ACCURACY CONTROL IMPLEMENTATION MANUAL

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Accuracy Control Implementation Manual

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On behalf of the
Shipyard Production Process Technologies Panel

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Executive Summary

This manual is intended to help further implementation of accuracy control in U. S. shipyards. The manual covers a small amount of theory, but concentrates on practical considerations in implementation. It contains concrete examples from U. S. practice and also shows the progression of accuracy control in mature applications, especially in Japan. Additionally, it provides examples from related industries. Thus, it can also be useful in indicating potential future directions for A/C activities.

The manual is in nine chapters, plus a final chapter that contains a glossary of important terms and notation. Chapter one is a brief theoretical introduction to key topics in statistical quality control, as well as a description of the basic meaning of accuracy control. Chapter two is the most important chapter, providing a how to description of all aspects of A/C, with some brief examples. Chapter three provides examples and pictures of many aspects of A/C implementation, drawing on U. S. experience as well as Japanese experience. Chapter four presents A/C and dimensional control implementation in related industries, including aerospace and heavy truck manufacturing. Chapter five presents the current state of the art in A/C hardware and chapter six does the same for A/C software. Chapter seven introduces organizational aspects of A/C implementation and chapter 8 describes human resource considerations. Chapter 9 is a brief review of the key material presented in more detail in the preceding chapters.

The manual can be used as a training tool as well as reference. It is intended to be a living document, which can be updated and customized to the specific needs of individual shipyards.

Acknowledgement:

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Chapter 1. Accuracy Control Theory

1. 1 Introduction to Accuracy Control

Accuracy control, which is based on statistical quality control, is defined as the reduction of variability in processes and products. In the shipbuilding industry, accuracy control means the use of statistical techniques to monitor, control and continuously improve shipbuilding design details and work methods so as to reduce variation and maximize productivity.[1] Accuracy control must involve everyone to ensure success. This means everyone from top management to the lowest technician including all office support staff. It must be a culture change within the company in order for it to be successful long term. A review of the history of the quality control movement is given below.

Early in the 20th century, the concepts of quality and productivity were introduced to different industries. However, at that time, quality control was implemented by inspection. That means, after products are finished, the workers check them one by one and qualified products will be shipped to the customers. Such 100% inspection increases the quality cost and also decreases the productivity. During the 1920's, W.A. Shewhart introduced the control chart concept while working at Bell Laboratories. This is considered to be the first formal statistical quality control tool. In his book *The Economic Control of Quality of Manufactured Product*, he pointed out that through the statistical analysis of the data collected in an industrial process, it could be determined if the process could be considered to be in control or if it was being affected by special causes.

However, during the following 40 years, except during World War II, the statistical quality control method was not widely used.

This situation lasted until Japan began to rebuild its industrial base after World War II. In the late 1940's, Deming was invited to introduce the statistical quality control method to Japanese industry. Japanese industry quickly accepted this quality control method and applied it to its production lines. The result was amazing. It not only helped to improve the productivity, but also to build customer satisfaction in Japanese products based on their high quality. Today, most Japanese products such as Toyota and Honda cars, Sony and Mitsubishi electronics and so on, are very famous for their top quality. Twenty years after Deming's quality control seminars in Japan, U.S. industry finally realized the importance of statistical quality control and began to make its way to the implementation of total quality management. Today, nearly all big manufacturing companies have their own quality department, and quality of products has become extremely important to the customers, as well to the manufacturers. [2]

Accuracy control in the U.S. shipbuilding industry started later than the world leader - Japan. In fact, as part of the national movement to quality control in the 60's-70's, Japanese shipyards began to introduce accuracy control to ship production. In 1967, the Society of Naval Architects of Japan confirmed the great effect on improving the performance of work processes by using statistical control methods. The process innovation of ship designs and building methods, together with accuracy control, helped Japanese shipyards become the most productive and competitive shipbuilders in the world. [3] In contrast, the U.S. shipbuilding industry began the movement to accuracy control very late. During the cold war period, the biggest client of U.S. shipyards was the U.S. government, primarily the U.S. Navy. Due to lack of competition, the importance of accuracy control in shipbuilding was not recognized by the U.S. shipbuilding industry. However, as the cold war ended, the drawdown in the defense budget put many U.S. shipyards in trouble. Their low productivity and lack of statistical quality control procedures made them noncompetitive in the world commercial shipbuilding market.

In a recent investigation about accuracy control in Japanese, South Korean, European and U.S. shipyards, it was reported that [5,6,7]

For Japanese and South Korean shipyards:

- All have full dimensional control and quality control departments and systems through the pre-production and production activities.
- Complete procedures and standards for the accuracy control activities
- A self-check statistical process control system is fully implemented
- Effective implementation and documentation to ISO-9000 or equivalent
- A/C system is effective in improving quality and minimizing costs

For the European shipyards:

- Most yards have high levels of implementing accuracy control activities
- Self-check statistical process control is normal

- Most yards can minimize the use of excess material while keeping the high level of confidence in the dimensional accuracy of all components

For the U.S. shipyards:

- Most shipyards use modern equipment to implement dimension control instead of traditional methods

- Only a few yards use self-checking and statistical accuracy control

- Most units and blocks are with excess material even on the final stage, which adds more cost in terms of direct man-hours and crane hanging times

- The installation and connection of outfit systems often costs more due to lack of accuracy in steelwork

From the 1990's, most U.S. shipyards realized that accuracy control was the keystone of quality and productivity in shipbuilding, and began to implement accuracy control programs to improve the competitive advantage of the U.S. shipbuilding industry. This manual intends to be helpful in the movement toward full implementation and utilization of accuracy control in the U.S. shipbuilding industry.

1.2 Accuracy Control Theory

The variation of product quality characteristics is inevitable. Due to such variation, we need to determine which products have requisite quality, and which products do not. Furthermore, we need to determine whether or not the production process is under control. A simple example is given to illustrate the types of questions that can arise in the manufacturing.

Example 1: suppose the design length of one batch of flat bars is 5m (see the following picture).

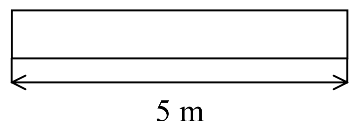


Figure 1. Flat bar

The design length of 5 m is called the "target value" in accuracy control (A/C) theory. However, in the real manufacturing process, we cannot produce every part with the exact length of 5m. Suppose the first batch of 5 bars are sampled and their lengths are:

5.01m, 4.95m, 5.02m, 4.97m, 5.04m.

This grouping of numbers will raise several questions: Does this machine operate normally? Are the worker's skills enough to finish the cutting work? Can we continue to produce the flat bars without changing any production condition? After we understand accuracy control theory, we can answer these questions easily.

Before we introduce accuracy control theory, let us review some background knowledge in statistical fundamentals, which are often used in A/C theory.

1.2.1 Basic statistical concepts

Mean

In statistics, the Mean is the average value for a random sample of size n. Consider the process of cutting flat bars of identical target length. We measure n pieces, and the length of each piece is: $x_1, x_2, x_3 ... x_n$. So the mean length is:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

In Example 1, the mean of the first 5 flat bars is

$$\bar{x} = \frac{\sum_{i=1}^{5} x_i}{5} = \frac{5.01 + 4.95 + 5.02 + 4.97 + 5.04}{5} = 4.998$$

In A/C theory, the data is often sampled by subgroup. The following example shows 10 subgroups of five measurements on the critical dimension of a part produced by a machining process. [11]

Example 2:

Table 1 Data in Subgroup

Subgroup	Measurements					Average
Number	x_1	x_2	x_3	x_4	x_5	$\bar{x}$
1	138.1	110.8	138.7	137.4	125.4	130.1
2	149.1	142.1	105.0	134.0	92.3	124.5
3	115.9	135.6	124.2	155.0	117.4	129.6
4	118.5	116.5	130.2	122.6	100.2	117.6
5	108.2	123.8	117.1	142.4	150.9	128.5
6	102.8	112.0	135.0	135.0	145.8	126.1
7	120.4	84.3	112.8	118.5	119.3	111.0
8	132.7	151.1	124.0	123.9	105.1	127.4
9	136.4	126.2	154.7	127.1	173.2	143.5
10	135.0	115.4	149.1	138.3	130.4	133.6

$\overline{\overline{x}}$ = 127.19

For each subgroup, we can calculate the mean $\overline{x}$ of these five individual data points. Also, the laws of statistics state that the mean of these subgroup means, $\overline{\overline{x}}$ is equal to the mean of all the measurements of these parts made by this process.

So,

$$\overline{\overline{x}} = \frac{\sum_{i=1}^{n} \overline{x}_i}{n}$$

Standard Deviation

Besides the mean value, the standard deviation is another important statistical parameter obtained from the raw data. Standard deviation describes the spread of the distribution of the observed data around the mean value. Its notation is:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \overline{x})}{n-1}}$$

If the standard deviation is small, that means observed data tend to concentrate around the mean. If this value is large, then the observed data tend to be diverse from the mean value. Figure 2 shows the comparison between a small and large standard deviation.

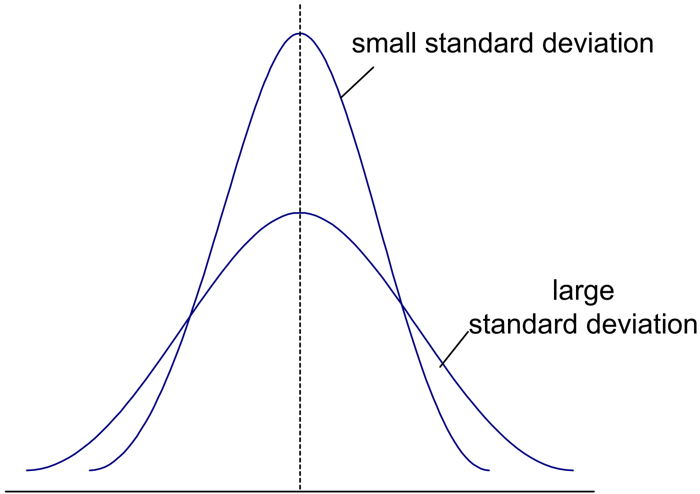


Figure 2.

Consider the above example of producing flat bars. Suppose the design length is 5m and we have two groups of measured data. The observed values are:

First Group: 5.015m, 4.955m, 5.025m, 4.975m, 5.030m

Second Group: 5.005m, 4.995m, 4.985m, 5.010m, 5.005m

First we can calculate the mean of these two groups. Each group has the mean value of 5m. So considering the design length of 5m, which group of data is better? Intuitively, we can guess that the second group is better than the first group, since each observed value in this group is closer to the design value of 5m than the first group. By calculating the standard deviation, we can confirm this point:

$$\sigma_1 = \sqrt{\frac{(5.015-5)^2+(4.955-5)^2+(5.025-5)^2+(4.975-5)^2+(5.030-5)^2}{5-1}} = 0.03317$$

$$\sigma_2 = \sqrt{\frac{(5.005-5)^2 + (4.995-5)^2 + (4.985-5)^2 + (5.010-5)^2 + (5.005-5)^2}{5-1}} = 0.01$$

It is clear that the standard deviation of the second group is smaller than that of the first group.

The standard deviation is widely used in the A/C theory. Instead of calculating standard deviation as shown above, we often use the "range method" to get it. A discussion of this approach appears in a later section.

Normal distribution

The Normal distribution is the most important statistical distribution used in A/C theory. It is also called the bell-shaped curve or Gaussian distribution.

The probability distribution function is

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{x-\mu}{\sigma})^2} \qquad -\infty < x < +\infty$$

The Normal distribution is defined by two parameters: the mean μ and the standard deviation σ. Its curve is perfectly symmetrical (bell shaped) around the mean μ.

Generally, we use $N(\mu,\sigma^2)$ to denote the Normal distribution. For example, given $N(3,2^2)$, we can plot its curve,

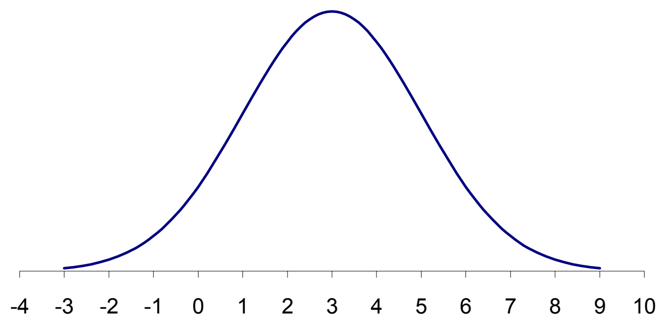


Figure 3 Normal distribution curve

The curve is symmetrical around the mean value of 3.

The literature calls a normal distribution with a mean of 0 and a standard deviation of 1 a standard normal distribution. We often use Z (0, 1) to denote the standard normal distribution, or the Z distribution. The standard normal distribution can be used to calculate the percent of parts within tolerance. A table that shows the proportion of the area of the normal curve between two given points can be found in the appendix of any statistics book. For a given normal distribution, first we need to transform it to the standard normal distribution, and then by the table, we can calculate the probability within tolerance. (In the past, due to limitations in calculation capability, it was very inconvenient to directly calculate the value of a given normal distribution. That's why people made the table for the standard normal distribution. Any given normal distribution needs to be transformed first. However, due to the development of computers, now it is very easy to get the value of any normal distribution by using some software such as EXCEL. In this part, we still introduce the method of hand calculation.) Let's look at the following example.

Example 3: Suppose the critical dimension of a part produced by a machining process follows the normal distribution of N (3, 0.2^2), and the design specification limits are 3 ± 0.4. What percent of parts will not satisfy the specification limits?

According to the laws of statistics, if the random variable x ~ $N(\mu, \sigma^2)$, then the random variable z

$$z = \frac{x-\mu}{\sigma}$$

will follow the standard normal distribution.

In this example, x ~N(3, 0.2^2), thus the random variable z

$$z = \frac{x-\mu}{\sigma} = \frac{x-3}{0.2}$$

will follow the standard normal distribution.

So, the probability that items will be within the specification limits is

$$P\{LSL \le x \le USL\} = P\{2.6 \le x \le 3.4\}$$

LSL: lower specification limit

USL: upper specification limit

Transform x to z

$$P\{2.6 \le x \le 3.4\} = P\{\frac{2.6-3.0}{0.2} \le \frac{x-3.0}{0.2} \le \frac{3.4-3.0}{0.2}\}$$

$$= P\{-2 \le z \le 2\}$$

$$= \Phi(2) - \Phi(-2)$$

$$= 2\Phi(2) - 1$$

Check the table for standard normal distribution; we can get the value of $\Phi(2)$. Then

$$P\{2.6 \le x \le 3.4\} = 2\Phi(2) - 1 = 2 \times 0.97725 - 1 = 0.95545$$

So, the percent of parts that cannot satisfy the specification limits is

$$1 - P\{2.6 \le x \le 3.4\} = 1 - 0.95545 = 0.0455 = 4.55\%$$

For the normal distribution, we often define 2σ, 4σ, and 6σ areas under the curve.

2 σ area:

The area between $\mu - \sigma$ and $\mu + \sigma$ is equal to 68.27% of the total area under the curve. That means, for a normal distribution, that 68.27% of the population values fall in this area.

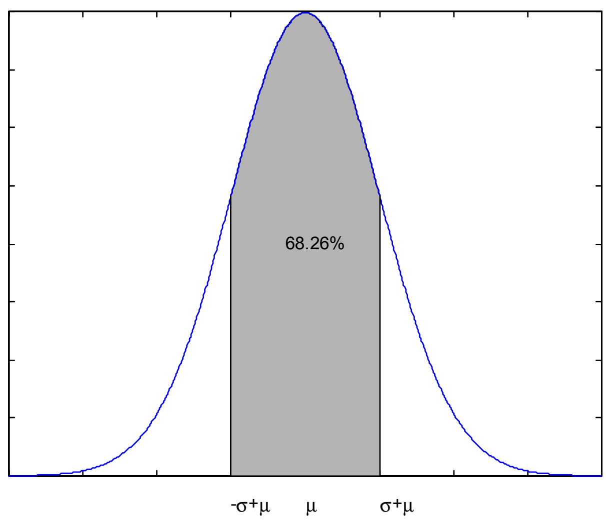


Figure 4. 2 σ area:

4 σ area:

The area between $\mu - 2\sigma$ and $\mu + 2\sigma$ is equal to 95.46% of the total area under the curve. That means, for a normal distribution, that 95.46% of the population values fall in this area. Actually, in example 3, the LSL and USL are $\pm 2\sigma$ from the mean.

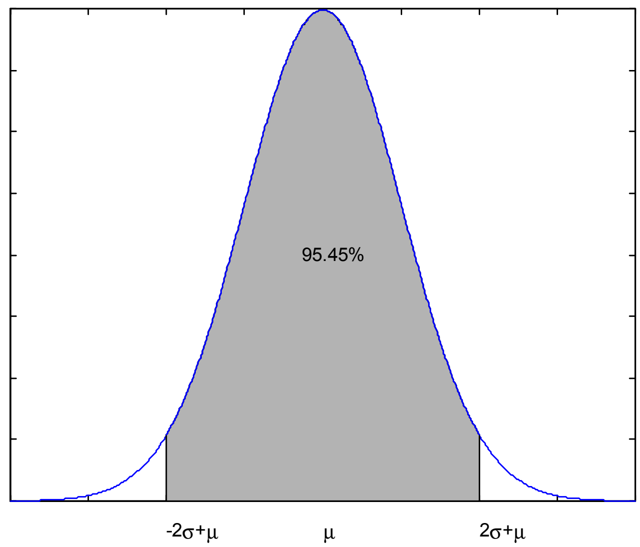


Figure 5. 4 σ area:

6 σ area:

The area between $\mu - 3\sigma$ and $\mu + 3\sigma$ is equal to 99.73% of the total area under the curve. That means, for a normal distribution, that 99.73% of the population values fall in this area.

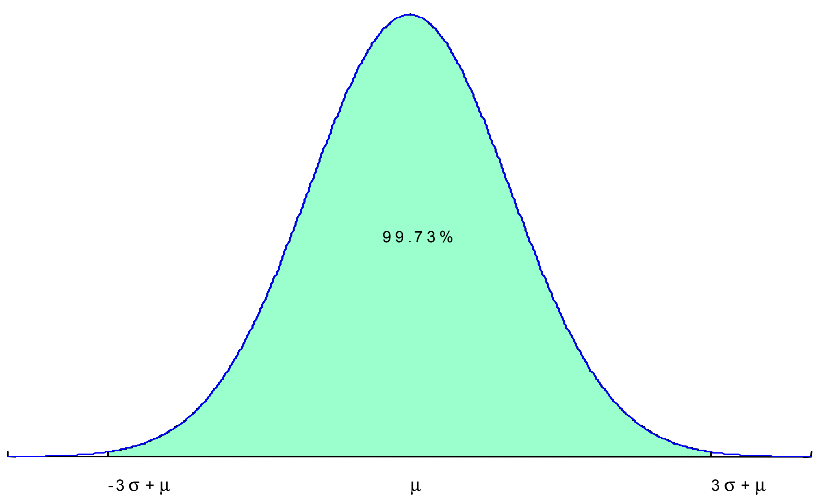


Figure 6. 6 σ area:

Central Limit Theorem

In accuracy control, we often hope the data follows the normal distribution. Although most manufacturing processes will follow the normal distribution, some do not. The central limit theorem can solve this problem. The central limit theorem is one of the fundamental theorems of probability. The importance of the central limit theorem is hard to overstate; indeed it is the reason that many statistical procedures work.

The central limit theorem can be explained in a simple way.

For any random variable w, no matter what distribution it follows, if we take random samples from the distribution and compute the mean of each random sample, then develop a distribution of these means $\overline{w}$, the new distribution will have the following characteristics:

1. It is normally distributed
2. The mean of the new distribution is the same as the original distribution,

$$\mu_w = \mu_{\overline{w}}$$

3. The standard deviation of the new distribution is related to that of the original distribution, by a factor based on the sample size used

$$\sigma_{\overline{w}} = \sigma_w / \sqrt{n}$$

In the above characteristic 2, even if we do not know the exact distribution of the manufacturing process, by calculating the $\overline{x}_i$, we know that $\overline{x}_i$ will follow the Normal distribution.

Thus, by the central limit theorem and a sampling plan, we can easily convert any distribution to the Normal distribution, and then make use of all characteristics of the Normal distribution.

1.2.2 Statistical process control

In A/C theory, one of the most important technical tools is statistical process control (SPC). Instead of inspecting for quality after production, SPC focuses on online statistical quality control. In fact, SPC not only controls the process, but also has the capability to improve the process as well. Through analyzing data from the process itself, SPC can be used as a powerful tool for reducing process variability and achieving process stability.

Among all seven SPC tools, including Flowchart, Check Sheet, Pareto Diagram, Cause-and–Effect Diagram, Scatter Plot, Histogram and Control Chart, the Control Chart is considered as the most powerful one. In the rest of this Chapter, control charts will be introduced by defining different types of Control Charts. Before exploring the different Control Chart's it is necessary to review two basic types of factors that may affect the production process.

Common causes and Special causes

As we mentioned above, the variability of processes is unavoidable. However, such variability can be due to two different types of causes.

Common causes: the variability is produced naturally. That means, though the process is well designed or carefully maintained, natural variability always exists. If only common causes exist, the process performance will be predictable. In such a situation, we will say, the process is "in statistical control." If this process can be graphed as a bell-shaped curve, that is the process follows the normal distribution, most data points (99.7%) will fall in the 6 σ area.

Special causes: the variability is from some specific source, such as an improperly adjusted machine, defective raw materials or operator errors.[8] If special causes exist, the process performance will not be predictable and repeatable. In this situation, the process is said to “out of statistical control.”

Once a process has achieved statistical control, the process will operate in a predictable and repeatable fashion most of the time. Occasionally, special causes will occur, causing the process to go out of control. If such special causes are not detected and eliminated, the process will continue to be out of control, potentially producing unacceptable products. Therefore, it becomes extremely important to locate the special causes once they occur. Control charts are a quick and powerful tool used to identify the presence of out of control conditions. Although a control chart itself cannot identify what those special causes are, they help to identify the existence of such special causes immediately. Then operators can stop the “out-of-control” process, analyze the reasons for the existence of special causes, remove them and return the process is it’s previous state of operating in statistical control.

Control charts

Shewhart control charts are thought of as the most popular tool used in statistical quality control. Control charts are used to distinguish between common causes and special causes. When the process is not running consistently, the existence of special causes of variation can be detected.

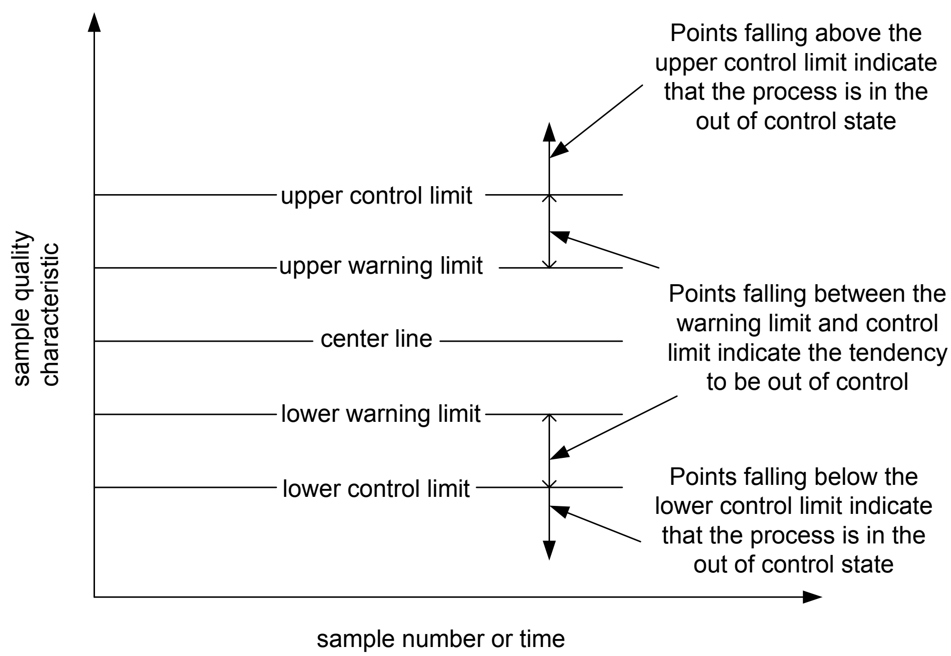
Control charts have had a long history of use in industry. The main benefits from control charts are: [8]

- Control charts are a proven technique for improving productivity
- Control charts are effective in defect prevention
- Control charts prevent unnecessary process adjustments
- Control charts provide diagnostic information
- Control charts provide information about process capability

There are two major types of Control charts:

- Variables control charts
- Attributes control charts

The following picture shows a typical control chart[13]



Central line: present average value of all data

Upper Control Limit (UCL): established at +3σ from the central line

Lower Control Limit (LCL): established at -3 σ from the central line

Upper Warning Limit: established at +2 σ from the central line

Lower Warning Limit: established at -2 σ from the central line

Figure 7. Main components in a control chart

Based on the distribution characteristics of a normal curve, 99.73% of the points will fall in the 6 σ areas. Therefore, it is expected that 997 points out of 1000 will fall between the upper and lower limits. Then if points are falling above the upper control limit or below the lower control limit, it can be assumed to indicate that the process is in an out-of-control state. If points are falling between the warning limit and control limit, it may indicate the tendency to be out of control. In such cases, we need to collect more data and watch for additional indications of the existence of special causes.

Besides the rule of points beyond the control limits, there are several other rules used to indicate out of control conditions: [11]

- Two out of three consecutive points plot beyond the 2 σ warning limits
- Four out of five consecutive points plot at a distance of 1 σ or beyond from the center line
- Eight consecutive points plot on one side of the centerline.

Control chart for variables

A quality characteristic measured on a numerical scale is called a variable. Examples include the length of a flat bar or the temperature in the workshop. The control chart used to monitor and control a variable is called a control chart for variables. In practice, variables control charts are posted at individual machines or work centers to control a particular quality characteristic.[12] Variables control charts include one $\bar{x}$ chart and one R chart. The $\bar{x}$ chart is used to control the central tendency and R chart is used to control the dispersion.

The following picture shows a typical example of a $\bar{x}$ chart and R chart.

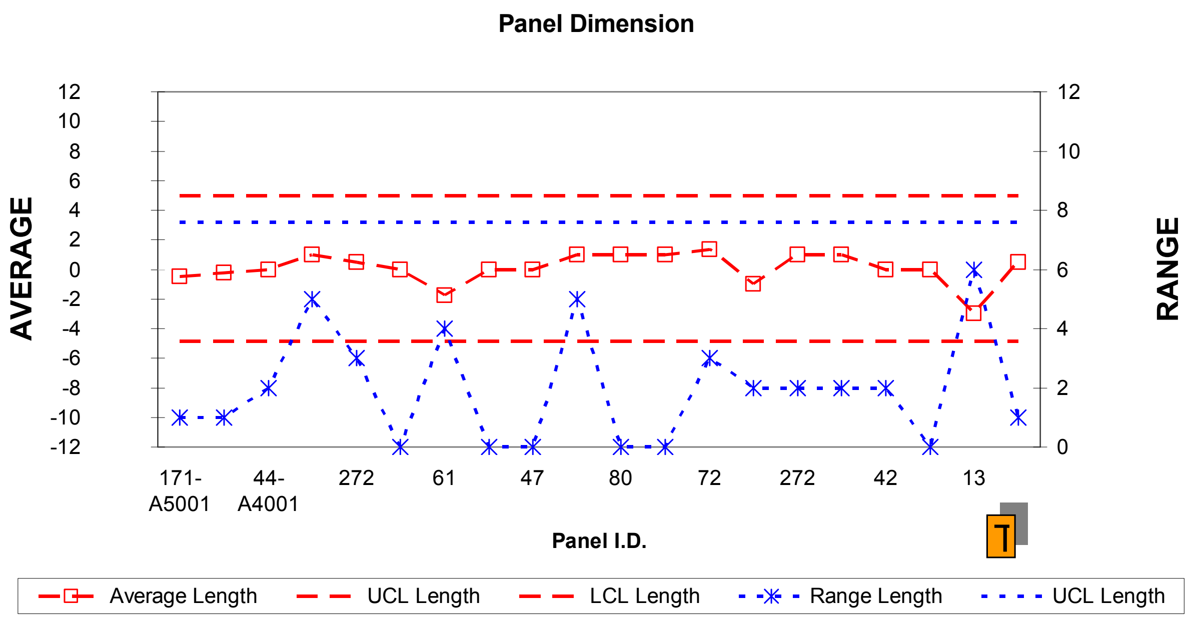


Figure 8. X-bar/R chart

The $\overline{X}$ control limits are easy to calculate. The central line is calculated as follows:

$$C.L. = \bar{\bar{x}} = \frac{\sum \bar{x}_i}{k}$$

where k is the number of subgroups. After we determine the central line, next we need to calculate the upper control limit (UCL) and lower control limit (LCL). According to the definition of control limits, we can get the following equations:

$$UCL_x = \bar{\bar{X}} + 3\sigma_{\bar{x}}$$

$$LCL_x = \bar{\bar{X}} - 3\sigma_{\bar{x}}$$

However, in practice, in order to simplify the calculation, derived equations are developed and used:

$$\text{UCL}=\bar{\bar{x}} + A_2\bar{R}$$

$$\text{LCL}=\bar{\bar{x}} - A_2\bar{R}$$

These calculations are derived using a constant A_2 based on the number of objects in the sample. This constant can be found on the chart in Chapter 10. As discussed previously, the $\overline{X}$ chart measures the central tendency while the R chart controls dispersion. The R chart uses $\bar{R}$ as the value of the central line on the R control chart.

$$\text{C.L.}=\bar{R} = \frac{\sum R_i}{k}$$

After we determine the central line, next we need to calculate the upper control limit (UCL) and lower control limit (LCL). According to the definition of control limits, we can get the following equations:

$$UCL_R = \bar{R} + 3\sigma_R$$

$$LCL_R = \bar{R} - 3\sigma_R$$

However, in practice, in order to simplify the calculation, derived equations are developed and used:

$$\text{UCL} = D_4\bar{R}$$

$$\text{LCL} = D_3\bar{R}$$

The constants D_4 and D_3 vary with the subgroup size (n). These coefficients can be found in many statistical quality control textbooks and in Chapter 10. For an example of the above control chart, see Chapter 3.

Attributes control chart

Sometimes we cannot measure some quality characteristics, such as the number of scratches in a painted surface, or we do not want to measure them because of the cost or time. In such cases, attributes control charts can be used.

