choosing a Response Surface Design

<table>
<thead>
<tr>
<th>Design Type</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCC</td>
<td>CCC designs provide high quality predictions over the entire design space, but require using settings outside the range originally specified for the factorial factors. 5 levels are required for each factor.</td>
</tr>
<tr>
<td>CCI</td>
<td>CCI designs use only points within the factor ranges originally specified, but provide lower quality predictions compared to the CCC. 5 levels are required for each factor.</td>
</tr>
<tr>
<td>CCF</td>
<td>CCF designs provide relatively high quality predictions and do not require using points outside the original factor range, however, they give poor precision for estimating pure quadratic coefficients. They require 3 levels for each factor.</td>
</tr>
<tr>
<td>Box-Behnken</td>
<td>Requires fewer treatment combinations than a central composite design in cases involving 3 or 4 factors. The Box-Behnken design is rotatable but it contains regions of poor prediction quality like the CCI. Requires 3 levels for each factor.</td>
</tr>
</tbody>
</table>
EVOP emphasizes a conservative experimental strategy for continuous process improvement. Tests are carried out in phase A until a response pattern is established. Then phase B is centered on the best conditions from phase A. This procedure is repeated until the best result is determined. When nearing a peak, switch to smaller step sizes or examine different variables. EVOP can entail small incremental changes so that little or no process scrap is generated.
VIII. SIX SIGMA METHODOLOGY - IMPROVE

QUESTIONS

8.2. In every experiment there is experimental error. Which of the following statements is true?

   a. This error is due to lack of uniformity of the material used in the experiment and to inherent variability in the experimental technique
   b. This error can be changed statistically by increasing the degrees of freedom
   c. The error can be reduced only by improving the material
   d. In a well-designed experiment there is no interaction effect

8.6. Which of the following is a correct statement?

   a. Variables are confounded if they are difficult to study
   b. Two or more variables are confounded if their effects cannot be separated given the experimental data
   c. Variables are confounded if they form a linear combination
   d. Two or more variables are confounded if they produce the same effects

8.9. A $3^2$ experiment means that we are considering:

   a. Two levels of three factors
   b. Two dependent variables and three independent variables
   c. Two go/no-go variables and three continuous variables
   d. Three levels of two factors

Answers 8.2 a, 8.6 b, 8.9 d
VIII. SIX SIGMA METHODOLOGY - IMPROVE

QUESTIONS

8.14. The power of efficiency in designed experiments lies in the:

a. Random order of performance
b. The sequential and cyclical procedure of conjecture to design, to analysis and back to conjecture
c. Hidden replication
d. The large number of possible combinations of factors

8.16. A Latin square design is an experimental design which:

a. Cannot be used when estimation of the interaction effects is desired
b. Affords a good estimate of interaction effects
c. May not permit all treatments in every block
d. May require the need to estimate the parameters during the experimentation

8.19. In a full factorial experiment with 4 factors at 3 levels each, how many trials are required?

a. 24  c. 64
b. 12  d. 81

Answers 8.14 c, 8.16 a, 8.19 d
VIII. SIX SIGMA METHODOLOGY - IMPROVE

QUESTIONS

8.23. An experiment is being run with 8 factors. Two of the factors are temperature and pressure. The levels for temperature are 25, 50 and 75. The levels for pressure are 14, 28, 42 and 56. How many degrees of freedom are required for this experiment to determine the effect of the interaction between temperature and pressure?

a. 1  b. 2  c. 4  d. 6

8.24. The following is an example of what type of response surface?

a. Rising ridge  
b. Maximum or minimum  
c. Stationary ridge  
d. Minimax

8.27. When considering EVOP as a statistical tool:

a. A change in the means indicates that we are using the wrong model  
b. An external estimate of the experiment error is necessary  
c. EVOP may be extended beyond the two level factorial case  
d. We are limited to one response variable at a time.

Answers 8.23 d, 8.24 a, 8.27 c
VIII. SIX SIGMA METHODOLOGY - IMPROVE

QUESTIONS

8.34. Which answer correctly describes the experimental design below?

<table>
<thead>
<tr>
<th>Position</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aα</td>
<td>Bβ</td>
<td>Cχ</td>
<td>Dδ</td>
</tr>
<tr>
<td>2</td>
<td>Bχ</td>
<td>Aδ</td>
<td>Dα</td>
<td>Cβ</td>
</tr>
<tr>
<td>3</td>
<td>Cδ</td>
<td>Dχ</td>
<td>Aβ</td>
<td>Bα</td>
</tr>
<tr>
<td>4</td>
<td>Dβ</td>
<td>Cα</td>
<td>Bδ</td>
<td>Aχ</td>
</tr>
</tbody>
</table>

- a. Graeco-Latin Square
- b. Latin Square
- c. Randomized Complete Block
- d. Youden Square

8.38. Experiments can have many different objectives. Which of the following would be included in the options?

I. Comparative objective
II. Screening objective
III. Optimized mixture proportions objective
IV. Response surface determination

- a. I, II and III only
- b. II and III only
- c. I, III and IV only
- d. I, II, III and IV

8.40. Identify the assumption that is NOT made when conducting an experiment:

- a. That the measurement system is capable for all included responses
- b. That the factors be the only ones of importance
- c. That the process remains relatively stable during the duration of the testing
- d. That residuals are well behaved

Answers 8.34 a, 8.38 d, 8.40 b
VIII. SIX SIGMA METHODOLOGY - IMPROVE QUESTIONS

8.42. A hyper-Graeco-Latin (4 x 4) design is constructed as follows:

<table>
<thead>
<tr>
<th>Car</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AαMφ</td>
<td>BβNX</td>
<td>CγOψ</td>
<td>DδPΩ</td>
</tr>
<tr>
<td>2</td>
<td>BδNΩ</td>
<td>AγMΨ</td>
<td>DβPΧ</td>
<td>CαOφ</td>
</tr>
<tr>
<td>3</td>
<td>CβOX</td>
<td>DαPφ</td>
<td>AβMΩ</td>
<td>BγNψ</td>
</tr>
<tr>
<td>4</td>
<td>DγPΨ</td>
<td>CδOΩ</td>
<td>BαNφ</td>
<td>AβMX</td>
</tr>
</tbody>
</table>

Assume that car mileage is the output factor. If the above design were converted to a full factorial design, how many tests would be required for a full factorial?

a. 256  b. 1024  c. 1296  d. 4096

8.46. A basic L4 Taguchi design is the same as:

a. A two factor, two level, full factorial
b. A two factor, two level, 1/2 fractional factorial
c. A three factor, two level, full factorial
d. A test of a single variable at 4 levels

8.50. In the following Simplex-Lattice design, what is the proportion of component X₃ at the indicated test location?

a. 1.000  c. 0.500
b. 0.667  d. 0.333

Answers 8.42 b, 8.46 a, 8.50 d
VIII. SIX SIGMA METHODOLOGY - IMPROVE

QUESTIONS

8.54. When attempting to go in the direction of steepest ascent, in a two independent factor experiment, the best general approach is to:

a. Use a modified simplex model
b. Go perpendicular to the contour lines and adjust as necessary
c. Use the equation generated from the experiment as a roadmap
d. Make sure there are no minimax conditions

8.56. When comparing a Box-Behnken design with central composite designs, which of the following statements are FALSE?

I. Box-Behnken designs require fewer runs for 3 factors than CC designs
II. Box-Behnken designs require fewer runs for 2 and 5 factors than CC designs
III. Box-Behnken designs require fewer factor levels than all CC designs

a. I and II only c. II and III only
b. I and III only d. I, II and III

8.57. For a full factorial CCC design for four factors, what is the $\alpha$ value?

a. 1.3333 b. 1.6820 c. 2.0000 d. 2.3785

Answers 8.54 b, 8.56 c, 8.57 c
A STATE OF STATISTICAL CONTROL IS NOT A NATURAL STATE FOR A MANUFACTURING PROCESS. IT IS INSTEAD AN ACHIEVEMENT, ARRIVED AT BY ELIMINATING ONE BY ONE, BY DETERMINED EFFORT, THE SPECIAL CAUSES OF EXCESSIVE VARIATION.

W. EDWARDS DEMING
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
   1. OBJECTIVES AND BENEFITS

Six Sigma Improvement - Control

Six Sigma Methodology - Control is presented in the following topic areas:

- Statistical process control
- Advanced statistical process control
- Lean tools for control
- Measurement system re-analysis

Statistical Process Control

Statistical process control is described in the following topics:

- Objectives and benefits
- Selection of variable
- Rational subgrouping
- Selection and application of control charts
- Analysis of control charts
- Pre-control
Objectives and Benefits

Statistical process control (SPC) is a technique for applying statistical analysis to measure, monitor, and control processes. The major component of SPC is the use of control charting methods.

The basic assumption made in SPC is that all processes are subject to variation. This variation may be classified as one of two types, random or chance cause variation and assignable cause variation.

Benefits of statistical process control include the ability to monitor a stable process and identify if changes occur that are due to factors other than random variation. When assignable cause variation does occur, the statistical analysis facilitates identification of the source so that it may be eliminated.

The objectives of statistical process control are to determine process capability, monitor processes and identify whether the process is operating as expected or whether the process has changed and corrective action is required.
Objectives and Benefits (Continued)

Interpretation of control charts may be used as a predictive tool to indicate when changes are required prior to production of out of tolerance material. As an example, in a machining operation, tool wear can cause gradual increases or decreases in a part dimension. Observation of a trend in the affected dimension allows the operator to replace the worn tool before defective parts are manufactured.

An additional benefit of control charts is to monitor continuous improvement efforts. When process changes are made which reduce variation, the control chart can be used to determine if the changes were effective.

Costs associated with SPC include the selection of the variable(s) or attribute(s) to monitor, setting up the control charts and data collection system, training of operators, and investigation and correction when data values fall outside control limits.
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
2. SELECTION OF VARIABLE

Selection of Variable

The risk of charting many parameters is that the operator will spend so much time and effort completing the charts, that the actual process becomes secondary. When a change does occur, it will most likely be overlooked.

In the ideal case, one process parameter is the most critical, and is indicative of the process as a whole. Some specifications identify this as a critical to quality (CTQ) characteristic. CTQ may also be identified as a key characteristic.

Key process input variables (KPIVs) may be analyzed to determine the degree of their effect on a process. For some processes, an input variable such as temperature, may be so significant that control charting is mandated. Key process output variables (KPOVs) are candidates both for determining process capability and process monitoring using control charting.

Design of experiments (DOE) and analysis of variance (ANOVA) methods may also be used to identify variable(s) that are most significant to process control.
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
3. RATIONAL SUBGROUPING

Rational Subgrouping

A control chart provides a statistical test to determine if the variation from sample to sample is consistent with the average variation within the sample.

Generally, subgroups are selected in a way that makes each subgroup as homogeneous as possible. This provides the maximum opportunity for estimating expected variation from one subgroup to another.

In production control charting, it is very important to maintain the order of production. Data from a charted process, which shows out of control conditions, may be mixed to create new $\bar{X}$ - $R$ charts which demonstrate remarkable control. By mixing, chance causes are substituted for the original assignable causes as a basis for the differences among subgroups.
Subgrouping Schemes

Where order of production is used as a basis for subgrouping, two fundamentally different approaches are possible:

- The subgroup consists of product all produced as nearly as possible at one time.
- The subgroup consists of product intended to be representative of all the production over a given period of time.

The second method is sometimes preferred where one of the purposes of the control chart is to influence decisions on acceptance of product.

In most cases, more useful information will be obtained from five subgroups of 5 than from one subgroup of 25. In large subgroups, such as 25, there is likely to be too much opportunity for a process change within the subgroup.
Sources of Variability

The long term variation in a product will, for convenience, be termed the product (or process) spread. One of the objectives of control charting is to markedly reduce the lot-to-lot variability.

The distribution of products flowing from different streams may produce variabilities greater than those of individual streams. It may be necessary to analyze each stream-to-stream entity separately. Another main objective of control charting is to reduce time-to-time variation.

Physical inspection measurements taken at different points on a given unit are referred to as within-piece variability.

Another source of variability is the piece-to-piece variation. Often, the inherent error of measurement is significant. This error consists of both human and equipment components. The remaining variability is referred to as the inherent process capability.
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
3. RATIONAL SUBGROUPING

Breakdown of Variation

- Within Lot Variation
- Lot to Lot Variation
- Within Stream Variation
- Stream to Stream Variation
- Within Time Variation
- Time to Time Variation
- Within Piece Variation
- Piece to Piece Variation
- Inherent Process Variation
- Error of Measurement
  - Equipment
  - Human
Control Charts

Control charts are the most powerful tools to analyze variation in most processes - either manufacturing or administrative. Control charts were originated by Walter Shewhart in 1931 with a publication called *Economic Control of Quality of Manufactured Product*.

**Upper control limit (UCL)**

**Process average**

**Lower control limit (LCL)**

Control charts using variables data are line graphs that display a dynamic picture of process behavior.

Control charts for attributes data require 25 or more subgroups to calculate the control limits.

A process which is under statistical control is characterized by plot points that do not exceed the upper or lower control limits. When a process is in control, it is predictable.
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
4. SELECTION OF CONTROL CHARTS

Types of Charts

1. Control Charts for Variables
   Plots specific measurements of a process characteristic (temperature, size, weight, sales volume, shipments, etc.).

Types:
- *X* - R Charts (when data is readily available)
- *M* - MR Charts (moving average/moving range)
- *X* - MR Charts (I - MR, individual moving range)
- *X* - S Charts (when sigma is readily available)
- Median Charts
- Short Run Charts
Types of Charts (Continued)

2. Control Charts for Attributes

Plots general measurement of the total process (the number of complaints per order, number of orders on time, etc.).

Types:  
p Charts (for defectives - sample size varies)  
np Charts (for defectives - sample size fixed)  
c Charts (for defects - sample size fixed)  
u Charts (for defects - sample size varies)  
Short Run Varieties of p, np, c and u Charts
### X and R Chart Terms

- **n** Sample size (subgroup size)
- **X** A reading (the data)
- **X̄** Average of readings in a sample
- **X̄̄** Average of all the X̄s. It is the value of the central line on the X̄ chart.
- **R** The range. The difference between the largest and smallest value in each sample.
- **R̄** Average of all the Rs. It is the value of the central line on the R chart.
- **UCL/LCL** Upper and Lower control limits. The control boundaries for 99.73% of the population. They are not specification limits.
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
4. SELECTION OF CONTROL CHARTS

Typical $\bar{X}$ - $R$ Control Chart

$\bar{X}$ - Average

$R$ - Range

UCL$_{\bar{X}}$ - 20.0
LCL$_{\bar{X}}$ - 17.8
$\bar{X}$ - 18.9
UCL$_R$ - 4.0
LCL$_R$ - 0
$\bar{R}$ - 1.9

Graph showing control chart with UCL and LCL values for $\bar{X}$ and $R$.
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
4. SELECTION OF CONTROL CHARTS

Steps for Constructing $\bar{X}$ - R Charts

1. Determine the sample size ($n = 3, 4, or 5$) and the frequency of sampling.

2. Collect 20 to 25 sets of time - sequenced samples.

3. Calculate the average $= \bar{X}$ for each set of samples.

4. Calculate the range $= R$ for each set of samples.

5. Calculate $\bar{X}$ (the average of all the $\bar{X}$’s). This is the center line of the $\bar{X}$ chart.

6. Calculate $\bar{R}$ (the average of all the R’s). This is the center line of the R chart.

7. Calculate the control limits:
   
   $\bar{X}$ CHART: $UCL_\bar{X} = \bar{X} + A_2 \bar{R}$
   $LCL_\bar{X} = \bar{X} - A_2 \bar{R}$
   
   R CHART: $UCL_R = D_4 \bar{R}$
   $LCL_R = D_3 \bar{R}$

8. Plot the data and interpret the chart for special or assignable causes.
IX. SIX SIGMA METHODOLOGY - CONTROL  
A. STATISTICAL PROCESS CONTROL  
4. SELECTION OF CONTROL CHARTS

