

CHAPTER 5

PRODUCING RELIABLE SYSTEMS

5-1. Control configuration

The concept of Configuration Control was introduced in chapter 4. The process of managing the configuration must continue throughout the manufacturing and production process. Manufacturing and production includes not only the process, machines, and people organic to the developer but also those of suppliers. Preferred parts and supplier lists not only assist designers in selecting parts and materials, but they can help in controlling configuration.

a. *Control of processes, tools, and procedures.* Just as the configuration of the design must be controlled, so too must the configuration of the processes, tools, and procedures used to manufacture the system. Even changes that at first appear to be minor and inconsequential can seriously degrade the system reliability. Changes to processes, tools, and procedures must be made with the same level of discipline used for design changes.

b. *Configuration of purchased items.* A variety of criteria can be used in selecting suppliers, including on-time delivery, price, and reliability and quality. Good selection criteria and supplier relationships, especially for critical parts, materials, and assemblies, can help maintain configuration control in several ways.

(1) The supplier is more likely to notify the buyer of unexpected failures, changes in processes or technology, and other changes that could affect the performance of the system.

(2) The supplier is more likely to implement design practices consistent with those being used for the system.

(3) Without insight into or control of the configuration of purchased items, the configuration of the system cannot be determined.

5-2. Design processes

Industrial engineers and manufacturing specialists are responsible for designing the processes, tools, and procedures that will be used to transform the design into a system. In chapter 4, the idea of including the manufacturing staff in the system design process was introduced. Including them has several benefits.

a. *Allows for lead time.* Many parts, some materials, manufacturing machines, and new processes require time to acquire or develop; in other words, they are not readily available "off-the-shelf." This time is referred to as lead time. Without sufficient and timely information as to what manufacturing equipment or processes will be needed, advance planning cannot be done and schedules will not include sufficient lead times. By including manufacturing early in the design process, the manufacturing people will have the information they need to plan for new manufacturing equipment and processes.

b. *Enhances manufacturability.* Some designs are inherently easier to manufacture than others. Certainly, the ease of manufacture is related to the nature of the system: it is easier to make a lamp than a radar. However, the degree of manufacturability is first and foremost a function of conscious efforts to design for manufacture. Including industrial engineers and manufacturing specialists in the design process affords them the opportunity to influence the design to enhance manufacturability. Although ease of manufacture cannot always take precedence over other requirements, it should always be considered in trade-offs. The objective of ease of manufacture can be achieved only if it receives conscious and continual attention during design.

5-3. Train personnel

Table 5-1 includes training in the list of factors affecting production readiness. Training can be required for a variety of reasons and may include certification or similar requirements.

a. *Training for new processes and equipment.* When it is necessary to acquire new production equipment or to acquire or develop new processes to manufacture a product, the operators of the new equipment or processes must be adequately trained. As a matter of practicality, such training should be conducted early enough to allow some level of verification of the effectiveness of both the training and the operation of the equipment and processes. Ideally, operators, equipment, and processes will be "mature" before production begins. In reality, some amount of "learning" will be experienced during the early stages of production. This learning will evidence itself in manufacturing defects, analysis of those defects, development of improvements to eliminate (or reduce to an acceptable level) those defects, and implementation and verification of the improvements.

Table 5-1. Examples of parameters measured for process control

Category	Examples
Physical	Size (length, width, height), weight, strength, etc.
Performance	Gain, frequency, power output, etc.
Failure-related	Service life, failure rate, defect rate, reject rate, etc.
Cycle time	Time to produce, time from order to delivery, design cycle, etc.
Cost	Cost to produce, warranty costs, scrap produced, rework costs, overhead rate, etc.

b. *Retaining current certifications.* Even when no new equipment or processes are needed, it is important that the machine and process operators are fully qualified. For some machines and processes, certifications (required by a government agency, the customer, or the company) are required. Such certifications usually expire unless recertification is earned. It is important that all such certifications be kept up to date.