An attribute is defined in quality as those characteristics that conform to specifications or do not conform to specifications.[12] There are two different types of attribute control charts: p chart and c & u charts.

A p chart is used to monitor the parameter of the fraction nonconforming. Fraction nonconforming means the ratio of the number of nonconforming items in a population to the total number of items in that population. For example, suppose we had 30 parts, and among these 30 parts, three did not satisfy the requirement and needed rework. We can say the fraction nonconforming of this sample group is p = 3 / 30 = 0.10.

We use the following equation to calculate the centerline and control limits of a p chart.

$$\overline{p} = \sum p/kn$$

$$UCL = \overline{p} + 3\sqrt{\frac{\overline{p}(1-\overline{p})}{n}}$$

$$LCL = \overline{p} - 3\sqrt{\frac{\overline{p}(1-\overline{p})}{n}}$$

where

$\overline{p}$ = average proportion nonconforming for subgroups

p = proportion nonconforming in each subgroup

k = the number of subgroups

n = number inspected in each subgroup

C and u charts belong to the same type of control charts, although both of them have their respective centerline and control limits. Both c and u charts are for nonconformities. "Nonconformities" is a different concept from "nonconforming". A nonconforming item is a unit of product that does not satisfy one or more of the specifications for that product. Nonconformity means each specific point at which a specification is not satisfied.[11]

For c chart:

$$UCL = \overline{c} + 3\sqrt{\overline{c}}$$

$$C.L. = \overline{c}$$

$$LCL = \overline{c} - 3\sqrt{\overline{c}}$$

$\overline{c}$ is equal to the total number of nonconformities divided by total number of items sampled.

For a u chart:

$$UCL = \overline{u} + 3\sqrt{\frac{\overline{u}}{n}}$$

$$C.L. = \overline{u}$$

$$LCL = \overline{u} - 3\sqrt{\frac{\overline{u}}{n}}$$

Where $\bar{u}$ is equal to the average number of nonconformities per inspection unit.

For examples of how these control charts are used, see Chapter 3.

Control Charts for Individuals

There are many situations in which the sample size used in monitoring the process has just one unit, n=1. In these types of situations, the control chart for individual units is often times extremely useful. In many instances when using this type of control chart, the moving range of two successive observations as the basis for estimating the process variability is used. The moving range is defined as: $MR_i = \left| x_i - x_{i-1} \right|$ After developing the moving range, a control chart can then be built from this procedure. See Chapter 3 for an example.

Short-Run Control Chart

From the above description, we will find that control charts can be easily applied in manufacturing processes where a large number of identical parts are being produced. However, shipbuilding is often a one of a kind production industry, which means that batch sizes are very small, sometimes only one. For this situation, short run control charts were developed and are in common use today.

The difference between short run control charts and the standard control chart is: in the short run control chart, the measured quality characteristics values are replaced by deviation from nominal or target value. This can be expressed in the form of the following equation[10,11}

$$x_{i,w} = M_{i,w} - N_w$$

where

$M_{i,w} = i$ th actual sample measurement of the quality characteristic of w,

$N_w =$ Nominal value of the quality characteristic of w,

$x_{i,w} =$ Deviation of the actual measurement from nominal of the i th sample of the quality characteristic w

Then, the principals of standard control charts are utilized. See example in Chapter 3.

1.3 Plan & Check Sheets

Plan sheets are used in preparing check sheets for recording measurements and for documentation of vital point planning. They are the means by which the A/C planning group communicates with those having the responsibility for the execution phase of A/C. Check sheets form the basis of the data collection system. These sheets provide the format for establishing existing performance levels and therefore are a critical check on tolerance limits determined initially by estimation. Additionally, check sheets for subassemblies and blocks will provide information necessary for establishing standards for excess and sequences for using these excesses. The check sheets are the medium on which all data are recorded. The check sheet provides the exact location for the measurement and provides a space to record it. The heading of a check sheet contains information necessary to identify things such as the ship, block, part, and the stage of construction it is supposed to be measured. The check sheet can be confusing so it is better to use one check sheet per location to measure and not several locations on a single check sheet. The remainder of the blanks contains spaces for the data, time of measurement, and all other pertinent information. A corresponding plan sheet can identify each check sheet and a plan sheet can have more than one check sheet attached to it.

1.4 Variation Merging

Ships are built by a lot of steps: first procure or fabricate parts, and then join these parts to create subassemblies. After that, subassemblies are put together for blocks and so on. The basic steps can be described as:

Parts---> Subassemblies--->Assemblies--->Blocks--->Ship

If each work process is in statistical control, its normal distribution of variations can be determined. Then, with the data collected from each interim work process, the final variation of the structure can be predicted.

As we know, the output of each work process represents an independent normal distribution. Those distributions can be added to determine the expected normal performance at the following stages of construction**.** So for the completed hull, we can get the variation merging equation:[9]

$$Z = \sum P_i + \sum S_i + \sum A_i + \sum E_i$$

where:

$\sum P_i$ = merged variations from all parts fabrication processes

$\sum S_i$ = merged variation from all subassembly processes

$\sum A_i$ = merged variations from all block assembly processes

$\sum E_i$ = merged variation from all erection processes

The variation merging equation is based on the "theorem of addition of variance." For independent distributions, the theorem of addition of variance states:

$$S_F^2 = S_1^2 + S_2^2 + S_3^2 + \ldots = \sum S_i^2$$

where s_i are the standard deviations of earlier processes and s_F is the standard deviation of a final process.

Considering variation merging, we will find that if the accuracy of interim products at each stage of construction can be reduced, the amount of rework at the erection stage will be decreased. Also, this equation is helpful to predict the probability of rework at erection, which will in turn be beneficial to production planning and scheduling.

1.5 Process Capability Analysis

In the previous sections, we described statistical techniques that can be used to monitor the process and to find error signals provided by the process itself. However, control charts only tell us if the process is in control or not. In fact, "in control" does not tell us if the process is "capable," which means that most of the parts produced by the process will satisfy the specification requirements. In order to determine if the process is capable, we need to perform process capability analysis by statistical techniques.

First let us look at the difference between several concepts. USL/LSL (upper/lower specification limits) represent the specification requirements on the product. Design engineers often develop these numbers in the design phase. In most cases, USL/LSL also stands for the customer's voice for the product. For example, for a flat bar made in a certain process, the USL/LSL of the length is 5 ± 0.05m. That means, if the length of any flat bar is more than 5.05m or lower than 4.95m, the flat bar will be considered unacceptable and in need of rework.

$UCL_{\bar{x}} / LCL_{\bar{x}}$ **(upper/lower control limits for** $\bar{x}$ **)**

$UCL_{\bar{x}} / LCL_{\bar{x}}$ represent the upper/lower control limits for $\bar{x}$. These numbers are determined by the process itself such as the skill of operators, the capability of the machines and equipment, etc.

UNTL/LNTL (upper/lower natural tolerance limits)

UNTL/LNTL represent the upper/lower natural tolerance limits for x. The process determines these values. In most cases, we sample from the distribution of x values and develop information about the distribution of sample means. We then use the Central Limit Theorem to determine the distribution of x values. The means are the same:

$$\mu_x = \mu_{\bar{x}}$$

The relationship between their standard deviation is:

$$\sigma_{\bar{x}} = \frac{\sigma_x}{\sqrt{n}}$$

Where n is the sample size.

In process capability analysis, we often focus on two indicators: C_p and C_{pk}

C_p is defined as:

$$C_p = \frac{USL - LSL}{6\sigma}$$

C_p is often called potential capability, which states the maximum manufacturing capability of current process provided that the mean of the process is equal to the target value.

C_{pk} is defined as:

$$C_{pk} = \min\left(\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right)$$

C_p is often called actual capability. If the process is running off-center, then C_{pk} should be less than C_p. Typically, if both C_p and C_{pk} are greater than 1, we say that the process is capable.

When making the process capability analysis, we should make sure that the process is in control. If the process is not in control, data from the process will provide meaningless information for the capability analysis.

The following table shows the possible situations we may meet when doing the process capability analysis:

Table 3 Process Capability Analyses

Process capability	**Status**	**Solution**
$C_p = C_{pk} > 1$	The process is capable	Both C_p and C_{pk} are greater than 1, so the process is capable. Furthermore, C_{pk} is equal to C_p, which indicates the mean of the process is equal to the target value. Thus, no process improvement action is needed.

$C_p > C_{pk} > 1$	The process is capable	Both C_p and C_{pk} are greater than 1, so the process is capable. However, C_{pk} is less than C_p, which indicates the process is running off-center. We may change the machine setting to make the mean of the process return to the target value. Thus the actual process capability can be increased to the same as the potential level.
$C_p > 1$, $C_{pk} < 1$	The process is not capable	Since C_{pk} is less than 1, the process is not capable. However, C_p is greater than 1, which indicates the potential capability of the process is satisfactory, but the current process is running substantially off-center. We must change the machine setting to make the mean of the process return to the target value. Thus the actual process capability can be increased as the same as the potential level.
$C_p < 1$, $C_{pk} < 1$	The process is not capable	Both C_p and C_{pk} are less than 1, the process is not capable. Since the potential capability is lower than 1, even if we change the machine settings to make the mean of the process return to the target value, the process will still not be capable. We need more process improvement, such as increasing the worker's skills or improving the accuracy of the machine to decrease the standard deviation of the process.

1.6 Example

The following example highlights the majority of the concepts described above.

Consider the process of making ignition keys for automobiles. Groove dimensions are critical to the proper functioning of the keys. Specifications for the groove dimension are 0.0072 $\pm$ 0.0020. In order to analyze the process capability, we choose five keys every 20 minutes at random and measure the critical groove dimension. Then we get the following data:

Subgroup	x1	x2	x3	x4	x5	$\bar{x}$		R
1	0.0087	0.0094	0.0086	0.0073	0.0071	0.0082		0.0023
2	0.0061	0.0084	0.0076	0.0076	0.0044	0.0068		0.0040
3	0.0074	0.0081	0.0086	0.0083	0.0087	0.0082		0.0013
4	0.0088	0.0083	0.0076	0.0074	0.0059	0.0076		0.0029
5	0.0081	0.0065	0.0075	0.0089	0.0097	0.0081		0.0032
6	0.0080	0.0080	0.0094	0.0075	0.0070	0.0080		0.0024
7	0.0067	0.0076	0.0064	0.0071	0.0088	0.0073		0.0024
8	0.0078	0.0098	0.0081	0.0062	0.0084	0.0081		0.0036
9	0.0087	0.0084	0.0088	0.0094	0.0086	0.0088		0.0010
10	0.0071	0.0052	0.0072	0.0088	0.0052	0.0067		0.0036
11	0.0087	0.0065	0.0068	0.0078	0.0089	0.0077		0.0024
12	0.0087	0.0075	0.0089	0.0076	0.0081	0.0082		0.0014
13	0.0084	0.0083	0.0072	0.0100	0.0069	0.0082		0.0031
14	0.0074	0.0091	0.0083	0.0078	0.0077	0.0081		0.0017
15	0.0069	0.0093	0.0064	0.0060	0.0064	0.0070		0.0033
16	0.0077	0.0089	0.0091	0.0068	0.0094	0.0084		0.0026
17	0.0089	0.0081	0.0073	0.0091	0.0079	0.0083		0.0018
18	0.0081	0.0090	0.0086	0.0087	0.0080	0.0085		0.0010
19	0.0074	0.0084	0.0092	0.0074	0.0103	0.0085		0.0029
					$\bar{\bar{x}}$ =	0.0079	$\bar{R}$ =	0.0025

First, Let us construct the control charts to see if the process is in control.

$$\bar{\bar{x}} = \frac{\sum_{i=1}^{m} \bar{x}_i}{k} = 0.007927,$$

$$\bar{R} = \frac{\sum_{i=1}^{m} R_i}{k} = 0.002468$$

Since sample size n =5, check the appendix of a statistical quality control book to get

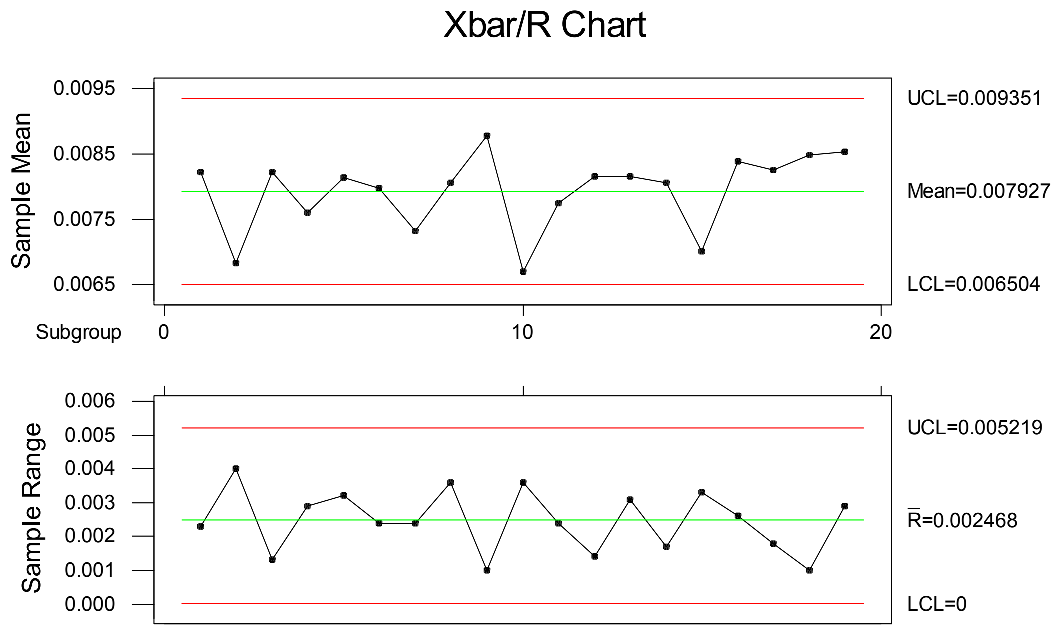
$$A_2 = 0.577,\ D_3 = 0,\ D_4 = 2.115$$

$$UCL_{\bar{x}} = \bar{\bar{x}} + A_2\bar{R} = 0.009351$$

$$LCL_{\bar{x}} = \bar{\bar{x}} - A_2\bar{R} = 0.006504$$

$$UCL_R = D_4\bar{R} = 0.005219$$

$$LCL_R = D_3\bar{R} = 0$$



Since all points are between the UCL and LCL, the process is in statistical control.

From the same table used to get the three constants above, we can get d_2 =2.326. Then calculate the standard deviation of the process:

$$\hat{\sigma} = \frac{\overline{R}}{d_2} = 0.002468/2.326 = 0.001061$$

USL = 0.0092 and LSL=0.0052

$$C_p = \frac{USL - LSL}{6\sigma} = (0.0092 - 0.0052)/(6 * 0.001061) = 0.6283$$

$$C_{pk} = \min(\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}) = (0.0092 - 0.007927)/(3 * 0.001061) = 0.3999$$

Since both $\boldsymbol{C_p}$ and $\boldsymbol{C_{pk}}$ are less than 1, the process is not capable. That means if we do nothing to improve the current process, even though the process is in statistical control, it cannot satisfy the specification limits successfully.

Suppose some process improvement efforts such as training workers and purchasing new machines were employed after we made the process capability analysis. We collect new data after the improvements. The following table shows the new data.

Since the data were collected after the process improvement, we need to build new control charts based on these data.

Subgroup	x1	x2	x3	x4	x5	x-bar		R
1	0.0074	0.007	0.0075	0.0068	0.0078	0.007300		0.001000
2	0.0069	0.0072	0.0078	0.0065	0.0076	0.007200		0.001300
3	0.0073	0.0065	0.0079	0.0063	0.007	0.007000		0.001600
4	0.0068	0.008	0.0074	0.0071	0.0075	0.007360		0.001200
5	0.0074	0.0075	0.0064	0.0068	0.0071	0.007040		0.001100
6	0.0075	0.0065	0.0068	0.0072	0.0073	0.007060		0.001000
7	0.009	0.006	0.0088	0.0085	0.0058	0.007620		0.003200
8	0.0067	0.0073	0.0076	0.0065	0.0072	0.007060		0.001100
9	0.0075	0.0071	0.0067	0.0065	0.0073	0.007020		0.001000
10	0.0075	0.0076	0.0068	0.0067	0.0072	0.007160		0.000900
					$\overline{\overline{x}}$ =	0.007182	$\overline{R}$ =	0.001340

The sample number k=10,

$$\overline{\overline{x}} = \frac{\sum_{i=1}^{m} \overline{x}_i}{k} = 0.007182, \quad \overline{R} = \frac{\sum_{i=1}^{m} R_i}{k} = 0.00134$$

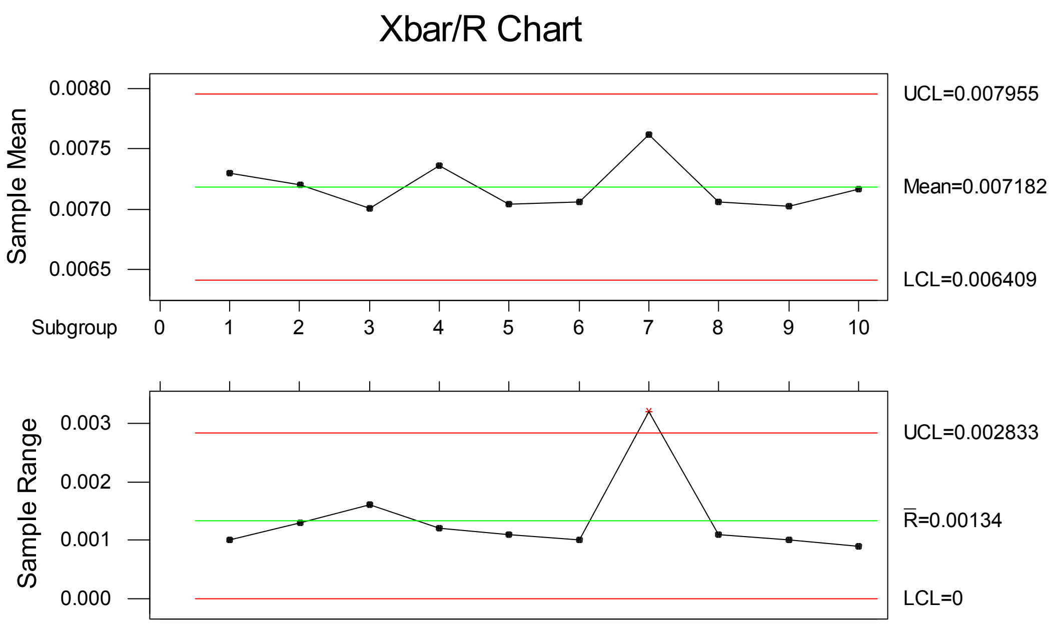
Since n=5, then $A_2 = 0.577$, $D_3 = 0$, $D_4 = 2.115$

$$UCL_{\overline{x}} = \overline{\overline{x}} + A_2\overline{R} = 0.007955$$

$$LCL_{\overline{x}} = \overline{\overline{x}} - A_2\overline{R} = 0.006409$$

$$UCL_R = D_4\overline{R} = 0.002833$$

$$LCL_R = D_3\overline{R} = 0$$



In the control chart, Point 7 is beyond the control limit, so the process is out of control. Assume that an assignable cause was found and removed. So we remove Point 7 and recompute the control charts.

The sample number k=9,

$$\bar{\bar{x}} = \frac{\sum_{i=1}^{m} \bar{x}_i}{k} = 0.007133, \; \bar{R} = \frac{\sum_{i=1}^{m} R_i}{k} = 0.001133$$

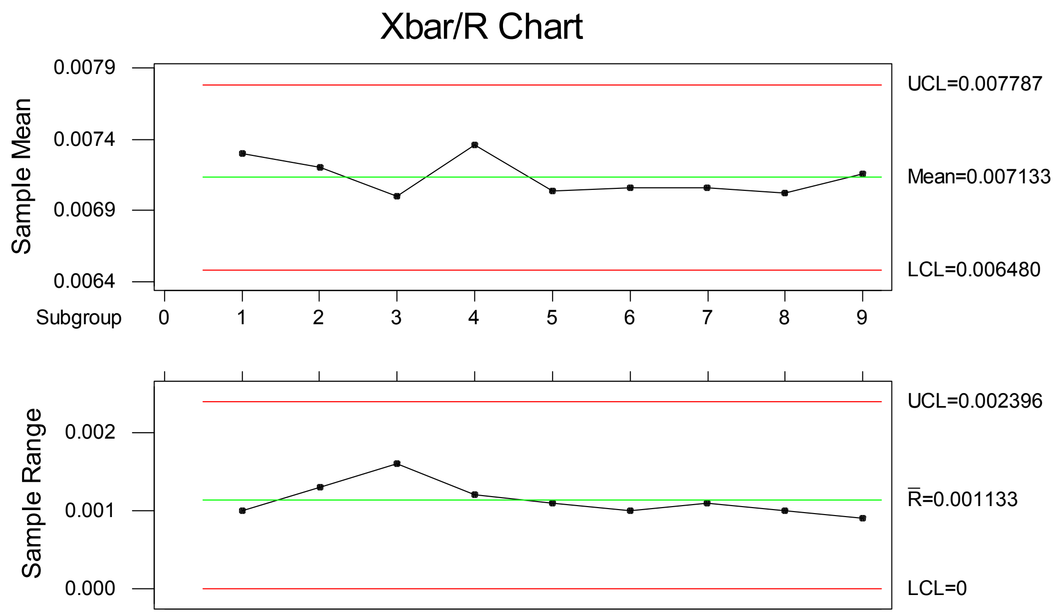
Since n=5, then $A_2 = 0.577$, $D_3 = 0$, $D_4 = 2.115$

$UCL_{\bar{x}} = \bar{\bar{x}} + A_2\bar{R} = 0.007787$

$LCL_{\bar{x}} = \bar{\bar{x}} - A_2\bar{R} = 0.006480$

$UCL_R = D_4\bar{R} = 0.002396$

$LCL_R = D_3\bar{R} = 0$



Since all points are between the UCL and LCL, the process is in statistical control. Thus we can begin the process capability analysis.

Since n =5, d_2=2.326

$\hat{\sigma} = \frac{\overline{R}}{d_2}$ =0.001133/2.326=0.000487

USL = 0.0092 and LSL=0.0052

$C_p = \frac{USL - LSL}{6\sigma}$ =(0.0092-0.0052)/(6*0.000487) =1.368

$C_{pk} = \min(\frac{USL-\mu}{3\sigma}, \frac{\mu - LSL}{3\sigma})$ =(0.007133-0.0052)/(3*0.000487) =1.323

Since both C_p and C_{pk} are greater than 1, the process is capable if the process is running under the statistical control. That means the efforts are successful compared with the previous process.

Before the improvement, the mean value is 0.007927 and the $\hat{\sigma}$ is 0.001061. After the improvement, the mean value is 0.7133 and the $\hat{\sigma}$ is 0.000487. We can say, after the improvement, the mean value is closer to the specification mean value 0.0072, and the standard deviation is smaller. That is why the process capability is increased dramatically after process improvement.

1.7 Conclusion

This Chapter has given a basic introduction to what accuracy control is and gave a brief review of the statistics needed to implement an accuracy control program in a shipyard environment. Chapter 2 will give some basic implementation techniques for implementing and using accuracy control in a shipyard.

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Chapter 2. Basic Shipbuilding Accuracy Control Implementation

2.1 Introduction

Accuracy Control (A/C) involves the regulation of accuracy as a management technique for improving the productivity of the entire shipbuilding system. This is accomplished by focusing attention on individual areas where improvements offer significant benefits. When fully operational, A/C forms a major part of a complete management system. A/C can be considered to have two primary goals, one short term and one long term. The short-term goal is to monitor the construction of interim products to minimize delays and rework during erection. The more important long-term goal is the establishment of a management system that permits the development of quantitative information that can be used to continuously improve productivity. Viewed as a complete system, A/C includes three major parts: (1) planning, which prepares for accuracy work to be performed on a specific shipbuilding project (2) executing, which is the actual work involved, including development of specific check sheets, methods for measuring, and recording of data and (3) evaluating or analysis, which provides documentation for use in planning, executing, and evaluating the next shipbuilding project (see Figure 1). Each of these parts is important, but by their nature they will receive different emphasis during start-up at different shipyards. The effectiveness of an A/C program is directly dependent upon the application of group technology to ship production, that is, the use of a product oriented work breakdown structure (PWBS). The underlying assumption in the collection and analysis of A/C data is that production processes are (at least initially) in a state of statistical control. This in turn requires well-defined work processes, procedures, and coding so that observed variations can be validly interpreted using statistical theory from Chapter 1. The second prerequisite to full-scale implementation of accuracy control is the establishment of an A/C database. This database is

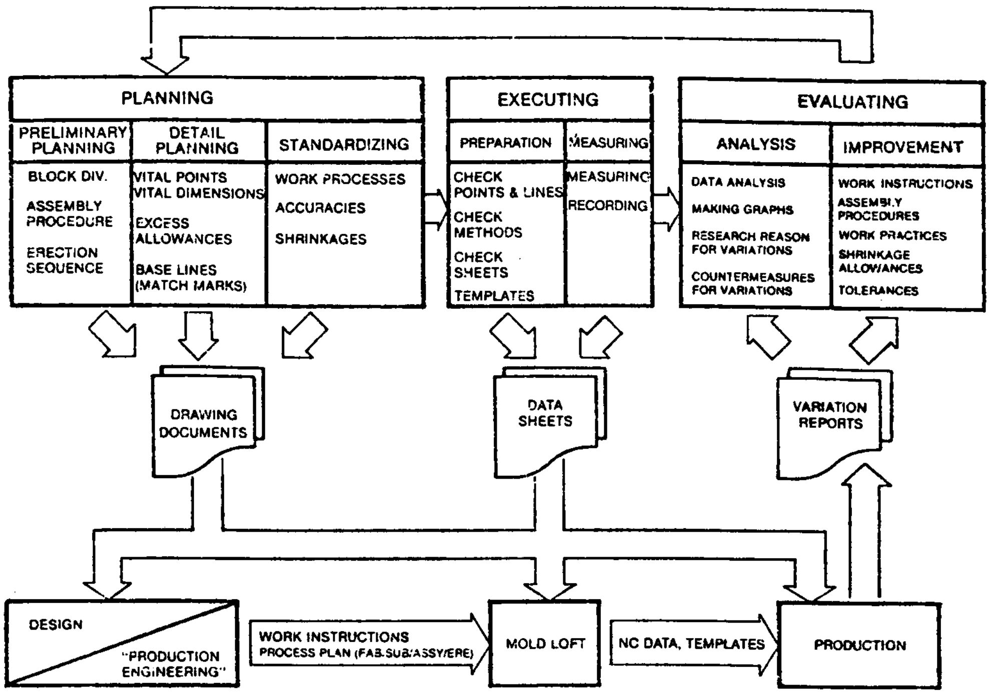


Fig. 1 Accuracy control cycle

nothing more than a statistical history of the accuracy of the work processes employed at the yard. The database, once established, serves two purposes. First, it provides the basis of standards for individual work processes. Second, the database provides the information necessary to begin process analysis, the major benefit to be obtained from an accuracy control system. The objective of process analysis is productivity improvement such as cutting costs, improving quality, and shortening lead times all done simultaneously, rather than at the expense of each other.

2.2 Implementation of An A/C System

Start-up of An A/C System

The following nine steps can summarize the start-up procedure for A/C:

1. Commitment to PWBS and A/C by top management
2. Choice of construction project for initiation of system.
3. Informational meetings involving engineering, planning, shop and trades foremen, quality control assurance, and welding engineers.
4. Establishment of written and welding sequences by engineering based on input from planning and production.
5. Establishment of initial estimated tolerance limits from engineering based on information from planning and production.
6. Establishment of initial estimated excess standards by Numerical Control loft based on input from planning, production, and engineering.
7. Development of check sheets to identify check points and dimensions for measurement by engineering based on input from planning and production.
8. Collection of data on check sheets and review of assembly and welding sequences by production.
9. Analysis of data and sequences by A/C group.

Establishing an A/C system at a shipyard involves an understanding of the goals discussed earlier. It must also be based on the existing organizational structure. The short-range goal is a relatively straightforward, less important part of the total system. However, for these and other reasons it is likely to be the first area addressed by a shipyard beginning A/C. The temptation to ignore or delay implementing the long-term goal is strong. This responsibility will fall on the upper management who must be strong willed to ensure this does not happen. The lack of a long term A/C plan will not allow for the realization of the full potential to be gained from the A/C program. Since a large database must be collected before the system can be effective, most shipyards will begin to address A/C in conjunction with the initiation of a PWBS system, which is driven by the desire to minimize rework at erection. This eventual changing work environment can provide top management with an opportunity to begin data collection at a low level of effort. Middle managers are likely to grasp quickly the need for achieving and assuring accuracy in interim products. Of course the hard and more important part is the need for documentation and analysis. After the selection of which project to implement this system on, it will be useful to begin a series of meetings involving representatives from the two organizations most impacted, engineering and planning, while also including representatives from each of the trades at the foreman level. The purpose of these meetings is to share information vital to the success of A/C. Communication cannot be stressed enough if a successful implementation is to take place. The iterative nature and the time span required to achieve a working A/C system must be made clear. The difficulty of initiating a system yard-wide is readily apparent. This difficulty results in a choice of one or two specific areas for initial implementation to ease the start-up and eventually facilitate transition throughout the yard. With time, responsibilities for specific tasks within the overall framework must be assigned to the management team and the employees in each area. Tolerance limits and standards for excess must be initially estimated and included on work instructions and drawings. As more data and information is collected, these tolerance limits and standards will be revised and refined.

Prior to the initial data-measuring phase, the establishment of written procedures detailing assembly and welding sequences must be prepared. The importance of these procedures comes with the collection of data and that data being statistically significant. These procedures should be based on input from production and planning personnel which will in turn initiate the vital communication lines between engineering, planning, and production. Check sheets form the basis for data collection and were referred to in Chapter 1. As time passes, data collection should become a normal part of production. The importance of production allowing time for these checks and measurements cannot be emphasized enough. Without these measurements, A/C will never become a reality. The measurements will serve multiple functions such as: the short-term goal of A/C is achieved, provide statistical performance indicators, satisfy customers, regulatory bodies, and classification societies requirements through the quality assurance department, and will help management and the workers take pride in the A/C program by achieving clearly stated requirements.