### Factors used for $\bar{X}$ - R Control Limits

<table>
<thead>
<tr>
<th>$n$</th>
<th>$A_2$</th>
<th>$D_3$</th>
<th>$D_4$</th>
<th>$d_2$</th>
</tr>
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<tbody>
<tr>
<td>2</td>
<td>1.88</td>
<td>0</td>
<td>3.27</td>
<td>1.13</td>
</tr>
<tr>
<td>3</td>
<td>1.02</td>
<td>0</td>
<td>2.57</td>
<td>1.69</td>
</tr>
<tr>
<td>4</td>
<td>0.73</td>
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<td>2.06</td>
</tr>
<tr>
<td>5</td>
<td>0.58</td>
<td>0</td>
<td>2.11</td>
<td>2.33</td>
</tr>
<tr>
<td>6</td>
<td>0.48</td>
<td>0</td>
<td>2.00</td>
<td>2.53</td>
</tr>
</tbody>
</table>

### $\bar{X}$-R Control Chart Data

#### Closure Removal Torques (in-lbs)

- $\text{UCL}_X = \bar{X} + A_2(\bar{R}) = 15.4 + (0.58 \times 3.6) = 17.5$
- $\text{LCL}_X = \bar{X} - A_2(\bar{R}) = 15.4 - 2.1 = 13.3$
- $\text{UCL}_R = (D_4) \bar{R} = 2.11 \times 3.6 = 7.6$
- $\text{LCL}_R = (D_3) \bar{R} = 0 \times 3.6 = 0$
# IX. SIX SIGMA METHODOLOGY - CONTROL

## A. STATISTICAL PROCESS CONTROL

### 4. SELECTION OF CONTROL CHARTS

## X-R Control Chart Chart Closure Torques

<table>
<thead>
<tr>
<th>Product Name: Tablets</th>
<th>Process Closure Department</th>
<th>Operator Bill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable: Removal Torques</td>
<td>Specification Limits: LSL = 10 LBS USL = 22 LBS</td>
<td>Units of Measure: LBS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date Start 1/12/98</th>
<th>Time</th>
<th>Sample Measurement</th>
<th>Total</th>
<th>Average X</th>
<th>Range R</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/12</td>
<td>1</td>
<td>12 15 13 10 13 15 12 22 16 15 16 17 16 15 17 16 17 16 19 19 16 17 19 14</td>
<td>64 83 74 54 72 66 77 74 85 81 82 79 79 83 85 83 80 82 76 85 74</td>
<td>12.8 16.6 14.8 10.8 14.4 13.2 15.4 14.8 17 16.2 16.4 15.8 15.8 16.6 17 16.8 16 16.4 15.2 17 14.8</td>
<td>3 3 5 2 3 4 1 5 8 3 2 3 2 3 4 4 5 3 4 4 4</td>
</tr>
<tr>
<td>1/13</td>
<td>2</td>
<td>12 17 18 12 16 12 16 17 17 15 18 16 15 15 19 17 19 15 13 18 17</td>
<td>64 83 74 54 72 66 77 74 85 81 82 79 79 83 85 83 80 82 76 85 74</td>
<td>12.8 16.6 14.8 10.8 14.4 13.2 15.4 14.8 17 16.2 16.4 15.8 15.8 16.6 17 16.8 16 16.4 15.2 17 14.8</td>
<td>3 3 5 2 3 4 1 5 8 3 2 3 2 3 4 4 5 3 4 4 4</td>
</tr>
<tr>
<td>1/13</td>
<td>3</td>
<td>13 16 14 11 14 13 15 16 15 17 16 17 16 18 17 15 16 17 17 17 17 16</td>
<td>64 83 74 54 72 66 77 74 85 81 82 79 79 83 85 83 80 82 76 85 74</td>
<td>12.8 16.6 14.8 10.8 14.4 13.2 15.4 14.8 17 16.2 16.4 15.8 15.8 16.6 17 16.8 16 16.4 15.2 17 14.8</td>
<td>3 3 5 2 3 4 1 5 8 3 2 3 2 3 4 4 5 3 4 4 4</td>
</tr>
<tr>
<td>1/13</td>
<td>4</td>
<td>15 17 14 10 15 16 14 17 15 16 17 15 18 15 15 15 16 15 15 15 15 15</td>
<td>64 83 74 54 72 66 77 74 85 81 82 79 79 83 85 83 80 82 76 85 74</td>
<td>12.8 16.6 14.8 10.8 14.4 13.2 15.4 14.8 17 16.2 16.4 15.8 15.8 16.6 17 16.8 16 16.4 15.2 17 14.8</td>
<td>3 3 5 2 3 4 1 5 8 3 2 3 2 3 4 4 5 3 4 4 4</td>
</tr>
<tr>
<td>1/13</td>
<td>5</td>
<td>12 18 15 11 14 11 15 12 14 18 16 14 16 16 17 17 14 18 14 16 16 13</td>
<td>64 83 74 54 72 66 77 74 85 81 82 79 79 83 85 83 80 82 76 85 74</td>
<td>12.8 16.6 14.8 10.8 14.4 13.2 15.4 14.8 17 16.2 16.4 15.8 15.8 16.6 17 16.8 16 16.4 15.2 17 14.8</td>
<td>3 3 5 2 3 4 1 5 8 3 2 3 2 3 4 4 5 3 4 4 4</td>
</tr>
</tbody>
</table>

Chart No. 1

![X-R Control Chart](chart.png)
X-Bar and Sigma Charts

X-bar ($\bar{X}$) and sigma ($S$) charts are often used for increased sensitivity to variation (especially when larger sample sizes are used). The sample standard deviation ($S$) formula is:

$$ S = \sqrt{\frac{\Sigma(\bar{X} - \bar{X})^2}{n-1}} $$

The $\bar{X}$ chart is constructed in the same way as described earlier, except that sigma ($\bar{S}$) is used for the control limit calculations via the following formulas:

$$ UCL_{\bar{X}} = \bar{X} + A_\sigma (\bar{S}) \quad LCL_{\bar{X}} = \bar{X} - A_\sigma (\bar{S}) $$

$$ UCL_S = B_4 (\bar{S}) \quad LCL_S = B_3 (\bar{S}) $$

Capability from $\bar{X}$-S Charts

The estimated standard deviation ($\hat{\sigma}$), called sigma hat, can be calculated by:

$$ \hat{\sigma} = \frac{\bar{S}}{C_4} $$

The $A_3$, $B_3$, $B_4$ and $C_4$ factors are based on sample size and are obtained from tables.
Median Control Charts

There are several varieties of median control charts. The control limits for the median chart are calculated using the same formulas as the $\bar{x}$- $R$ chart:

$$UCL_{\bar{x}} = \bar{x} + \tilde{A}_2 \bar{R} \quad LCL_{\bar{x}} = \bar{x} - \tilde{A}_2 \bar{R}$$

The $\tilde{A}_2$ values are somewhat different than the $A_2$ values for the $\bar{x}$ - $R$ chart since the median is less efficient and therefore exhibits more variation.

<table>
<thead>
<tr>
<th>n</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{A}_2$</td>
<td>1.88</td>
<td>1.19</td>
<td>0.80</td>
<td>0.69</td>
<td>0.55</td>
</tr>
</tbody>
</table>

$\tilde{A}_2$ Factors for Median Control Charts

The range factors ($D_3$ and $D_4$) and process standard deviation factor ($d_2$) are the same as used for the $\bar{x}$ - $R$ chart.

The specific advantages of a median chart are:
- It is easy to use and requires fewer calculations
- It shows the process variation
- It shows both the median and the spread
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
4. SELECTION OF CONTROL CHARTS

\( \bar{\bar{X}} \)-MR Charts

\( \bar{\bar{X}} \)-MR (moving average-moving range) charts are a variation of the \( \bar{X} \)-R chart where data is less readily available. There are several construction techniques, the one most sensitive to change is \( n = 3 \). Control limits are calculated using the \( \bar{X} \)-R formulas and factors.

X-MR Charts

Control charts plotting individual readings and a moving range may be used for short runs and in the case of destructive testing. X-MR charts are also known as I-MR, individual moving range charts. The formulas are:

\[
\begin{align*}
\text{UCL}_x &= \bar{\bar{X}} + E_2 \overline{MR} \\
\text{LCL}_x &= \bar{\bar{X}} - E_2 \overline{MR} \\
E_2 &= A_2 \sqrt{n}
\end{align*}
\]

The control limits for the range chart are calculated exactly as for the \( \bar{X} \)-R chart.

The X-MR chart is the only control chart which may have specification limits shown. \( \bar{\bar{X}} \)-MR charts with \( n = 3 \) is recommended by the authors when information is limited.
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
4. SELECTION OF CONTROL CHARTS

Attribute Charts

Attributes are discrete, counted data, such as defects or no defects. Only one chart is plotted for attributes.

<table>
<thead>
<tr>
<th>Chart</th>
<th>Records</th>
<th>Subgroup size</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Fraction Defective</td>
<td>Varies</td>
</tr>
<tr>
<td>np</td>
<td>Number of Defectives</td>
<td>Constant</td>
</tr>
<tr>
<td>c</td>
<td>Number of Defects</td>
<td>Constant</td>
</tr>
<tr>
<td>u</td>
<td>Number of defects per unit</td>
<td>Varies</td>
</tr>
<tr>
<td>100p*</td>
<td>Percent Defectives</td>
<td>Varies</td>
</tr>
</tbody>
</table>

* The p chart reflected in %

- Normally the subgroup size is greater than 50 (for p charts).
- The average number of defects/defectives is equal to or greater than 4 or 5.
- The most sensitive attribute chart is the p chart. The most sensitive and expensive chart is the X-R.
p Chart Example

\[ \bar{n} = \frac{22,500}{20} = 1125 \]
\[ \bar{p} = \frac{\text{total defective}}{\text{total inspected}} = \frac{52}{22,500} = 0.23\% \]

\[ \text{UCL}_p / \text{LCL}_p = \bar{p} \pm 3 \sqrt{\frac{\bar{p}(100 - \bar{p})}{\bar{n}}} \]

\[ = 0.23\% \pm 3 \sqrt{\frac{0.23\%(100\% - 0.23\%)}{1125}} \]
\[ = 0.23\% \pm 3 (0.143\%) \]

\[ \text{UCL}_p = 0.66\% \quad \text{LCL}_p = -0.20\% = 0\% \]
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
4. SELECTION OF CONTROL CHARTS

p Chart Example

Attributes Control Chart Form

PART: ____________________________
DESCRIPTION: UNCOATED TABLETS
CHARACTERISTIC: % DEFECTIVES
DATE: 5-1-99
SOURCE: TABLET DEPARTMENT
OPERATOR: VARIOUS
INSPECTOR: BILL

UCL: ________ LCL: ________ AVERAGE: ________

\[ UCL_p = \bar{p} + 3\sqrt{\frac{\bar{p}(100 - \bar{p})}{n}} \]

\[ = \frac{23}{100} + 3\sqrt{\frac{\frac{23}{100}(100 - \frac{23}{100})}{n}} \]

\[ = 0.66\% \]

\[ UCL_p = 0.66\% \]

Sample

Number

Fraction

Date/Time

Notes

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

25 0 12 3 5 0 2 2 1 3 0 5 10 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

\[ \bar{p} = 0.23\% \]

\[ \bar{p} = 0.23\% \]
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
4. SELECTION OF CONTROL CHARTS

c Chart Example

\[ n = 100 \quad \bar{c} = \frac{\text{total defective}}{\text{no. of lots}} = \frac{114}{25} = 4.6 \]

\[ \text{UCL}_c = \bar{c} + 3\sqrt{\bar{c}} = 4.6 + 3\sqrt{4.6} = 11 \]

\[ \text{LCL}_c = 4.6 - 3\sqrt{4.6} = -1.8 = 0 \]

np Chart Example

\[ n = 100 \quad \bar{np} = \frac{\text{total defective}}{\text{no. of lots}} = \frac{112}{25} = 4.5 \]

\[ \text{UCL}_{\text{np}} = \bar{np} + 3\sqrt{\bar{np}(1 - \bar{p})} \quad \text{LCL}_{\text{np}} = \bar{np} - 3\sqrt{\bar{np}(1 - \bar{p})} \]

\[ = 4.5 + 3\sqrt{4.5(0.955)} \quad = 4.5 - 3\sqrt{4.5(0.955)} \]

\[ = 10.7 \quad = -1.72 = 0 \]
### Attribute Chart Formulas

#### Defectives (Binomial Distribution)

<table>
<thead>
<tr>
<th>Chart Type</th>
<th>Formula</th>
</tr>
</thead>
</table>
| **p Chart** | \[ p = \frac{np}{n} \text{ for fraction} \]  
|           | \[ p = \frac{np}{n} \times 100 \text{ for } \% \]  
|           | \[ \bar{p} = \frac{\sum np}{k} \]  
|           | \[ UCL_p = \overline{p} + 3\sqrt{\frac{\overline{p}(1-\overline{p})}{n}} \]  
|           | \[ LCL_p = \overline{p} - 3\sqrt{\frac{\overline{p}(1-\overline{p})}{n}} \]  
| **np Chart** | \[ n\bar{p} = \frac{\sum np}{k} \]  
|          | \[ UCL_{np} = n\overline{p} + 3\sqrt{n\overline{p}(1-\overline{p})} \]  
|          | \[ LCL_{np} = n\overline{p} - 3\sqrt{n\overline{p}(1-\overline{p})} \]  

- **k = number of samples**

| Sample Size | Varies | Sample Size Fixed |
### Attribute Chart Formulas (Continued)

#### Defects (Poisson Distribution)

<table>
<thead>
<tr>
<th>u Chart, Average Number of Defects</th>
<th>c Chart Number of Defects</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u = \frac{c}{n}$</td>
<td>$\bar{c} = \frac{\sum c}{k}$</td>
</tr>
<tr>
<td>$UCL_u = \bar{u} + 3\frac{\sqrt{u}}{\sqrt{n}}$</td>
<td>$UCL_c = \bar{c} + 3\sqrt{\bar{c}}$</td>
</tr>
<tr>
<td>$LCL_u = \bar{u} - 3\frac{\sqrt{u}}{\sqrt{n}}$</td>
<td>$LCL_c = \bar{c} - 3\sqrt{\bar{c}}$</td>
</tr>
<tr>
<td>$\bar{n} = \frac{\sum n}{k}$</td>
<td>$k = \text{number of samples}$</td>
</tr>
<tr>
<td>$\bar{u} = \frac{\sum c}{\sum n}$</td>
<td></td>
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</tbody>
</table>

#### Sample Sizes

| Sample Size Varies | Sample Size Fixed |
Basic Control Chart Interpretation Rules

1. **Specials** are any points above the UCL or below the LCL.

2. A **run** violation is seven or more consecutive points on one side of the centerline.

3. A **1-in-20** violation is more than one point in twenty consecutive points close to the control limits.

4. A **trend** violation is any upward or downward movement of 5 or more consecutive points or drifts of 7 or more points.
Out-of-control

If a process is “out-of-control,” then special causes of variation are present in either the average chart or range chart, or both. These special causes must be found and eliminated in order to achieve an in-control process. A process out-of-control is detected on a control chart either by having any points outside the control limits or by unnatural patterns of variability.

![Diagram showing control limits]

- $\pm 1S = 68\%$
- $\pm 2S = 95\%$
- $\pm 3S = 99.7\%$
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
5. ANALYSIS OF CONTROL CHARTS

1. Process Average Out-of-control

2. Process Variation Out-of-control
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
5. ANALYSIS OF CONTROL CHARTS

3. Process Average & Variation Out-of-control

4. Process In-control

Average Shifting Variation Changing

Average Stable Variation Stable
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
5. ANALYSIS OF CONTROL CHARTS

Trends

Jumps in Process Level

Recurring Cycles
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
5. ANALYSIS OF CONTROL CHARTS

Points Near or Outside Limits

Lack of Variability
IX. SIX SIGMA METHODOLOGY - CONTROL
A. STATISTICAL PROCESS CONTROL
   5. ANALYSIS OF CONTROL CHARTS

Runs Test for Randomness

A run is a sequence of data that exhibit the same characteristic. Time sequence analysis can apply to both variable and attribute data. Results of surveys of individuals who prefer Diet Pepsi or Diet Coca Cola:

Test I  PPPPPPPPPPPCCCCCCCCCC
Test II PCPCPCPCPCPCPCPCPCPCPC

In both examples, eighteen samples were taken. Test I, there were only 2 runs. In Test II, there were 18 runs. Both examples suggest non-random behavior.