5-4. Institute quality control

Assuring that the materials and parts, processes, and personnel needed to manufacture a system is the responsibility of quality. A comprehensive quality plan will include many activities. Key among these activities will be incoming inspection, process control, and acceptance testing.

a. *Incoming inspection.* Ensuring that the materials, parts, assemblies, and other items purchased from outside sources meet all design requirements is an important part of quality control. Often, as part of source selection, suppliers will be authorized and required to conduct the acceptance testing. Otherwise, such testing is done at the point of receipt. In any case, the types of tests, test procedures, sample size or 100% inspection, pass/fail criteria, and so forth must be established well in advance of production.

b. *Process control.* Every process has some variation in its output. Supposedly identical manufactured products will vary in size, strength, defect content, etc. The greater the variation, the less often the customer will be satisfied. Keeping a process in control is key to manufacturing products that meet requirements and faithfully reflect the designer's ideas. Statistical process control (SPC) is the default standard in nearly every company and industry. Implementing statistical process control basically involves the use of statistical tools to measure and analyze variability in work processes. The objective is to monitor process output and maintain the process to a fixed level of variation. Usually SPC is considered a part of statistical quality control, which refers to using statistical techniques for measuring and improving the *quality* of processes. These include sampling plans, experimental design, variation reduction, process capability analysis, and process improvement plans.

(1) The first task in measuring variation is to determine the parameters that most impact the customer's satisfaction. These will be measures of quality. Some possibilities are shown in table 5-1.

(2) Control charts. A key SPC tool is the control chart. A control chart is a graphical representation of certain descriptive statistics for specific quantitative measurements of a process. These descriptive statistics are displayed in the control chart and compared with their "in-control" sampling distributions. The comparison will reveal any unusual variation in the process, which could indicate a problem. Several different descriptive statistics can be used in control charts and there are several different types of control charts that can test for different causes. Control charts are also used with product measurements to analyze process capability and for continuous process improvement efforts. Table 5-2 shows some typical control charts.