A/C Planning

A/C planning consists of three parts. They are preliminary planning, detail planning and standards development, as shown in Fig. 1. This planning work must be closely coordinated with design, engineering, production, production planning, and with certain aspects of purchasing from outside vendors. This would indicate that A/C planning would best be viewed as a normal part of these functions, rather than as a separate activity. The close liaison required between these above-mentioned groups, which traditionally act independently, will not flourish if A/C planning is seen as the responsibility of a separate independent group. This will be avoided if A/C planning responsibilities are added to traditional planning responsibilities. There are several advantages for this method of organization. By avoiding the creation of a totally separate accuracy control group, the tendency to confuse A/C with quality assurance will be reduced. A/C is part of everyone's job and must become part of everyone's daily routine to continuously monitor work in progress, not viewed as an added task at the end of the job. The next advantage is that the liaison required could be accomplished with a minimum of paperwork because A/C planners will be in the shipyard departments with which they must coordinate their work. This will also add weight to the idea that A/C is an integral part of all aspects of shipbuilding. The A/C planning must begin with a set of standards, which specify the required dimensions and the special requirements that are negotiated with the customer. In the absence of data, these standards must initially be based on experience, rules of thumb, operational requirements, and estimation of reasonable tolerances. As data is collected, these will then be revised, refined, and extended to additional areas. This is an accuracy control planning function. Analysis and revision of these standards also facilitate a movement towards

Table 1 Selection of vital points

Type of Vital Check Points or Baselines	Examples	Why These Measurements Are Important
Characteristic hull dimensions	1. straightness and level of hull baseline 2. length, draft, breadth of various points 3. hull volume—offsets at chine or bilges 4. tonnage/tankage measurements	1. satisfy regulatory bodies 2. establish capacity/tonnage 3. quality assurance to customer 4. feedback to yard—A/C analysis 5. feedback to standards organizations—modify standards 6. affect erection productivity
Dimensions related to operating requirements	1. relative position of stern tube, shaft bearings, engine foundation and rudderpost 2. location/alignment of special components—roll-on/roll-off ramps, gun mounts, etc. 3. special customer requirements	1. affect performance, operation of vessel 2. feedback to yard—A/C analysis 3. feedback to standards agency 4. affect productivity of component installation 5. satisfy special customer requir ments
Major structural intersections at butt joints	1. shell plate offsets at butt 2. chine offsets 3. locations of major bulkheads 4. large structural foundations—location, flatness	1. affect strength, rework requirements, deformation during fabrication 2. feedback to yard—A/C analysis 3. feedback to standards agency 4. affect fabrication productivity
Outfit component intersections at butt joints	1. pipe ends which mate to another component on adjoining unit 2. machinery components mating to component on another unit 3. pipe penetration locations	1. affect proper operation of machinery 2. affect productivity of zone outfitting 3. feedback to yard—A/C analysis 4. feedback to standards agency
Process-related measurements	1. fit-up gaps 2. welding shrinkage 3. welding distortion 4. bending accuracy 5. line heating 6. cutting, marking accuracy 7. curvature of components fabricated on pin jig	1. assist determination of process accuracy 2. affect productivity of subsequent processes 3. feedback to yard process evaluation 4. feedback to standards agency
Measurements to facilitate fabrication	1. platen level 2. jig alignment/accuracy 3. building dock baseline aligment 4. baselines on parts, blocks to facilitate measurement, alignment, assembly, outfit, painting and erection	1. assist fabrication 2. affect productivity 3. feedback to yard—A/C analysis of alternative methods/processes

design for production. Alternate work procedures, assembly sequences, and hull division schemes can be evaluated and the necessary changes incorporated into the design. Assuming that accuracy standards already exist, the first task of A/C planning is the selection of vital points and baselines for the hull as a whole. These, of course, will vary depending on ship type and other notable differences based on the job at hand. Vital points must be chosen which reflect all accuracy requirements involved in the fabrication of the ship and its components. Table 1 lists the types of vital points and baselines, and lists the considerations involved in their selection. Vital points for blocks, subassemblies, and parts can be selected only following definition of the

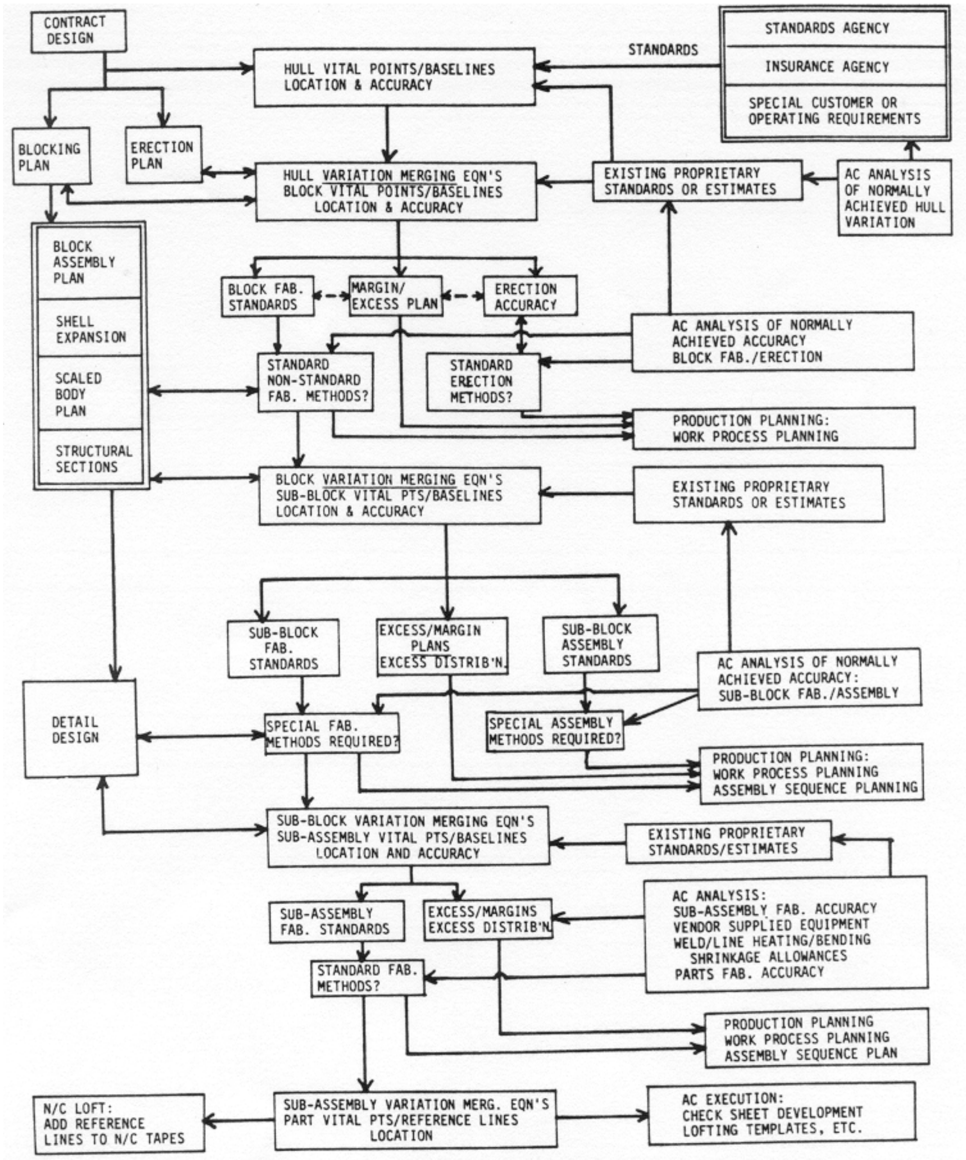


Fig. 2 Accuracy control planning process

block and erection plans and assembly sequences. Process-related measurements can be selected only for well-defined processes. This means that A/C planning must proceed in phase with the design, engineering and planning work as shown in Fig. 2. The initial planning review by A/C should be done way ahead of the design, during conceptual design if possible. A/C requirements must be given to designers prior to starting design work to allow for full implementation of required tolerances, gaps, excesses, etc. Reviewing deigns during iterative reviews is too late and can result in cost/schedule conflicts with design. The next task of the A/C planning process is to specify the desired accuracy of the vital point dimensions. These will be based on the standards and special customer demands defined earlier. In the case of nonstandard requirements, such as customer requests, specification of the required accuracy of vital points will impact the design, engineering, and planning processes. This need to distinguish between standard and nonstandard items, based upon required accuracy, again points up the need to establish an A/C database. In order to facilitate an efficient system, A/C planning group members should be familiar with all aspects of shipbuilding, and in particular with the fabrication, assembly and erection methods used at that yard. The design and planning for items, which have special accuracy requirements, make use of that experience. Once the hull vital points are specified, the A/C planning group can develop the vital point plan for each block. The hull block plan will thus be required from design at this point. Engineers with A/C responsibilities should participate in the development of the block plan, so that blocks are created which facilitate accurate fabrication. Block vital points chosen reflect the contribution of variation in a block dimension to the merged variation of a hull vital point dimension. Block vital points would also include critical structural locations on the butt joint with the adjoining block and critical outfit points such as a pipe end which mates to a pipe on the adjoining block. Baselines to facilitate block fabrication, erection, or measurement would also be established at this time. These block vital points mentioned above, are indicated on an A/C plan sheet. The plan sheet includes a sketch of the block showing vital points and baselines, and lists the location of points in three dimensions. A sample plan sheet is shown in Fig. 3. These plan sheets in turn are used in preparing check sheets for recording measurements and for documentation of vital point planning. They are the means by which the A/C planning group communicates with those having responsibility for the execution phase of A/C. Another important task facing A/C planners is to develop a plan for block excesses. These excesses should be based on statistical analysis. If work processes are under statistical control, and excess amounts are chosen to exactly compensate for the statistically derived average deviation, then there will be a small

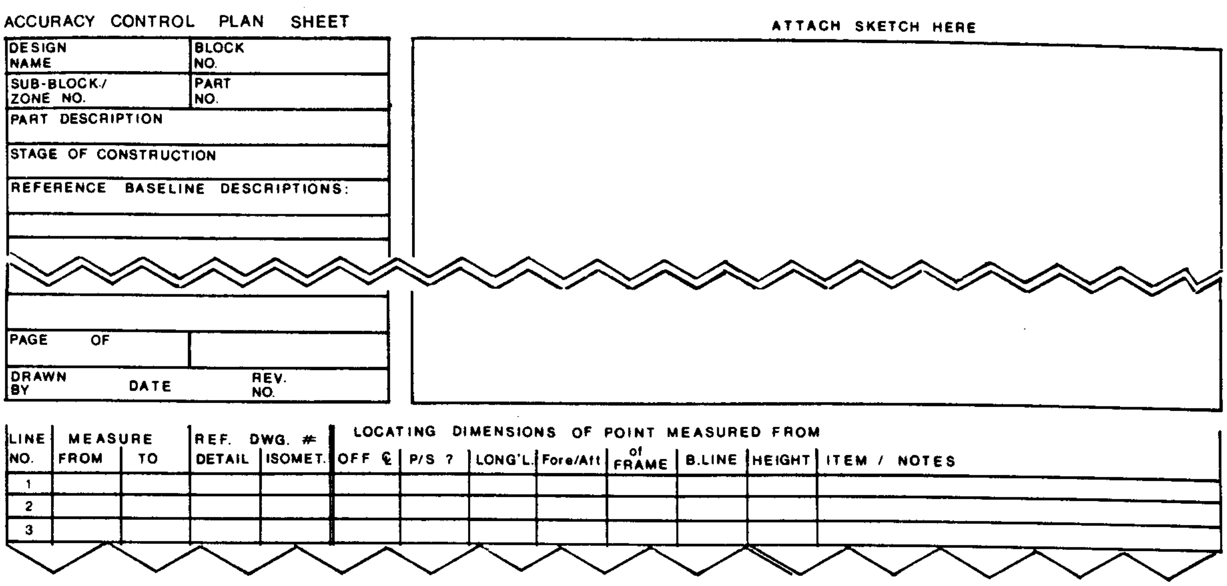


Fig. 3 Accuracy control plan sheet

percentage of rework at the block butt joints. Prior to the development of the A/C database it may be desirable to incorporate an appropriate margin based on past experience. Margins imply a commitment to rework and should be kept to a minimum.

As a project progresses, A/C data may be used to eliminate margins. The planning of block vital points is done simultaneously with the writing of the hull variation merging equations. These equations will specify hull vital point variations in terms of two variables, which are block vital point variations and erection variations. It is because of this geometric relationship between hull variation and block vital point location that the hull variation merging equations are written in conjunction with the block vital point planning (more on variation merging equations will be presented later). The next stage for accuracy control planning is the development of A/C tolerances for block fabrication. These tolerances will normally follow standards established from statistical analysis of past performances. An important task for planners is the identification of standard versus nonstandard parts and assemblies. Standard parts are identified by comparing expected statistical variations for parts with required accuracy as specified by the tolerance limits required by the design. Non-standard parts are exceptional and are to be avoided. Repeatability of production methods is crucial to improving productivity through the use of accuracy control, and this implies standardization of materials, methods and tolerances. A nonstandard part may require special accuracy control planning and may be disruptive of workflow and will almost always be more costly. Once the A/C database has been built up and analyzed, block fabrication standards can be established for each size and type of block. The beauty of the A/C system is that these standards remain more or less unchanged from one design to another. For example, the methods and accuracy of fabricating a double bottom block for part of a parallel mid-body will vary little for ships about the same overall size. At this point in the A/C planning process, a number of items are needed from engineering for each block. They are: the block assembly plan, shell expansion, scaled drawings, structural sections, and an excess material plan. Preparation of the block assembly plan, shell expansion, and excess material plan should involve personnel having A/C responsibilities. The excess material plan should be statistically derived to reflect normal variations and shrinkage. The block assembly plan should be based on assembly sequences, which minimize distortion. Once the various items mentioned above have been supplied by engineering, vital point planning at the subassembly level can begin. Choice of vital points at this level is similar to choosing points for block vital points. Subassembly vital point selection proceeds at the same time as development of variation-merging equations for the blocks. Recording of these vital points is done on the A/C plan sheets as was done with block vital points. Vital point planning for parts and writing variation-merging equations for subassemblies proceeds exactly as above with only one difference. That difference is an additional task at the parts level. It is advantageous to establish reference lines on parts to facilitate measuring for accuracy control. It is also necessary at this stage to develop a sampling frequency plan for each work process based on statistical theory. Sampling should cover all aspects of shipyard production. The purpose of this sampling is to ensure that the work processes are in a state of statistical control. A/C personnel responsible for execution will develop control charts as discussed in Chapter 1. Critical items such as large bulkheads or engine foundations will require 100% inspection but more standard statistical sampling is suitable for high-volume processes such as parts cutting or pipe cutting. At this point the vital point planning is complete down to the level of parts, and variation-merging equations are written for all subassemblies. All vital point planning will have been documented through the use of the A/C plan sheets. Of primary importance in filling out plan sheets and check sheets is clear identification of the exact location of the point to be checked. A space is provided on plan sheets for a sketch for this purpose. The planning phase of A/C is at this point complete and the documents needed to support the execution phase have been prepared. This planning must be completed prior to the start of production in order to allow for measuring to occur throughout the shipbuilding process. This planning phase outlined above is aimed at shipyards that do not have much experience in the application of such a system. As experience is gained it may be possible to alter the sequence of planning. For example, it may prove unnecessary to write the variation-merging equations during the planning phase once planners have sufficient experience to ensure that all measurements necessary for interpretation of the equations will be provided for in the planning.

A/C Executing

Accuracy control execution is concerned with two tasks: the first is to define who, when, and how to measure, and the second is taking the measurements and recording of the data. Before looking into the various aspects of the execution phase, it is useful to review the purpose of all this effort. The objectives of an A/C program may be summarized as follows: determine that work processes are in a state of statistical control, maintain that state of control, and provide information to management to facilitate process analysis and improvement. The first two are important both in the short and long terms. Production workers can monitor the work processes with the aid of control charts, and make adjustments when necessary to maintain the desired state of control. This has obvious short-term benefits in decreasing product variability and hence improving productivity. Maintaining processes in control has the additional purpose of ensuring the validity of a statistical analysis of those processes, which is the third objective. This is the analysis, which provides the principal motivation and benefit of an accuracy program. This third objective can be thought of as the most important goal as it is the long-term goal, which will eventually determine the success of the A/C program. An important aspect in connection with process monitoring is development of preventive maintenance programs for tooling and equipment. Another important aspect is to ensure the lathes and other machine tools are monitored for wear, slop and alignment and to check gages, jigs, and guides for wear. Performing these checks and prescribing tolerances for equipment performance and a normal preventative maintenance program is related to accuracy control in two ways. The first is performing regular checks may be considered part of the A/C measurement program and the second is by limiting variability in equipment functioning may be considered part of clearly defining standard work processes which in turn applies group technology in the shipyard. The basis for prescribing standard limits for work processes is the information contained in the accuracy control database. The mean and range of process variation are used to prepare "X-bar – R" charts which are called Shewart-type control charts. The preparation of these control charts is done using standard statistical procedures reviewed in Chapter 1. These control charts are used by production workers and their supervisors, who regularly plot the values obtained by process sampling. The purpose of the control chart is to act as a visual aid to tell workers whether the process is in control or out of control. If values fall outside the control limits, the cause must be determined, a decision on rework must be taken, and a correction made to eliminate the problem causing the variation. Depending on the nature of the problem, this may involve the workers themselves, supervisors, management or the entire shipyard. One major advantage to using control charts is that the production workers become directly involved in managing their own work. This can be a source of pride and motivation for the workers. It may also stimulate them to suggest creative ideas and workable process improvements. This can eventually promote greater job satisfaction and produce tangible rewards for the organization. The long-term purpose of the analysis discussed above is to create conditions, which facilitate a statistical analysis of work processes. Data collection can be facilitated through provision of a variety of baselines and references marked directly on the structural parts and assemblies. The use of jigs, templates, and other aids quickly becomes self-evident when A/C execution is underway. Both temporary and reusable aids can be advantageously employed to facilitate production and to help with worker self checking and measuring. The A/C check sheets are the medium on which all data are recorded. The check sheet is explained in Chapter 1 with a blank check sheet shown in Fig. 4. Preparation of check sheets should begin as soon as all information is available from planning personnel. Check sheets, once developed, become part of work instruction packages. This has the previously discussed benefit of involving production workers in A/C work. It also ensures that measuring is done at the proper time. Secondary checks will also be made by supervisors and others having A/C responsibilities. Personnel having A/C measurement as a significant part of their jobs may need to be handling a large number of check sheets. The tooling and methods used for A/C measurements will vary somewhat with the type, size, location, and complexity of the interim product being measured. Those responsible for taking measurements may vary as a function of the maturity of the A/C program at a shipyard. Initially, measurements may be taken by an A/C group.

Eventually, the goal is to transition to a point where workers perform self-checking and record measurements as a part of this process. There may be a need for some random checking by an A/C group or by production supervisors, and some critical dimensions may be checked or double checked by the A/C group or production supervisors.

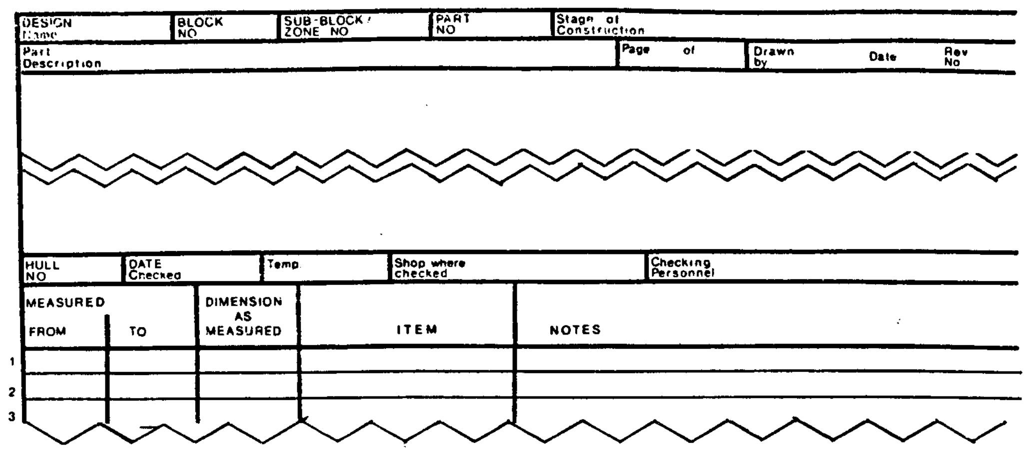


Fig. 4 Accuracy control check sheet

It is therefore useful to examine the measurement process at each stage of production. There are several tasks to be done at the parts fabrication stage in connection with A/C. Overall dimensions, relative positions of lofting marks, and angle of cuts need to be measured. Even if a partial sampling scheme is employed, there will be a great many parts to measure. For this reason it may be desirable to use special jigs or gages for repetitive measurements. As larger assemblies are fabricated, measurement becomes more complex. Overall dimensions are still measured with relative ease using conventional tools and methods. Curvature, twist, and distortion, which have a significant impact on productivity of subsequent assembly, are more difficult to assess.

Triangulation by transit, photogrammetry or laser measurement tools may become attractive alternatives as structures become larger and more complex (See Chapter 5).

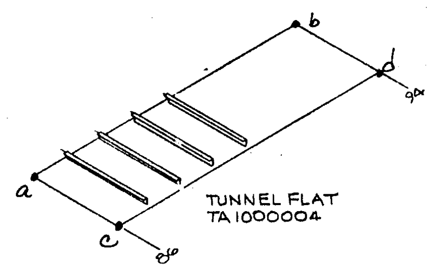
An example of A/C check sheets and the related analysis is shown in Figures 5 - 7. Note the completed measurements on specific parts, and how these are combined used short run SPC techniques to develop a control chart.

ACCURACY CONTROL CHECK SHEET

jrg '82

DESIGN Name	BLOCK NO.	SUB-BLOCK/ZONE NO.	PART NO.	Stage of Construction
TAGOS	6	603	TA 1000004	Prior to stiffener fit

Part Description	Page	of	Drawn by	Date	Rev No.
TUNNEL FLAT	1	1	jrg	6/26/82	



HULL NO.	DATE Checked	Temp.	Shop where checked	Checking Personnel
1	6/29/82		panel line	jrg and RLS

	MEASURED FROM	TO	DIMENSION AS MEASURED	ITEM	NOTES
1	a	b	192 9/16"		
2	a	c	59 7/8"		
3	b	d	59 7/8"		
4	c	d	192 9/16"		
5	a	d	201 4/16"	⊥ Check	
6					
7					
8					

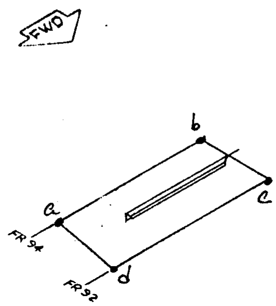
Figure 5 – A/C check sheet for a part

DESIGN Name	BLOCK NO.	SUB-BLOCK/ZONE NO.	PART NO.	Stage of Construction
TAGOS	6	603	TA 1000047	Prior to stiffener fit

Part Description	Page	of	Drawn by	Date	Rev No
OT LONG'L BHD 48" OFF ℄ PORT	1	1	jrg	6/26/82	

jrg '82

ACCURACY CONTROL CHECK SHEET



TA1000047
OT LONG'L BHD
FR 92 AFT TO FR 94, 48 OFF ℄ (PORT)

HULL NO.	DATE Checked	Temp.	Shop where checked	Checking Personnel
1	6/29/82		panel line	jrg and RLS

	MEASURED FROM	TO	DIMENSION AS MEASURED	ITEM	NOTES
1	a	b	105 5/16"		
2	a	d	47 5/8"		
3	c	d	113 3/4"		
4					
5					
6					
7					

Figure 6 – A/C check sheet for a part

ACCURACY CONTROL DATA WORKSHEET

DESIGN NAME TAGOS	HULL NO. 1, 2	PLATE THK. 5/16"	NAME jrg	DATE 1/30/83

PROCESS NC BURNING	STAGE OF CONSTR. PARTS	MEASUREMENT DESCRIPTION OVERALL DIMENSION

	PART NO.	MEASURED FROM	MEASURED TO	DIM. AS MEAS'D. (A)	TARGET DIM. (T)	Variation (X=A-T)	NOTES
1	TA1000004	a	b	192.56"	192.69"	-0.13"	tunnel flat } Hull #1
2	↓	c	d	192.56	192.69	-0.13	↓
3	↓	a	c	59.87	59.84	+0.03	↓
4	↓	b	d	59.87	59.84	+0.03	↓
5	TA1000047	a	d	47.63	47.84	-0.21	long'l bhd 48" off ℄
6	TA1000046	FWD EDGE	AFT EDGE	192.75	192.69	+0.06	long'l bhd on ℄ — Hull #2
7							
8							
9							
10							
11							
12							

X_{min} = -0.21
X_{max} = +0.06

ΣX = -0.35

sample size .... N = 6
ave. variation .... $\overline{X}$ = -0.06"
range .... R = 0.27 in.

FORMULAS:

$$\overline{X} = \frac{\Sigma X}{N}$$

$$R = X_{min} - X_{max}$$

jrg U.W. '83

Figure 7 – A/C data work sheet for, showing mean and range computation for parts

A/C Evaluation/Analysis

The goals of an A/C system are obtained by analysis of the data collected and recorded. The analysis can be subdivided into two main areas: regular and urgent. Urgent analysis takes place when sampling indicates an interim product is not built within tolerance limits and therefore has the potential to disrupt ensuing work. This analysis is used to determine the best course of action, such as immediate rework and rescheduling of succeeding work packages, alteration of succeeding design details or any other method to correct the variations. Regular analysis is the foundation upon which the A/C system is built. A survey conducted at four European shipyards[6] indicates that simple statistics as well as control charts are used to monitor and analyze the production processes. Regular analysis is employed at a number of levels, including a comprehensive initial phase during system start-up. Typical regular analysis functions include:

1. Determination of normal performance by work station or process, required during system start-up or following an alteration of a work process only,

2. Establishment of X-bar –R control charts by work station or process, also required during start-up or following an alteration of a work process,

3. Monitoring of work performance by work station or process, using a pre-established sampling plan following establishment of X-bar –R charts, as described in #2 above,

4. Writing and evaluation of variation merging equations, based on design details, assembly sequence, block plan, etc., and employing the results of A/C sampling measurements by work station as described in Function 1 above,

5. Process analysis, employing normal work performance data and variation merging equations, aimed at identifying specific work processes whose alteration would improve overall productivity.

Of these five specific types of A/C analysis, Types 1 and 2 have already been addressed, Type 3 is dependent on 1 and 2, and Type 4 (Variation merging equations) will be addressed later in this Chapter. Once a shipyard has progressed through the development and evaluation of variation merging equations, it is in a position to complete Type 5, which is to scientifically perform process analysis which is the type of analysis that provides the ultimate payback of continuously improving productivity. An example will be given in Chapter 3, which is the example section.

2.3 Variation Merging Equations

The term variation-merging equations actually encompass two distinct but related sets of equations: an equation, which expresses the addition of the mean variations of the processes, and an equation, which expresses the merging of the statistical variance of those same processes. Although there are two separate equations for any particular case, there is a term-by-term correspondence between the two equations. The reason for this is that they both express the same geometric relationship between the various parts of an assembly, the joining process and the final assembly. The equation expressing the mean variation is an algebraic expression. An assumption is made that on average the parts of an assembly tend to vary from their design dimensions by a certain amount. Then, once they are joined together, the assembled piece will vary from its designed dimension by an amount equal to the sum of the variations of its respective parts. This, of course, must be modified slightly to take into account the variation introduced by the joining process and assembly methods used. Since the joining process and assembly methods themselves may introduce some additional variation, terms are added to the equation to express that fact. The final equation states that the average variation in some principle dimensions of an assembly will be equal to the sum of the average variations of its components and of the joining processes used. The term variation-merging equation will be used to mean this type of equation except where it is clear in context that both types are being discussed. The second type of equation states that the variance in the principal dimension of some assembly will, on the average, be equal to the sum of the variances in the dimensions of its component parts, plus the variances introduced by the assembly process. This type will be referred to as a variance-merging equation. A family of components, each being fabricated by a similar process, brings with it some average variation from its design dimensions, and some variance in those dimensions which expresses how the variations are distributed statistically. This idea is also true for the joining process. These variations are additive when viewed from the standpoint of their effect on the assembly which results from their joining. The variation-merging equations are developed to predict what effect the accuracy of component parts and joining processes will have on the accuracy of assemblies. The form of the variation-merging equations associated with a particular hull is a function of several factors, including:

1. Structural geometry
2. Assembly sequencing
3. Fabrication methods

If a shipyard is employing a PWBS, these factors will not change much for a given type and size of ship, since the basic design and fabrication methods do not change from one ship to the next. This basically implies that the variation-merging equations will remain roughly of constant form within a ship, and from ship to ship within a shipyard. Development and interpretation of these variation equations is greatly simplified by the repetitious character of the equations. Once a series of equations has been developed, it should be straightforward to adapt these to a new hull and to new designs. These variation-merging equations are also partially determined by the assembly sequence used during the assembly process. This will be shown in detail in the example given in

Chapter 3. Similar structural intersections can be governed by different variation-merging equations if the assembly method varies slightly. With traditional shipbuilding methods, the detailed sequence of operations used to fit pieces together is left to the discretion of the fitter. In order to make use of A/C analysis tools, that detailed sequence of operations must be recorded, preferably as part of the work package produced by the detail planners and provided to the fitter. Knowing the intended purpose of the variation-merging equations is crucial in determining which equations need to be written. The main purpose for using variation-merging equations is to reduce rework at the erection stage. The fundamental purpose behind A/C work is improvement of productivity. Productivity in a shipyard cannot be significantly improved without attending to problems encountered at the erection stage. This dominating application of variation-merging equations results in a focus on equations, which describe joint gap variations at master butt intersections. Rework of these weld joints can be minimized through selection of the structural details and fabrication procedures, which minimize merged variation of the width of the weld joint. Variation-merging equations facilitate an analysis of the alternative procedures. In addition, the use of variation-merging equations permits balancing the trade off between different types of rework through adjustments of excess allowances. Excesses are provided to account for shrinkage caused by hot work and may need to be trimmed at some later stage of construction. By reducing the excess of a master butt, one increases the likelihood of rework involving back-strip welding, while decreasing the likelihood that trimming of the excess will be required. A/C analysis of variation-merging equations permits a prediction of what percentage of the joint gaps will require each type of rework, for any given length of excess allowance. Another possible use of variation-merging equations is in the determination of the accuracy of an intermediate process, when direct measurement is not possible, for example, the measurement of weld shrinkage. When developing the variation-merging equations there are a number of simplifying assumptions that must be made. It must be assumed that the blocks, sub blocks, and subassemblies, which contribute to merged variation, are within specified tolerance limits of rectangularity and flatness. If this is not done, the geometry associated with a variation-merging equation can become very complex, and obscure the basic relationships which the equation expresses. These assumptions of rectangularity and flatness are not unreasonable if lower-level processes are maintained in a state of statistical control through the use of control charts and other A/C methods. The use of variation-merging equations presumes that variations are cumulative during an assembly process. While this is in general true, the assumption breaks down when components and assemblies are fabricated in such a manner that distortion due to locked in stresses is present. Variations in the measurements of assemblies may change from day to day due to variations in temperature, restraint forces, or movement of heavy objects, when locked in stress levels are significant. The predictability of A/C is lost in such circumstances. Shipbuilders considering implementing an A/C system should also employ line heating as a method of minimizing distortion due to locked in stresses. In order to insure that all the vital block dimensions and the necessary work process statistics are available for analysis, the variation-merging equations should be developed in some detail during the planning phase. Variation-merging equations are an aid to defining what information will be needed for a thorough post-analysis of achieved accuracy for each work process at each stage of construction. Variation-merging equations express relationships between an assembly and its component parts. Development of the variation-merging equations for a given stage of construction therefore requires that other A/C planning be complete down to the stage of fabrication of the component parts of a structure. The information necessary for development of variation-merging equations for a given assembly includes:

1. The structural geometry of the assembly and its components.
2. The assembly sequence to be used for fabrication of the assembly.
3. The assembly procedure to be used in fabrication the assembly.