To perform a runs test:

1. Determine the value of $n_1$ and $n_2$ (either the total of two attributes or the readings above and below the center line on a run or control chart).
2. Determine the number of runs ($R$).
3. Consult a critical value table or calculate a test statistic.

Consult the Critical Value Table for the expected numbers of runs. The expected number of runs can be approximated by adding the smallest and largest values together and dividing by two.
Example 9.1: As an illustration of the use of the critical value table, consider the following run chart.

There are 24 plot points with 5 total runs above and below centerline. The Critical Value Table indicates that we should expect between 8 and 18 total runs. If there are 7 or fewer or 19 or more runs, then we can say with 95% confidence that non-random variation exists. The above example would fail the runs test.
The Pre-control Technique

Pre-control was developed by a group of consultants (including Dorin Shainin) in an attempt to replace the control chart. Pre-control is most successful with processes which are inherently stable and not subject to rapid process drifts once they are set up.

It can be shown that 86% of the parts will be inside the P-C lines with 7% in each of the outer sections, if the process is normally distributed and $C_{pk} = 1$.

The chance that two parts in a row will fall outside either P-C line is $1/7 \times 1/7$, or $1/49$. This means that only once in every 49 pieces can we expect to get two pieces in a row outside the P-C lines just due to chance.
The Pre-control Technique (Continued)

Pre-control rules:

- **Set-up:** The job is OK to run if five pieces in a row are inside the target

- **Running:** Sample two consecutive pieces
  - If the first piece is within target, run (don’t measure the second piece)
  - If the first piece is not within target, check the second piece
  - If the second piece is within target, continue to run
  - If both pieces are out of target, adjust the process, go back to set up
  - Any time a reading is out-of-specification, stop and adjust

The ideal frequency of sampling is 25 checks until a reset is required. Gauges for the target area may be painted green. Yellow is used for the outer zones and red for out-of-specification.
Short Run SPC

Short run charting may be desirable when the production lot size is extremely small (10-20) pieces or when the sample size, under typical operating conditions, is small. Two limited data charts may be used:

- X - MR Charts
- M X - MR Charts

Various techniques have been suggested by several authors. However, the recommendations of some are not without controversy. The emphasis has been on short runs and multiple variables per chart.

Consider a part which has four key dimensions. Each dimension has a different target but expected similar variances. The X’s for each variable are coded by subtracting the target value.

Calculating Centerlines:

Set Range: \( \bar{R} = \frac{\sum R}{(\text{No. of sets}) (\text{No. of variables per set})} \)

Set (X - Target): Coded \( \bar{X} = \frac{\sum \text{Coded } X}{(\text{No. of sets}) (\text{No. of variables per set})} \)
Short Run SPC (Continued)

Set (\(\bar{X}\) - Target) and Range Charts

Note changes in Dimension D on both charts.

There are no control limits for this kind of charting. The set chart is an exploratory and monitoring tool rather than a process control tool.
Other Short Run Approaches

\( \bar{X} \) and \( R \) data may be coded and control limits calculated for means and variation charts so that short runs of a single product, short runs of multiple products produced on a single machine, and different measurements on the same part can be plotted onto the same short run control chart.

Using similar logic, short run charts may be applied to attribute data (p, np, c and u charts).

Q charts permit maintaining statistical limits from the start of production whether or not prior information for estimating the parameters is available. Starting with the earliest observations, sequentially compute measures of the mean, \( \mu \) and variance \( \sigma^2 \). At each \( x \), update the following equation:

\[
\bar{x}_k = \frac{1}{k} (x_k + (k - 1)\bar{x}_{k-1}), \quad k = 2, 3, \ldots
\]

Using the appropriate reference distribution, determine the probability of the statistic under the usual null hypothesis. Determine the probability of \( t_v \geq t_{v, \text{observed}} \) Determine the normal deviate \( Z \) associated with this probability and plot \( Z \) on a control chart with upper and lower limits at \( \pm 3 \).
Exponentially Weighted Moving Average (EWMA)

The exponentially weighted moving average (EWMA) is a statistic for monitoring a process by averaging the data in a way that gives less and less weight to data as they are further removed in time.

By the choice of a weighting factor, $\lambda$, the EWMA control procedure can be made sensitive to a small or gradual drift in the process. The statistic that is calculated is:

$$\text{EWMA}_t = \lambda Y_t + (1 - \lambda) \text{EWMA}_{t-1} \quad \text{for} \quad t = 1, 2, ..., n$$

- $\text{EWMA}_0$ is the mean of historical data (target)
- $Y_t$ is the observation at time $t$
- $n$ is the number of observations to be monitored, including $\text{EWMA}_0$
- $0 < \lambda \leq 1$ is a constant that determines the depth of memory of the EWMA

The parameter, $\lambda$ determines the rate at which “older” data enters into the calculation of the EWMA statistic. A large value of $\lambda$ gives more weight to recent data and a small value of $\lambda$ gives more weight to older data. The value of $\lambda$ is usually set between 0.2 and 0.3 although this choice is somewhat arbitrary.
EWMA (Continued)

The estimated variance of the EWMA statistic is approximately:

$$ S_{EWMA}^2 = \left( \frac{\lambda}{2 - \lambda} \right) S^2 $$

when $t$ is not small, and where $s$ is the standard deviation calculated from the historical data.

The center line for the control chart is the target value or $EWMA_0$. The control limits are:

$$ UCL = EWMA_0 + ks_{EWMA} $$
$$ LCL = EWMA_0 - ks_{EWMA} $$

Where the factor $k$ is either set equal to 3 or chosen using the Lucas and Saccucci tables. The data are assumed to be independent and these tables also assume a normal population.
Example 9.2: Parameters calculated from historical data:

\[ \text{EWMA}_0 = 50, \ s = 2.0539, \ \text{and} \ \lambda = 0.3 \]

\[ \text{UCL} = 50 + 3 \times (0.4201)(2.0539) = 52.5884 \]

\[ \text{LCL} = 50 - 3 \times (0.4201)(2.0539) = 47.4115 \]

The EWMA Plot of Example Data

The process is in control however, there seems to be a trend upwards for the last 5 sample periods.

The EWMA is often superior to the CuSum charting technique for detecting “larger” shifts.
Cumulative sum (CuSum) control charts have been shown to be more efficient in detecting small shifts in the mean of a process than Shewhart charts. They are better to detect 2 sigma or less shifts in the mean.

To create a CuSum chart, collect m sample groups, each of size n, and compute the mean $\bar{X}_i$ of each sample. Determine $S_m$ or $S'_m$ from the following equations:

$$S_m = \sum_{i=1}^{m} (\bar{X}_i - \mu_0) \quad \text{or} \quad S'_m = \frac{1}{\sigma_{\bar{X}}} \sum_{i=1}^{m} (\bar{X}_i - \mu_0)$$

Where $\mu_0$ is the estimate of the in-control mean and $\sigma_{\bar{X}}$ is the known (or estimated) standard deviation of the sample means. The CuSum control chart is formed by plotting $S_m$ or $S'_m$ as a function of m. If the process remains in control, centered at $\mu_0$, the CuSum plot will show variation in a random pattern centered about zero.

A visual procedure proposed by Barnard, known as the V-Mask, may be used to determine whether a process is out of control. A V-Mask is an overlay V shape that is superimposed on the graph of the cumulative sums.

As long as all the previous points lie between the sides of the V, the process is in control.
CuSum Control Charts (Continued)

The behavior of the V-Mask is determined by the distance $k$ (which is the slope of the lower arm) and the rise distance $h$. Note that we could also specify $d$ and the vertex angle (or, as is more common in the literature, $q = \frac{1}{2}$ the vertex angle).

For an alpha and beta design approach, we must specify:

- $\alpha$, the probability of concluding that a shift in the process has occurred, when in fact it did not.

- $\beta$, the probability of not detecting that a shift in the process mean has, in fact, occurred.

- $\delta$ (delta), the detection level for a shift in the process mean, expressed as a multiple of the standard deviation of the data points.

Assume a process has an estimated mean of 5.000 with $h$ set at 2 and $k$ at 0.5. As $h$ and $k$ are set to smaller values, the V-Mask becomes sensitive to smaller changes in the process average. Consider the following 16 data points, each of which is average of 4 samples ($m=16$, $n=4$).
CuSum Control Charts (Continued)

The CuSum control chart with 16 data groups and shows the process to be in control.

If data collection is continued until there are 20 data points \((m=20, n=4)\), the CuSum control chart shows the process shifted upward, as indicated by data points 16, 17 and 18 below the lower arm of the V-Mask.
Moving Average

Past data may be summarized by computing the mean of successive sets of data. Single moving average is a method of smoothing the data and is then used as an estimate of future values. Single moving average is:

\[ M_t = \frac{1}{N} \left( X_t + X_{t-1} + \ldots + X_{t-N+1} \right) \]

\( X \) are individual data values, \( t \) is the current time period, and \( N \) is the moving group size.

Moving average is best used when the process mean is stable, but is a poor predictor when the process exhibits trends.

Single Moving Average with \( N = 3 \)
Lean Tools for Control Introduction

Various lean manufacturing techniques are used in the Six Sigma control phase: 5S, visual factory, kaizen, kanban, poka-yoke, total productive maintenance, and standard work.

5S Housekeeping, Workplace Organization

5S is a fundamental first step for any manufacturing company, wishing to call itself world class. The presence of a 5S program is indicative of the commitment of senior management to workplace organization, lean manufacturing and the elimination of muda (Japanese for waste). The 5S program mandates that resources be provided in the required location, and be available as needed to support work activities.

The five Japanese “S” words for workplace organization are:

- Seiko (proper arrangement)
- Seiton (orderliness)
- Seiketso (personal cleanliness)
- Seiso (cleanup)
- Shitsuke (personal discipline)
5S (Continued)

For American companies, the S’s are translated into approximate English equivalents:

• Sort: Separate out all that is unneeded and eliminate it.

• Straighten: Put things in order, everything has a place.

• Scrub (or shine): Clean everything, make the workplace spotless.

• Systematize: Make cleaning and checking routine.

• Standardize: Sustain the previous 4 steps and improve continually on them.

The 5S approach exemplifies a determination to organize the workplace, keep it neat and clean, establish standardized conditions, and maintain the discipline that is needed to do the job. 5S structure can be reduced to 4S or modified to a 5S + 1S or 6S program, where the sixth S is safety. The 5S concept requires that a discipline of will be installed and maintained.
Visual Factory

Visual control systems can be described as the use of production boards, schedule boards, tool boards, jidohka devices, and kanban cards on the factory floor. The intent of these techniques is to provide management and workers with a visible display of what is happening at any moment.

Visual controls assist the operators by providing them with information regarding order status, product quality, lead times, customer demand and costs.

Kaizen

Kaizen is Japanese for continuous improvement. The word Kaizen is taken from the Japanese kai “change” and zen “good.” This is usually referred to as incremental improvement but on a continuous basis and involving everyone. Kaizen is an umbrella term for:

- Productivity
- Total quality control
- Zero defects
- Just-in-time
- Suggestion systems
The Kaizen Blitz

A Kaizen event, Kaizen workshop, or Kaizen Blitz, involves a Kaizen activity in a specific area within a short time period. The Kaizen Blitz, using cross-functional volunteers in a 3 to 5 day period, results in a rapid workplace change on a project basis.

A 5 day Kaizen Blitz starts with 2 days of intense sessions on continuous improvement concepts. This is followed by 3 days of hands on data collection, analysis, and implementation at the source. Management must trust the decision making by the Kaizen Blitz team.

Every project has the possibility of bringing immediate changes and benefits. Kaizen Blitz events must occur with minimum expense and maximum use of people. The basic changes are in the process flow and methodology.

Measures of the outcomes of a Kaizen Blitz:

- Floor space saved
- Increased quality levels
- Line flexibility
- Safe work environment
- Improved work flow
- Improvement ideas
- Reduced non-value added time
Muda, The Seven Wastes

Muda are non-valued added activities in the workplace. The elimination of muda is essential for providing a cost-effective and quality product. There are 7 types of muda or waste:

- Overproduction
- Inventory
- Repairs/rejects
- Motion
- Processing
- Waiting
- Transport

Kanban

Kanban is the Japanese word for “sign.” It is a signal to internal processes to provide some product. Kanbans are usually cards, but they can be flags, a space on the floor, etc. Kanban provides some indication of material control:

- Part number
- Quantity
- Delivery frequency
- Time of delivery
- Location
IX. SIX SIGMA METHODOLOGY - CONTROL
C. LEAN TOOLS FOR CONTROL

Poka-Yoke

Shigeo Shingo is widely associated with a Japanese concept called Poka-Yoke which means to mistake proof the process or “fail-safing” a task. Mr. Shingo recognized that human error does not have to create resulting defects.

The success of poka-yoke is to provide some intervention device or procedure to catch the mistake before it is translated into nonconforming product. Mistake proofing is a preventive technique.

Other than eliminating the opportunity for errors, mistake proofing is relatively inexpensive to install and engages the operator in a contributing way. Design improvements to “error proof” the process include:

- Elimination of error-prone components
- Amplification of human senses
- Redundancy in design (back-up systems)
- Simplification by using fewer components
- Consideration of functional and physical environmental factors
- Providing failsafe cut-off mechanisms
- Enhancing product producibility and maintainability
- Selecting components and circuits that are proven
Total Productive Maintenance (TPM)

Total productive maintenance (TPM) is an activity that promotes coordinated group activities for greater equipment effectiveness and requires operators to share responsibility for routine machine inspection, cleaning, maintenance, and minor repairs.

The professional maintenance staff retains responsibility for major maintenance activities and act as coaches for the routine and minor items.

Productive maintenance combines preventive, predictive, maintainability improvement techniques, and equipment life cycle costs of equipment to increase reliability and ease of maintenance. One TPM effort had 6 elements:

1. Autonomous maintenance
2. Eliminating the six big losses
3. 100% production quality
4. A planning system for new machines
5. Training for all operators
6. Increased office efficiency

Efforts resulted in improvements in absenteeism, employee suggestions, scrap, rejects, training and inventory.
Standard Work

The operation of a plant depends on the use of policies, procedures, and work instructions. These could be referred to as standards. Maintaining and improving standards leads to improvement of the processes and plant effectiveness.

If things go wrong in gemba, the workplace, efforts are made to seek out the root causes, implement corrective action, and change work procedures. If no problems are encountered in routine daily work, the process is under control. With a system under control, an improvement stage can be started.

Once the changes have been made, efforts should commence to standardize the new procedures.
IX. SIX SIGMA METHODOLOGY - CONTROL
C. LEAN TOOLS FOR CONTROL

Standard Work (Continued)

Standards have the following features:

1. Standards are the best, easiest, and safest way to do a job.

2. They preserve know-how and expertise.

3. They provide a way to measure performance.

4. Correct standards show the relationship between cause and effect, leading to desired effects.

5. Standards provide a basis for maintenance and improvement.

6. They provide a set of visual signs on how to do the job.

7. Standards are a basis for training.

8. They are a basis for auditing.

9. They are a means to prevent recurrence of errors.

10. Standards minimize variability.
Measurement System Re-Analysis

Continuous improvement efforts resulting in reduced process variation, may require a re-evaluation of the measurement systems.

Micrometers that measured to 0.001" were replaced by micrometers with the ability to measure to 0.0001". “Supermicrometers” capable of measurements to 1 millionth or 0.1 millionth of an inch may be required for some length measurements.

An old rule of thumb was that the measurement instrument needed an accuracy of one tenth that of the specification tolerance, also stated as the “10:1” rule. Other sources used a “4:1” ratio or the equivalent 25% as a guide for the measurement uncertainty as compared with the specification tolerance.

The new quality system standards require “…an estimation of the measurement uncertainty as well as statistical techniques for analysis of test and/or calibration data.”
IX. SIX SIGMA METHODOLOGY - CONTROL
D. MEASUREMENT SYSTEM RE-ANALYSIS

Measurement System Re-Analysis (Cont.)