Table 5-2. Typical control charts

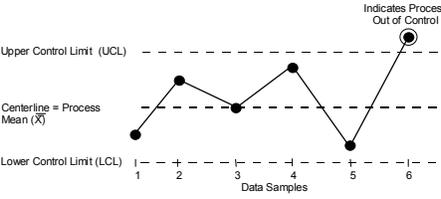
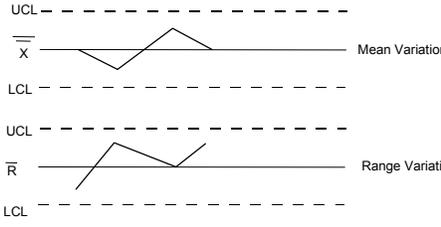
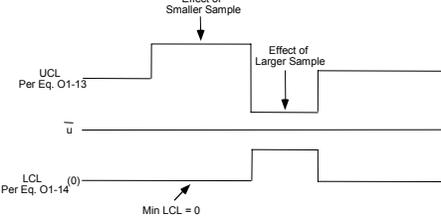
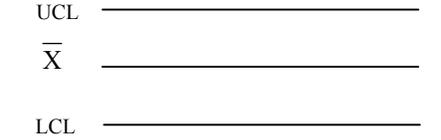
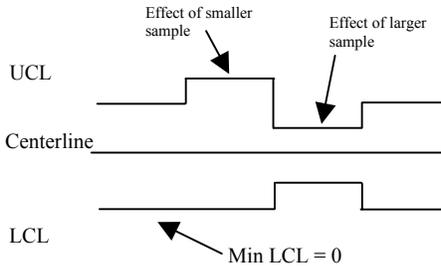
Chart	Equation	Notes
<p>Variable</p>  <p>Upper Control Limit (UCL)</p> <p>Centerline = Process Mean (\bar{X})</p> <p>Lower Control Limit (LCL)</p> <p>Data Samples</p>	$UCL = \bar{X} + \frac{3\sigma}{\sqrt{n}}$ $LCL = \bar{X} - \frac{3\sigma}{\sqrt{n}}$ <p>\bar{X} = Process mean</p> <p>σ = Process standard deviation</p> <p>n = sample size</p>	<p>Chart shown assumes constant sample size</p>
<p>Variable and Range</p>  <p>UCL</p> <p>\bar{X}</p> <p>LCL</p> <p>Mean Variation</p> <p>UCL</p> <p>\bar{R}</p> <p>LCL</p> <p>Range Variation</p>	$UCL \bar{X} = \bar{X} + A_2 \bar{R}$ $LCL \bar{X} = \bar{X} - A_2 \bar{R}$ $UCL (\bar{R}) = D_4 \bar{R}$ $LCL (\bar{R}) = D_3 \bar{R}$ <p>\bar{X} = Process Mean</p> <p>\bar{R} = Mean Range</p>	<p>Range = Highest value measured in sample minus lowest value</p> <p>\bar{R} = Mean range of many samples</p> <p>A_2, D_3, D_4 are constants based on sample size (available in statistics texts).</p>
<p>Proportions</p>  <p>UCL</p> <p>Per Eq. O1-13</p> <p>\bar{p}</p> <p>LCL</p> <p>Per Eq. O1-14⁽⁰⁾</p> <p>Min LCL = 0</p> <p>Effect of Smaller Sample</p> <p>Effect of Larger Sample</p>	$UCL = \bar{P} + 3 \sqrt{\frac{\bar{P}(1-\bar{P})}{n}}$ $LCL = \bar{P} - 3 \sqrt{\frac{\bar{P}(1-\bar{P})}{n}}$ <p>Centerline = \bar{P}</p> <p>\bar{P} = Proportion of product with attribute of interest</p> <p>n = Sample size</p>	<p>\bar{P} could be the proportion of product which is defective, determined from experience, or it may be the specified allowable proportion defective</p>
<p>Proportions – Constant sample size</p>  <p>UCL</p> <p>\bar{X}</p> <p>LCL</p>	$\bar{X} = n \bar{P}$ $UCL = \bar{X} + 3\sqrt{\bar{X}(1-\bar{P})}$ $LCL = \bar{X} - 3\sqrt{\bar{X}(1-\bar{P})}$ <p>n, P as for Proportions</p>	<p>\bar{X} = Average number of units in a sample size with the attribute of interest</p>
<p>Rates</p>  <p>UCL</p> <p>Centerline</p> <p>LCL</p> <p>Effect of smaller sample</p> <p>Effect of larger sample</p> <p>Min LCL = 0</p>	$UCL = \bar{\mu} + \frac{3\sqrt{\bar{\mu}}}{\sqrt{n}}$ $UCL = \bar{\mu} - \frac{3\sqrt{\bar{\mu}}}{\sqrt{n}}$ <p>Centerline = $\bar{\mu}$</p> <p>$\bar{\mu}$ = Average rate</p> <p>n = Sample size</p>	<p>$\bar{\mu}$ could be the average number of defects per unit from experience, or the specified allowable defect rate</p>

Table 5-2. Typical control charts (Cont'd)

Chart	Equation	Notes
Rates – Constant sample size		
UCL _____	$UCL = \bar{\mu} + 3\sqrt{\bar{\mu}}$	\bar{r} could be the average number of defects per unit from experience, or the specified allowable defect rate
\bar{R} _____	$UCL = \bar{\mu} - 3\sqrt{\bar{\mu}}$	
LCL _____	\bar{R} = Average rate per sample	