If all of the above information is available, development of the equations is relatively straightforward. The use of variation-merging equations will be illustrated with a case study in Chapter 3.

It is also possible to use software to perform variation-merging analysis, and to extend this analysis to include simulation as a means of early prediction of likely rework. Dimensional tolerance simulation is the computer's emulation of an assembly to predict the amount of variation resulting from a process sequence. In addition, dimensional simulation helps determine the key tolerances that contribute to a particular variation. The typical approach using available CAD data is described below.

a. Identify Build Objectives or conditions to be modeled
b. Import or create point data for all relevant components
c. Determine the assembly sequence and create the assembly tree
d. Define the proper move for each component or subassembly
e. Visually verify move behavior through animation
f. Define tolerances based on GD&T

g. Visually verify tolerance points and directions

h. Define measurements for the required outputs

i. Visually verify measurement points and directions

j. Validate overall point movement and direction at the piece part and assembly levels

k. Perform Monte Carlo simulations to create measurement distributions

l. Perform Sensitivity Analysis and evaluate tolerance contributions

2.4 References

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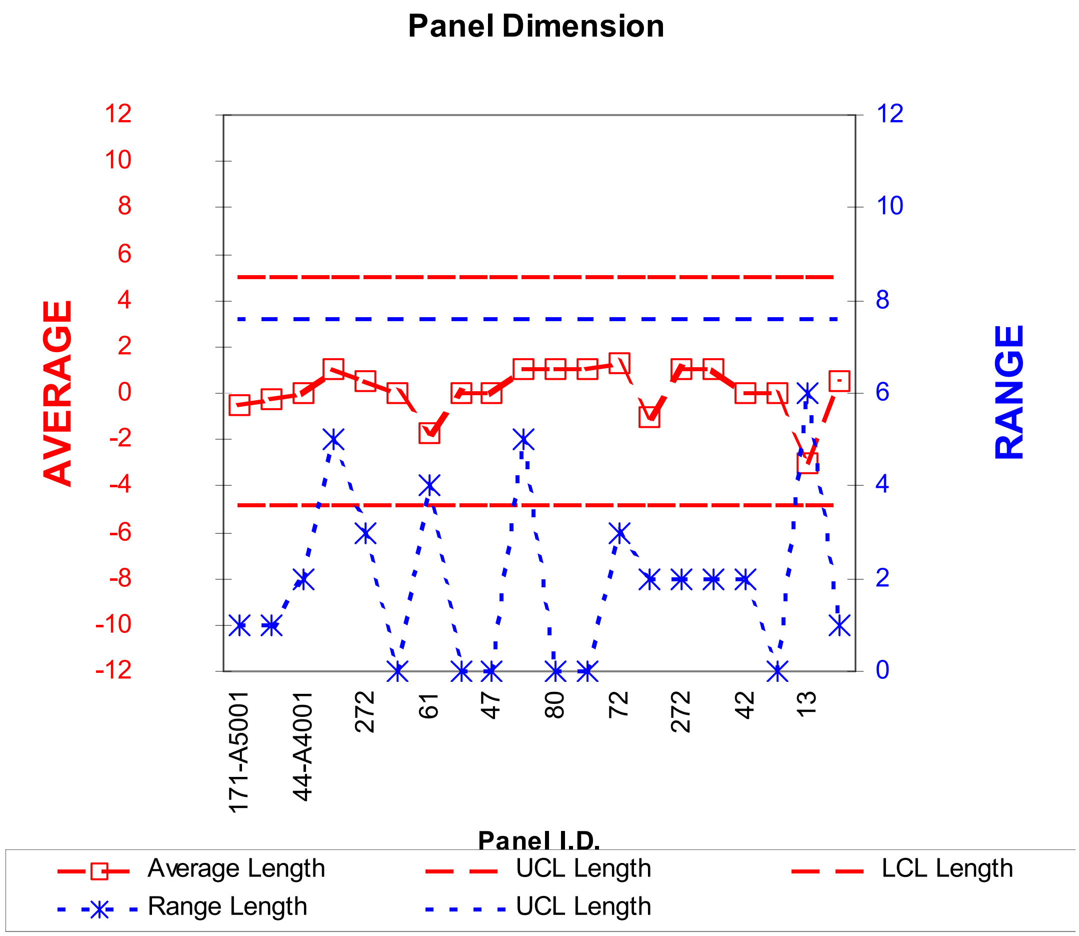
Chapter 3. Examples of Shipbuilding Accuracy Control Implementation

This chapter contains examples of basic approaches to accuracy control, and where possible, actual examples of the implementation and use of the principles of accuracy in shipyards. These examples can serve as guidelines for implementing these principles at any shipyard.

3.1 Example 1

$\overline{X}$ and R charts can be plotted against control limits, employing quality characteristics such as panel length and range. Measurements outside the control limits indicate the process gets out of control and needs to be rectified.



3.2 Example 2

This example covers some of the commonly used accuracy control tools and techniques in the shipbuilding industry.

3.2.1 Source Inspection Profile Audits

In a Source Inspection Profile Audit report, the measurement accuracy is plotted against the tolerance goals. The tolerance goals may be totally different from the statistically derived tolerance limits also known as Natural Tolerance Limits. This audit report helps workers and supervisors in analyzing the trends or other patterns present in the data. Moreover, profile audits also help in knowing the current process status with respect to the target goals. If the measurements fall outside the target goals, then either the process needs to be improved or the tolerance goals should be revised.

The tolerance goals for individual components are based on the designer's view of the requirements, whereas the natural tolerance limits are determined by using statistical methods indicating the capability of the process.

UNTL = X bar + 3*Sigma

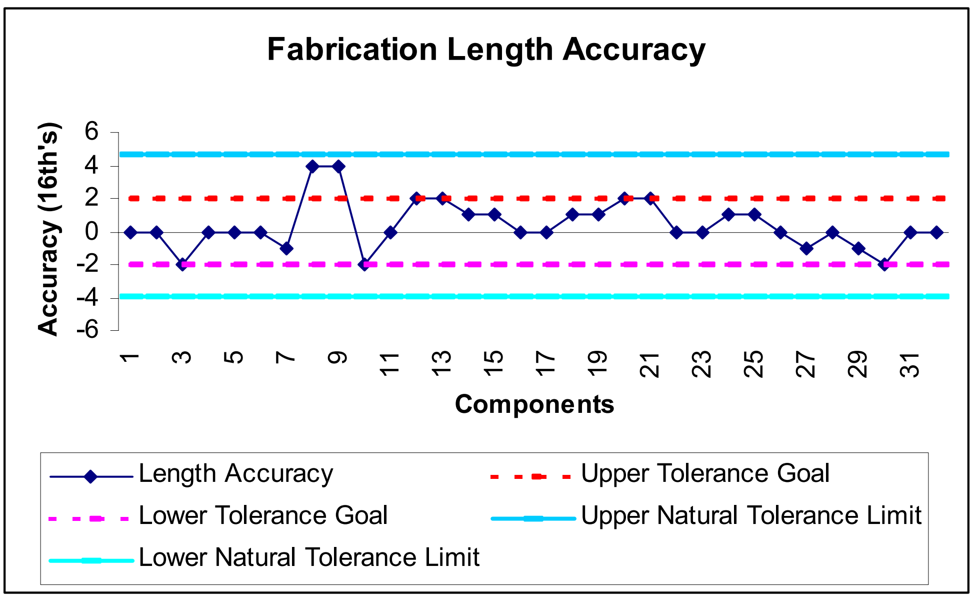
LNTL = X bar - 3*Sigma

where UNTL = Upper Natural Tolerance Limit

LNTL = Lower Natural Tolerance Limit

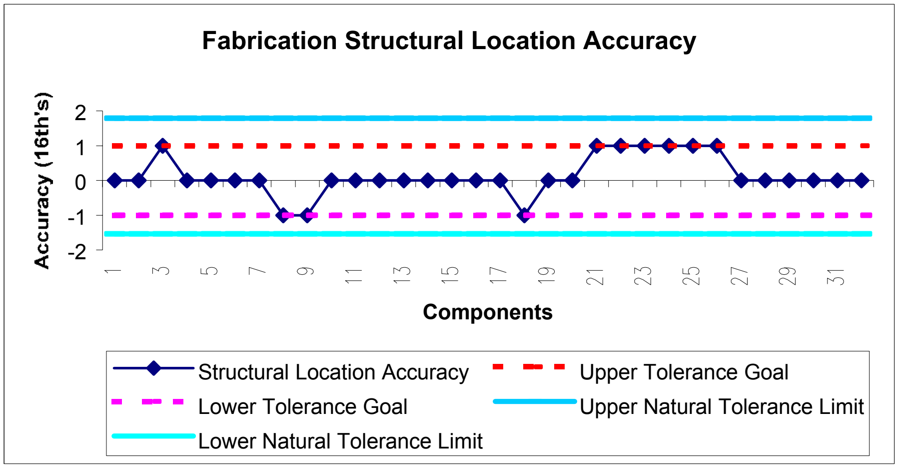
Fabrication Length Accuracy				
Accuracy (16th's)	Upper Tolerance Goal	Lower Tolerance Goal	Upper Natural Tolerance Limit	Lower Natural Tolerance Limit
0	2	-2	4.71	-3.89
0	2	-2	4.71	-3.89
-2	2	-2	4.71	-3.89
0	2	-2	4.71	-3.89
0	2	-2	4.71	-3.89
0	2	-2	4.71	-3.89
-1	2	-2	4.71	-3.89
4	2	-2	4.71	-3.89
4	2	-2	4.71	-3.89
-2	2	-2	4.71	-3.89
0	2	-2	4.71	-3.89
2	2	-2	4.71	-3.89
2	2	-2	4.71	-3.89
1	2	-2	4.71	-3.89
1	2	-2	4.71	-3.89
0	2	-2	4.71	-3.89
0	2	-2	4.71	-3.89
1	2	-2	4.71	-3.89
1	2	-2	4.71	-3.89
2	2	-2	4.71	-3.89
2	2	-2	4.71	-3.89
0	2	-2	4.71	-3.89
0	2	-2	4.71	-3.89
1	2	-2	4.71	-3.89

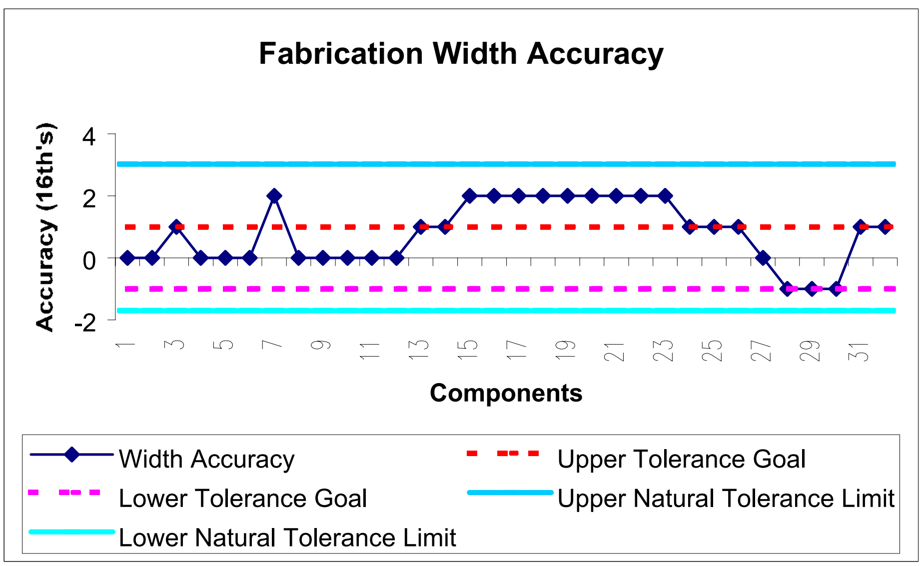
1	2	-2	4.71	-3.89
0	2	-2	4.71	-3.89
-1	2	-2	4.71	-3.89
0	2	-2	4.71	-3.89
-1	2	-2	4.71	-3.89
-2	2	-2	4.71	-3.89
0	2	-2	4.71	-3.89
0	2	-2	4.71	-3.89
Mean (X bar)	**0.40**			
Standard Deviation (Sigma)	**1.43**			
Upper Natural Tolerance Limit	**X bar + 3*Sigma**	**4.71**		
Lower Natural Tolerance Limit	**X bar - 3*Sigma**	**-3.89**		

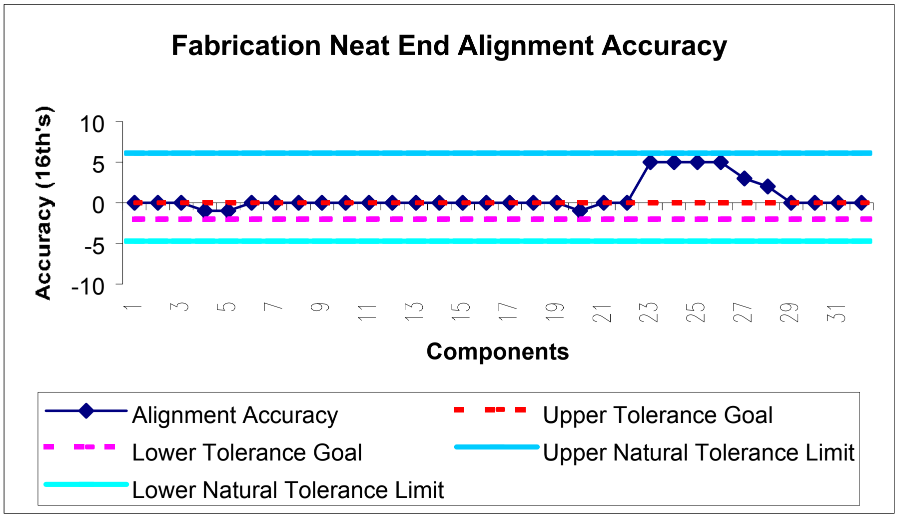


The fabrication length accuracy of 32 components is plotted. It should be noted that the tolerance goals for fabrication length accuracy are set much tighter than the upper and lower tolerance limits. Some components are falling outside the tolerance goals. It reflects that even if the process is in-control based on the natural tolerance limits, the components produced will not be able to meet the tolerance goals. It will lead to either revising the tolerance goals or improving the process further by reducing the variability so that all the components produced meet the tolerance goals.

Similar charts for fabrication structural location accuracy, width accuracy and neat end alignment accuracy are plotted.

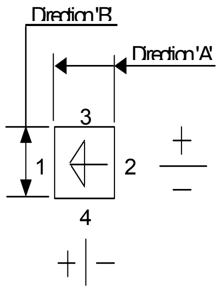


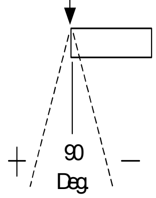




3.2.2 Data Recording Sheet

Data Recording Sheet facilitates systematic recording of data or measurements observed directly from a process. The data-recording sheet of 100 mm coupons cut on all NC cutting machines on each shift to ensure proper alignment of cutting and marking heads is shown below.





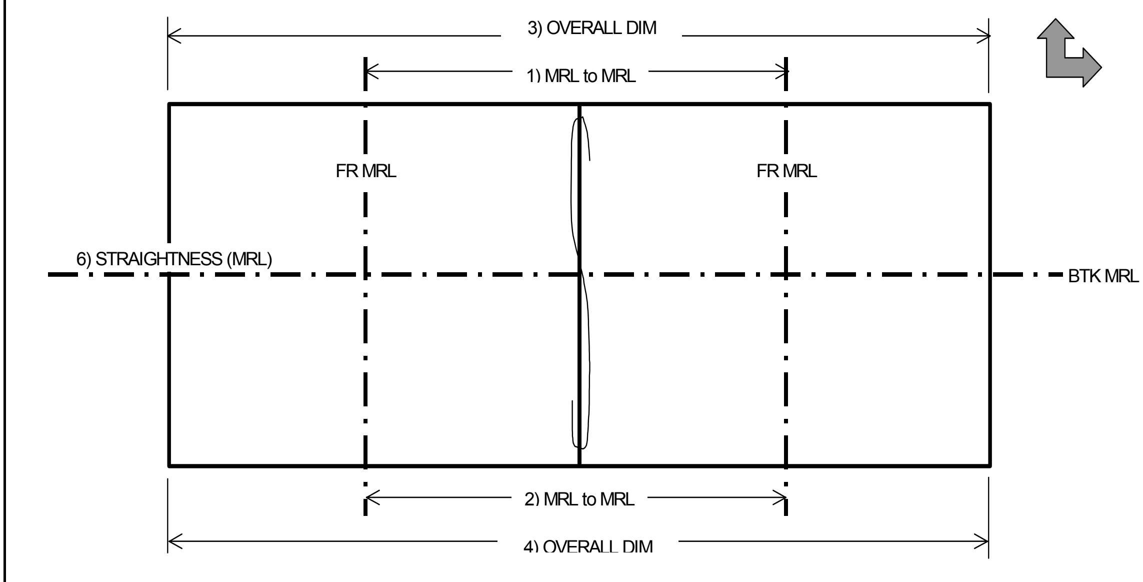
Description									Area				
ACE Test Plate Coupons													
Check Types:			1) Center Marks (L/O)				2)Overall Dimensions (in mm's)				3) Side Cut Angles (Degree)		
						Center		Overall Size		Side Cut Angles			
Date	Shift	Time	Checker	Quad	Thk	Dr. A	Dr. B	Dr. A	Dr. B	Side1	Side2	Side3	Side4

3.2.3 Source Inspection Check Sheet

In source inspection check sheet, the actual dimensions are compared against the designed dimensions to check if the difference exceeds the tolerance level. If the difference between the actual and design dimension exceeds the tolerance level, then the corrective action is taken and also recorded on the check sheet for future reference.

SOURCE INSPECTION CHECK I. D. 5-3,4,6

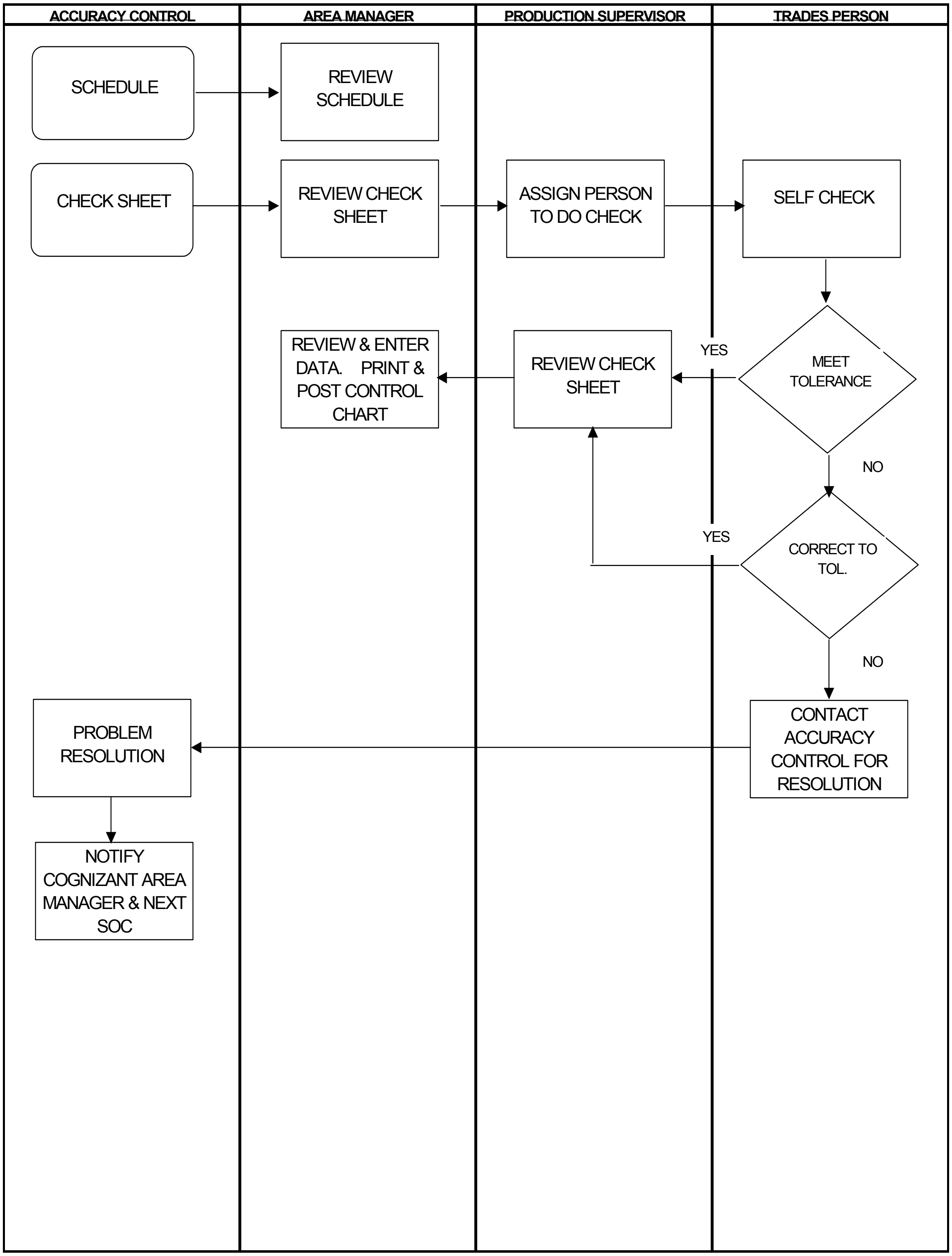
CHECKER NAME:		DATE:
HULL #: 490	Assembly #:	AREA: ON BLOCK
CHECK DESCRIPTION: DIMENSIONS MRL to MRL (S5-3), OVERALL (S5-4), STRAIGHTNESS (S5-6)		



DIMENSIONS	*DESIGN	ACTUAL	DIFF	TOLERANCE	ACTION	CHECK I.D.
1) MRL TO MRL	*			± 4mm	Correct to tolerance	S5-3
2) MRL TO MRL	*			± 4mm		S5-3
3) OVERALL LENGTH	*			± 4mm		S5-4
4) OVERALL LENGTH	*			± 4mm		S5-4
5) STRAIGHTNESS (MRL)				± 3mm		S5-6

3.2.4 Source Inspection Flow Chart

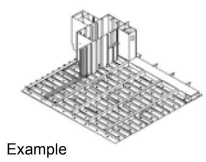
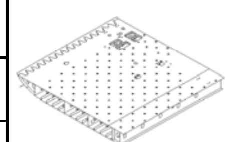
Source Inspection Flow Chart depicts the sequences of accuracy control related activities performed across different departments in an organization. . This chart helps in maintaining and controlling the product as well as process quality at different stages of production. Moreover, feedback from the customer department facilitates in improving the process on a continuous basis.


ACCURACY CONTROL
AREA MANAGER
PRODUCTION SUPERVISOR
TRADES PERSON
SCHEDULE
REVIEW SCHEDULE
CHECK SHEET
REVIEW CHECK SHEET
ASSIGN PERSON TO DO CHECK
SELF CHECK
MEET TOLERANCE
YES
REVIEW CHECK SHEET
REVIEW & ENTER DATA. PRINT & POST CONTROL CHART
NO
CORRECT TO TOL.
YES
NO
CONTACT ACCURACY CONTROL FOR RESOLUTION
PROBLEM RESOLUTION
NOTIFY COGNIZANT AREA MANAGER & NEXT SOC

3.2.5 Tolerance matrix

The following figure shows a tolerance matrix diagram. Note that each tolerance corresponding to a critical parameter has as action associated with it if the tolerance is not achievable.

SOC-3 , ASSEMBLY

Description	Sample	ID	Measurements	Tol.	Action	Comments
Flat Single Skin	All A-2s	S3-1	Flatness	+6, -6	Correct to tolerance	 Example
	All panels of 4 or more plates. Post cutting of NA	S3-2	Panel length from MRL	+3, -3	>+/- 4 contact AC	
		S3-3	Panel width from MRL	+3, -3	>+/- 4 contact AC	
		S3-4	Panel squareness	+5, -5	>+/- 5 contact AC	
		S3-5	MRL squareness	+2, -2	Correct to tolerance	
	All A-2s	S3-6	Plumbness of vertical structure	+5, -5	Correct to tolerance	
Flat Single Skin (Cont)	All even numbered blocks @ A2	S3-7	MRL of structure to MRL of skin plate	+2, -2	>2 contact AC	
		S3-8	Edge of Long to edge of skin plate	+2, -5	>3 Trim, <5 Build up edge with weld to tolerance	
		S3-9	Long spacing at panel edge measured to MRL	+2, -2	Correct to tolerance	
		S3-10	Web spacing at panel edge measured to MRL	+2, -2	Correct to tolerance	
Flat Double Skin	All A-2s	S3-11	Flatness	+6, -6	Correct to tolerance	 Example
	All panels of 4 or more plates. Post cutting of NA	S3-12	Panel length from MRL (Upper & lower)	+3, -3	>+/-4 contact AC	
		S3-13	Panel width from MRL (Upper & lower)	+3, -3	>+/-4 contact AC	
		S3-14	Panel squareness (Upper & lower)	+5 ,-5	>+/-5 contact AC	
		S3-15	MRL squareness (Upper & lower)	+2, -2	Correct to tolerance	
Flat Double Skin (Cont)	All even numbered blocks @ A2	S3-16	MRL of structure to MRL of skin plate (Upper & lower)	+2, -2	>2 contact AC	
		S3-17	Edge of Long to edge of skin plate (Upper & lower)	+2, -5	>3 Trim, <5 Build up edge with weld to tolerance	
		S3-18	Long spacing at panel edge measured to MRL	+2, -2	Correct to tolerance	
		S3-19	Web spacing at panel edge measured to MRL	+2, -2	Correct to tolerance	
	All A-2s	S3-20	Deviation of MRLs between upper & lower panels at erection edges	+3, -3	Correct to tolerance	

3.3 Accuracy Control Implementation Pictures

Shell Stringer Girth Checks

- AC Engineer checking girth dimensions with mechanic
- Engineer verifies and corrects errors on site
- Training/root cause analysis completed at point of execution

Shell Stringer Girth Checks

- Standard AC check sheets used to direct mechanics and record actual dimensional data
- Results rolled up to dimensional analysis tool used to measure trends
- All checks accomplished “at tack”

Deck Stringer Dimensional Checks

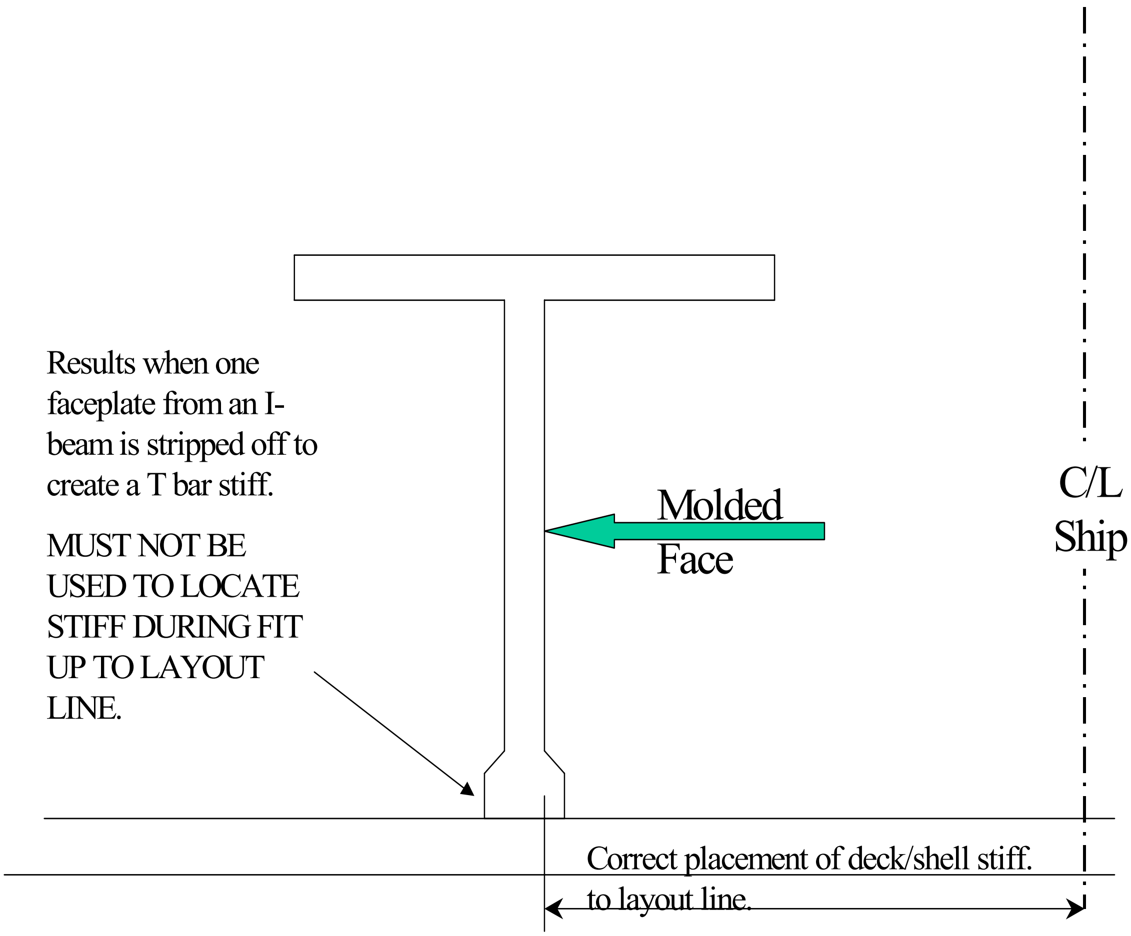
- Stringer checks using girth tapes
- All stringers checked "at tack" prior to welding
- AC engineer verifies all stringer locations prior to welding