The Quality System Requirements states “Appropriate statistical studies shall be conducted to analyze the variation present in the results of each type of measuring and test equipment system ... (e.g. bias, linearity, stability, repeatability and reproducibility studies).”


- < 10% error The measurement system is acceptable.
- 10% to 30% error May be acceptable based upon importance of application, cost of gage, cost of repairs, etc.
- > 30% error Measurement system needs improvement.

The expression of measurement uncertainty includes both a range and the level of confidence at which the statement is made. Each organization needs to determine the measurement system requirements and evaluate if the measurement system capability meets those requirements.
IX. SIX SIGMA METHODOLOGY - CONTROL QUESTIONS

9.1. A p-chart has exhibited statistical control over a period of time. However, the average fraction defective is too high to be satisfactory. Internal improvement can be obtained by:

I. A change in the basic design of the product
II. Instituting 100% inspection
III. A change in the production process through substitution of new tooling or machinery

a. I only  c. II and III only
b. I and III only  d. I, II and III

9.7. The most common subgrouping scheme for $\bar{X}$ - R control charts is to separate the variation:

a. Within stream versus stream to stream  
b. Within time versus time to time  
c. Within piece versus piece to piece  
d. Inherent process versus error of measurement

9.10. Since many variables are important in control charting, what is the risk in having an operator plot a large number of characteristics?

a. None, if the operator is trained and knowledgeable  
b. Danger in overlooking a CTQ characteristic  
c. Distraction from the actual process itself  
d. It is non value added work in the lean philosophy

Answers 9.1 b, 9.7 b, 9.10 c
### IX. SIX SIGMA METHODOLOGY - CONTROL QUESTIONS

9.12. Control limits are set at the three-sigma level because:

   a. This level makes it difficult for the output to get out of control
   b. This level establishes tight limits for the production process
   c. This level reduces the probability of looking for trouble in the production process when none exists
   d. This level assures a very small type II error

9.15. A process is in control at $\bar{X} = 100$, $\bar{R} = 7.3$ with $n = 4$. If the process level shifts to 101.5, with the same range, what is the probability that the next $\bar{X}$ point will fall outside the old control limits:

   a. 0.016  
   b. 0.029  
   c. 0.122  
   d. 0.360

9.16. An $\bar{X}$ and $R$ chart was prepared for an operation using twenty samples with five pieces in each sample; $\bar{X}$ was found to be 33.6 and $\bar{R}$ was 6.20. During production, a sample of five was taken and the pieces measured 36, 43, 37, 25, and 38. At the time, this sample was taken:

   a. Both the average and range were within control limits
   b. Neither the average nor range were within control limits
   c. Only the average was outside control limits
   d. Only the range was outside control limits

Answers 9.12 c, 9.15 a, 9.16 d
IX. SIX SIGMA METHODOLOGY - CONTROL QUESTIONS

9.22. An X-bar chart has shown control for a long time. You see that points for the last 50 samples are all very near the center line on the chart. In fact, they are all within one sigma of the center line. This probably indicates that:

   a. It is a desirable situation
   b. It is an undesirable situation
   c. The process standard deviation has decreased during the time the last 50 samples were taken
   d. The control limits are incorrectly computed

9.24. An operator takes a routine sample using the pre-control method and notes that the first piece is within specifications but not within target. What does the operator do next?

   a. Stops the process and adjusts it
   b. Checks a second sample
   c. Confirms that the next 5 consecutive pieces are within target
   d. Continues to run

9.29. Which of the following control charts are most sensitive to small but gradual drifts in process?

   I. X - R charts      III. EWMA charts
   II. CuSum charts     IV. Moving average charts

   a. I and II only  c. II and III only
   b. I and III only  d. III and IV only

Answers 9.22 c, 9.24 b, 9.29 c
IX. SIX SIGMA METHODOLOGY - CONTROL QUESTIONS

9.31. Which of the following Japanese techniques is most clearly identified with small incremental change?
   a. Kaizen  c. Poka-yoke
   b. Kanban  d. 5S strategy

9.32. As with the 7 quality management tools, the Japanese concept of workplace organization, 5S, has been Americanized. Of the five original tools, which two are hardest to find in the American system?
   a. Seiko and Seiton  c. Seiketso and Shitsuke
   b. Seiton and Seiso  d. Seiko and Seiso

9.40. About 9 months after embarking on a Six Sigma effort, a company moved from measurement with traditional mikes and verniers to digital mikes and two piece linear scales. Why was this action necessary?
   a. They probably wanted to show prospective customers their level of measurement precision
   b. If changes were made they did not want to be caught “asleep at the switch”
   c. Processes have improved and they needed finer product measurements
   d. This would be required in the control phase of the DMAIC process

Answers 9.31 a, 9.32 c, 9.40 c
THERE IS THE REALIZATION THAT YOU CAN BE OUT OF BUSINESS IN THREE YEARS.

JOHN CHAMBERS
CEO, CISCO SYSTEMS
Lean Enterprise

Lean Enterprise is presented in the following topic areas:

- Lean concepts
- Lean tools
- Total productive maintenance (TPM)

Lean concepts is described in the following topics:

- Theory of constraints
- Lean thinking
- Continuous flow manufacturing (CFM)
- Non-value-added activities
- Cycle-time reduction
X. LEAN ENTERPRISE  
A. LEAN CONCEPTS  
1. THEORY OF CONSTRAINTS

Constraint Management

Goldratt authored a book titled *The Goal* which describes a process of ongoing continuous improvement. Constraint management could be described as removing the bottlenecks in a process that limits production or throughput.

If a process of ongoing improvement is to be effective, management must find out what to change. In this situation, the idea is to find the system constraint that is limiting production or throughput. A process chart is a good first step toward finding a constraint.
The Goal reminds readers that there are three basic measures to be used in the evaluation of a system.

- Throughput
- Inventory
- Operational expenses

These measures are more reflective of the true system impact than machine efficiency, equipment utilization, downtime or balanced plants.
Theory of Constraints (Continued)

A few widely used TOC concepts are:

- Bottleneck resources are: “resources whose capacity is less than the demand placed upon it.”

- Balanced plants are not good. “Balance the flow of product in the plant with demand from the market.”

- Dependent events and statistical fluctuations are important. A subsequent event depends upon the ones prior to it.

- Throughput is: “the rate at which the system generates money through sales.” The finished product must be sold before it generates money.

- Inventory is: “all the money the system has invested in purchasing things which it intends to sell.”

- Operational expenses are: “All the money the system spends to turn inventory into throughput.”

- Throughput, inventory and operational expenses define money as: incoming money, money stuck inside and money going out.
Theory of Constraints (Continued)

Theory of Constraints using the 5 step method:

1. Identify the system’s constraints.

2. Decide how to exploit the system’s constraints.

3. Subordinate everything else to the above decisions.

4. Elevate the system’s constraints. Try to eliminate the problems of the constraint. Strive to keep improving the system.

5. Back to step 1. After the constraint has been broken, look for new constraints.
Theory of Constraints (Continued)

TOC Work Time Example

<table>
<thead>
<tr>
<th>Station</th>
<th>Work Time (seconds)</th>
<th>Option 1</th>
<th>Option 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45</td>
<td>53</td>
<td>59</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>53</td>
<td>56</td>
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<td>3</td>
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<td>53</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>53</td>
<td>47</td>
</tr>
<tr>
<td>Total</td>
<td>265</td>
<td>265</td>
<td>265</td>
</tr>
</tbody>
</table>

If the operations are modified so that each station requires the same amount of time, as shown as Option 1, the sequence of operations is “balanced.” Balanced work loads almost never work, any delay at station 2 will affect the following stations.

A better choice might be Option 2, each station requires less time and work flows smoothly. There is a minimum of work-in-process, and less inventory builds up between stations.
Lean Thinking

Womack introduced the term lean production to the Western World in 1990 with the publication of *The Machine that Changed the World*.

After several years, Womack wrote *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. This book describes the concepts of converting a mass production plant into a lean organization. Womack offers five guiding principles for consideration:

- Specify value by product
- Identify the value stream for each product
- Make value flow
- Let the customer pull value from the producer
- Pursue perfection
Lean Thinking (Continued)

Value

Value is defined by the customer. The customer wants specific products, with specific capabilities, at specific prices. Specifying value is the first step in lean thinking. New methods must be developed to talk to customers, to get closer to them, and to find out what they want. Once value is found, the firm must go back again and again to determine if they really have the right answers.

Once value is defined, the target cost of the product may be determined. This target cost is more than the “market cost” of the product. The market cost is typically the manufacturing cost of the product plus the selling expenses and profit.

In lean thinking, the target cost is the mixture of current selling prices by competitors and the examination of and the elimination of muda (waste) through lean methods. This analysis results in a target price which is below current selling prices. The firm then applies lean thinking to its processes.
Lean Thinking (Continued)

Value Stream (Value Chain)

The benefits of reducing waste can be magnified many times by concentrating on the set of activities that link a process together. For the product or business, there are three streams or chains that are required:

- Problem solving
- Information management
- Transformation

Value streams can be constructed for each major product (or process) that an individual organization or plant produces. Efforts must be made to eliminate the muda (waste) in value streams.

A value stream map is created to identify all of the activities involved in the product. The activities are viewed in terms of the following criteria:

- It adds value as perceived by the customer
- It adds no value, but is required by the process
- It adds no value, and can be eliminated
Lean Thinking (Continued)

Value Stream (Value Chain)

Steps for documenting the value stream mapping are:

1. Product development
2. Process design
3. Record current status
4. Planning: Develop a future state map

Value Flow

Traditional mass production is often accomplished by the batch technique within a plant. The objective is to produce many units of a specific part at a given time, in order to maintain the production efficiency of the machines and the overall efficiency of the departments.

However, optimization of the individual operation unknowingly leads to sub-optimization of the process as practiced by non-lean companies.
The lean effort requires the conversion of a batch process to a continuous flow process or one-piece flow, without WIP, arranged in a sequence, straight line, U-shaped, or in a cell. Inside this flow concept, the work of each station and operator must be performed with complete reliability.

There are zero breakdowns and high quality, achieved using a variety of defect elimination and detection techniques:

- Poka-yoke to prevent defects
- Source inspection to correct the process
- Self-check to correct the process
- Successive checks by the next process
Lean Thinking (Continued)

Pull Value

Instead of creating product in response to an estimated sales forecast, the plant manufactures product as the customer requires it. This is the “pull” system in action which results in many positive things for the organization:

- Cycle times decrease in several areas
- Finished inventories are reduced
- Work-in-process (WIP) is reduced
- The customer stabilizes their ordering
- Pricing is stabilized

Problems in any area will stop the process, disrupting the pull process. Problems of any sort are magnified and must be immediately corrected.

Significant reduction in cycle times or throughput times are the result of lean thinking methods.
Lean Thinking (Continued)

Perfection

Perfection is accomplished via:

- Product teams working with the customer to find better ways to specify value, enhance flow, and achieve pull

- Using technologies to eliminate muda

- Developing new products

- Using joint collaboration between the value stream partners to uncover more value and reduce muda

Perfection is a journey.
Lean Thinking Journey

Some possible improvement results from lean thinking:

<table>
<thead>
<tr>
<th>Improvement Area</th>
<th>Reduction/ Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor productivity</td>
<td>100% increase</td>
</tr>
<tr>
<td>Throughput times</td>
<td>90% reduction</td>
</tr>
<tr>
<td>Inventories</td>
<td>90% reduction</td>
</tr>
<tr>
<td>Customer errors</td>
<td>50% reduction</td>
</tr>
<tr>
<td>In-house scrap</td>
<td>50% reduction</td>
</tr>
<tr>
<td>Safety injuries</td>
<td>50% reduction</td>
</tr>
<tr>
<td>Product development time</td>
<td>50% reduction</td>
</tr>
<tr>
<td>Capital investment</td>
<td>Modest</td>
</tr>
</tbody>
</table>

A starting point for new travelers to learn:

- See a successful application at another plant
- Develop plans for applying it to a line
- Commit to trying it
- Apply it successfully
- Spread it to other areas of the plant

Lean thinking is also a journey.
The Shingo Prize

The most notable criteria of judging a firm’s progress towards becoming a lean enterprise is the Shingo Prize for Excellence in Manufacturing. This prize is named for Dr. Shigeo Shingo, who was one of the world’s leading experts in manufacturing techniques. The Shingo Prize Business Model elements are:

<table>
<thead>
<tr>
<th>Elements</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leadership</td>
<td>75</td>
</tr>
<tr>
<td>Empowerment</td>
<td>75</td>
</tr>
<tr>
<td>Manufacturing Vision, Strategy</td>
<td>50</td>
</tr>
<tr>
<td>Innovations in Market Service and Product</td>
<td>50</td>
</tr>
<tr>
<td>Supplier Partnering</td>
<td>75</td>
</tr>
<tr>
<td>World Class Manufacturing Operations</td>
<td>250</td>
</tr>
<tr>
<td>Non-Manufacturing Support Function</td>
<td>125</td>
</tr>
<tr>
<td>Quality and Quality Improvement</td>
<td>75</td>
</tr>
<tr>
<td>Cost and Productivity Improvement</td>
<td>75</td>
</tr>
<tr>
<td>Delivery and Service Improvement</td>
<td>75</td>
</tr>
<tr>
<td>Customer Satisfaction and Profitability</td>
<td>75</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1000</strong></td>
</tr>
</tbody>
</table>
Continuous Flow Manufacturing (CFM)

Continuous flow manufacturing is one of the basic principles in a lean thinking environment. Material should always be moving one-piece at a time, at a rate determined by the needs of the customer. The flow of product must be smooth and uninterrupted.

Continuous flow or one-piece flow will:

- Deliver a flow of products to the customer with less delay
- Require less storage and transport
- Lower the risk of losses through damage, deterioration, or obsolescence
- Provide a mechanism to solve other production problems

In a continuous flow manufacturing layout, each station and operator (in fact, the whole system) must operate with complete reliability and high quality levels to achieve continuous flow and the desired takt time.
Takt Time

Takt time is a term used to define a time element that equals the demand rate. In a CFM or one-piece flow line, the time allowed for each line operation is limited. The line is ideally balanced so that each operator can perform their work in the time allowed. The work pace is at a certain pace or rhythm.

Takt Time Example

<table>
<thead>
<tr>
<th>Station</th>
<th>Work Time</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
<th>Option 4 after Kaizen</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45</td>
<td>53</td>
<td>59</td>
<td>66.25</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>53</td>
<td>56</td>
<td>66.25</td>
<td>60</td>
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<tr>
<td>3</td>
<td>60</td>
<td>53</td>
<td>53</td>
<td>66.25</td>
<td>60</td>
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<tr>
<td>4</td>
<td>70</td>
<td>53</td>
<td>50</td>
<td>66.25</td>
<td>60</td>
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<tr>
<td>5</td>
<td>50</td>
<td>53</td>
<td>47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>265</td>
<td>265</td>
<td>265</td>
<td>265</td>
<td>240</td>
</tr>
</tbody>
</table>

A line has 5 stations. If the takt time for the line is 60 seconds, the immediate observation is that station 4 exceeds the takt time and will not be able to maintain the pace.
Takt Time Example (Continued)

An option would be to have some of the time eliminated by moving work to another station. Option 1 is to balance the line at 53 seconds. This will provide 7 seconds of slack for each operator. Option 2 is the theory of constraints method.

Option 3 reduces the number of operators and redistributes the work load. The redesign has an initial takt time of 66.25 seconds. This is 6.25 seconds too much. A call for a Kaizen Blitz or Kaizen Event might eliminate the non-value added time reducing it to 60 seconds or lower, as shown in Option 4.

The choice of the best option depends upon how well the process is controlled, whether operations can be shifted from one station to another, and whether available process improvement opportunities exist.