(3) Process capability. The capability of a process is defined as the inherent variability of a process in the absence of any undesirable special causes. Special causes include part wear, environmental disturbances, loose fasteners, untrained workers, substandard materials, changes in shift or suppliers, etc. The process capability is the smallest variability of which the process is capable with variability due solely to common causes. A common cause is inherent process randomness. Typically, processes follow the Normal probability distribution (see table 5-3). When the Normal is applicable, a high percentage of the process measurements fall between $\pm 3\sigma$ (plus or minus 3 standard deviations) of the process mean or center. That is, approximately 0.27% of the measurements would naturally fall outside the $\pm 3\sigma$ limits, with the balance (approximately 99.73%) within the $\pm 3\sigma$ limits. Since the process limits extend from $\pm 3\sigma$ to $\pm 3\sigma$, the total spread amounts to about 6 σ total variation. The two primary measures of process capability are shown in table 5-4.

Table 5-3. Normal distribution

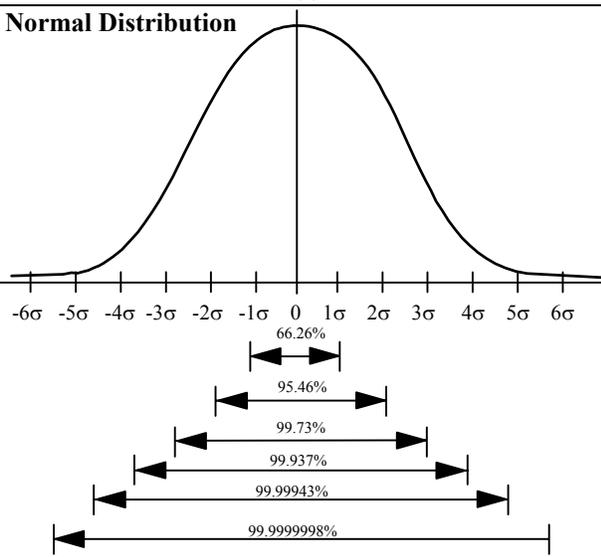
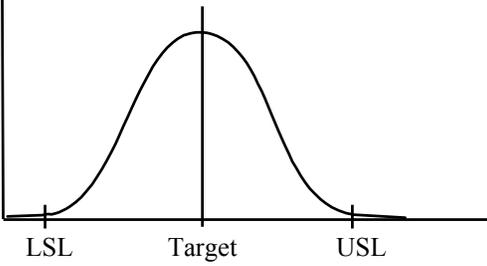
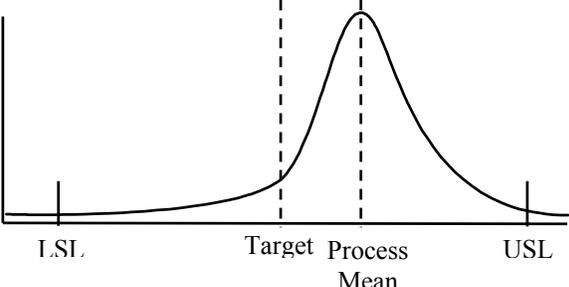
Tool	Equation
<p>Normal Distribution</p>  <p>The figure shows a normal distribution curve centered at 0. The x-axis is marked with standard deviations from -6σ to 6σ. Horizontal double-headed arrows indicate the percentage of data falling within each interval:</p> <ul style="list-style-type: none"> ±1σ: 66.26% ±2σ: 95.46% ±3σ: 99.73% ±4σ: 99.937% ±5σ: 99.9943% ±6σ: 99.99998% 	$\sigma = \sqrt{\frac{\sum_{i=1}^j (\bar{X}_i - \bar{\bar{X}})^2}{j-1}}$ <p>\bar{X}_i = mean of the i^{th} sample $\bar{\bar{X}}$ = Mean of all samples j = Number of samples σ = standard deviation A fixed proportion of the product falls between any given values of σ. Hence, σ increases as variation increases</p>