Stringer Dimensional Checks

- Ship fitter checking shell stringer locations
- Check ensures proper alignment at unit erection
- Checks validate dimensional accuracy to design requirements

Structural Stringer Placement Direction - Provided by Accuracy Control

- AC engineers provide direction/training to fitters



Capability for Fitting Bulkheads Without Collars

- Accuracy control assures tight tolerances on cut, tee bar dimension and stiffener location
- These tight tolerances eliminate the need for collars
- These tight tolerances can be achieved using statistical methods to control variation in processes or by adding an additional mechanical planer processing step

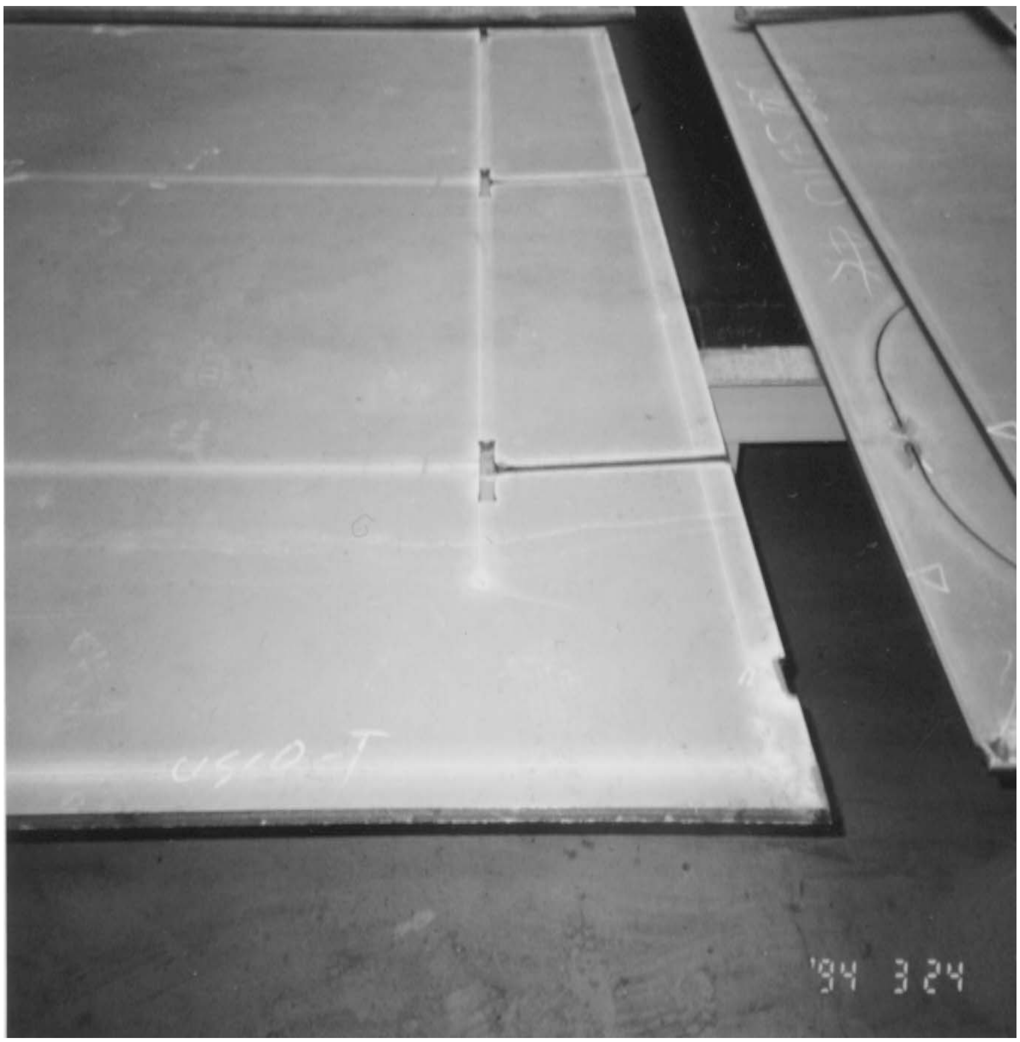


Plate Edge Straightness Check

- Inboard edge checked for straightness using piano wire. Plate within 1/16” in 46’

Plate Edge Straightness Check

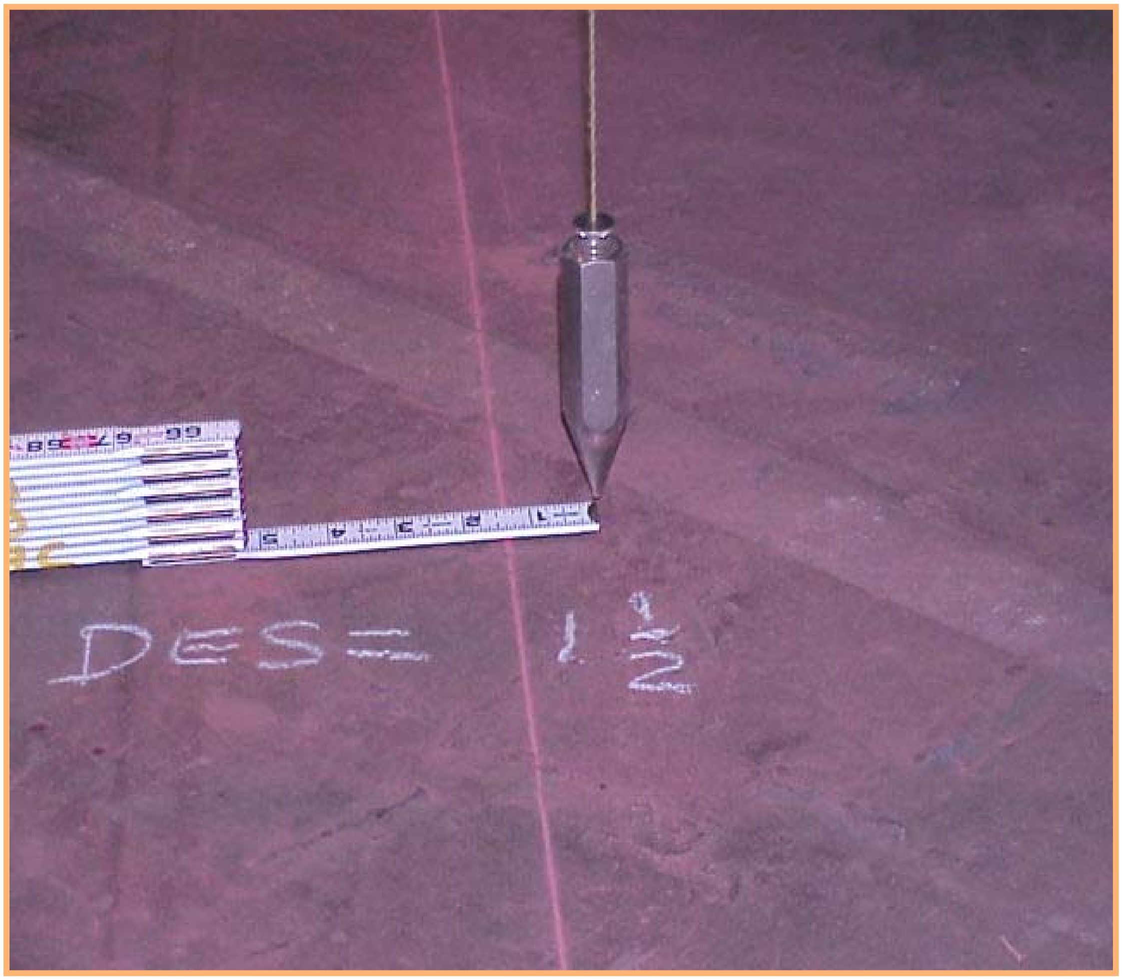
- The plate edges being checked for straightness from the reference line.
- This plate (0835) found to have a 1/4” bow.

Bulkhead Alignment Checks Using Work Points (WP)

- Checking alignment of back up structure to molded line layout on floor.

Bulkhead Alignment Checks Using Work Points (WP)

- Fwd-Outboard most point within 1/8”



Bulkhead Alignment Checks Using Work Points (WP)

- WP fwd of Frame on Port side. Bhd location to design molded line is OK.

Bulkhead Alignment Checks Using Work Points (WP)

- Bhd location to design molded line is OK.

Critical Shape Check using Jig

- Typical shape checks at the trough ends.

Panel to Mock Check

- Panel fit to mock check. Monitor shape of panel to desired shape on mock

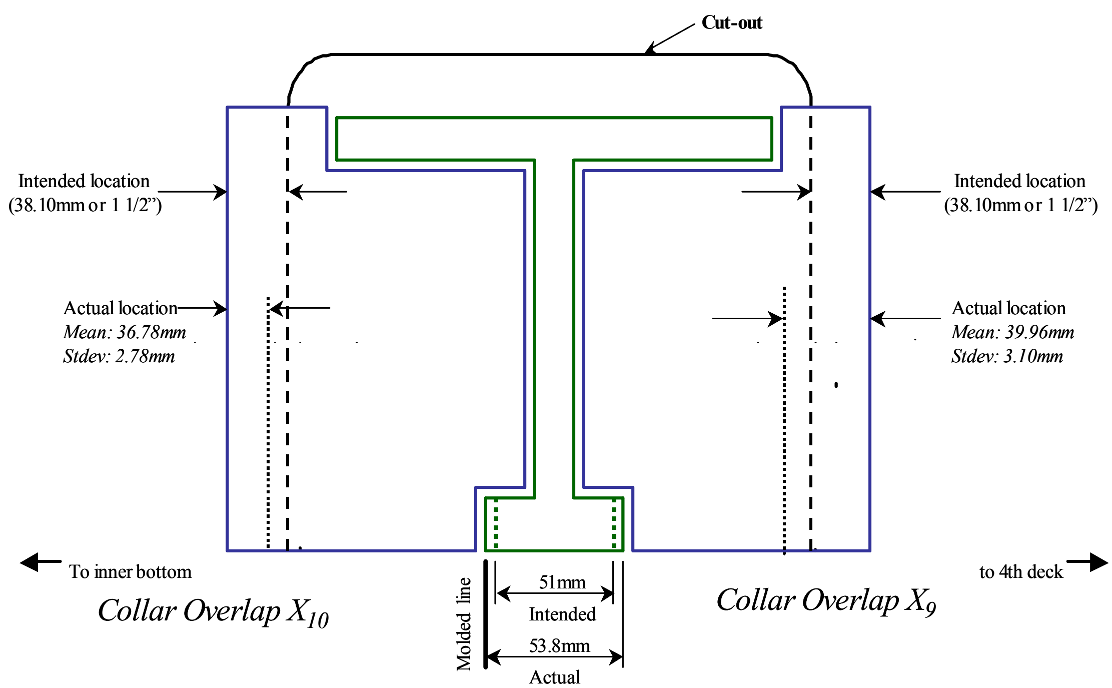
Panel to Mock Check

- Panel fit to mock check. Monitor shape of panel to desired shape on mock

3.4 Example 3

Consider a process in which it is critical to maintain a minimum 1 ½ inch overlap on the collar to intercostal lap joint on either side of the panel stiffeners to eliminate fit-up problems.

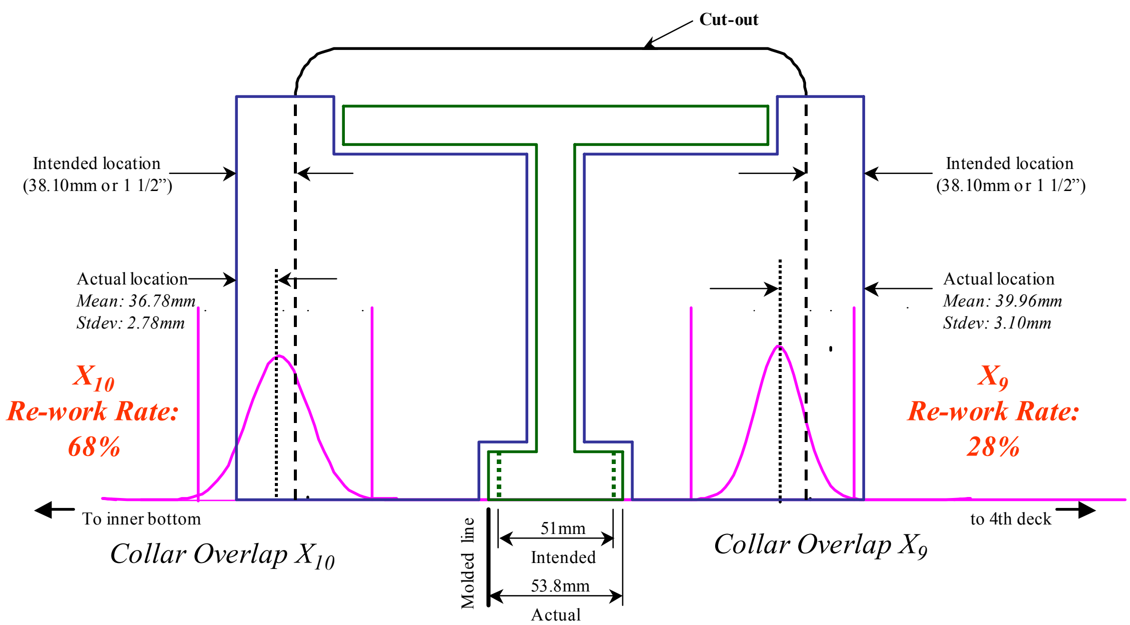
Collar width analysis



There are various methods available to maintain the specified overlap. For example, increasing the root gap at the collar to stiffener web or increasing the collar width by fabricating a custom wider piece or trimming the collar or increasing the slot width on the other extreme.

Merged variance analysis technique was used to understand the root cause of the problem. The measured mean (differences from intended) and respective variances of the respective contributing variables influencing the outcome of the collar lap width were added together.

Collar width analysis

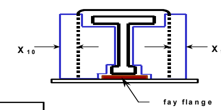


The two bell shaped distribution curves show the resulting probability of rework on each side of the stiffener. For the right X9 side, the area of the distribution curve to the right of the dashed, hidden cutout line shows a 28% probability of the lap width being less than 1 ½ inch. The left X10 side shows a 68% probability of the lap width from the left dashed hidden cutout line being less than 1 ½ inch.

The problem is analyzed by adding different shrinkage factors to maintain the specified overlap. The effect of addition of different shrinkage factors on the rework rate as well as on the symmetry of the curves with respect to each other was studied carefully.

Analysis of Applied Weld Shrinkage in the Z direction for Unit 1204D - BB #2

CONCLUSION:
Based on the data, a shrinkage factor of 0.00034 inch/inch added to the panel in the *z-direction* would offer the optimum collar overlap design. Although the added shrinkage value may reduce rework by the mechanics, *shrinkage alone* would not completely eliminate fit-up problems on this assembly.



Measured - No Shrinkage				
X9 Statistics		Re-work	X10 Statistics	
count	30	68.1%	count	30
average	**39.96**		average	**36.78**
stdev	3.01		stdev	2.78

Shrinkage Factor of 0.00030 inch/inch				
X9 Statistics		Re-work	X10 Statistics	
count	30	48.8%	count	30
average	**38.55**		average	**38.19**
stdev	3.02		stdev	2.77

Shrinkage Factor of 0.00032 inch/inch				
X9 Statistics		Re-work	X10 Statistics	
count	30	47.6%	count	30
average	**38.46**		average	**38.28**
stdev	3.03		stdev	2.77

Shrinkage Factor of 0.00034 inch/inch				
X9 Statistics		**Re-work**	**X10 Statistics**	
count	**30**	**46.8%**	***count***	**30**
average	**38.37**		***average***	**38.38**
stdev	**3.03**		***stdev***	**2.78**

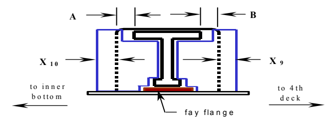
Ideal Shrinkage

Shrinkage Factor of 0.00035 inch/inch				
X9 Statistics		Re-work	X10 Statistics	
count	30	47.2%	count	30
average	**38.32**		average	**38.42**
stdev	3.03		stdev	2.78

Note: *All dimensions are in millimeters. The minimum design collar overlap for the dishplate cut-outs on BB #2 is* ***38.1mm (1-1/2").***

Re-scaling the panel to increase in length in the Z direction by a factor of .00034 inches per inch helped in getting the two distribution curves symmetric. The rework rate was minimized to 46.8% but not eliminated completely. Therefore, the shrinkage factor alone would not be able to completely eliminate fit-up problems.

In order to reduce the rework rate significantly, a sufficient margin was added to the width of the collar plate to compensate for the merged variance of all the remaining input factors. By adding 5/16 inch to the individual collar plate width, the probability of rework to achieve the 1½ inch minimum lap joint width dropped to less than1%.



Actual Measurements			
Atttribute	Mean	Stdev	Chance of Re-work
X9	39.96	3.01	
X10	36.78	2.78	68%

1/16" Added to Collar Width			
Atttribute	Mean	Stdev	Chance of Re-work
X9	41.54	3.01	
X10	38.37	2.78	46%

1/8" Added to Collar Width			
Atttribute	Mean	Stdev	Chance of Re-work
X9	43.13	3.01	
X10	39.95	2.78	25%

3/16" Added to Collar Width			
Atttribute	Mean	Stdev	Chance of Re-work
X9	44.72	3.01	
X10	41.54	2.78	11%

1/4" Added to Collar Width			
Atttribute	Mean	Stdev	Chance of Re-work
X9	46.30	3.01	
X10	43.13	2.78	3%

5/16" Added to Collar Width			
Atttribute	Mean	Stdev	Chance of Re-work
X9	47.89	3.01	
X10	44.72	2.78	1%

3.5 Example 4

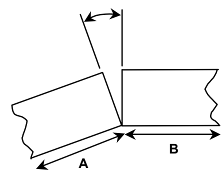
A shop producing box units observed that all of the plates with cold-formed knuckles in the units were coming-up short. The number of knuckles in the plate were correlated to the extent the corresponding plate was short. After doing the initial analysis, it was found that the length was short by 0.125 inch per knuckle for the given thickness and bend angle.

Analysis of Cold-formed Knuckled Plates

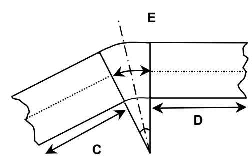
		Unit Number			
		112A	**113A**	**114A**	**115A**
Number of Knuckles on Recess Plate		1	2	1	0
Angle of First Knuckle		15.05°	15.24°	16.09°	-
Angle of Second Knuckle		-	15.16°	-	-
End Alignment Measurements (+ is short and - is full)		0.25	0.38	0.19	-0.13
		0.25	0.44	0.25	-0.06
		0.25	0.38	0.19	-0.06
		0.25	0.44	0.25	-0.06
		0.25	0.38	0.31	-0.06
		0.19	0.38	0.19	0.06
		0.19	0.44	0.25	0.00
		0.25	0.50	0.25	-0.06
End Alignment	**Count**	8	8	8	8
	Means	0.23	0.41	0.23	-0.05
	Std Dev	0.03	0.05	0.04	0.06
End Alignment Mean divided by Number of knuckles on Recess Plate		**0.23**	**0.21**	**0.23**	**N/A**

The difference between the current method and the proposed method is approximately 0.125".

*- Current method for calculating material length for knuckle plates - **A + B.***

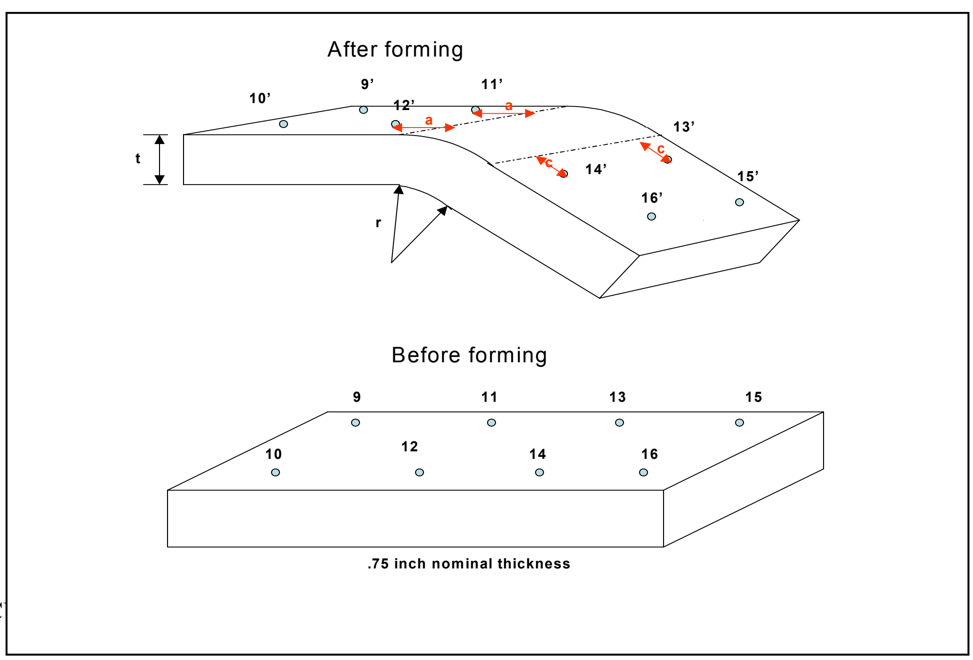


*- Proposed method for calculating material length for knuckle plates -**C + D + E.***



E is the arc length of the knuckle at 1/2 the thickness of the plate.

The measurement procedure was analyzed thoroughly. The existing procedure for developing the neat length was using an approximation based on the sum of the two inside legs assuming no radius in the knuckle.



ACC

To incorporate knuckle radius in the plate length measurement, a test was done to determine the application of cold forming (rolling) rule in calculating plate's total length. The rolling rule assumes the neat length through the half-thickness stays the same before and after rolling. This requires knowing the thickness, bend radius and bend angle to compute the girth between tangents of the bend at the neutral axis of the plate (center of area of the section).

A plate to be knuckled was taken, and targeted for a total station survey before and after forming.

	Before-forming			
point	x	y	z	
9	0	0	0	
10	-0.04	-50.058	0	
11	96.042	0	0	
12	96.026	-50.019	0.131	
13	186.025	0.002	0.354	
14	186.026	-50.026	0.509	
15	226.052	-0.002	0.45	
16	226.042	-50.071	0.56	
p11p13	89.983	0.002	0.354	89.9837
p12p14	90	-0.007	0.378	90.00079
	After-forming			tiB
9'	0	0	0	
10'	-0.0389	-50.0532	0	
11'	96.014	0	0	66.06912
12'	96.0031	-50.012	0.2631	66.63159
13'	183.7263	-0.0424	-9.528	23.64766
14'	183.7427	-50.0968	-9.2707	23.0542
15'	220.3641	-0.1188	-25.6571	
16'	220.3695	-50.1815	-25.3573	
p9p11	96.014	0	0	96.014
p10p12	96.042	0.0412	0.2631	96.04237
p13p15	36.6378	-0.0764	-16.1291	40.03101
p14p16	36.6268	-0.0847	-16.0866	40.00385
p11p13	89.984	Measured distance between targets before forming		
p11'p13'	89.983	Girth through neutral axis after forming		
p12p14	90.001	Measured distance between targets b4 forming		
p12'p14'	90.000	Girth through neutral axis after forming		

The measured data was used to calculate the location of the neutral axis, the bend angle, and the distance between tangents of the bend and the target locations. By measuring the bend radius directly, the girth through the neutral axis between tangents was calculated.

Comparing the measured lengths before rolling to the computed girths after rolling yielded less than 0.001-inch difference in both cases. Therefore, it was concluded that the rolling method for detailing the neat length could be used for detailing the neat length of a plate for the knuckling process.

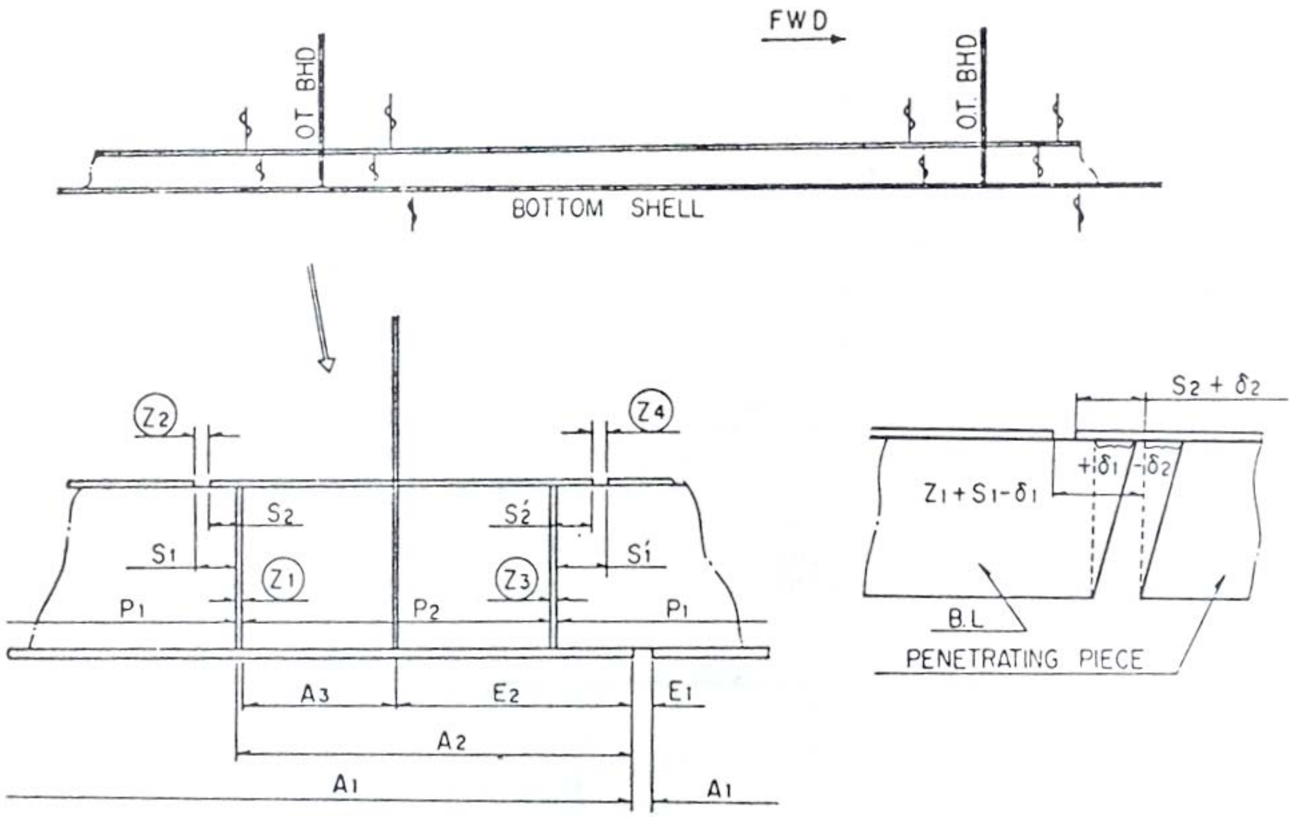
3.6 Example 5

Variation-Merging Equations

Variation- merging equations, as described in chapter 2, are developed as an accuracy control tool used in ship building industries. These equations are used with normal accuracy performances and propose optimum design details, assembly and erection sequences, tolerances etc.

The impact of any kind of variation on the final product /assembly can be predicted by using different statistical techniques. In order to control the variability of the final product, it is crucial to identify and control the variation at each and every stage of production or assembly. Therefore, it becomes very important to reduce the standard deviation and control the mean value of each process considering their effect on the final product. It is assumed that the variations generated by each work process follow a normal distribution and accumulate as another normal distribution at the last stage. At each design stage, accuracy planners predict the merged variation within every manufacturing cell. For example, for block assembly, normal distributions are used for each work process, i.e., panel assembly, panel making, panel finish cutting and internal member welding to predict the normal distribution for blocks currently being planned.

A detailed procedure describing the variation merging equation method to predict gap sizes, which will occur during hull erections and probability for rework, is shown below in the figures. The entire assembly operation is broken down into sub-levels and variation-merging equations are applied to estimate the merged variation.



Assembly Procedure:

1. Fit the flange on the web shifted by S_1 (fwd end of longitudinal).
2. Fit the flange on the web shifted by S_2 (aft end of penetrating piece).
3. After the plates are welded together to create the bottom panel, incorporate a 3mm excess allowance and finish cut the panel's forward edge.
4. Fit the longitudinals to the bottom panel shifted by A_2 where A_2 = the designed dimension + 2mm.
5. Fit the penetrating piece to the transverse bulkhead at the distance A_3.

Variation Merging Equations for the Joint Gaps During Hull Erection:

$$Z_1 = A_2 - (A_3 + E_2)$$

$$Z_2 = Z_1 + [(S_1 - \delta_1) - (S_2 + \delta_2)]$$

$$Z_3 = [E_2 - (P_2 - A_3)] - [(P_1 + A_2) - (A_1 + E_1)]$$

$$Z_4 = Z_3 + [(S_1{}^1 - \delta_1{}^1) - (S_2{}^1 + \delta_2{}^1)]$$

- A negative value for Z predicts overlaps, i.e., negative gap.
- The value for every A, E, etc. is dependent upon a similar lower-tier equation which accumulates variations for marking, cutting, etc. as measured from a reference line.

ESTIMATED MERGED VARIATION (Z)

Dimension	Sample size n	Mean value $\bar{x}$	Variance s^2	Remarks
P_1	126	+0.4	0.91	Length of bottom longitudinal after web is welded to flange.
P_2	50	+0.5	0.79	Length of penetrating piece after web is welded to flange.
d_1, d_2	156	0	0.51	Perpendicularity of bottom longitudinal and penetrating piece ends.
d_1', d_2'				
S_1	140	+1.1	0.61	Fitting position of bottom longitudinal flange.
S_1'	140	+0.5	1.61	Shift between web and flange at the after end of bottom longitudinal.
S_2	50	−0.4	0.61	Fitting position of flange of penetrating piece.
S_2'	50	+0.6	1.82	Shift between web and flange at the forward end of penetrating piece.
A_1	36	+2.9	1.38	Length of bottom panel after finish cut.
A_2	83	+1.6	1.64	Fitting position of bottom longitudinal.
A_3	70	−0.8	2.02	Fitting position of penetrating piece.
E_1	42	−0.4	2.43	Accuracy of gap between bottom panels measured between reference lines after welding.
E_2	44	+1.9	4.60	Erected position of Transverse Bulkhead; Distance from butt of bottom panel.
Estimated Gap				
Z_1	______	+0.5	8.26	______ ______ * 7%
Z_2	______	+2.0	10.70	______ ______ * 17%
Z_3	______	+1.0	13.79	______ ______ * 14%
Z_4	______	+1.0	18.22	______ ______ * 17%

* Estimated occurrence of gaps which are 5 or more mm wide; back-strip welding is required. The method for calculating these estimates is described in Appendix E, Figure 8.