The takt time is defined as the time needed to produce to customer requirements.
X. LEAN ENTERPRISE  
A. LEAN CONCEPTS  
3. CONTINUOUS FLOW MANUFACTURING (CFM)

Calculation of Takt Time

Given 480 minutes per shift available, less two 10 minute breaks and one 30 minute lunch is 430 minutes of net operating time. If the customer requirements are 6,000 units per month and there are 20 working days per month, then 300 units per day are required.

\[
\text{Takt Time} = \frac{\text{Net Operating Time Per Period}}{\text{Customer Requirements Per Period}}
\]

\[
\text{Takt Time} = \frac{430 \text{ minutes per day}}{300 \text{ units per day}} = 1.433 \text{ minutes per unit}
\]

The takt time in this example will be 1.433 minutes per unit or about 86 seconds per unit. The ideal pace of each operation is set at 86 seconds.
Illustration of Batch vs. One-piece Flow

The following three cases assume a series of three operations, and each operation can process one unit per minute.

Case 1: Orders are manufactured in batches of 100 units. Processing time is 201 minutes before the first unit is available. Total order time through the process is 300 minutes for 100 units.

Case 2: Orders are manufactured in batches of 10 units. Processing time is 21 minutes before the first unit is available. Total order time through the process is 30 minutes for 10 units.

Case 3: Orders are manufactured in batches of 1 unit. Processing time is 3 minutes before the first unit is available. Total order time through the entire process is 3 minutes for 1 unit.

If a customer changes requirements, the one-piece flow concept is able to shift production and provide the first units rapidly.
Non-Value-Added Activities

Non-value-added activities are classified as muda. It is another term for waste that exists in the process. Useful activities that the customer will pay for is considered value-added. Activities that the customer will not pay for are muda.

Overproduction

The muda of overproduction is producing too much at a particular point in time. Producing too early is as bad as producing too late.

Inventory

Parts, raw materials, work-in-process, inventory, supplies, and finished goods are all forms of inventory. Inventory is considered muda since it does not add value to the product.

Repair/ Rejects

The repair, rework or scrap of defective parts are a waste of resources. Design changes can also be muda.
Non-Value-Added Activities (Continued)

**Motion**

The efficient use of the human body is critical to the well being of the operator. Extra motions are muda. Operators should not have to walk excessively, lift heavy loads, repeat motions, etc. Each work station should be analyzed for proper ergonomic and motion requirements.

**Processing**

Processing muda consists of additional steps or activities in the manufacturing process.

**Waiting**

The muda of waiting occurs when an operator is ready for the next operation, but must remain idle.

**Transport**

All forms of transportation are muda. This describes the use of forklifts, conveyors, pallet movers, and trucks.
Cycle-time Reduction

Cycle time is defined as the amount of time needed to complete a single task and to move it forward in the process. The standard work is analyzed for value and nonvalued-added work.

The reduction in cycle time is customarily undertaken for many of the following reasons:

- To please a customer
- To reduce internal or external waste
- To increase capacity
- To simplify the operation
- To reduce product damage (improve quality)
- To remain competitive

Using the situation described earlier in this Section’s discussion on continuous flow manufacturing, reconsider the example of a line with 5 stations and observed cycle times.

One idea is to have 4 stations at 60 seconds each. A kaizen team could be empowered to improve the 5 station line. A significant cycle time improvement may be possible using a kaizen event.
Cycle-time Reduction (Continued)

The kaizen event format:

- Training to familiarize team members with lean thinking techniques
- A time limit of 5 days to accomplish the change (some use 3 days)
- 2 days of training on lean manufacturing techniques
- 2-1/2 days for collecting data and making changes
- 1/2 day presentation on the results to the workforce
Cycle-time Reduction (Continued)

Training

Some of the training concepts and principles include:

- Introduction to the total systems concept
- Problem solving tools such as the “5 Why’s”
- “Next process as the customer”
- Non-judgmental attitude to problem solving
- Identification of value and non-value added work
- Identification of muda (the 7 wastes)
- Principles of motion study
- Work flow patterns (simple flow, U-shaped)
- Standard operations
- 5 S workplace organization
- Visual management principles
- Just-in-time
- Poka-yoke principles
- Team dynamics
X. LEAN ENTERPRISE
   A. LEAN CONCEPTS
      5. CYCLE-TIME REDUCTION

Cycle-time Reduction (Continued)

Data Collection and Application

The team members collect and analyze data, perform work sampling, pace studies, line balancing, elemental analysis, motion studies, and takt time calculations.

The work sampling studies will provide a picture of the work content of the station. This will reveal the content and ratio of work, inspection, walking, and other factors. The activities of inspection, delay, walking, and other are considered muda and are nonvalue added.

The team will investigate ways to eliminate (or reduce) the four muda elements.

Pace studies of each station will provide a clearer picture of the cycle times. A line balancing chart will be made and compared to the desired takt time.

A study of the stations reveals the motions used by the operators. In this study, an approximation of the operator effort will suffice.
X. LEAN ENTERPRISE  
A. LEAN CONCEPTS  
5. CYCLE-TIME REDUCTION

Cycle-time Reduction (Continued)

Data Collection and Application (Continued)

The Shingo technique of classifying human motions is divided into 4 grades:

1. Assemble, disassemble, and use

2. Transport empty, grasp, transport loaded, and release load (nonvalue added)

3. Search, find, select, reposition, hold, inspect, and pre-position (nonvalue added)

4. Rest, frequent planning, unavoidable delays, avoidable delays (nonvalued added)

On the following page, in the spaghetti chart there is 1 operator per station, and the U-shaped line illustrates the operation with only 3 operators. The U-shape results in less wasted motion.
Cycle-time Reduction (Continued)

Data Collection and Application (Continued)

Spaghetti Chart of Existing Line

U-Shaped Line
Cycle-time Reduction (Continued)

Value Stream Mapping

A value stream map is created to identify all of the activities involved in product manufacturing from start to finish. This value stream may include suppliers, production operations and the end customer. This is the large view, looking at the entire system for improvement opportunities.

Benefits of a value stream map include:

- Seeing the complete process flow
- Identifying sources of waste in the value stream
- Providing common terminology for process discussions
- Helping make decisions about the flow
- Tying multiple lean concepts and techniques together
- Providing a blueprint for lean ideas
- Showing the linkage between the information and material flows
- Describing how the process will change
- Determining effects on various metrics
The value stream mapping process is:

Define product family  Use a product matrix
---
Draw current state map  Do this personally
---
Create future state map  Use creative concepts
---
Implementation planning  Can take months to finish

Define Product Family

Map one product family. A product family is defined as a group of products that pass through similar processing steps and over common equipment. A product and equipment matrix can be used to indicate common features. A work cell could be formed to handle a particular flow. The product with the highest volume should be used for the model line.
Cycle-time Reduction (Continued)

Value Stream Manager

The value stream for a product family may cross department boundaries in the company. To coordinate an effective value stream project calls for creation of the position of Value Stream Manager. This manager must have the authority to make things happen, would monitor all aspects of the project and should be a hands-on person.

Current State Mapping

A current state map of the process is developed to facilitate process analysis. Follow the material and information flows, map the whole stream.

Some of the typical process data includes: cycle time (CT), changeover time (COT), uptime (UT), number of operators, pack size, working time (minus breaks, in seconds), WIP, and scrap rate. An analysis of the current status can provide the amount of lead and value-added time.
X. LEAN ENTERPRISE
   A. LEAN CONCEPTS
      5. CYCLE-TIME REDUCTION

Cycle-time Reduction (Continued)

Current State Mapping (Continued)

Value stream mapping definitions worth noting include:

Value-added time (VAT) - The amount of time spent transforming the product, which the customer is willing to pay for.

Lead time (LT) - The time it takes one piece of product to move through all the processes.

Cycle time (CT) - The time a piece is completed by an individual process.

Future State Map

The future stream map is an attempt to make the process lean. This involves creativity and teamwork on part of the Value Stream Manager and the lean team to identify creative solutions.
Cycle-time Reduction (Continued)

Future State Map (Continued)

When developing a future state map ask:

- What is the required takt time?
- How do manufactured items move?
- Is continuous flow processing applicable?
- Where is the pacemaker process?
- Can the process be leveled?
- What is the increment of work to be released?
- What process improvements can be used

Implementation Planning

Develop the implementation plan for establishing the future state. This includes measurable goals, and checkpoints to measure progress. Several factors determine the speed of the plan, including available resources and funding.
X. LEAN ENTERPRISE
A. LEAN CONCEPTS
  5. CYCLE-TIME REDUCTION

Value Stream Mapping Icons

- Electronic Flow
- FIFO
- Finished Goods
- Go See
- Inventory
- Kaizen Burst
- Kanban Batches
- Kanban Post
- Kanban Production
- Kanban Signal
- Kanban Withdrawal
- Load Leveling
- Manual Information Flow
- Operator
- Process Box
- Pull Arrow
- Pull Circle
- Push Arrow
- Schedule Box
- Source
- Supermarket
- Truck Shipment
- Buffer Stock
- Data Box
Lean Tools

Lean tools includes the following topics:

- Visual factory
- Muda, the seven wastes
- Kanban
- Poka-Yoke
- Standard work
- SMED

Visual Factory

Three reasons for using visual management tools:

- To make problems visible
- To help workers and management stay in direct contact with gemba (the workplace)
- To clarify targets for improvement

Production boards and schedule boards are examples of a visual factory. Before the start of a shift, the department supervisor uses the boards for a short discussion on planned activities for the day and any specific problems.
Visual Factory (Continued)

Jidohka is defined as a device that stops a machine whenever a defective product is produced. It is autonemation, that is, a form of automation with human elements attached.

When an equipment malfunction occurs, a light turns red or a signal comes on to indicate a problem. The operator or maintenance personnel must respond to find the source of the problem and to resolve it.

The kanban system provides material control for the factory floor. The cards control the flow of production and inventory.

The visual factory places an emphasis on setting and displaying targets for improvement. The concept is that various operations have a target or goal to achieve. The standard time is initially set higher than the target. However, as the operation is performed, the operator tries to beat the old time, until the goal is met.

In summary, the visual factory enables management and employees to see the status of the factory floor at a glance. The current conditions and progress are evident and any problems can be seen by everyone.
Muda, The Seven Wastes

Muda are non-valued added activities in the workplace. The elimination of muda is essential for providing a cost-effective and quality product. There are 7 types of muda or waste:

- Overproduction: Producing more than is required.
- Inventory: Extra inventory does not add value to the product.
- Repairs/rejects: It is expensive to have repair work or rejects.
- Motion: The physical activities must be analyzed to reduce lost motion.
- Processing: This refers to modifying a work piece or piece of information.
- Waiting: When the operator is idle due to machine imbalances, lack of parts, or machine downtime.
- Transport: Any and all transport of the product is waste. Moving the product adds no value.
T. Ohno was the originator of the Kanban method. Kanban is a method of material control in the factory. It is intended to provide product to the customer with the shortest possible lead times. Inventory and lead times are reduced through Heijunka (leveling of production).

The order to produce parts at any one station is dependent on receiving an instruction, the kanban card. Only upon receiving a kanban card will an operator produce more goods. This system aims at simplifying paperwork, minimizing WIP and finished goods inventories.

Due to the critical timing and sequencing of a kanban system, improvements are continually made. A kanban system can not have production halted by machine failures or quality problems. Every effort is made to eliminate causes of machine downtime, to eliminate sources of errors in production, promoting production efficiency and improving quality.

Kanban systems are applicable in repetitive production plants, but not in one-of-a-kind production operations.
If a Kanban system is used, with cards indicating the need to resupply, the method of feeding an assembly line could be achieved using the following process:

1. Parts are used on the assembly line and a withdrawal kanban is placed in a designated area.

2. A worker takes the withdrawal kanban to the previous operation to get additional parts. The WIP kanban is removed from the parts pallet and put in a specified spot. The original withdrawal kanban goes back to the assembly line.

3. The WIP kanban card is a work instruction to the WIP operator to produce more parts. This may require a kanban card to pull material from an even earlier operation.

4. The next operation will see that it has a kanban card and will have permission to produce more parts.

5. This sequence can continue further upstream.
Poka-Yoke

Shingo lists characteristics of poka-yoke devices:

- 100 percent inspection is possible
- Devices avoid sampling for monitoring and control
- Poka-yoke devices are inexpensive

Mistake-proofing can be accomplished through a control method by preventing human errors or by using a warning mechanism to indicate an error. Some of the control methods to prevent human errors include:

- Designing a part so it can not be exchanged by mistake
- Using tools and fixtures that will not load a mis-positioned part
- Having a work procedure controlled by an electric relay

A signaling mechanism warns about possible sources of error. Root cause analysis and corrective action is required before work resumes.
Standard Work

Standard work is regarded to be one of the most important techniques for achieving a perfect process. This approach provides the discipline for attaining perfect flow in a process. Under normal work conditions, with no abnormalities in the system, the flow is perfect. Sharma’s definition of standard work:

“The best combination of machines and people working together to produce a product or provide a service at a particular point in time.”

A standard work sheet combines the 3 elements of materials, workers, and machines in a work environment. The standard work conditions are determined for:

- Takt time
- Ergonomics
- Parts flow
- Maintenance procedures
- Routines

Standard work is the documentation of each action required to complete a specified task. Standard work should always be displayed at the workplace. If abnormalities appear in the system, those items can be spotted and eliminated.
Standard Work (Continued)

The elements that comprise the standard work operations are:

- **Cycle time**: the time allowed to make a piece of production.

- **Work sequence**: the order of operations that the worker must use to produce a part, the same order of work must be done every time.

- **Standard inventory**: the minimum allowable in-process material in the work area, including the amount of material on the machinery, needed to maintain a smooth flow.

Standard charts also include:

- Capacity charts by part
- Standard task combination sheets
- Task manuals
- Task instruction manuals
- Standard operating sheets
SMED

Single Minute Exchange of Die (SMED) concept is to take a long setup change of perhaps 4 hours in length and reduce it to 3 minutes. Shigeo Shingo, developer of the SMED system has used it quite effectively in the Toyota Production System for just-in-time production.

Single minute exchange of die does not literally require die changes to be performed in only one minute, it merely implies that die changes are to be accomplished under a single digit of time (nine minutes or less).

SMED is a system that reduces the dependence on the long term experience of operators to perform an effective changeover. SMED will have a system to reduce the skill level needed for setup changes.

Quick changeover methods do away with the economic order quantity (EOQ) method. The EOQ tries to balance the cost of inventory to the cost of setup. The result is that excess inventory will be carried by the firm. The value of long production runs through EOQ theory is no longer valid.

SMED will enable a factory using lean manufacturing to produce to what is ordered by the customer.
SMED (Continued)

Setup Improvement Steps

The beginning of a SMED project is to recognize that setups can be improved by distinguishing between internal and external setup conditions. Identify what can be performed before shutting down the machine (external setup times), and identify what has to be done when the machine is shut down (internal setup time).

In planning a SMED project, the actual conditions and steps of the die changeover must be detailed. Every step in the setup process from start to finish is broken down and classified.

External setup operations should include:

- Preparation of parts
- Finding parts
- Measuring parts
- Maintenance
- Cleaning of spares, etc.

A second look must be made to re-examine the existing internal setup elements and to convert more of those elements into external setup.
The setup team will need to generate some creative options to what is currently being done. Brainstorming sessions and problem solving sessions are needed to continuously improve the setup process.

All elements of internal and external setup must be reviewed in detail and streamlined in order to move to the 1 digit goal. Perhaps the goal is unattainable, but efforts are made to go as low as possible. Once a SMED procedure is agreed upon, the setup team should practice the process and critique itself for improvements.

Based on specific applications, the reduction of cycle time can have a considerable impact on the containment of costs and improvement in productivity. Particularly in the forging and molding industries, the SMED process has received attention from the production and engineering professionals in this country, based on outstanding success in countries like Japan.
X. LEAN ENTERPRISE  
C. TOTAL PRODUCTIVE MAINTENANCE (TPM)

Total Productive Maintenance (TPM)

The most important features of total productive maintenance (TPM) are:

1. Efforts to maximize equipment effectiveness

2. A system of productive maintenance for a machine’s life span

3. Implementation by engineering, operations, and maintenance

4. Involvement of every employee, from top management to the floor employees

5. Autonomous maintenance by operators

6. Company led small group activities

The goal of maximizing equipment effectiveness requires the complete elimination of failures, defects, waste and loss due to equipment related operations. The objectives of TPM are zero breakdowns and zero defects.
Total Productive Maintenance (Cont.)