Table 5-4. Measures of process capability

<p>Process Capability</p> 	$C_p = \frac{USL - LSL}{6\sigma}$ <p>USL = Upper specification limit LSL = Lower specification limit σ = Standard deviation Cp < 1 Generally considered poor Cp = 1 Generally considered marginal (99.7% in spec) Cp ≥ 1.3 Generally considered good</p>
<p>Process Performance</p> 	$C_{pk} = \frac{\text{Min} \{(USL - \mu); (\mu - LSL)\}}{3\sigma}$ <p>Min {a;b} = Smaller of the two values USL, LSL, σ = As for Cp μ = Process mean Cpk < 1 Considered poor Cpk = 1.5 Considered excellent (Goal of "6σ" programs)</p>

c. *Acceptance testing.* For products that are relatively expensive and complex, some form of product-level testing is desirable. The purpose of such testing is two-fold. First, it is better business to find a faulty product before shipping the product and having a customer find it. Second, by periodic tests, negative trends in product reliability can be detected and corrective action taken before too many products have been shipped. When tests are conducted for the latter purpose, the test used to demonstrate the product reliability during development (see Paragraph 4-7) can be repeated on a sample basis.

5-5. Conduct screening and testing

Screening eliminates unacceptable parts, thereby preventing them from being used in a finished system. Screening is one type of testing commonly conducted during testing. Another important type of testing often used during production is additional reliability testing.

a. *Burn-in.* Burn-in is one type of screening test. Burn-in is an attempt to eliminate early or infant failures. Using burn-in, we select the best items from a production run or lot, eliminating substandard or unacceptable ones. Ideally, we would have no unacceptable items – our design, quality control, and production control would maintain the variation in quality of individual items within acceptable limits. Even with the best controls, however, some quantity of unacceptable parts will exist due to our limited ability to design in and control reliability. Burn-in does not and cannot increase the inherent reliability of the system but controls the number of defective parts and items used in the system.

b. *Reliability testing.* Analyses and tests were used during design to achieve the required level of reliability and provide some measure of the inherent reliability. During production, especially long production runs, when changes can occur in even well-managed manufacturing, reliability is often used to ensure that no degradation in reliability due to manufacturing is occurring. The idea is to catch any negative trends before a large number of systems with inadequate reliability are delivered to the customer and take corrective action.

5-6. Production readiness

Being ready to start production on schedule can mean the difference between success and failure for many companies. Including manufacturing in the design process increases the probability of being ready to start production on schedule. Many factors determine readiness to start production. Table 5-5 lists some of the factors already discussed in this chapter with some key readiness questions.

Table 5-5. Some of the factors affecting production readiness

Factors	Key Questions
Processes	<ol style="list-style-type: none"> 1. Are all processes developed and proved out? 2. Is there a plan for quality control, including statistical process control?
Manufacturing equipment	<ol style="list-style-type: none"> 1. Is all manufacturing equipment in place and calibrated? 2. Has the equipment been proved out (e.g., pilot production)?
Personnel	<ol style="list-style-type: none"> 1. Have the people with the requisite experience and skills been hired in the necessary numbers?
Training	<ol style="list-style-type: none"> 1. Have the equipment operators and other manufacturing staff received the necessary training, earned any required certifications, and met any other requirements associated with the manufacture of the system?
Burn-in or screening	<ol style="list-style-type: none"> 1. Have burn-in and screening plans been developed and checked for realism and practicality?
Suppliers	<ol style="list-style-type: none"> 1. Are contracts in place with all suppliers? 2. Do the contracts include delivery, quality, and reliability requirements consistent with the system requirements?*
Packaging, Handling, and Transportation	<ol style="list-style-type: none"> 1. Has the packaging been identified (standard packaging) or designed (custom packaging)? 2. Are plans in place to transport the system to the customer? If applicable, do the plans address transport of hazardous materials; any waivers to Federal, state, or local laws; or special arrangements (e.g., security)?

*Usually only for critical items – not for common items commercially available.