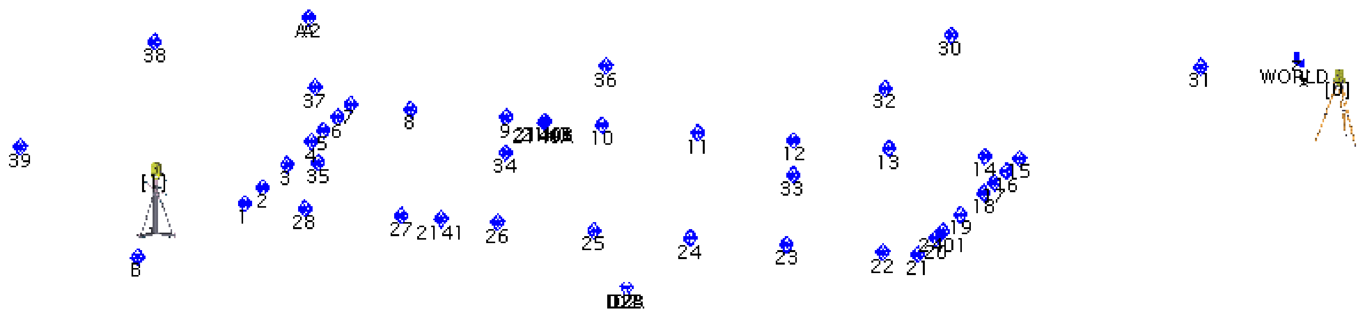
ACTUAL MERGED VARIATIONS

Actual Gap	Sample size n	Mean value $\bar{x}$	Variance s^2	Actual occurence of back-strip welding
Z_1	85	+0.8	7.61	4%
Z_2	82	+2.3	9.71	12%
Z_3	78	+1.1	10.02	6%
Z_4	72	+2.2	13.75	13%

3.7 Example 6

Accuracy control using linear regression technique

The following example explains a before-weld to after-weld survey comparison of approx. 30ft by 40ft thin plate deck by using linear regression techniques. Retroreflective targets are placed around the perimeter of the deck at the structural intersections. The target arrangement is shown the figure below.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The targets that appear outside of the plane of the part are used to support multiple positions of the total station and are not used in the analysis. To get a crisp data (high signal to noise metrics) on weld shrinkage studies, before-weld baseline survey is required to take out the variability of marking and cutting. When design intent or tool-path command data is used for marking and cutting the plate panel as the baseline for comparison, the standard error (1sigma) would be 2 or 3 times the mean, and the quality statistics would suffer. By comparing the two surveys with a linear regression analysis in a common local coordinate system, the true shrinkage in the longitudinal and transverse directions from welding the structure on the panel is the slope of the respective linear regression lines. No intercept is used in the regression since both data sets were transformed to the same zero-point, target 1. Using the "linest" function in EXCEL for the regression analysis, all the related quality statistics are obtained.

Table 1 shows the as-measured data in the coordinate system of the each instrument set-up (z points to gravity). Table 2 shows the translation and rotation of the before-weld data into a 3-point orthogonal basis defined by targets 1,21 & 7. The line through targets 1 & 21 points transversely with constant y. Data in table 3 spreadsheet does the same (Table 2) for after-weld survey data. Table 4 shows the summary of regression analysis for common target numbers for the "x" & "y" directions.

Note that a constant to correct for the temperature difference (19 deg. F x CTE for steel) in the deck between the two surveys had to be added to the measured regression slope result; otherwise the deck appears to have gotten "bigger" as a result of weld shrinkage. Same results will be obtained if the before-weld raw data is rescaled by the same factor +1 (=1.000134) after the transformation to the common coordinate system. The surveys were performed with Leica total stations.

After weld					Before weld			
1	-334.9358	-838.5975	-43.00404		1	511.5423	203.463	-42.61287
2	-366.6476	-789.3318	-43.93667		2	461.1611	173.9512	-42.33741
3	-410.0035	-722.1074	-43.86943		3	392.1286	133.4823	-42.92913
4	-453.2703	-655.0862	-43.50732		4	323.2798	93.09587	-42.55192
5	-474.758	-621.7778	-43.7791		5	289.0266	73.03175	-42.25818
6	-500.2954	-582.3189	-43.75034		6	248.5023	49.19509	-42.33993
7	-523.552	-546.1138	-43.55943		7	211.2627	27.4774	-43.47308
8	-480.2197	-521.1118	-43.66616		8	188.1204	71.77357	-42.05497
9	-410.9167	-481.0864	-43.57266		9	151.1395	142.8066	-41.61934
10	-341.5335	-441.0899	-43.70704		10	114.1027	213.8728	-41.75286
11	-272.1458	-401.0641	-43.51137		11	77.09365	284.9312	-41.99964
12	-202.8202	-361.0794	-43.34216		12	40.08963	355.9675	-41.92383
13	-133.4681	-321.0258	-43.44424		13	3.04296	426.9602	-42.26278
14	-64.1334	-281.0444	-43.5881		14	-33.95181	497.9643	-42.14225
15	-38.92528	-266.4936	-43.15834		15	-47.40278	523.804	-42.44943
16	-15.58578	-302.7542	-43.39625		16	-10.17453	545.5202	-42.59665
17	6.135009	-336.3403	-43.37543		17	24.32887	565.7624	-42.80693
18	24.89961	-365.3665	-43.76349		18	54.14012	583.2631	-42.9532
19	66.52429	-429.9242	-43.46878		19	120.4653	622.1566	-42.84969
21	142.5589	-547.7793	-42.77869		20	189.6494	662.669	-42.66427
20	109.9945	-497.2769	-43.57538		21	241.436	692.9794	-43.06976
22	117.6586	-562.8652	-43.31628		22	255.4972	667.5649	-42.52364
23	49.33866	-604.48	-43.00052		23	294.1311	597.485	-42.61776
24	-18.92647	-646.029	-43.48941		24	332.7625	527.43	-41.87562
25	-87.2663	-687.6623	-43.51683		25	371.4271	457.3694	-40.97763
26	-155.5824	-729.2839	-42.76093		26	410.0809	387.3243	-40.78767
27	-223.9326	-770.8924	-43.39174		27	448.7454	317.264	-41.37147
28	-292.2784	-812.5108	-43.37378		28	487.4043	247.187	-42.11328

Table 1: As-measured data in the coordinate system of the each instrument set-up

Before Weld	X	Y	Z	ΔFR	ΔHW	ΔHT		Xi-X1	Yi-Y1	Zi-Z1	Ui	Vi	Wi	ΔFRi-ΔFR1	ΔHWi-ΔHW1	ΔHTi-ΔHT1
1	511.5423	203.463	-42.61287	0	0	0	ORIGIN	0	0	0	0	0	0	0	0	0
21	241.436	692.9794	-43.06976	0	1	0		-270.1063	489.5164	-0.456888	559.092	-5.55E-17	9.24E-15	0	1	0
7	211.2627	27.4774	-43.47308	1	1	0		-300.2797	-175.9856	-0.860213	-9.014643	0	-347.9343	1	1	0
1	511.5423	203.463	-42.61287	0	0	0		0	0	0	0	0	0	0	0	0
2	461.1611	173.9512	-42.33741	58.36843	-1.499517	-0.419777		-50.38127	-29.51186	0.275458	-1.499517	0.419777	-58.36843	58.36843	-1.499517	-0.419777
3	392.1286	133.4823	-42.92913	138.3626	-3.581037	-0.025828		-119.4138	-69.98068	-0.316255	-3.581037	0.025828	-138.3626	138.3626	-3.581037	-0.025828
4	323.2798	93.09587	-42.55192	218.1537	-5.680035	-0.600284		-188.2625	-110.3671	0.060954	-5.680035	0.600284	-218.1537	218.1537	-5.680035	-0.600284
5	289.0266	73.03175	-42.25818	257.8368	-6.69926	-0.992144		-222.5157	-130.4313	0.354695	-6.69926	0.992144	-257.8368	257.8368	-6.69926	-0.992144
6	248.5023	49.19509	-42.33993	304.8341	-7.991556	-1.026526		-263.0401	-154.2679	0.272944	-7.991556	1.026526	-304.8341	304.8341	-7.991556	-1.026526
7	211.2627	27.4774	-43.47308	347.9343	-9.014643	0		-300.2797	-175.9856	-0.860213	-9.014643	0	-347.9343	347.9343	-9.014643	0
8	188.1204	71.77357	-42.05497	346.7929	40.94839	-1.456103		-323.422	-131.6894	0.557902	40.94839	1.456103	-346.7929	346.7929	40.94839	-1.456103
9	151.1395	142.8066	-41.61934	344.8533	121.0075	-1.952326		-360.4028	-60.65643	0.993535	121.0075	1.952326	-344.8533	344.8533	121.0075	-1.952326
10	114.1027	213.8728	-41.75286	342.948	201.1231	-1.879516		-397.4396	10.40978	0.860006	201.1231	1.879516	-342.948	342.948	201.1231	-1.879516
11	77.09365	284.9312	-41.99964	341.0225	281.2186	-1.693395		-434.4487	81.46822	0.613233	281.2186	1.693395	-341.0225	341.0225	281.2186	-1.693395
12	40.08963	355.9675	-41.92383	339.1025	361.292	-1.829849		-471.4527	152.5045	0.689039	361.292	1.829849	-339.1025	339.1025	361.292	-1.829849
13	3.04296	426.9602	-42.26278	337.2419	441.3482	-1.551683		-508.4994	223.4972	0.350091	441.3482	1.551683	-337.2419	337.2419	441.3482	-1.551683
14	-33.95181	497.9643	-42.14225	335.3292	521.3889	-1.732857		-545.4942	294.5013	0.470625	521.3889	1.732857	-335.3292	335.3292	521.3889	-1.732857
15	-47.40278	523.804	-42.44943	334.6234	550.5117	-1.447714		-558.9451	320.341	0.163444	550.5117	1.447714	-334.6234	334.6234	550.5117	-1.447714
16	-10.17453	545.5202	-42.59665	291.537	551.54	-1.193893		-521.7169	342.0572	0.01622	551.54	1.193893	-291.537	291.537	551.54	-1.193893
17	24.32887	565.7624	-42.80693	251.5487	552.5942	-0.884763		-487.2135	362.2994	-0.194059	552.5942	0.884763	-251.5487	251.5487	552.5942	-0.884763
18	54.14012	583.2631	-42.9532	216.9929	553.5148	-0.653079		-457.4022	379.8001	-0.340329	553.5148	0.653079	-216.9929	216.9929	553.5148	-0.653079
19	120.4653	622.1566	-42.84969	140.1313	555.5254	-0.566574		-391.077	418.6936	-0.236821	555.5254	0.566574	-140.1313	140.1313	555.5254	-0.566574
20	189.6494	662.669	-42.66427	59.98436	557.5722	-0.553818		-321.8929	459.206	-0.051402	557.5722	0.553818	-59.98436	59.98436	557.5722	-0.553818
21	241.436	692.9794	-43.06976	-9.24E-15	559.092	5.55E-17		-270.1063	489.5164	-0.456888	559.092	-5.55E-17	9.24E-15	-9.24E-15	559.092	5.55E-17
22	255.4972	667.5649	-42.52364	-0.034522	530.0466	-0.522295		-256.0451	464.1019	0.089227	530.0466	0.522295	0.034522	-0.034522	530.0466	-0.522295
23	294.1311	597.485	-42.61776	-0.003512	450.0232	-0.362859		-217.4113	394.022	-0.004891	450.0232	0.362859	0.003512	-0.003512	450.0232	-0.362859
24	332.7625	527.43	-41.87562	0.015568	370.022	-1.039674		-178.7799	323.967	0.737251	370.022	1.039674	-0.015568	0.015568	370.022	-1.039674
25	371.4271	457.3694	-40.97763	0.00783	289.9999	-1.872257		-140.1153	253.9064	1.635244	289.9999	1.872257	-0.00783	0.00783	289.9999	-1.872257
26	410.0809	387.3243	-40.78767	0.003868	209.997	-1.996824		-101.4614	183.8612	1.825199	209.997	1.996824	-0.003868	0.003868	209.997	-1.996824
27	448.7454	317.264	-41.37147	-0.000187	129.9763	-1.347619		-62.79697	113.801	1.241399	129.9763	1.347619	0.000187	-0.000187	129.9763	-1.347619
28	487.4043	247.187	-42.11328	0.009093	49.9438	-0.540425		-24.138	43.72393	0.499587	49.9438	0.540425	-0.009093	0.009093	49.9438	-0.540425
		MATRIX			MATRIX											
		B			A											
	-0.483116	0.875556	-0.000817	0	1	0		STEPS:	*TO CONVERT SHOP TO SHIP COORDINATES OR VICE VERSA WHEN THREE*							
	-0.002578	-0.000489	0.999997	0	0	-1			*NONCOLINEAR POINTS ARE KNOWN IN BOTH REF. SYSTEMS*							
	0.875553	0.483116	0.002494	-1	0	0		1	*ASSIGN ORIGIN TO A KNOWN POINT. POINT 1 IS PRESENTLY ORIGIN.*							
								2	*FILL IN KNOWN DATA IN COLUMNS B,C,D & E,F,G*							
								3	*RANGE E5:G11 CONTAIN THE FORMULAS TO CONVERT SHOP TO SHIP COORDINATES*							

Table 2: Translation and rotation of the before-weld data

After Weld	X	Y	Z	ΔFR	ΔHW	ΔHT		Xi-X1	Yi-Y1	Zi-Z1	Ui	Vi	Wi	ΔFRi-ΔFR1	ΔHWi-ΔHW1	ΔHTi-ΔHT1
1	-334.9358	-838.5975	-43.00404	0	0	0	ORIGIN	0	0	0	0	0	0	0	0	0
21	142.5589	-547.7793	-42.77869	0	1	0		477.4947	290.8182	0.225353	559.0854	-2.78E-17	-1.92E-14	0	1	0
7	-523.552	-546.1138	-43.55943	1	1	0		-188.6161	292.4837	-0.555391	-8.949915	-1.11E-16	-347.9123	1	1	0
1	-334.9358	-838.5975	-43.00404	0	0	0		0	0	0	0	0	0	0	0	0
2	-366.6476	-789.3318	-43.93667	58.57291	-1.457867	0.83915		-31.7118	49.26568	-0.932632	-1.457867	-0.83915	-58.57291	58.57291405	-1.457866772	0.839149755
3	-410.0035	-722.1074	-43.86943	138.539	-3.518533	0.644245		-75.06764	116.4901	-0.865383	-3.518533	-0.644245	-138.539	138.5389624	-3.518533482	0.644244972
4	-453.2703	-655.0862	-43.50732	218.2847	-5.608809	0.154819		-118.3345	183.5113	-0.503276	-5.608809	-0.154819	-218.2847	218.2847029	-5.60880854	0.154819264
5	-474.758	-621.7778	-43.7791	257.9098	-6.634805	0.363346		-139.8222	216.8197	-0.775061	-6.634805	-0.363346	-257.9098	257.9097874	-6.634804969	0.363346217
6	-500.2954	-582.3189	-43.75034	304.8939	-7.920074	0.25955		-165.3595	256.2786	-0.746299	-7.920074	-0.25955	-304.8939	304.8938632	-7.920074253	0.259549998
7	-523.552	-546.1138	-43.55943	347.9123	-8.949915	1.11E-16		-188.6161	292.4837	-0.555391	-8.949915	-1.11E-16	-347.9123	347.9122811	-8.949914822	1.11022E-16
8	-480.2197	-521.1118	-43.66616	346.7257	41.06385	0.128764		-145.2838	317.4857	-0.662114	41.06385	-0.128764	-346.7257	346.7257337	41.0638516	0.128764287
9	-410.9167	-481.0864	-43.57266	344.8607	121.0729	0.070472		-75.9809	357.5111	-0.568614	121.0729	-0.070472	-344.8607	344.8607418	121.0729421	0.070471672
10	-341.5335	-441.0899	-43.70704	342.9297	201.1355	0.240187		-6.597696	397.5076	-0.702995	201.1355	-0.240187	-342.9297	342.929714	201.1354979	0.240186646
11	-272.1458	-401.0641	-43.51137	341.0207	281.2173	0.079829		62.79009	437.5334	-0.507331	281.2173	-0.079829	-341.0207	341.0207289	281.2172921	0.079828972
12	-202.8202	-361.0794	-43.34216	339.1091	361.2246	-0.054104		132.1156	477.5181	-0.338118	361.2246	0.054104	-339.1091	339.1091005	361.224585	-0.054103504
13	-133.4681	-321.0258	-43.44424	337.2429	441.2903	0.083207		201.4678	517.5717	-0.440196	441.2903	-0.083207	-337.2429	337.2429158	441.2902988	0.083206859
14	-64.1334	-281.0444	-43.5881	335.3242	521.3035	0.262367		270.8024	557.5531	-0.584062	521.3035	-0.262367	-335.3242	335.3241888	521.3034957	0.262367441
15	-38.92528	-266.4936	-43.15834	334.6384	550.4019	-0.154585		296.0106	572.1039	-0.154294	550.4019	0.154585	-334.6384	334.6384183	550.401893	-0.154584677
16	-15.58578	-302.7542	-43.39625	291.5295	551.4736	0.152127		319.3501	535.8433	-0.392203	551.4736	-0.152127	-291.5295	291.5295201	551.4736333	0.152126773
17	6.135009	-336.3403	-43.37543	251.5464	552.5542	0.195162		341.0709	502.2572	-0.37139	552.5542	-0.195162	-251.5464	251.5464297	552.5541961	0.195161943
18	24.89961	-365.3665	-43.76349	216.9961	553.4817	0.638388		359.8355	473.231	-0.759445	553.4817	-0.638388	-216.9961	216.9961206	553.4817251	0.638387658
19	66.52429	-429.9242	-43.46878	140.2075	555.4511	0.466257		401.4601	408.6733	-0.464735	555.4511	-0.466257	-140.2075	140.207466	555.4511178	0.466256862
21	142.5589	-547.7793	-42.77869	1.92E-14	559.0854	2.78E-17		477.4947	290.8182	0.225353	559.0854	-2.78E-17	-1.92E-14	1.92009E-14	559.0853862	2.77556E-17
20	109.9945	-497.2769	-43.57538	60.07242	557.5427	0.700792		444.9303	341.3206	-0.571334	557.5427	-0.700792	-60.07242	60.07242004	557.5427093	0.700792192
22	117.6586	-562.8652	-43.31628	0.068807	529.9716	0.525751		452.5945	275.7323	-0.312241	529.9716	-0.525751	-0.068807	0.068806943	529.9715603	0.52575054
23	49.33866	-604.48	-43.00052	0.064416	449.9754	0.177749		384.2745	234.1175	0.003523	449.9754	-0.177749	-0.064416	0.064416332	449.9753983	0.177748633
24	-18.92647	-646.029	-43.48941	0.089004	370.06	0.634388		316.0094	192.5686	-0.485367	370.06	-0.634388	-0.089004	0.089004443	370.0599901	0.634388394
25	-87.2663	-687.6623	-43.51683	0.079587	290.037	0.629573		247.6695	150.9352	-0.512792	290.037	-0.629573	-0.079587	0.079587385	290.0370363	0.62957312
26	-155.5824	-729.2839	-42.76093	0.06673	210.0408	-0.158555		179.3534	109.3136	0.243111	210.0408	0.158555	-0.06673	0.066729597	210.0408043	-0.158554976
27	-223.9326	-770.8924	-43.39174	0.084884	130.0217	0.439975		111.0032	67.70507	-0.387701	130.0217	-0.439975	-0.084884	0.084883687	130.0216748	0.439975372
28	-292.2784	-812.5108	-43.37378	0.091281	50.00153	0.389751		42.65748	26.0867	-0.369741	50.00153	-0.389751	-0.091281	0.09128126	50.00153032	0.389751087
		MATRIX			MATRIX											
		B			A											
	0.854064	0.520168	0.000403	0	1	0		STEPS:	TO CONVERT SHOP TO SHIP COORDINATES OR VICE VERSA WHEN THREE NONCOLINEAR							
	-0.001169	0.001145	0.999999	0	0	-1		1	POINTS ARE KNOWN IN BOTH REF. SYSTEMS							
	0.520167	-0.854063	0.001586	-1	0	0		2	ASSIGN ORIGIN TO A KNOWN POINT. POINT 1 IS PRESENTLY ORIGIN.							
								3	FILL IN KNOWN DATA IN COLUMNS B,C,D & E,F,G							
									RANGE E5:G11 CONTAIN THE FORMULAS TO CONVERT SHOP TO SHIP COORDINATES							

Table 3: Translation and rotation of the after-weld data

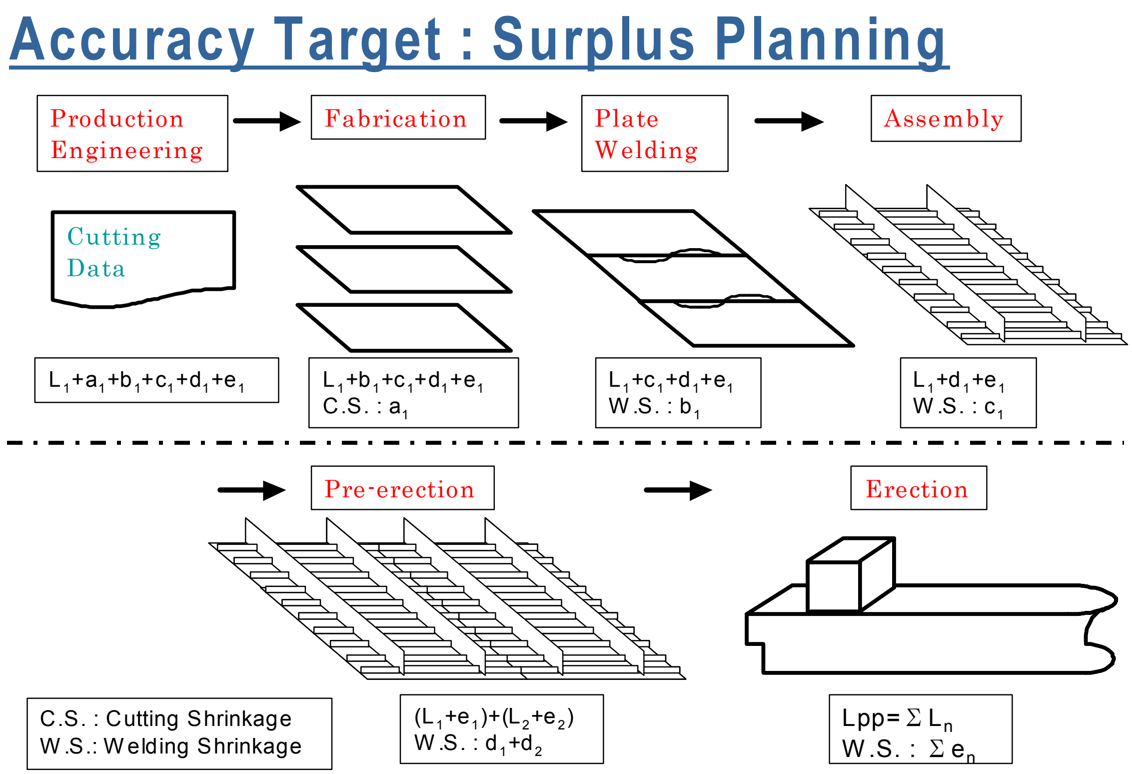
	After Weld Y	Before Weld Y		After Weld X	Before Weld X	
1	0	0		0	0	
2	58.57291405	58.36842635		-1.457866772	-1.499516946	
3	138.5389624	138.3626427		-3.518533482	-3.581036511	
4	218.2847029	218.153745		-5.60880854	-5.68003532	
5	257.9097874	257.8367983		-6.634804969	-6.699259733	
6	304.8938632	304.8340863		-7.920074253	-7.991555917	
7	347.9122811	347.9343057		-8.949914822	-9.014642561	
8	346.7257337	346.7928705		41.0638516	40.94839463	
9	344.8607418	344.8532751		121.0729421	121.0074796	
10	342.929714	342.948003		201.1354979	201.1230999	
11	341.0207289	341.0224976		281.2172921	281.2186101	
12	339.1091005	339.102457		361.224585	361.292044	
13	337.2429158	337.2418678		441.2902988	441.3482422	
14	335.3241888	335.3292032		521.3034957	521.3889338	
15	334.6384183	334.6234177		550.401893	550.5116741	
16	291.5295201	291.5370212		551.4736333	551.5400166	
17	251.5464297	251.5486767		552.5541961	552.5942019	
18	216.9961206	216.9928677		553.4817251	553.5148358	
19	140.207466	140.1313406		555.4511178	555.525415	
21	1.92009E-14	-9.24412E-15		559.0853862	557.5721933	
20	60.07242004	59.98436187		557.5427093	559.0920429	
22	0.068806943	-0.034522261		529.9715603	530.0466296	
23	0.064416332	-0.003512326		449.9753983	450.0231502	
24	0.089004443	0.015567706		370.0599901	370.0220389	
25	0.079587385	0.007829504		290.0370363	289.9998585	
26	0.066729597	0.003867737		210.0408043	209.9969609	
27	0.084883687	-0.000187292		130.0216748	129.9763459	
28	0.09128126	0.00909288		50.00153032	49.94379928	
	1.000057871	0		0.999917386	0	
se	6.23619E-05	#N/A	se	0.000219822	#N/A	
r2	0.999999738	0.07626115	sey r2	0.999996723	0.420102754	sey
F	103096339.2	27	df F	8239095.471	27	df
	599583.874	0.157025601		1454087.671	4.765130742	
	measured	delta T corr		measured	delta T corr	
+2sigma	1.000066856	1.000200856		1.000522266	1.000656266	
mean	0.999942132	1.000076132		1.000082621	1.000216621	
-2sigma	0.999817408	0.999951408		0.999642977	0.999776977	

Table 4: Summary of regression analysis

3.8 Accuracy Control at Kawasaki Heavy Industry Ltd[1]

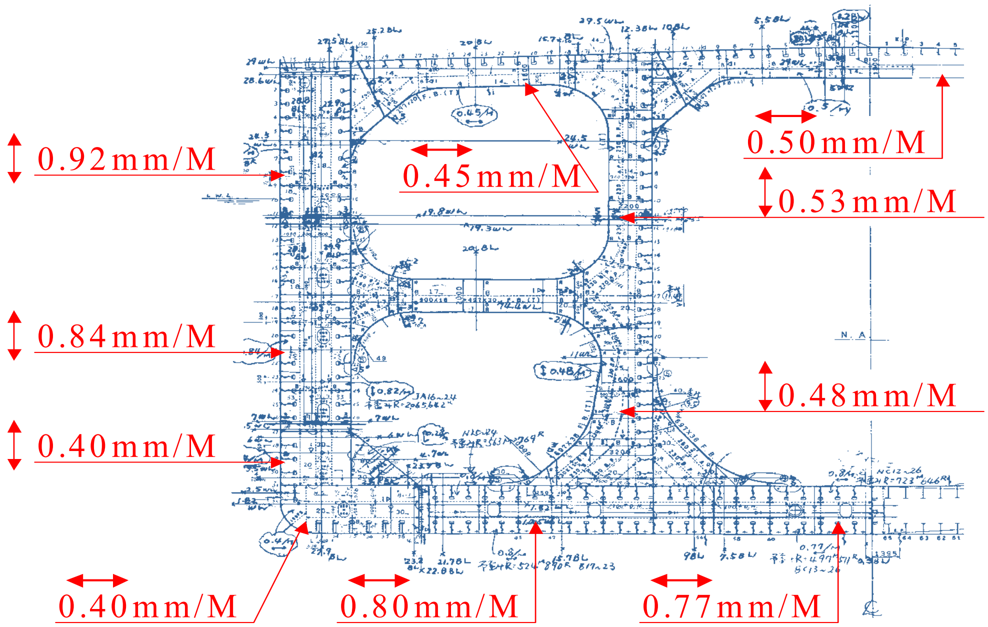
The primary purpose of adopting accuracy control techniques is to reduce the wastes caused by inaccuracy, maintaining uniform accuracy for automation and target actual dimensions for a ship.