The “total” in total productive maintenance has the following meanings:

1. Total effectiveness in the pursuit of economic efficiency and profitability.

2. Total maintenance system includes maintenance prevention, maintainability, and preventive maintenance.

3. Total participation of all employees includes autonomous maintenance by operators and small group activities.

The “six big losses” that contribute negatively to equipment effectiveness:

1. Equipment failure
2. Setup and adjustment
3. Idling and minor stoppages
4. Reduced speed
5. Process defects
6. Reduced yield

Elimination of the six big losses, if fully achieved, will lead to dramatically improved plant conditions.
TPM Metrics

Overall equipment effectiveness is the prime measure used to evaluate TPM. There are several formula variations. The formulas are:

\[
\text{Overall Equipment Effectiveness} = \text{Availability} \times \frac{\text{Performance Efficiency}}{\text{Rate of Quality Products}}
\]

\[
\text{Availability} = \frac{\text{Operation Time}}{\text{Loading Time}} = \frac{\text{Loading Time} - \text{Downtime}}{\text{Loading Time}}
\]

Loading time is the available time per shift or per unit minus planned downtime. Planned downtime includes scheduled maintenance and morning meetings. Operation time is loading time minus unscheduled downtime.

\[
\text{Loading Time} = \text{Available Time per Shift} - \text{Planned Downtime}
\]

Performance efficiency is defined as the operating speed rate multiplied by the net operating rate. The operating speed rate is the ratio of the theoretical cycle time to its actual operating cycle time.

\[
\text{Operating Speed Rate} = \frac{\text{Theoretical Cycle Time}}{\text{Actual Cycle Time}}
\]
The net operating rate measures the stability of the equipment, the losses from minor stoppages, small problems and adjustment losses.

\[
\text{Net Operating Rate} = \frac{\text{Actual Processing Time}}{\text{Operating Time}}
\]

\[
\text{Net Operating Rate} = \frac{\text{Processed Amount} \times \text{Actual Cycle Time}}{\text{Operating Time}}
\]

Now, the performance efficiency can be calculated:

\[
\text{Performance Efficiency} = \text{Operating Speed Rate} \times \text{Net Operating Rate}
\]

Overall equipment effectiveness (OEE) is equal to (availability) x (performance efficiency) x (rate of quality products).

TPM prize winning companies have OEE’s above 85%. The ideal conditions are:

- Availability greater than 90%
- Performance efficiency greater than 95%
- Rate of quality greater than 99%
Steps to Implement TPM

The Japan Institute of Plant Maintenance (JIPM) awards an annual preventative maintenance (PM) prize. The criteria is based on improvements from TPM, such as increased productivity and quality. Factors include the following:

1. Reduced costs
2. Reduced inventory
3. Accident reduction/elimination
4. Pollution control
5. Work environment

The proper integration of the philosophy of TPM within the company will bring about improved worker and equipment utilization. These changes are aided by improving employee attitudes, increasing their skills, and providing a supporting work environment.
X. LEAN ENTERPRISE
C. TOTAL PRODUCTIVE MAINTENANCE (TPM)

Steps to Implement TPM (Continued)

Twelve steps are recommended as a path towards achieving prize winning TPM results with a 3 year time table.

Step 1: Announce top management commitment to TPM
Step 2: Introduce TPM with company communication programs
Step 3: Organize every functional level to promote TPM
Step 4: Establish TPM policies and goals
Step 5: Prepare a detailed master plan for TPM
Step 6: Hold the TPM kick-off
Step 7: Form project teams to improve the effectiveness of equipment
Step 8: Develop the autonomous maintenance program by building skills
Step 9: Develop a scheduled maintenance program
Step 10: Conduct training for operator and maintenance skills
Step 11: Develop early equipment management programs
Step 12: Have TPM implemented and aim for perfection.
Designing for Maintainability and Availability

In many situations involving corrective or preventive maintenance, ease of maintenance concerns time, material and money. Ease of maintainability is a design feature that affects these factors.

Guidelines for designing for maintainability which would increase maintainability and availability:

- Standardization
- Modularization
- Functional packaging
- Interchangeability
- Accessibility
- Malfunction annunciation
- Fault isolation
- Identification
Lean Glossary

**Andon Board** - A visual control device in a production area. Typically a lighted overhead display, giving the current status of the production system.

**Continuous Flow Manufacturing (CFM)** - Material moves one-piece at a time, at a rate determined by the needs of the customer, in a smooth and uninterrupted sequence, and without WIP.

**Just-in-Time (JIT)** - A system for producing and delivering the right items at the right time in the right amounts.

**Level Loading** - The smoothing or balancing of the work load in all steps of a process.

**Muda** - A Japanese term meaning any activity that consumes resources but creates no value.

**Poka-Yoke** - A mistake-proofing device or procedure to prevent or detect an error which adversely affects the product and results in the waste of correction.

**Pull** - A system of cascading production and delivery instructions from downstream to upstream activities.
Lean Glossary (Continued)

**Single Minute Exchange of Dies (SMED)** - Rapid changeovers of production machinery, the objective is zero setup time.

**Single-Piece-Flow** - A situation in which one complete product proceeds through various operations like design, order-taking, and production, without interruptions, back flows, or scrap.

**Standard Work** - A precise description of each work activity, specifying cycle time, takt time, the work sequence of specific tasks, and the minimum inventory needed.

**Takt Time** - The available production time divided by the rate of customer demand.

**Value Stream** - The specific activities required to design, and provide a specific product.

**Visual Control** - The placement in plain view of all the tools, parts, production activities, and indicators of production system performance, such that the status of the system can be understood easily and quickly.
X. LEAN ENTERPRISE
QUESTIONS

10.2. Which of the following are goals of TOC?

I. Increased throughput
II. Reduced inventory
III. Reduced operating expenses
IV. Capacity balanced with demand

a. I, II and III only   c. II, III and IV only
b. I, II and IV only   d. I, II, III and IV

10.5. What is the best definition of takt time?

a. It is a calculated time element that equals customer demand
b. It is the speed at which parts must be manufactured in order to satisfy demand
c. It is the heartbeat of any lean system
d. It is the application of Kaizen to continuous flow manufacturing

10.11. Which of the following would be a device associated with the visual factory?

a. Standard work
b. Andon board
c. Queue time
d. Work cell

Answers 10.2 a, 10.5 a, 10.11 b
10.13. One would say that the Kanban method would be most closely associated with:

a. The elimination of non-value added activities in the process
b. The development of a future state process stream map
c. Making problems visible in a process, thus clarifying targets for improvement
d. The control of material flow

10.15. Poka-yoke uses a number of devices to mistake proof a process. Which of the following would NOT be included?

a. Fixture templates
b. Electric relays
c. Buzzer or light signals
d. Self-check inspections

10.17. Standard work sheets are required for standard operations. What elements are included on the sheets?

I. Cycle time based on takt time
II. Work sequence - the order of operations
III. Standard inventory on hand
IV. The annual or semi-annual review date

a. I, II and III only c. I, III and IV only
b. I, II and IV only d. II, III and IV only

Answers 10.13 d, 10.15 d, 10.17 a
WHEN WE BUILD, LET US THINK THAT WE BUILD FOREVER.

JOHN RUSKIN
Design for Six Sigma

Design for Six Sigma is covered in the following topic areas:

- DFSS Introduction
- Quality Function Deployment
- Robust Design and Process
- Failure Mode and Effects Analysis
- Design for X
- Special Design Tools
DFSS Introduction

Design for Six Sigma is the suggested method to bring order to product design. 70 - 80% of all quality problems are design related. Emphasis on the manufacturing side alone will concentrate at the tail end of the problem solving process.

One of the ways to increase revenues must include introducing more new products for sale to customers. Cooper provides more details of how winning products are obtained:

1. A unique, superior product
2. A strong market orientation
3. Predevelopment work
4. Good product definition
5. Quality of execution
6. Team effort for product development
7. Proper project selection
DFSS Introduction (Continued)

8. Prepare for the launch

9. Top management leadership

10. Speed to market

11. A new product process (screening or stage gate)

12. An attractive market

13. Strength of company abilities

There are many product development processes to choose from. Multi-functional team activities involving all departments, are necessary for effectiveness and speed to market. The process has two parts, idea generation and new product development (NPD), which includes:

- Concept study
- Feasibility investigations
- Development of the new product
- Maintenance
- Continuous learning
DFSS Introduction (Continued)

Stage Gate Process Clarification

A stage gate process is used by many companies to screen and pass projects as they progress through development stages. Each stage of a project has requirements that must be fulfilled. The gate is a management review of the particular stage in question. It is at the various gates that management should make the “kill” decision.

Product Development Stages:

- Get an Idea
- Prove it Works
- Financial Assessment
- Develop and Test
- Scale up
- Launch
- Post Delivery Support
- Continuous Learning

The individual organization should customize their process and allow a suitable time period for it to stabilize.
In the area of new product management, some commonly accepted new product terms are:

1. New-to-the-world products: These are inventions, and discoveries.
2. New category entries: These are products that are new to the company.
3. Additions to product lines: Extensions of the organization’s existing product line.
4. Product improvements: Current products made better.
5. Repositionings: Products that are retargeted for a new use.
6. Cost reductions: New products are designed to replace existing products, but at a lower cost.
XI. DESIGN FOR SIX SIGMA

DFSS INTRODUCTION

DFSS Introduction (Continued)

A four step model:

- Identify: Use team charter, voice of customer, QFD, FMEA and benchmarking.

- Design: Emphasize CTQs, identify requirements, develop alternatives, evaluate and select.

- Optimize: Use process capability information, a statistical tolerancing approach, and robust design.

- Validate: Test and validate the design.

A 5 step DMADV process for Six Sigma design for the creation of a new product is:

- Define: Define the project goals and customer needs
- Measure: Measure and determine customer needs and specifications
- Analyze: Determine the process options
- Design: Develop the details for producing to meet the customers needs
- Verify: Verify and validate the design
The design engineer will select a design process. A typical design process (The French model) is depicted:

- **Need** → **Analysis of Problem** → **Statement of Problem** → **Conceptual Design** → **Selected Schemes** → **Embodiment of Schemes** → **Detailing** → **Working Drawings, etc.**

The designer (and design team) will capture the needs, provide analysis, and produce a statement of the problem. The conceptual design will generate a variety of solutions to the problem. Embodiment of schemes step produces a concrete working drawing from the abstract concept. The detailing step consolidates and coordinates the fine points of producing a product.

The designer of a new product is responsible for taking the initial concept to final launch. In this effort, the designer will be part of a team. The project manager, product manager, or general manager for a new product or new design team will need to manage the process.
XI. DESIGN FOR SIX SIGMA
A. QUALITY FUNCTION DEPLOYMENT

Design Using Quality Function Deployment

Quality Function Deployment (QFD) is a tool that is sometimes referred to as the “voice of the customer,” or as the “house of quality.”

By describing the product in the language of the engineer, along the top of the house of quality, the design team lists those engineering characteristics that are likely to affect one or more of the customer attributes. “The interfunctional team fills in the body of the house, the ‘relationship matrix,’ indicating how much each engineering characteristic affects each customer attribute.” “By comparing weighted characteristics to actual component costs, creative design teams set priorities for improving components.”

The foundation of the house contains the benchmarking or target values. The values indicate “how much” for each of the measures. It is better to set the target values as single objectives, and then rate the engineering characteristics in terms of the ability of achieving the target values.

The right-hand wall of the house indicates the customer competitive assessment and other factors affecting the customer.
XI. DESIGN FOR SIX SIGMA  
A. QUALITY FUNCTION DEPLOYMENT  

Design Using QFD (Continued)  

Hypothetical CSSBB Primer House of Quality Example
Design Using QFD (Continued)

After setting the primary design characteristics, Hauser suggests using the “hows” from the house of quality as the “whats” of another house that depicts detailed product design. This process is repeated with a process planning house and then production planning house. In this way, the voice of the customer is carried through from design to manufacturing.

Linked House of Quality Example

Hauser states that “The house of quality is a kind of conceptual map that provides the means for interfunctional planning and communications.” “The principal benefit of the house of quality is quality in-house. It gets people thinking in the right directions and thinking together.”
XI. DESIGN FOR SIX SIGMA
B. ROBUST DESIGN AND PROCESS INTRODUCTION

Robust Design and Process is Presented in the following topic areas:

- Functional Requirements
- Noise Strategies
- Tolerance Design
- Tolerance and Process Capability

Robust Design Introduction

Dr. G. Taguchi wrote that the United States has coined the term “Taguchi Methods” to describe his system of robustness for the evaluation and improvement of the product development processes. He has stated that he preferred the term “quality engineering” to describe the process.
Robust Design Approach

Robust design processes can produce extremely reliable designs both during manufacture and in use. Robust design uses the concept of parameter control to place the design in a position where random “noise” does not cause failure.
Robust Design Approach (Continued)

The concept is that a product or process is controlled by a number of factors to produce the desired response. The Signal Factor is the signal used for the intended response. The success of obtaining the response is dependent on Control Factors and Noise Factors.

Control Factors are those parameters that are controllable by the designer that operate to produce a response when triggered by a signal. Control Factors are separated into those which add no cost and those that do add cost. Factors that add cost are frequently associated with selection of the tolerance of the components and are called Tolerance Factors. Factors that don’t add cost are simply Control Factors. Noise Factors are parameters or events that are not controllable by the designer and are generally random.

Noise factors have the ability to produce an error in the desired response. The function of the designer is to select Control Factors so that the impact of Noise Factors on the Response is minimized while maximizing the response to Signal Factors.
XI. DESIGN FOR SIX SIGMA

B. ROBUST DESIGN AND PROCESS

INTRODUCTION

A Robust Design Example

The most celebrated case of design of experiments was that of a parameter design experiment at a tile manufacturing company in Japan, as documented Genichi Taguchi. Factors (which were less expensive to control) were fixed at requisite levels such that the output (variation in tile dimension), was made insensitive to a noise factor (temperature variation).

A mid-size tile manufacturing company in Japan in 1953 was having a serious problem with extreme variation in the dimensions of the tile produced. The stacked tiles were baked inside a tunnel kiln as shown below. Tiles toward the outside of the stack tended to have a different average dimension and exhibited more variation than those toward the inside of the stack.
A Robust Design Example (Continued)

The cause of variation was due to an uneven temperature profile inside the kiln. To correct the cause, the company would have to redesign the kiln, which was a very expensive proposition. This company's budget didn't allow such costly action, but the kiln was creating a tremendous financial loss for the company, so something had to be done.

Although temperature was an important factor, it was treated as a noise factor. This meant that temperature was a necessary evil and all other factors would be varied to see if the dimensional variation could be made insensitive to temperature. In Dr. Taguchi's words, whether the “robustness of the tile design” could be improved.

People having knowledge about the process brainstormed and identified seven major controllable factors which they thought could affect the tile dimension. These were: (1) limestone content in the raw mix; (2) fineness of the additives; (3) amalgamate content; (4) type of amalgamate; (5) raw material quantity; (6) waste return content; and (7) type of feldspar.
A Robust Design Example (Continued)

After testing these factors over specified levels using an orthogonal design, the experimenters discovered that limestone content was the most significant factor, although other factors had smaller effects. It was found that by increasing the limestone content from 1% to 2%, the percent warpage could be reduced from 30% to less than 1%. Fortunately, limestone was the cheapest material in the tile mix. Moreover, they found through the experimentation that they could use a smaller amount of amalgamate without adversely affecting the tile dimension. Amalgamate was the most expensive material in the tile.

Some of the key principles of robust design are:

Concept Design - The selection of the process or product architecture is based on technology, cost, customer, or other considerations.

Parameter Design - The design is established using the lowest cost components and techniques. The response is then optimized for control and minimized for noise.

Tolerance Design - The tolerances are reduced until the design requirements are met.
Functional Requirements

In the development of a new product, the product planning department must determine the functions required. The designer will have a set of requirements that a new product must possess. The designer will develop various concepts, embodiments, or systems that will satisfy the customer’s requirements.

The product design must be “functionally robust,” which implies that it must withstand variation in input conditions and still achieve desired performance capabilities. The designer has two objectives:

- Develop a product that can perform the desired functions and be robust under various operating or exposure conditions
- Have the product manufactured at the lowest possible cost
Parameter Design

Parameter designs improve the functional robustness of the process so that the desired dimensions or quality characteristics are obtained. The process is considered functionally robust if it produces the desired part for a wide variety of part dimensions. The steps to obtain this robustness are:

1. Determine the signal factors (input signals) and the uncontrollable noise factors (error factors) and ranges.

2. Choose as many controllable factors as possible, select levels for these factors, and assign these levels to appropriate orthogonal arrays.

3. Calculate S/N ratios from the experimental data.

$$\eta = \frac{S}{N} = 10 \log \frac{1}{r} \left( \frac{s_\beta - V_e}{V_N} \right)$$

4. Determine the optimal conditions for the process derived from the experimental data.

5. Conduct actual production runs.
XI. DESIGN FOR SIX SIGMA
B. ROBUST DESIGN AND PROCESS
1. FUNCTIONAL REQUIREMENTS

Signal-to-Noise Ratio

A signal-to-noise ratio (S/N) is used to evaluate system performance. The combinations of the design variables that maximize the S/N ratio are selected for consideration as product or process parameter settings.

Case 1: S/N ratio for “smaller-is-better”:
\[ S/N = -10 \log_{10} \left( \frac{\sum y_i^2}{n} \right) \]

\[ \eta = S/N = -10 \log_{10} \frac{\sum y_i^2}{n} \]

Case 2: S/N ratio for “larger-is-better”:
\[ S/N = -10 \log_{10} \left( \frac{\sum 1}{\sum \frac{1}{y_i^2}} \right) \]

\[ \eta = S/N = -10 \log_{10} \left( \frac{\sum 1}{\sum \frac{1}{y_i^2}} \right) \]

Case 3: S/N ratio for “nominal-is-best”:
\[ \eta = S/N = 10 \log_{10} \left( \frac{\text{mean}^2}{\text{variance}} \right) = 10 \log_{10} \frac{y^2}{S^2} \]
XI. DESIGN FOR SIX SIGMA
B. ROBUST DESIGN AND PROCESS
1. FUNCTIONAL REQUIREMENTS

Parameter Design Case Study

An experiment was conducted to find a method of assembly for an elastomer connector to a nylon tube for use in automotive engine components. The objective was to minimize the assembly effort. There are 4 controllable factors and 3 noise factors. The controllable factors are at 3 levels; the noise factors at 2 levels.

Given 4 factors at 3 levels, this would amount to 81 experiments. Taguchi has provided orthogonal arrays to reduce the amount of testing required. They are fractional factorial experiments without regard for interactions, in most cases.

An L9 array can be used for the controllable factors with 9 experimental runs. The 3 noise factors are placed in an L8 array. There are 8 runs of noise conditions. This array induces noise into the experiment to help identify the controllable factors that are least sensitive to a change in noise level.

The two arrays are combined to form the complete parameter design layout. The L9 array is called the inner array, while the L8 array is the outer array.
XI. DESIGN FOR SIX SIGMA
B. ROBUST DESIGN AND PROCESS
1. FUNCTIONAL REQUIREMENTS

Parameter Design Case Study (Cont.)

Example Orthogonal Design Layout

The completed matrix contains the mean response results. The larger the S/N ratio the better. S/N ratios are computed for each of the 9 experimental conditions. An ANOVA can also be used in the calculations to supplement the S/N ratios.

The optimum combination of factors and levels can be determined from the analysis. A confirmation run should be conducted to verify the results.
XI. DESIGN FOR SIX SIGMA
B. ROBUST DESIGN AND PROCESS
1. FUNCTIONAL REQUIREMENTS

The Loss Function

The loss function is used to determine the financial loss that will occur when a quality characteristic, $y$, deviates from the target value, $m$. The quality loss is zero when the quality characteristic, $y$, is at the target value, $m$. The quality loss function is defined as the mean square deviation of the objective characteristics from their target values. The function is depicted as:

$$L(y) = k(y - m)^2$$

$$k = \frac{\text{cost of a defective product}}{(\text{tolerance})^2} = \frac{A}{\Delta^2}$$

$$\sigma^2 = \text{mean value of } (y - m)^2$$

The function $L(y)$ shows that the further away from the target, the quality characteristic is, the greater the quality loss. The “$A$” value is the cost due to a defective product. The amount of deviation from the target, or “tolerance” as Taguchi calls it, is the delta ($\Delta$) value.

The mean square deviation from the target ($\sigma^2$), as used by Taguchi, does not indicate a variance.
The Loss Function (Continued)

Example 11.1: Given that Professor Barker wished to buy a pair of size 7 shoes but the store was and he had to settle for a pair of 7.5 shoes. After 2 days, he found them to be ill fitting and had to discard them. The original cost of the shoes was $50. The quality loss function can be applied to this situation.

The target value $m$ is 7.0
The existing quality characteristic $y$ is 7.5
The cost of a defective product $A$ is $50.
The hypothetical tolerance $(6.75 - 7.25)$ is 0.5

Solving for the quality loss function:

$$L(y) = k(y - m)^2$$

$$k = \frac{A}{\text{tolerance}^2} = \frac{\$50}{(0.5)^2} = \frac{\$50}{0.25} = \$200$$

$$L(y) = \$200(0.5)^2 = \$200(0.25) = \$50$$

The above calculations shows the quality loss to be $50.$
Noise Strategies

The design engineers will specify the design parameters of the chosen system for improved quality and reduced cost. A variety of tools are used to make the new system robust to various factors. Primary sources of variation that will affect the product:

- Environmental effects
- Deteriorative effects
- Manufacturing imperfections

The purpose of robust design is to make the product less sensitive to the effects. It is not economical to reduce these sources of variation directly. The design & development department will shoulder the major responsibility for reducing sources of variation (noise).
The tolerances for all system components must be determined. This includes the types of materials used. In tolerance design, there is a balance between a given quality level and cost of the design. The measurement criteria is quality losses. Quality losses are estimated by the functional deviation of the products from their target values plus the cost due to the malfunction of these products. Taguchi describes the approach as using economical safety factors.

The functional limit $\Delta_0$ must be determined by methods like experimentation and testing. Taguchi uses a LD50 point as a guide to establish the upper and lower functional limits. The LD50 point is where the product will fail 50% of the time. The 50% point is called the median.

An example from Taguchi illustrates the determination of the functional limit: A spark plug has a nominal ignition voltage of 20 kV. The lower functional limit $\Delta_{01}$ is -12 kV. The upper functional limit $\Delta_{02}$ is +18 kV. These values are determined by testing. The resulting specifications will have a lower tolerance ($\Delta_1$) of 8 kV and upper tolerance ($\Delta_2$) of 38 kV.

$$20 \text{ kV} - 12 \text{ kV} = 8 \text{ kV} \quad \text{and} \quad 20 \text{ kV} + 18 \text{ kV} = 38 \text{ kV}$$
Tolerance Design (Continued)

The formulas for tolerance specifications, the functional limit, and safety factors are as follows:

Tolerance Specifications:

\[
\text{Tolerance Specification} = \frac{\text{Function Limit}}{\text{Safety Limit}}
\]

Functional Limit:

\[
A_i = \frac{\Delta_{0i}}{\phi_i} \quad (i = 1, 2) \quad \text{Commonly} \quad \Delta = \frac{\Delta_0}{\phi}
\]

The economical safety factor $\phi$ is determined as follows:

\[
\phi = \sqrt{\frac{\text{Loss when exceeding functional limit}}{\text{Loss when exceeding tolerance specs}}} = \sqrt{\frac{A_0}{A}}
\]

Given the value of the quality characteristic at $y$, and the target value at $m$, the quality loss function will appear as follows:

\[
L(y) = \frac{A_0}{\Delta_0^2} (y - m)^2
\]
Example 11.2: An example on setting the tolerance specifications from Taguchi follows: A power supply for a TV set has the functional limits at +/- 25% of output voltage. The average quality loss $A_0$ after shipment of a bad TV is known to be $300. The adjustment of a power supply in-house before shipping is $1.00. Phi, $\phi$, is the economical safety factor and is calculated as:

$$\phi = \sqrt{\frac{A_0}{A}} = \sqrt{\frac{300}{1}} = 17.3$$

The tolerance specs for the output voltage will be:

$$\Delta = \frac{\Delta_0}{\phi} = \frac{25\%}{17.3} = 1.45\%$$

Therefore, the tolerance specification for the output voltage of 120 volts will be:

$$120 \pm (120)(0.0145) = 120 \pm 1.74 \text{ volts}$$

Although the functional limits were initially established at 120 ± 25%, or ± 30 volts, the TV sets should have output voltages within 1.74 volts of the nominal.
Example 11.3: The nominal width (m) of a door is 36 inches. The functional limits $\Delta$ of the same door are ± 0.5 inches. The economic loss due to a poor door is $50 (A_0)$ and the average manufacturing cost is $6 (A)$. The economical safety factor $\phi$ and tolerance specification can be determined as follows:

$$\phi = \sqrt[2]{\frac{A_0}{A}} = \sqrt[2]{\frac{50}{6}} = 2.89$$

$$\Delta = \frac{A_0}{\phi} = \frac{0.5''}{2.89} = 0.173 \text{ inches}$$

The manufactured door should have a tolerance of 36 ± 0.173 inches.

Smaller-is-Better Tolerances

The same formulas for calculating tolerances are used:

$$\phi = \sqrt[2]{\frac{A_0}{A}} \quad \text{and} \quad \Delta = \frac{A_0}{\phi}$$
Tolerance and Process Capability (Cont.)

Larger-is-Better Tolerances

In larger-is-better situations, the quality characteristics are also nonnegative and should be as large as possible. The economical safety factor $\phi$ is calculated as before:

$$\phi = \sqrt{\frac{A_0}{A}}$$

The tolerance specification for a larger-is-better tolerance is given by:

$$\Delta = \phi \Delta_0$$

Where, $\Delta$ is the tolerance specification required; and $\Delta_0$ is the functional limit.

The quality characteristic, for the larger-is-better situation, is designated as $y$ and the loss function is $L(y)$. When $y$ is infinite, $L(y)$ is zero. A new equation for the average loss function $L(y)$ is:

$$L(y) = \frac{A_0 \Delta_0^2}{y^2}$$
Larger-is-Better Tolerances (Continued)

Example 11.4: The wire used to hold ceiling planters is 0.5 inches$^2$ in area. It is supposed to hold at least 30 lbs, ($\Delta_0$), of plants. The cost of producing wire is $3 (A); while the failure costs of the wire amounts to $100 (A_0). The tolerance specification is determined as follows:

$$\phi = \sqrt{\frac{A_0}{A}} = \sqrt{\frac{100}{3}} = 5.77$$

Then, the strength specification for the wire will be:

$$\Delta = \phi \Delta_0 = 5.77(30) = 173.1 \text{ lbs}$$

Due to the relative costs and the economical safety factor, the wire should be 5.77 times the functional limit of 30 lbs.
Taguchi’s Quality Imperatives

- Robustness is a function of product design. Quality losses are a loss to society.
- Increasing the signal-to-noise ratio will improve the robustness of the product.
- For new products, use planned experiments to seek out the parameter targets.
- To build robust products, use customer-use conditions.
- Tolerances are set before going to manufacturing. The quality loss function can be measured.
- Products that barely meet the standard are only slightly better than products that fail the specifications. The aim is for the target value.
- The factory must manufacture products that are consistent by reducing variation.
- Reducing product field failures will reduce the number of defectives in the factory. Part variation reduction decreases system variation.
- Proposals for capital equipment for on-line quality efforts should include the average quality loss.
XI. DESIGN FOR SIX SIGMA
C. FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

Failure Mode Effects Analysis and Criticality Analysis

A FMECA provides the design engineer, reliability engineer and others a systematic technique to analyze a system, subsystem, or item, for all potential or possible failure modes. This method then places a probability that the failure mode will actually occur and what the effect of this failure is on the rest of the system.

The criticality portion of this method allows one to place a value or rating on the criticality of the failure effect on the entire system. It is not uncommon to omit the criticality portion from the methodology leaving us with a Failure Modes and Effects Analysis (FMEA).

A FMEA or FMECA (in some cases there is little if any difference) is a detailed analysis of a system down to the component level. Once all items are classified as to the 1) Failure Mode, 2) Effect of Failure, and 3) Probability failure will occur, they are rated as to their severity via an index called a RPN (Risk Priority Number).
XI. DESIGN FOR SIX SIGMA
C. FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

FMEA (FMECA) Process Steps

1. FMEA Number: This should be a log controlled number for tracking the document

2. The part number, name, or other description

3. The design responsibility: Which department or group is responsible for this design?

4. The person responsible for FMEA preparation

5. The date the FMEA was prepared and any necessary revision level

6. The subsystem or component part number getting detailed analysis

7. The component function

8. The potential failure mode

9. The potential effect of failure

10. The potential cause of failure

11. What are the current controls in place to prevent the cause from occurring?
XI. DESIGN FOR SIX SIGMA
C. FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

Risk Assessment and RPN

12. P is the probability this failure mode will occur. This index is from 1 to 10 with 1 being virtually no chance and 10 being near certainty of occurrence.

13. S is the severity of the effect of the failure on the rest of the system if the failure occurs. Values are from 1 to 10. A value of 1 means the user will be unlikely to notice with a 10 meaning that the safety of the user is in jeopardy.

14. D is a measure of the effectiveness of the current controls to identify the potential weakness or failure prior to release to production. This index ranges from 1 to 10. A value of 1 means this will certainly be caught whereas a value of 10 indicates the design weakness would most certainly make it to final production without detection.

15. RPN. The Risk Priority Number is the product of the indices from the previous three columns.
   \[ RPN = P \cdot S \cdot D \]

16. The actions then are based upon what items either have the highest RPN and/or where the major safety issues are.
XI. DESIGN FOR SIX SIGMA
C. FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

Risk Assessment and RPN (Continued)

17. There is a column for actions to be taken to reduce the risk, a column for this responsibility and finally a column for the revised RPN once corrective action is implemented.

FMECA provides a disciplined approach for the engineering team to evaluate designs to ensure that all the possible failure modes have been taken into consideration.

System FMECA

<table>
<thead>
<tr>
<th>PART NUMBER NAME</th>
<th>FUNCTION</th>
<th>POTENTIAL FAILURE MODE(S)</th>
<th>POTENTIAL EFFECT(S) OF FAILURE</th>
<th>CURRENT CONTROLS</th>
<th>POTENTIAL CAUSE(S) OF FAILURE</th>
<th>RISK ASSESSMENT</th>
<th>RECOMMENDED CORRECTIVE ACTION(S)</th>
<th>ACTION(S) TAKEN</th>
<th>REVISED RISK ASSESSMENT</th>
<th>RESPONSIBLE DEPT OR INDIVIDUAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>WILTON POWER LOCK</td>
<td>CLAMP LEAK</td>
<td>HOUSE-KEEPING WEAR</td>
<td>ACCEPT SUPPLIER'S INFO</td>
<td>2 4 3 24</td>
<td>DISCUSS WITH SUPPLIER</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LOSES CLAMPING FORCE (SHIFTING)</td>
<td>MACHINING PARTS OVERSIZE</td>
<td>SELECTED INADEQUATE SIZE POWER LOCK</td>
<td>ENG. STANDARD</td>
<td>2 4 4 32</td>
<td>PERFORM LOAD TESTS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OVER PRESSURE</td>
<td>NONE</td>
<td></td>
<td>2 4 2 16</td>
<td>REVIEW NEED FOR SYSTEM TO PREVENT OVER-PRESSURIZATION</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PUMP SIZING</td>
<td>ENG. STANDARD</td>
<td></td>
<td>1 4 2 8</td>
<td>REVIEW PRESSURE DELIVERED IN FIELD AND ACTUAL NEED</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Risk Assessment

Risk assessment is the combination of the probability of an event or failure and the consequence(s) of that event or failure to a system’s operators, users, or its environment. The analysis of risk of failure normally utilizes two measures of failure. These measures are:

- **Severity of failure** - The effect of the failure on the system, operators, or mission
- **Probability of failure** - The likelihood of the failure occurring

### Hazard Severity Categories

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I Catastrophic</td>
<td>A failure that may cause death or mission loss</td>
</tr>
<tr>
<td>II Critical</td>
<td>A failure that may cause severe injury or major system damage</td>
</tr>
<tr>
<td>III Marginal</td>
<td>A failure that may cause minor injury or degradation in mission performance</td>
</tr>
<tr>
<td>IV Minor</td>
<td>A failure that does not cause injury or system damage but may result in system failure and unscheduled maintenance</td>
</tr>
</tbody>
</table>
Risk Assessment (Continued)

Another example, using the concept for commercial applications is a severity index based on a scale of 10.