The following two figures show the different steps involved with the surplus planning process associated with accuracy control:



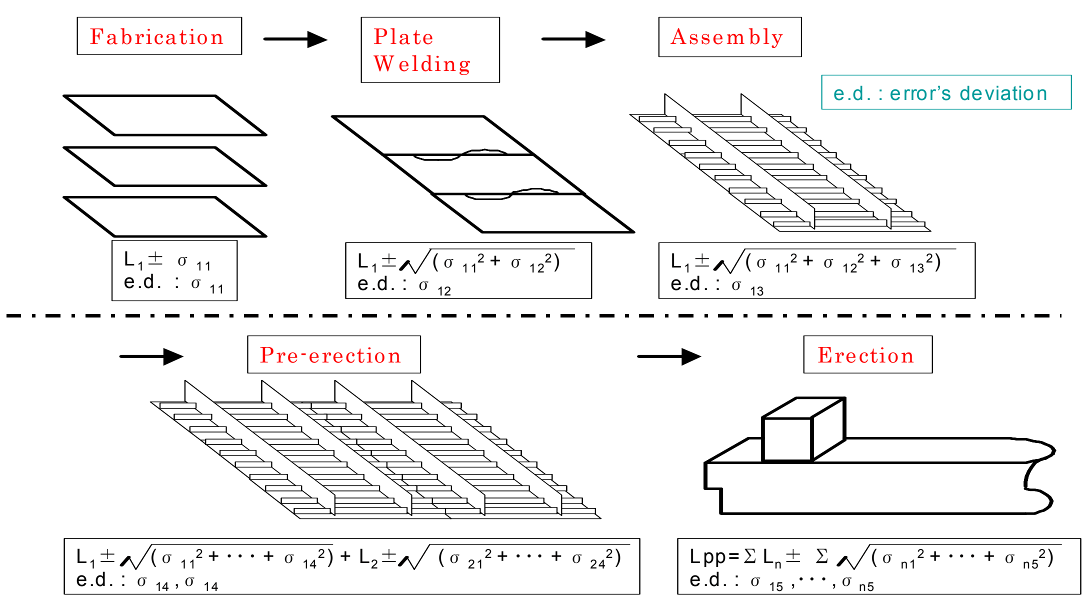
1 Kiyohisa Taniguchi, "KHI Accuracy Control," presentation (PowerPoint slides)

Surplus planning



The following two figures show how a shipyard strives to reduce the deviation at each stage of production during ship manufacturing:

Accuracy Target : Reduction of Deviation



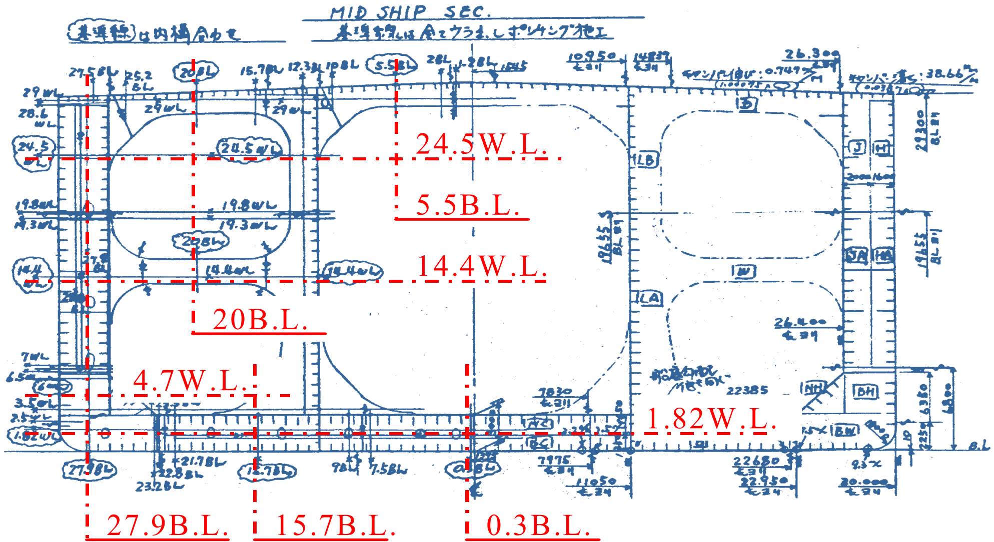
Reduction of Shrinkage Deviation

Process	Activity
Fabrication	Maintenance of NC Burning Machine Daily * Height Sensor * Height of Burning torch system * Verticality of Burning and Layout system * Offset between Burning and Layout torch Weekly * Diagonals check on Layout Monthly * Layout check by NC data for Test * Backlash check of Rack and Pinion
Assembly	Welding Leg Length Management in Welding process

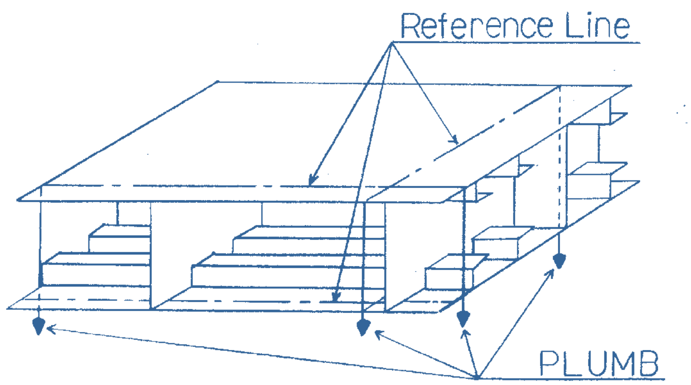
Reference Line Concept

The reference line concept basically involves drawing a 3-Dimensional Grid throughout the ship. The advantages of using the reference line concept in shipbuilding are that the data is more reliable than steelwork edges, it is easy to understand and use, everyone uses same data, and problem solving is easier and quicker.

Reference Lines



Usage of Reference Line



The following figures show the accuracy target and actual results obtained in different cutting processes:

Accuracy Target and Actual Result

Cutting

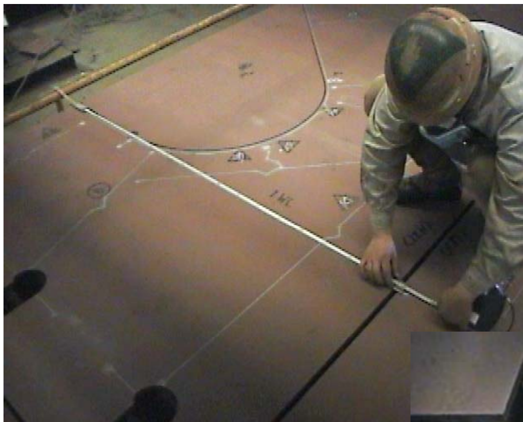
Accuracy control Item	Performance	KHI Target (mm)	KHI Actual result (mm)
Skin plate cutting (5F frame planer)	・Tack a x-R control chart at each stage ・ x-R chart was written by workers everyday	measure : 0 ± 1.0 difference of diagonals : 2σ =1.0	measure (2σ) 0.02 ± 0.86 (diagonals) 2σ =0.97
NC Marking/Cutting (6F/7F/2F/3F NC prazma/gas/laser Burning machine)		cutting : 0 ± 1.0 marking : 0 ± 1.1	cutting (2σ) prazma : -0.06 ± 1.11 gas : -0.04 ± 0.84 laser : -0.13 ± 0.57 marking : 0.03 ± 1.27
Flat bar cutting (6F flat bar cutting robot)		0 ± 1.0	(2σ) -0.11 ± 1.09
Profile cutting (4F Profile cutting robot)		0 ± 1.0	(2σ) -0.31 ± 1.21

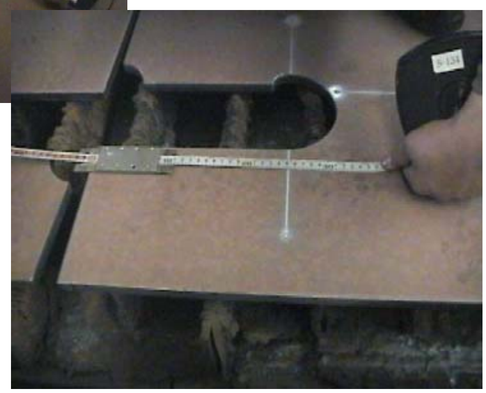
Measuring : Skin plate cutting

- Length ,Width, Diagonals

All plates

Measuring : NC Marking/Cutting





- Width, Marking

5 members / day / machine

Measuring : Flat bar cutting

- Length

10 members / day

Measuring : Profile cutting

- Length

5 members / day

The following figures show the accuracy target and actual results for web/face plate cutting and B/U longitudinal assembly:

Accuracy Target and Actual Result

B/U Longitudinal

Accuracy control Item	Performance	KHI Target (mm)	KHI Actual result (mm)
Web/Face plate cutting (1F Multi planer)	• Tack a x-R control chart at each stage • x-R chart was written by workers everyday	Length : 0±3.0 Width/Depth 0±1.0	Length (2σ) 0.09±3.10 Width/Depth (2σ) -0.37±1.21
B/U Longi. Assembly (2Y B/U Longi. Assembly shop)			Length (2σ) -0.07±4.50 Depth (2σ) -1.47±1.67

Measuring : Web/Face plate cutting

• Length

5 members / day

Measuring : B/U longi. Assembly

- Length, Depth

5 members / day

Accuracy targets and actual results for sub-assembly, like measuring plate length after plate welding and stiffener fitting are shown below in the figures:

Accuracy Target and Actual Result

Sub-assembly

Accuracy control Item	Performance	KHI Target (mm)	KHI Actual result (mm)
Plate length after plate welding (7F/2F HIVAS welding machine)	• Tack a x-R control chart at each stage • x-R chart was written by workers everyday	0±1.5	(2σ) -0.21±1.50
Stiffener fitting (8F conveyer line)		0±1.0	(2σ) -0.37±1.69

Measuring : Plate length after plate welding

- Length

5 plates / day

Measuring : Stiffener fitting

- Difference between marking line and stiffener end

5 members / day / machine

Accuracy targets and actual results for different assemblies are represented in the following figures:

Accuracy Target and Actual Result

Assembly

Accuracy control Item	Performance	KHI Target (mm)	KHI Actual result (mm)
Diagonal length after plate fitting (6A0 FCB welding machine 〈Mammoth melt〉)	Make check sheets	＜ 3.0	(measure all points) (dispersion)=2.19
Marking of the plate after plate welding (6A0 marking stage)		difference of diagonal lines : ＜ 3.0 50MK～ plate end : 0 ± 3.0	(measure all points) diagonal lines (dispersion)=1.47 50MK～ plate end -0.59 ± 2.41
Gap between base plate end and longi. end (6A structure framing and unit stage)		0 ± 3.0	(measure all points) fore 0.91 ± 4.19 aft(basis line side) 0.41 ± 3.59
Unit reversed block and skin plate(twist) (6A2 unite stage)		0 ± 3.0	(measure all points) -0.38 ± 1.62

Measuring : Diagonal length after plate fitting

- Diagonals

All plates

Measuring : Marking on the plate after plate welding

- Diagonals, 50mm MK

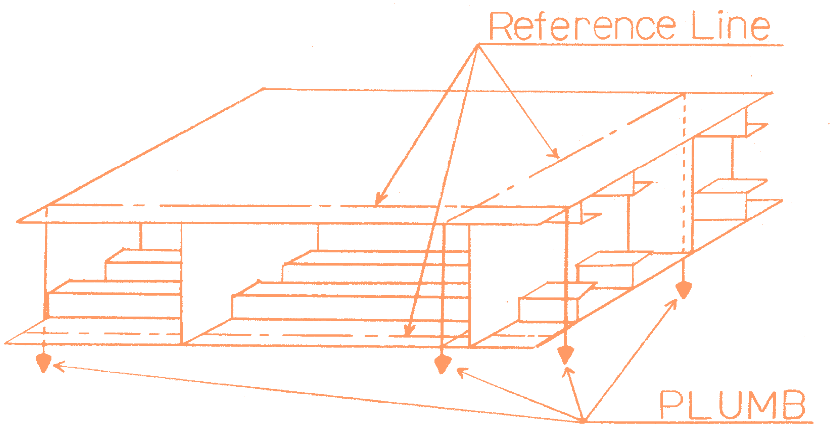
All plates

Measuring : Gap between base plate end and longitudinal end

- Difference between Skin plate and Internals

All blocks

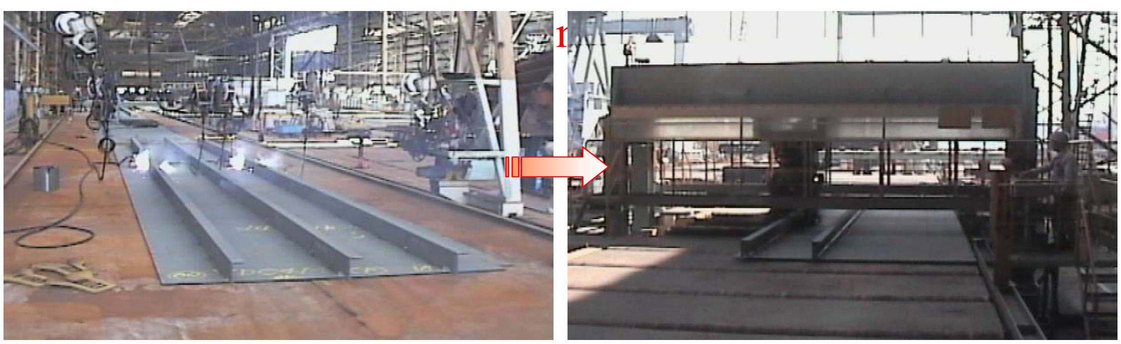
Measuring : Unite reversed block and skin plate



- Twisting from Reference Lines

All blocks

Accuracy Control in PCC Deck Panel



	Samples	Traditional Estimated Shrinkage	Shrinkage Result
Breadth	104	0.24 mm/M	0.07 mm/M
Length	104	0.13 mm/M	0.03 mm/M

Chapter 4. Accuracy Control Implementation in Related Industries

4.1. Introduction

The largest manufacturing industry in the United States is the Automobile Industry and it is also one of the major world manufacturing industries. Automobile production has made many contributions to quality engineering in manufacturing, such as tolerance analysis, the QS 9000 quality system, and many others. Furthermore, the automobile industry is leading other manufacturing industries in the creation of new technology, higher level of quality, and better-educated work force.

Let's review the history of automotive industry briefly:

- 1903: Henry Ford founded the Ford Motor Company.
- 1920s: Due to mass production and improved assembly line techniques, the production yield of cars substantially increased. Cars became affordable for general American families. The high demand for cars led to the quick development of the automobile industry as a leading industry.
- 1930s-1970s: The automobile industry employed over six million people. Thousands of jobs were created in related industries, including fabrics, rubber, glass, highway construction, service stations, and garages. With the development of the automobile industry more cars were produced and more roads were built to accommodate them.
- 1980 to 1983: Japan took first place as the top manufacturer of passenger cars. France, Germany, Italy, Spain, and the United Kingdom are other leading automobile manufacturing countries. Japanese cars gain a positive reputation for quality and fuel-efficiency.

- 1990s- present, a lot of new techniques and new industry standards are applied in the automotive industry. Each automaker places more emphasis on improving quality and lowering the cost.

4.2 Uniform Standards (QS 9000 Quality System)

In the 1970s, as customers demanded more quality, the Big Three automakers, General Motors, Ford and Chrysler wanted to improve their product quality. At that time, Ford developed its Q-101 quality system standard, General Motors had Target for Excellence, and Chrysler had Supplier Quality Assurance Program. Although all quality systems covered similar items from the design to the final process, the terms and the requirements were different. Such diversity caused potential errors, and also increased manufacturing and repair costs. In the 1980s, Japanese cars entered the U.S. market and gained a larger market share based on their high-quality and low price products. The stiff competition forced the American automakers to face their own problem seriously. In 1994, the big three automakers in the U.S., General Motors, Ford and Daimler-Chrysler, developed the QS 9000 quality system to combine their own unique set of quality standards. The QS 9000 quality system is comprehensive and addresses all phases of product and part development, engineering, manufacturing, storage, shipping and delivery.[1]

The QS-9000 system is based on the ISO 9001 system, but it contains additional requirements that are particular to the automotive industry. The QS–9000 system includes 20 basic elements and some customer-specific requirements. The 20 basic elements are:[2]

1. Management Responsibility
2. Quality Systems
3. Contract Review

4. Design Control

5. Documents and Data Control

6. Purchasing

7. Control of Customer-supplied Product

8. Product Identification and Traceability

9. Process Control

10. Inspection and Testing

11. Control of Inspection, Measuring and Test Equipment

12. Inspection and Test Status

13. Control of Nonconforming Material

14. Corrective and Preventive Action

15. Handling, Storage, Packaging, Preservation and Delivery

16. Control Quality Records

17. Internal Quality Audits

18. Training

19. Servicing

20. Statistical Techniques

The QS 9000 system places a strong emphasis on the application of effective quantitative and statistical techniques for suppliers of manufactured parts - from the beginning of design/development, through prototype development, initial production, and on into full-rate production. The requirements are an evolutionary extension of the automotive industry's quality requirements that deal with "product qualification" and "process control" and are similar to those contained in the FORD Q-101 and GM Targets for Excellence.

4.3 Implementation of QS-9000: Case Study

This section will give details about the methodology for implementing a QS-9000 quality control system in a manufacturing plant. In shipbuilding (as well as other industries), this would be analogous to obtaining ISO 9000 certification. Not only will the section detail how this process is accomplished, it will also give a detailed list of the team structure used, education and training details, corrective action challenges, lessons learned, and a few concluding thoughts.

4.3.1 Team Structure

The factory utilized a team approach to implement QS-9000. The following table summarizes the team approach used.

Title	Function
Factory Operations Manager	Act as project sponsor; actively support project and clear roadblocks
Project Manager	Lead implementation efforts within the factory and interface with sector team.
Steering Team	Define implementation strategies and act as champions for key elements.
Element Champions	Drive system development and implementation.
Element Teams	Implementation and execution of standard.

Before the actual implementation began, a Steering team comprised of key individuals met to define an implementation strategy for the factory. The members consisted of those from the internal structure and from an external quality organization. The Operations Manager was present and approved the plan. With the commitment of the Operations Manager, the Steering team was able to select a group of element champions who were experts in key areas such as maintenance, process control, and documentation. To solicit commitment and support for this implementation, the extended element teams were formed from the factory community. Every Thursday, each team would meet to develop and implement their respective portions of the quality system. Success was most notable for elements with cross-function teams. Success was assessed by a team's readiness prior to a system audit. The teams that included participation from both the engineering and manufacturing groups ensured agreement of functional systems.

4.3.2 Education and Training

The key tool used to communicate the importance and understanding of QS-9000 was education. This information was conveyed via training in a top down fashion to all levels of personnel in the organization from staff level managers, to engineers, technicians, and production operators. The Steering team attended a 2-day overview training session taught by an outside consulting firm. After completing this training the Steering team felt it was worthwhile so they had all managers within the organization attend the same training. This effort was to involve managers to give them the tools necessary to reinforce the requirements and benefits of the QS-9000 program with their respective staff. The Steering team and the members of the Internal Auditing team took part in a five-day seminar to learn how to perform internal audits in detail. At the manufacturing level, a 2-hour interactive session was developed to cover the key reasons why QS-9000 was implemented and how it would affect this particular factory. The class emphasized, at the employee level, what each individual could do to help implement this quality program. The class was kept light and fun with quizzes and prizes awarded to help keep the things informative and interactive. The last part of the education and training section was keeping regular communication of the QS-9000 updates flowing to all personnel. There were monthly presentations lasting 10-15 minutes to update plant personnel while the element champions and managers were kept up to date at weekly meetings. The operation manager was updated at his weekly meetings and a QS-9000 bulletin board was used as a constant source of timely information.

4.3.3 Corrective Action Challenges

The main challenge faced while implementing QS-9000 was ensuring that the 10-day requirement for corrective actions was kept. There were many times when the cycle time of a corrective action was as long as 60 days. There were three main factors that contributed to this problem. Lack of ownership and a cross-functional approach was the first. The implementation effort became the primary effort of the element champion and quality department instead of the whole factory. The second was a lack of meaningful metrics. While metrics were deployed, they did not drive ownership down to the responsibility level. The third was the under-scoping of the effort needed to implement a corrective action culture. Prior to QS-9000, customer complaints became bogged down in a bureaucracy that existed between manufacturing, sales, and the various product groups. This resulted in corrective actions and response times which were unacceptable. After the registration audit, the Steering team developed actions to improve the corrective action system. To help with ownership the operation's manager and his staff developed site goals that incorporated key components of the system. Specific goals included a 50% reduction in the number of complaints from the previous year and completion of the corrective action response in 8 days instead of the required 10. A plan for continuous improvement has been deployed with cross-functional team membership. A specific task is to streamline the components of the corrective action system. Meaningful metrics were implemented and tracked. These are shown in element champion meetings and reviewed weekly by the operations manager and his staff. Resources were deployed with special emphasis on cycle time and audit metrics during management reviews. Due to these efforts, the culture of the organization has changed and reflects that of an organization that strives to put customers first.

4.3.4 Cost Breakdown

INTERNAL RESOURCES = 86% TOTAL COST

DOCUMENTATION 1ST & 2ND TIER	21%
DOCUMENTATION 3RD TIER	11%
REVISING EXISTING DOCUMENTS	27%
TRAINING	18%
INTERNAL AUDITING	9%

EXTERNAL RESOURCES = 14% TOTAL COST

2ND PARTY EXTERNAL ASSESSMENTS	4%
CONSULTANT FEE	4%
3RD PARTY REGISTRAR AUDIT	6%

TOTAL = 100% This cost breakdown depends on the existing program in effect and how many changes need to occur to implement the quality system.

4.3.5 Lessons Learned

After implementing QS-9000, several key issues were brought to the attention of upper management about suggestions for improving the process if ever called in to consult for another business. There were three areas where the lessons learned would have made the transition smoother if implemented at the beginning. The first is to ensure the commitment and support from all areas of the factory early. Although commitment was made early, it began to waver as increased production demands caused conflicting priorities. The problem arose because QS-9000 was de-emphasized at this time for production reasons. Care needs to be taken to ensure the quality program does not become a low priority item. The second is to develop a detailed project plan and address schedule slippage as it occurs. To ensure all of the tasks are addressed, a detailed work structure and schedule with completion dates should be used. The problem arose as key tasks were highlighted but little action was taken to prevent slippage and to compensate for falling behind the existing schedule. The list only included key tasks and inadvertently left off several required actions, which as a result were not completed in time. These problems ended up causing a "hurry up and get ready" attitude just prior to inspections. It would have been better to be more prepared and spread the work out over time instead of "cramming" just to get the factory ready for inspections. The final lesson learned was to develop key quality systems first! These would include, for example, internal audits, corrective actions, and documentation. These key quality systems can be used to monitor the status of implementation and thus improve the efficiency overall. One big mistake was not training the internal audit team soon enough. The auditors were not fully functional until 8 months after the project kick-off. This caused problems with external audits as they found system breakdowns that would have been easily caught by an internal audit team.

4.3.6 Conclusion

Based upon this experience of implementation, several pieces of advice can be summarized below:

- Make the factory as a whole responsible for meeting QS-9000 goals.
- Solicit commitment early and develop strategies for conflicting priorities
- Institutionalize QS-9000 as business as usual
- Ensure the Steering committee is cross functional and include manufacturing right away
- Develop a detailed project plan ASAP and stick to it. If schedule slippage occurs, address it right away.
- Start the internal audits right away. This will help identify holes in the primary plan.
- Integrate approach into all aspects of the factory
- There is no such thing as to much communication. Use a variety of methods to ensure the information gets out to everyone in the plant.

4.4 Dimensional Control at Kenworth[6]

Kenworth adopted a Six Sigma methodology, especially Design for Six Sigma (DFSS) as a tool to study its critical processes. Basically, Six Sigma methodology is a collection of problem solving techniques in which all the business related decisions are based on the facts or data collected from different processes. The primary purpose of using the Six Sigma technique is to improve the existing product or process. The data is analyzed systematically to identify the potential root causes and alternate solutions of an existing problem. On the other hand, DFSS is a systematic problem solving methodology generally used at the time of new product development and dimensional management. Figure 4.1 represents the four-step DFSS approach Kenworth adopted for dimensional control.

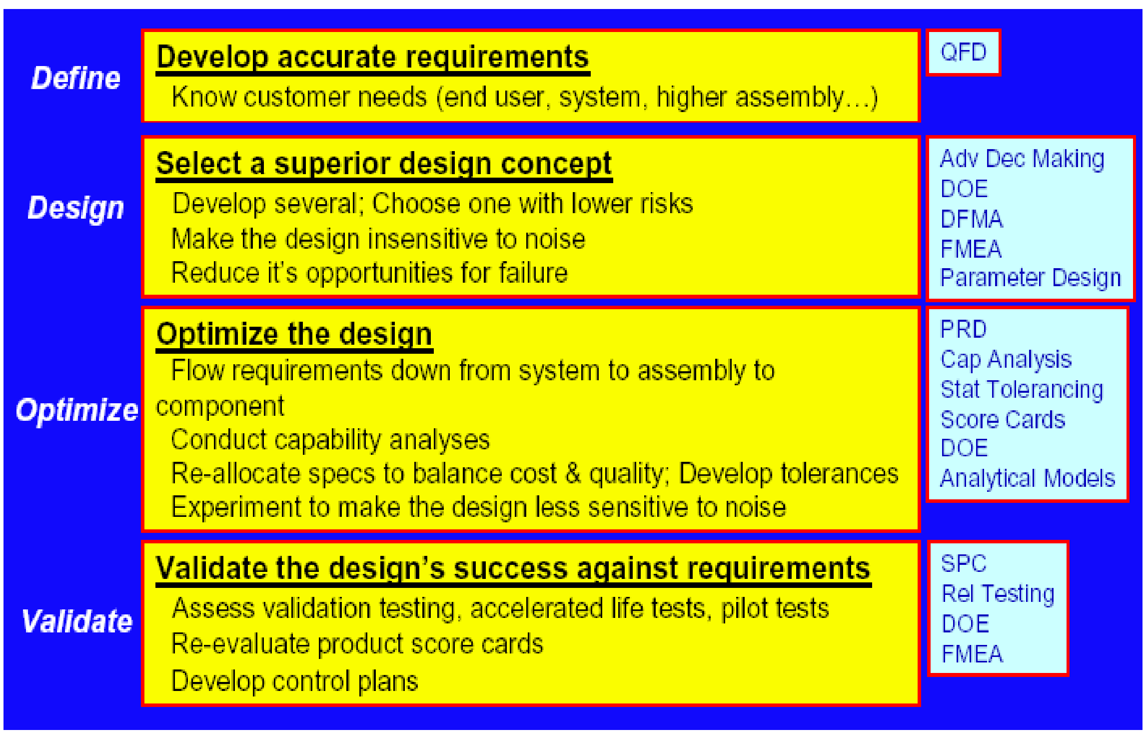


Figure 4.1: Achieving Design for Six Sigma

In this section, the following case studies are presented to analyze some of the major processes, using a Design for Six Sigma approach, in the manufacturing of a T800 truck:

- Cab assembly
- Assembly options to reduce variation
- Fan tip clearance investigation

4.4.1 Cab Assembly

Cab assembly operations were studied extensively to know the basic processes involved in the manufacturing of the T800 truck. On an average, there are about 140 holes per cab on which reaming and drilling operations are performed on different parts of the cab including side, back panel, and floor. It takes around 300 seconds per cab to perform reaming and drilling operations. Average total cost of reaming and drilling is about $68,875/year. Figures 4.2a, 4.2b, 4.3c, and 4.3d show reaming operations on different parts of a cab.

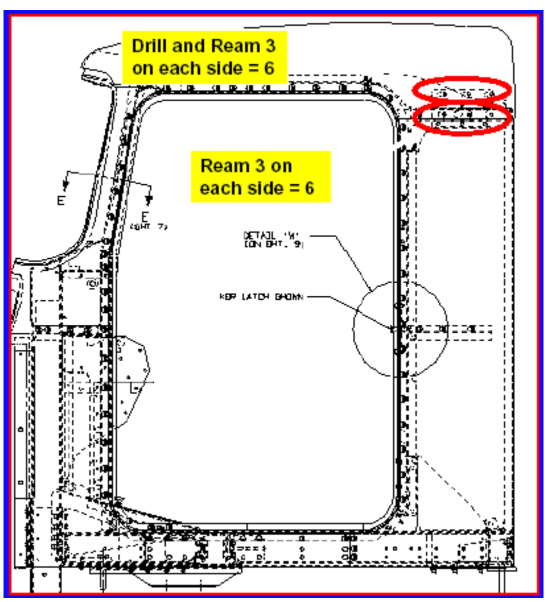


Figure 4.2 a. Side of a Cab Reaming

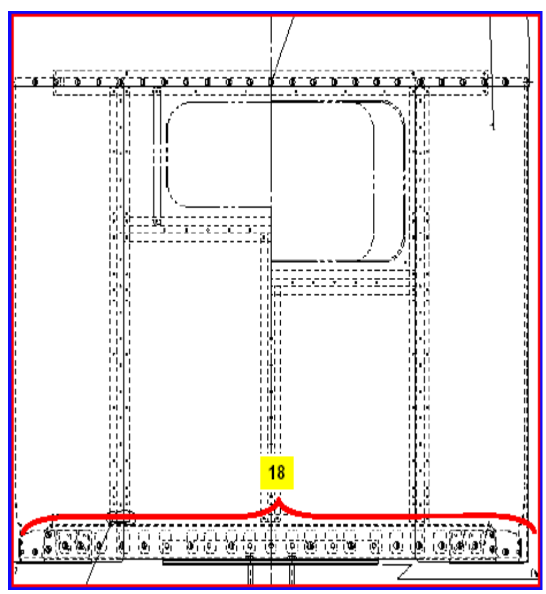


Figure 4.2 b. Back Panel Reaming

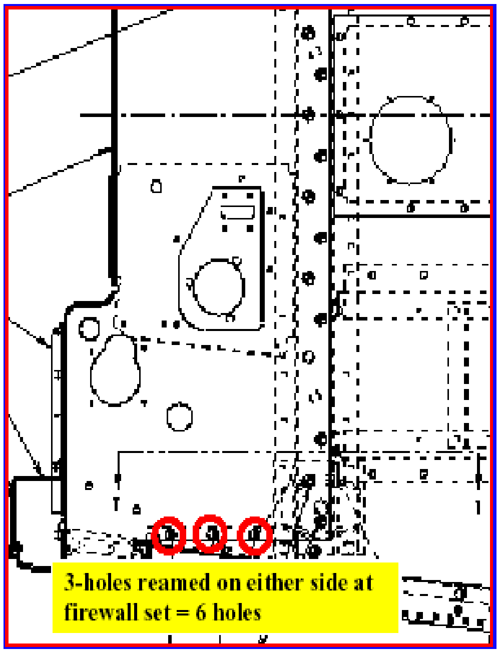


Figure 4.3 a. Floor Reaming

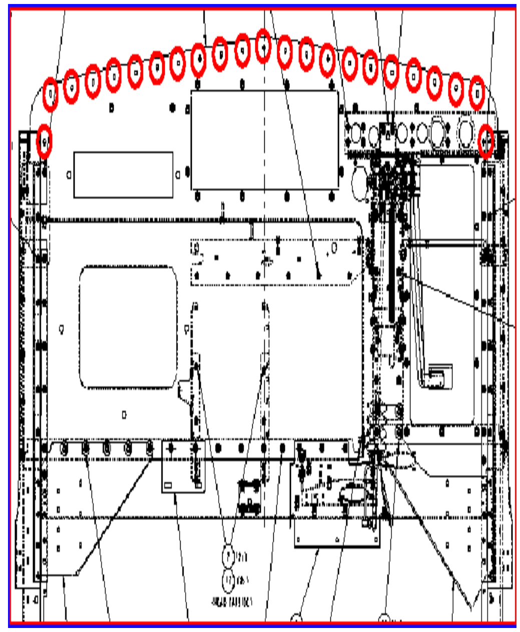
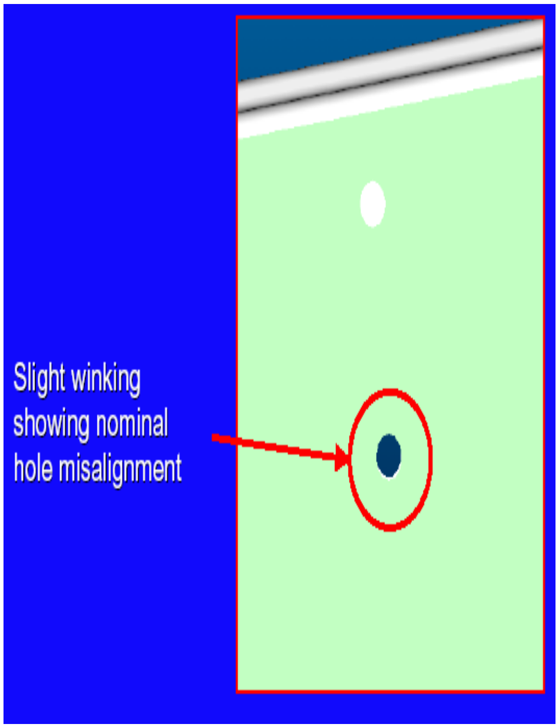


Figure 4.3 b. Firewall Reaming

4.4.2 Assembly Options to Reduce Variation

All critical holes locations are identified. From the study of the sequence of operations, it was found there was a slight winking showing nominal hole misalignment in the pinned hole. This led to a floating fastener problem and hence hole misalignment due to fastener to hole differences as shown in Figures 4.4a and 4.4b.