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unreasonable to expect that the minor nature of this failure will degrade the performance of the system</td>
</tr>
<tr>
<td>2 - 3</td>
<td>Minor nature of failure will cause slight annoyance to the customer. Customer may notice a slight deterioration of the system performance</td>
</tr>
<tr>
<td>4 - 6</td>
<td>Moderate failure will cause customer dissatisfaction. Customer will notice some system performance deterioration</td>
</tr>
<tr>
<td>7 - 8</td>
<td>High degree of customer dissatisfaction and inoperation of the system. Does not involve safety or noncompliance to government regulations</td>
</tr>
<tr>
<td>9 - 10</td>
<td>Very high severity ranking in terms of safety-related failures and nonconformance to regulations and standards</td>
</tr>
</tbody>
</table>

Commercial Severity Index (Scale 1 - 10)
Failure Mechanisms Versus Modes

The failure mode is the actual symptom of the failure. That is, the failure mode may be “Premature Engine Shut-down,” or “70% Degradation of Function,” or any other description of what external occurrence will be defined as a failure. These failure modes are the results of failure mechanisms.

Failure mechanisms are the individual, or multiple reasons that cause the failure mode. For instance, failure mechanisms might be “Corrosion,” or “Contamination,” or any other description of reasons that might cause a failure mode. Failure mechanisms cause failure modes.
XI. DESIGN FOR SIX SIGMA
C. FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

Types of FMEAs

- **Design FMEA** - performed on the product or service at the design level. The purpose is to analyze how failure modes affect the system, and to minimize failure effects upon the system.

- **Process FMEA** - performed on the manufacturing processes. They are conducted through the quality planning phase as an aid during production. Failure modes in manufacturing or potential sources of error are highlighted and corrective action taken.

- **System FMEA** - comprise part level FMEAs. All of the part level FMEAs will tie together to form the system. As a FMEA (part level FMEA) goes lower into the system, into more detail, more failure modes will be considered.

- **Functional FMEA** - also known as “Black Box” FMEAs focus on the performance of function of the intended part or device, rather than on the specific characteristics or specifications.
Design for X (DFX)

Design for X (DFX) is defined as a knowledge-based approach for designing products to have as many desirable characteristics as possible. The desirable characteristics include: quality, reliability, serviceability, safety, user friendliness, etc. This approach goes beyond the traditional quality aspects of function, features, and appearance of the item.

AT&T Bell Laboratories coined the term DFX to describe the process of designing a product to meet the above characteristics. In doing so, the life cycle cost of a product and the lowering of down-stream manufacturing costs would be addressed.

The DFX toolbox has continued to grow in number from its inception 15 years ago to include hundreds of tools today. The usual practice is to apply one DFX tool at a time. Multiple applications of DFX tools can be costly.

A systematic framework is not yet available of use of DFX methodology.
Usage of DFX Techniques and Tools

1. Design guidelines: Rules of thumb provide broad design rules and strategies. The rule to increase assembly efficiency requires a reduction in part count.

2. DFX analysis tools: Each DFX tool involves some analytical procedure that measures the effectiveness of the selected tool.

3. Determine DFX tool structure: A technique may require other calculations before the technique can be considered complete. An independent tool will not depend on the output of another tool.

4. Tool effectiveness and context: Each tool can be evaluated for usefulness by the user based on accuracy of analysis, reliability characteristics and/or integrity of the information generated.

5. The focus of activity and the product development process: If the product development process is understood by the design team will help determine when a particular tool can be used.

6. Mapping tool focus by level: Several levels of analysis may be involved with one individual tool. The structure may dictate the feasibility of tool use.
DFX Characteristics

The following characteristics and attributes should be considered by DFX projects.

- Function and performance
- Safety
- Quality
- Reliability
- Testability
- Manufacturability
- Assembly (Design for Assembly, DFA)
- Environment (Design for the Environment, DFE)
- Serviceability (Maintainability and Repairability)
- Maintainability
- User Friendliness, or Ergonomics
- Appearance (Aesthetics)
- Packaging
- Features
- Time to Market
TRIZ

TRIZ is a Russian abbreviation for “the theory of inventive problem solving.” Genrich Altshuller states that inventiveness can be taught. Creativity can be learned, it is not innate, one does not have to be born with it.

Altshuller solidified a theory that one solves problems through a collection of assembled techniques. Technical evolution and invention have certain patterns. One should be knowledgeable with them to solve technical problems. There is some common sense, logic and use of physics in problem solving.

There are three groups of methods to solve technical problems:

1. Various tricks (a reference to a technique)

2. Methods based on utilizing physical effects and phenomena (changing the state of the physical properties of substances)

3. Complex methods (combination of tricks and physics)
TRIZ (Continued)

Initially there were 27 TRIZ tools which were later expanded to 40 innovative, technical tools. The sequence of 9 action steps in the use of TRIZ:

1. Analysis of the problem
2. Analysis of the problem’s model: Use of a block diagram defining the “operating zone”
3. Formulation of the ideal final result (IFR): which will provide more details
4. Utilization of outside substances and field resources
5. Utilization of an informational data bank: Determining the constraints on the problem
6. Change or reformulate the problem
7. Analysis of the method that removed the physical contradiction: Is a quality solution provided?
8. Utilization of the found solution: Seeking side effects of the solution
9. Analysis of the steps that lead to the solution
Axiomatic Design

Axiomatic design is a design methodology that seeks to reduce the complexity of the design process. It accomplishes this by providing a framework of principles that guide the designer/engineer. The axioms appear simple, but applications are complicated. This method has attracted many converts in the last 20 years.

Nam P. Suh is the developer of this technique. “The goal of axiomatic design is to make human designers more creative, reduce the random search process, minimize the iterative trial-and-error process, and determine the best design among those proposed.”

The axiomatic design process consists of basic steps:

- Establish design objectives to meet customer needs
- Generate ideas to create solutions
- Analyze the possible solutions for the best fit to the design objectives
- Implement the selected design
Axiomatic Design (Continued)

Axiomatic design is a systematic, scientific approach which breaks the design requirements into 4 different parts or domains:

- **Customer domain**: The needs of customers are identified.

- **Functional domain**: These are the functional requirements (FRs) the customer wants.

- **Physical domain**: These are the design parameters (DPs) that will meet the functional requirements.

- **Process domain**: These are manufacturing variables to produce the product.

There is a “mapping” of requirements from one domain to the next.
Axiomatic Design (Continued)

In this methodology, each requirement is filled by one variable. That is, 5 functional requirements (FRs) will be matched up by 5 design parameters (DPs). If not, then the axiomatic design methodology is violated.

The solutions for each domain are described as:

- Mapping between customer and functional domains: concept design
- Mapping between functional and physical domains: product design (drawings, specs, tolerances)
- Mapping between physical and process domains: process design

Suh proposed that there must exist a fundamental set of principles that determine good design practices. A search was made for these principles, which were translated into axioms. An axiom is a formal statement of what is known or used routinely.
Axiomatic Design (Continued)

The design axioms are:

- **Axiom 1**: The independence axiom - The functional requirements (FRs) are independent of each other.
- **Axiom 2**: The information axiom - The best design has the minimal amount of information content.

Two constraints (design constraints and system constraints) represent the bounds on an acceptable solution.

A company wished to reduce its materials cost without loss of certain mechanical properties. The problem definition of FRs will be:

- **FR1** = Reduce material costs by 20%
- **FR2** = Maintain original mechanical properties
- **Constraint** = Overall manufacturing costs must be less than the current cost.

The design parameters are chosen to satisfy the FRs.
- **DP1** = Obtain a cheaper filler material
- **DP2** = The filler material should have the equivalent strength
Axiomatic Design (Continued)

Suh defined information as:

“The measure of knowledge required to satisfy a given FR at a given level of the FR hierarchy.”

For example, consider a requirement to machine a shaft to $4m \pm 0.1m$. The calculation follows:

Probability ($p$) = ratio of tolerance to dimension

$$p = \frac{\text{tolerance}}{\text{dimension}} = \frac{2(0.1)}{4} = \frac{1}{20}$$

Information = $I = \log_2 \left( \frac{1}{p} \right) = \log_2(20) = 4.32$ bits

Information is given in a logarithmic base 2. The best design has the lowest $I$ index. The natural log (base e) can also be used. If so, the unit of measurement will be in nats. 1 nat = 1.443 bits. The above calculation would become:

Information = $I = \ln(20) = 3.00$ nats
Axiomatic Design (Continued)

Axioms are fundamental truths that are always observed to be valid without exception. Theorems and corollaries are derived from axioms. Suh developed 2 axioms, 8 corollaries, and 16 theorems that form the framework of axiomatic design.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axiom 1</td>
<td>The independence axiom</td>
</tr>
<tr>
<td>Axiom 2</td>
<td>The information axiom</td>
</tr>
<tr>
<td>Corollary 1</td>
<td>Decoupling of coupled designs</td>
</tr>
<tr>
<td>Corollary 2</td>
<td>Minimization of FRs</td>
</tr>
<tr>
<td>Corollary 3</td>
<td>Integration of physical parts</td>
</tr>
<tr>
<td>Corollary 4</td>
<td>Use of standardization</td>
</tr>
<tr>
<td>Corollary 5</td>
<td>Use of symmetry</td>
</tr>
<tr>
<td>Corollary 6</td>
<td>Largest tolerance</td>
</tr>
<tr>
<td>Corollary 7</td>
<td>Uncoupled design with less information</td>
</tr>
<tr>
<td>Corollary 8</td>
<td>Effective reangularity of a scalar</td>
</tr>
</tbody>
</table>
### Axiomatic Design (Continued)

<table>
<thead>
<tr>
<th>Topic</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theorem 1</td>
<td>Coupling due to insufficient number of DPs</td>
</tr>
<tr>
<td>Theorem 2</td>
<td>Decoupling of coupled designs</td>
</tr>
<tr>
<td>Theorem 3</td>
<td>Redundant design</td>
</tr>
<tr>
<td>Theorem 4</td>
<td>Ideal design</td>
</tr>
<tr>
<td>Theorem 5</td>
<td>Need for a new design</td>
</tr>
<tr>
<td>Theorem 6</td>
<td>Path independency of uncoupled designs</td>
</tr>
<tr>
<td>Theorem 7</td>
<td>Path dependency of coupled and uncoupled designs</td>
</tr>
<tr>
<td>Theorem 8</td>
<td>Independence and tolerance</td>
</tr>
<tr>
<td>Theorem 9</td>
<td>Design for manufacturability</td>
</tr>
<tr>
<td>Theorem 10</td>
<td>Modularity of independence measures</td>
</tr>
<tr>
<td>Theorem 11</td>
<td>Invariance</td>
</tr>
<tr>
<td>Theorem 12</td>
<td>Sum of information</td>
</tr>
<tr>
<td>Theorem 13</td>
<td>Information content of the total system</td>
</tr>
<tr>
<td>Theorem 14</td>
<td>Information content of coupled versus uncoupled designs</td>
</tr>
<tr>
<td>Theorem 15</td>
<td>Design-Manufacture interface</td>
</tr>
<tr>
<td>Theorem 16</td>
<td>Equality of information content</td>
</tr>
</tbody>
</table>
Set-based Design

Set-based design is an engineering design methodology that pertains to Toyota’s set-based concurrent engineering design. Set-based concurrent engineering (SBCE) design begins with broad sets of possible solutions, converging to a narrow set of alternatives and then to a final solution.

Design teams from various functions can work sets of solutions in parallel, gradually narrowing sets of solutions. Information from development, testing, customers, others will help narrow the decision sets. Sets of ideas are viewed and reworked leading to more robust, optimized, and more efficient projects. This approach is deemed to be more efficient than working with one idea at a time.
Systematic Design

Systematic design is a step by step approach to design. It provides a structure to the design process using a German methodology. A method that is close to the guidelines as written by the German design standard: Guideline VDI 2221 “Systematic Approach to the Design of Technical Systems and Products.”

Four main phases in the design process:

- Clarification of the task: collect information, formulate concepts, identify needs
- Conceptual design: identify essential problems and sub-functions
- Embodiment design: develop concepts, layouts, refinements
- Detail design: finalize drawings, concepts and generate documentation

An abstract concept is developed into a concrete item, represented by a drawing. Synthesis involves search and discovery, and the act of combining parts or elements to produce a new form.
Systematic Design (Continued)

Modern German design thinking uses the following structure:

- The requirements of the design are determined
- The appropriate process elements are selected
- A step-by-step method transforms qualitative items to quantitative items
- A deliberate combination of elements of differing complexities is used

The main steps in the conceptual phase:

- Clarify the task
- Identify essential problems
- Establish function structures
- Search for solutions using intuition and brainstorming
- Combine solution principles and select qualitatively
- Firm up concept variants: preliminary calculations, and layouts
- Evaluate concept variants
Pugh Concept Selection

Stuart Pugh was a leader in product development (total design) methodology. QFD can be used to determine customer technical requirements. Pugh suggests a cross-functional team activity to assist in the development of improved concepts.

The process starts with a set of alternative designs. These early designs come from various individuals in response to the initial project charter. A matrix-based process is used to refine the concepts. During the selection process, additional new concepts are generated. The final concept will generally not be the original concept. The Pugh concept selection process has 10 steps:

- Choose criteria
- Form the matrix
- Clarify the concepts
- Choose the datum concept
- Run the matrix
- Evaluate the ratings
- Attack the negatives and enhance the positives
- Select a new datum and rerun the matrix
- Plan further work
- Iterate to arrive at a new winning concept
### Pugh Concept Selection (Continued)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Concepts</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<tbody>
<tr>
<td>A</td>
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<td>s</td>
<td>D</td>
<td>s</td>
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<td>-</td>
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<td>Pluses</td>
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<td>1</td>
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<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

**Pugh Evaluation Matrix**
XI. DESIGN FOR SIX SIGMA
QUESTIONS

11.1. A number of authors have recommended sequences by which the HOQ (QFD) can capture customer needs in the design. Please arrange the following design details in appropriate sequence from start to finish.

I. Production requirements
II. Key process operations
III. Parts characteristics
IV. Engineering characteristics

a. I, II, III, IV  
b. II, I, IV, III  
c. IV, II, III, I  
d. IV, III, II, I

11.6. The design steps in Taguchi's robust design sequence are:

I. Concept design
II. Parameter design
III. Tolerance design

a. I, II, III  
b. I, III, II  
c. II, I, III  
d. III, I, II

11.12. Failure modes and effects analysis involves what activity?

a. The determination of the probability of failure in a specified period of time
b. The expected number of failures in a given time interval
c. The study of the physics of failure to determine exactly how a product fails and what causes the failure
d. A study of the probability of success in a given time period

Answers 11.1 d, 11.6 a, 11.12 c
XI-60   (730)

XI. DESIGN FOR SIX SIGMA
QUESTIONS

11.18. Identify the design acronym(s) that would be considered (a) subset(s) of DFX:

I. DFSS
II. DFA
III. DFM

a. I only  c. I and III only
b. II and III only  d. I, II and III

11.20. When faced with a complex problem which requires an inventive solution, the method which produces the results with the least wasted time, effort and resources is:

a. Trial and error
b. Innate inventitiveness
c. Using ARIZ steps in the TRIZ method
d. Plan-do-check-act (PDCA)

11.22. Customer, functional, physical and process domains are considered component elements of which of the following DFSS approaches?

a. Axiomatic design
b. Design for X (DFX)
c. TRIZ
d. Set based concurrent engineering (SBCE)

Answers  11.18 b,  11.20 c,  11.22 a