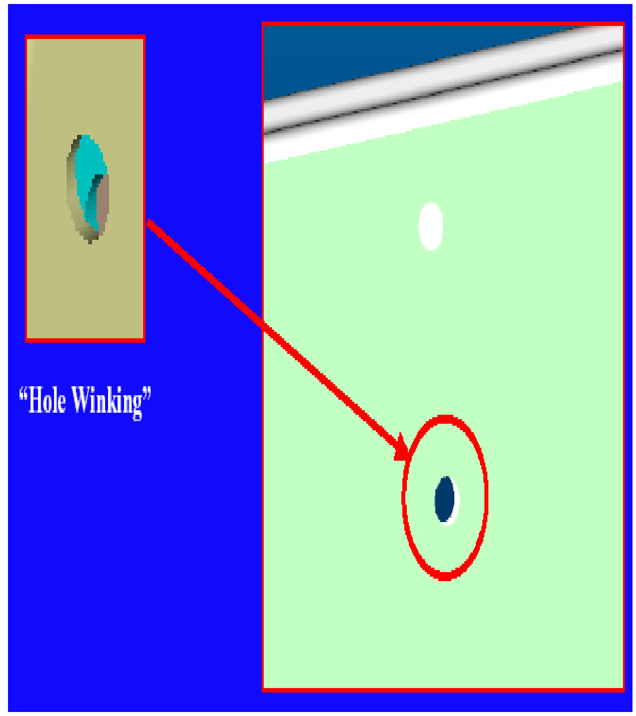


Figure 4.4 a. Pinned holes: current assembly sequence

Figure 4.4 b. Floating fasteners: hole misalignment due to fastener to hole differences

Tolerance analysis using network diagram technique was performed to improve product and process quality and reduce cost. Results were analyzed carefully to evaluate the impact of different tolerances on the part.

Different design methods were evaluated to choose the one with lower risk of failure. The following different design options were considered:

Locating Features

Current part design methodology might create assembly difficulties due to the fact that all locating features were toleranced equally (Kenworth cab assembly).

Exterior Fixture (T2000 cab assembly)

The exterior fixture option provides excellent assembly repeatability, however, it might lead to large capital costs and factory footprint increases.

Pin & Slot (4 way & 2 way)

Any type of variation can be easily captured early in the design process by providing a pin and a slot instead of two pins,

4.4.3 Fan Tip Clearance Investigation

Statistical Tolerance Analysis technique was used to identify the critical factors involved in engine fan to radiator shroud interaction. It was identified that the fan tip clearance, fan insertion and adjustment free assembly were the most significant factors, which play an important role in engine fan to radiator shroud interaction. After evaluating alternative designs and critical factors, the following critical measurement locations were identified as shown in Figure 4.5.

- Insertion depth at 9 o'clock, 3 o'clock, 6 o'clock, 12 o'clock
- Radial clearance at 3 o'clock, 6 o'clock, 9 o'clock, 12 o'clock

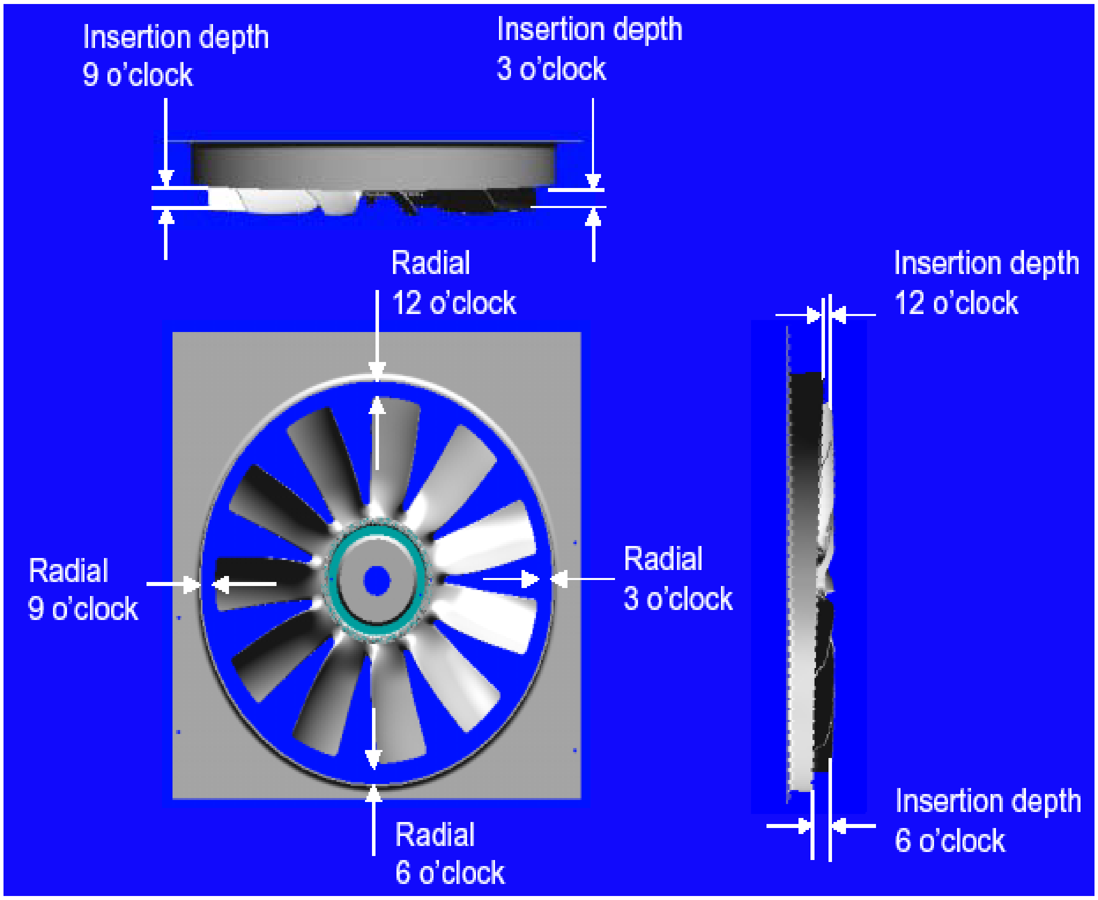


Figure 4.5: Measurement locations

Assembly sequences (Figure 4.6) were studied thoroughly to understand the flow requirement for the entire system for the subassembly from individual components. Different types of network diagrams, including top level, subassembly, and part level were drawn and investigated to comprehend the entire product and process flow from macro (assembly) to micro (part) levels.

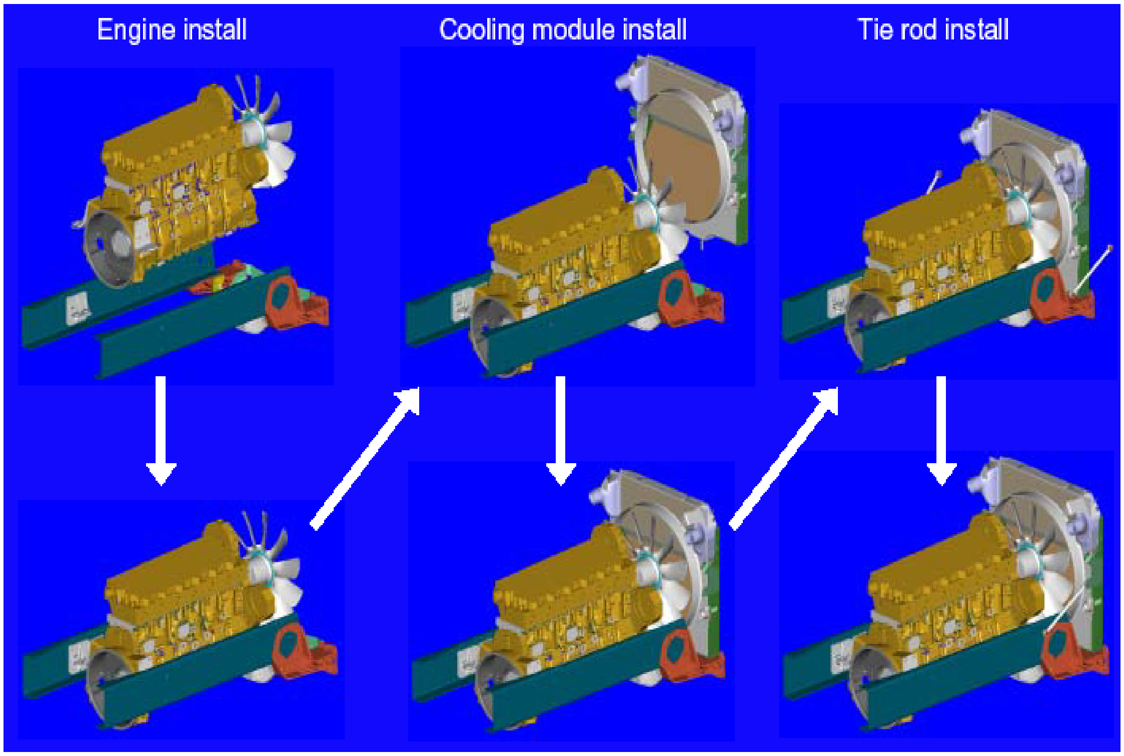


Figure 4.6: Assembly sequence

Critical parameters were measured carefully. Process capability study (Cp and Cpk), as shown in Figure 4.7, was performed on the measured dimensions to observe if the process was capable of producing the components within the pre-specified tolerance level. Moreover, the distribution pattern (Figure 4.8) of each critical dimension was analyzed to observe the mean position and the spread.

Measurement	Tolerance Specification	Mean	Std Dev	Cp	Cpk
1: Insertion 12 o'clock	53.46 +/- 5.0mm	53.37	1.258	1.32	1.3
2: Insertion 3 o'clock	55.52 +/- 5.0mm	55.45	1.131	1.47	1.45
3: Insertion 6 o'clock	57.15 +/- 5.0mm	57.1	0.5986	2.78	2.76
4: Insertion 9 o'clock	55.52 +/- 5.0mm	55.45	0.8863	1.88	1.85
5: Radial 12 o'clock	25mm to 50mm	41.12	0.9896	4.21	2.99
6: Radial 3 o'clock	25mm to 50mm	34.76	2.813	1.48	1.16
7: Radial 6 o'clock	25mm to 50mm	46.74	0.9897	4.21	1.10
8: Radial 9 o'clock	25mm to 50mm	35.24	2.813	1.48	1.21

Figure 4.7: Measurement locations

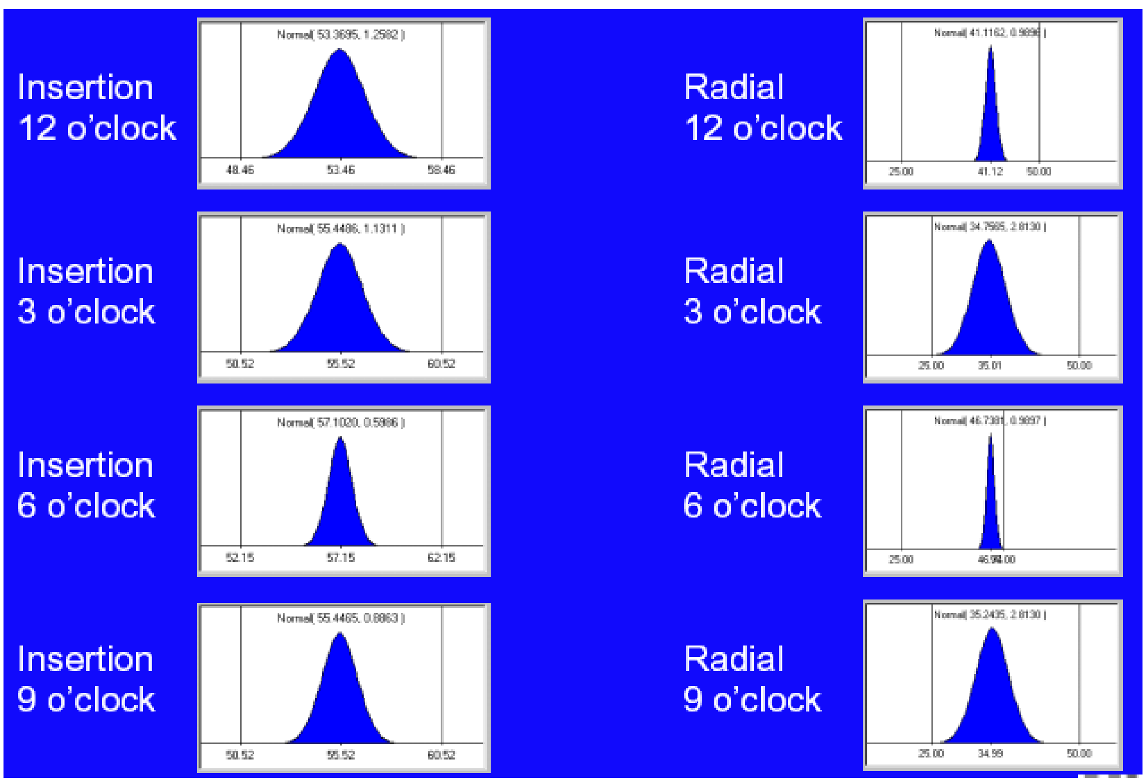


Figure 4.8: Distribution patterns of critical dimensions

A sensitivity analysis study was performed to evaluate the contribution and effect of changing one parameter on the output of the model as well as to make the design less sensitive to noise.

Principle Contributions & Sensitivities

	Key Contributor	%	Most Sensitive	mm/mm
Insertion 12 o'clock	Tie Rod Length	19.45%	Drive Bracket Hole Position	2.28
Insertion 3 o'clock	Rad X-Member	8.47%	Engine Mounting Hole Position	2.7
Insertion 6 o'clock	Module Side Channel Thickness	11.22%	Engine Mounting Hole Position	1.34
Insertion 9 o'clock	Tie Rod Length	13.71%	Engine Mounting Hole Position	2.72
Radial at 6 and 12 o'clock	Bushing Thickness	7.75%	Rad X-mbr Hole Pos	2.1
Radial at 3 and 9 o'clock	Radiator Puck	8.50%	Rad X-Member	6.5

Tie Rod length was found to be a key contributor to the overall variation. However, the study showed that the insertion depth quality level and radial position quality levels were operating at 4-sigma levels. This led to a conclusion that the non-adjustable tie rods provide an acceptable quality.

4.4.4 Lessons Learned

It was learned that the results obtained by using this methodology can be influenced by many factors. Tolerance model assumptions must support a model with empirical data. Joints must mirror actual assembly practices. Moreover, the results will be different for centered vs. non non-centered processes and when the reported process spread is not accurate. While multiple tools are available, the tool that best fits the requirements should be selected.

4.5 Dimensional Management for Quality Improvement At Boeing[7]

4.5.1 Background and History

The purpose of Boeing's implementation of the Advanced Quality System (AQS) was to improve the process/product quality, customer satisfaction and cost reduction in order to remain competitive in the market. The focus of this program was towards suppliers' management, not only to reduce variation but also manage variation of key or critical features (Crosby theory). The various tools including problem solving, statistical analysis, engineering and management techniques were incorporated in this system to improve the quality level.

This system was intended to reduce variation in the design phase in order to have fewer non-conformities in the production phase. The foundation of this system was laid in AQS method, but it included both internal and external 777 suppliers.

4.5.2 Design-Built Teams (DBT)

Design-Built teams (DBT), including engineering, manufacturing and other related functions, collectively ensure that the design is economically producible and reliable over a reasonable period of time. HVC/AQS had five primary elements managed by design-built teams.

1. Product design by concurrent product definition (CPD)
2. Key Characteristics
3. Manufacturing plans
4. Tool indexing plans
5. Statistical Process Control plan

Concurrent product definition

This technique deals with the issue of integration of process related activities like manufacturing plans, tool design, and quality inspection methods with the part definitions. It comes under the domain of concurrent product definition. Simulation of digitally assembled components using CATIA software helps in reducing variation in the final products.

Key characteristics

Key characteristics are the product's critical features whose variation has a significant impact on the performance. These key characteristics lead to process improvements resulting in more accurate assemblies.

Manufacturing plans

Manufacturing plans includes the development and maintenance of manufacturing instructions that incorporate the key characteristics from detail parts to subassemblies to final assemblies. Incorporation of manufacturing plans results in a significant reduction in non-conformities, which in turn leads to significant inspection savings.

Tool indexing plans

Coordinated tool indexes and engineering design datum's eliminated variation in assembly build up, resulting in significant improvements in product performance.

Statistical Process Control plans

Statistical process control (SPC) techniques provide sufficient evidence for process improvement without actually producing the components, thereby strengthening the early product improvement efforts. Moreover, SPC techniques eliminate the cost associated with 100% inspection.

4.5.3 Lessons Learned

Boeing realized that the development and deployment of key characteristics (KCs) were not always well thought out, and downstream impacts were large. In addition, how data was to be used for improvement was not well defined. Moreover, cost to external and internal manufacturing plants to measure and record data was high. Many KCs had multiple measurement points that added significant amount of cost. Statistical Process Control plans were often ineffective due to low production volume, poor data collection practices and unclear expectations

4.5.4 HVC/AQS Build Integration Tool (HABIT)

Although all the team members were working collectively, they were maintaining their own separate databases. These databases were very expensive to develop and maintain.

Moreover, it was very difficult to share the data across the different departments. In order to overcome this issue, Boeing started a new web-based system called HABIT in 1996. The purpose of HABIT was to connect all manufacturing plants to the design build teams and to make the production data available to everyone for product improvement activities and new designs. The ASQ and HVC were merged together to reduce variation across the entire supply chain.

4.5.5 HABIT Development Issues

Acceptance of concept by customers: The management must ensure that internal and external customers down the supply chain understand and incorporate the concept of HABIT in their own system.

Technology issues driven by the operating system: The data as well as database used should be compatible with the operating system used by all consumers down the line.

Value generated vs. development costs: Trade off between the development cost and benefits derived from the HABIT system should be analyzed carefully before actually implementing this system.

Leadership goals and methods: All the proposed methods should be evaluated carefully to see if the management goals can be accomplished satisfactorily.

Frequent schedule slides and missed deliverables: Chances of missing deliveries for last minute frequent schedule changes become very high when using one integrated database and should be carefully analyzed.

4.5.6 Future Plans

As we have seen, Concurrent Product definition (CPD) structure and product definition tools help in eliminating variation in a process. Boeing is developing a process similar to Design for Six Sigma to take advantage of this principle. Second, scheduling and performance of operations can be clearly monitored by using an integrated software package.

In an effort to use a single common database system across the supply chain, Boeing started implementing a data management system also known as 747 Data Management System which collects and stores all the information and generates the relevant automated reports.

4.6 747 Data Management System[8]

Boeing undertook Accurate Fuselage Assembly (AFA), Fuselage Assembly Improvement Team (FAIT), and Data Management System programs to reengineer its processes and operations. The new system required automatic gathering, analysis and storage of all the critical information related to its process/ processes. This in turn led to digitization of design, assembly, and testing methods in order to store all the data for further analysis. The various tools like CATIA, Tolerance analysis, Variance simulation, and NOAC were used in the 747-digitization program.

Several critical factors were identified to make the 747-digitization program a success. The following data requirements were laid out in the development of the digitization program.

4.6.1 Data Requirements

The following data requirements were identified:

1. All manual drawings showing customer critical features should be integrated with the CAD system.

2. The new system must be capable of recording all shop floor results so that the data can be analyzed in a very short time period.
3. The system must be able to produce statistical process charts instantaneously after recording the data.
4. The system is required to store different suppliers' as well as in-house data in a very secure database, thus prohibiting anyone from altering the data without prior approval.

4.6.2 Input Requirements

The system should be capable of handling manually collected data. Moreover it should be proficient in having an interface with 3D measurement devices as well as spreadsheet data so that the data can be directly accessed and stored in the central database system. For example, laser trackers, data loggers, electronic clippers, and portable coordinate measuring machines can be connected with the central database system and the measurements can be recorded directly.

4.6.3 Analysis Requirements

Because the measurements are used to assess the process and product quality and may have an influence on analysis and decision-making processes, the data collected should be stored as a permanent aircraft record. In addition, the collected data should be very easy to interpret and should provide real time information in a minimum time frame.

4.6.4 Report Out Requirements

The system should be able to generate automatic reports as per the requirements laid out by the company. Moreover, it should be capable of performing statistical analysis, control charting and automatically generating out-of-tolerance reports.

Figure 4.9 shows the 747 data management system including all input and output requirements.

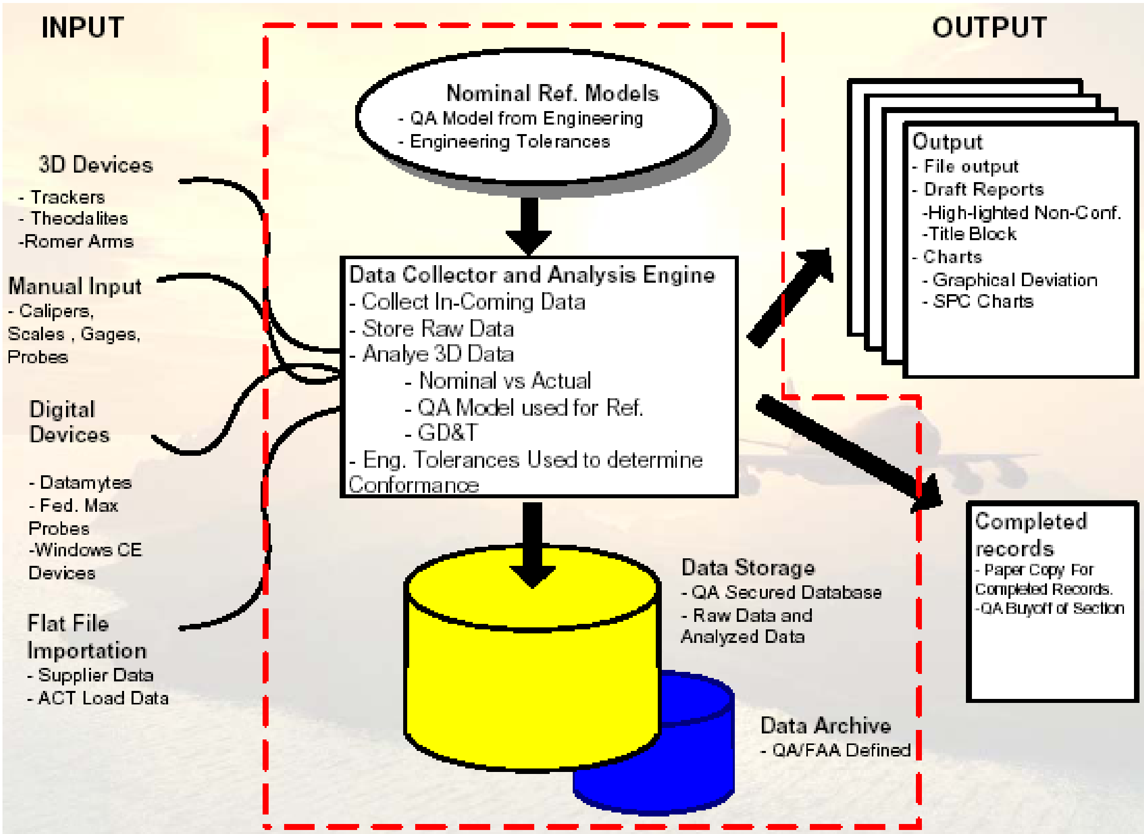


Figure 4.9: 747 Data Management System

4.6.5 DMS Graphical User Interface (GUI)

GUI is a graphical interface to a computer. The user basically points to an icon of what specific information he wants to see. Multiple windows (Figure 4.10) dealing with different issues like Quality, 3D graphs or data analysis can be opened and studied at the same time.

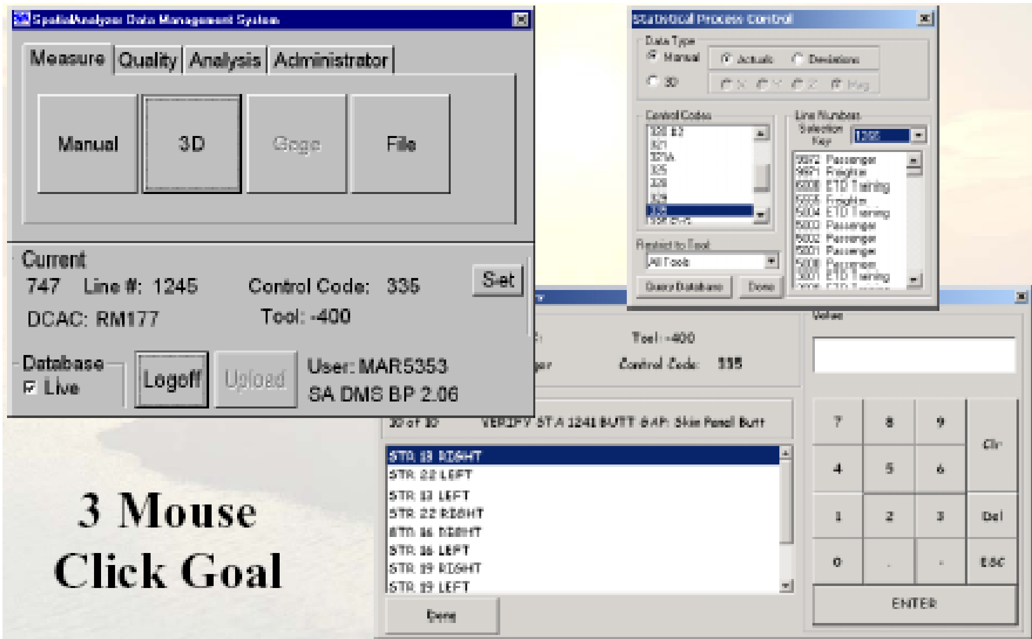


Figure 4.10: DMS Graphical User Interface

4.6.6 Engineering Conformance Report

The system should be able to report all the data in an engineering conformance report (Figure 4.11), which in turn may be used to analyze the data online.

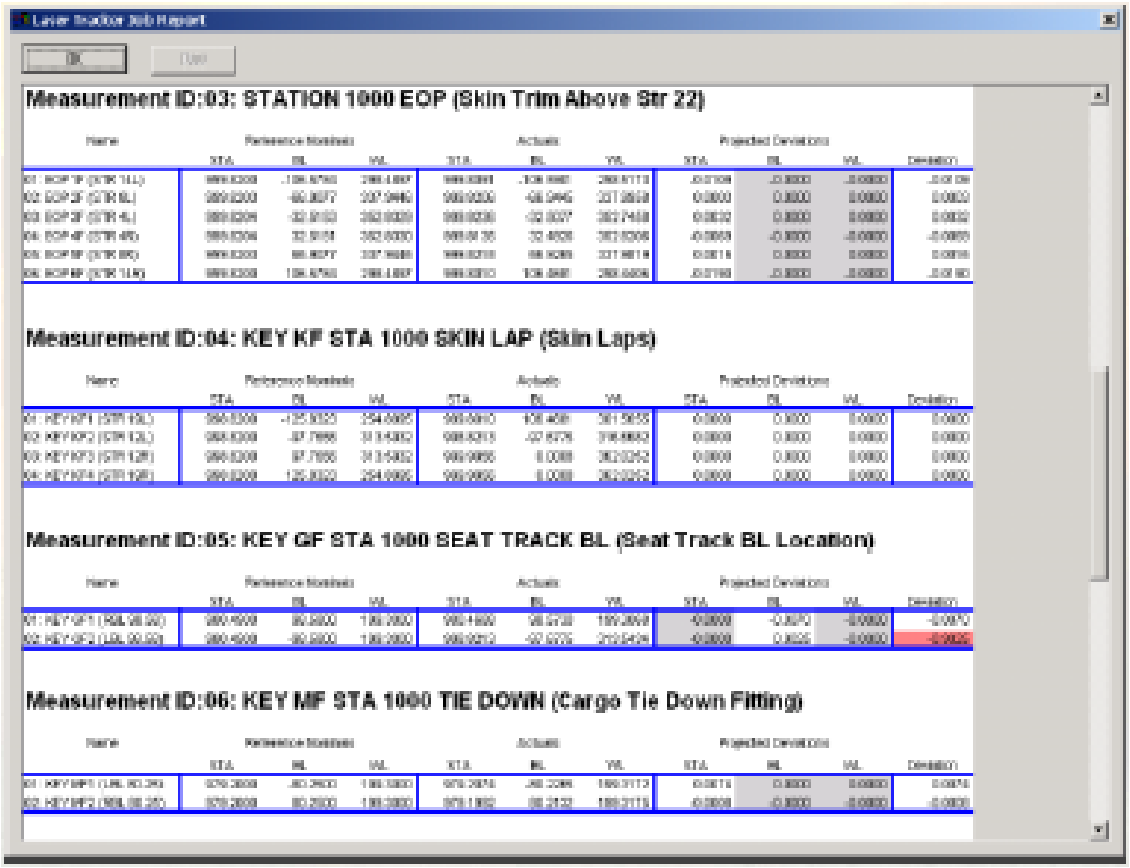


Figure 4.11: Engineering Conformance Report

4.6.7 Graphical Analysis

With graphical analysis programs, graphs, data tables, histograms and other specific reports can be easily created, printed, and interpreted (Figure 4.12). The reports prepared can be used to provide specific feedback to the suppliers. Moreover, any kind of variation can be related to attributable processes by analyzing the information graphically.

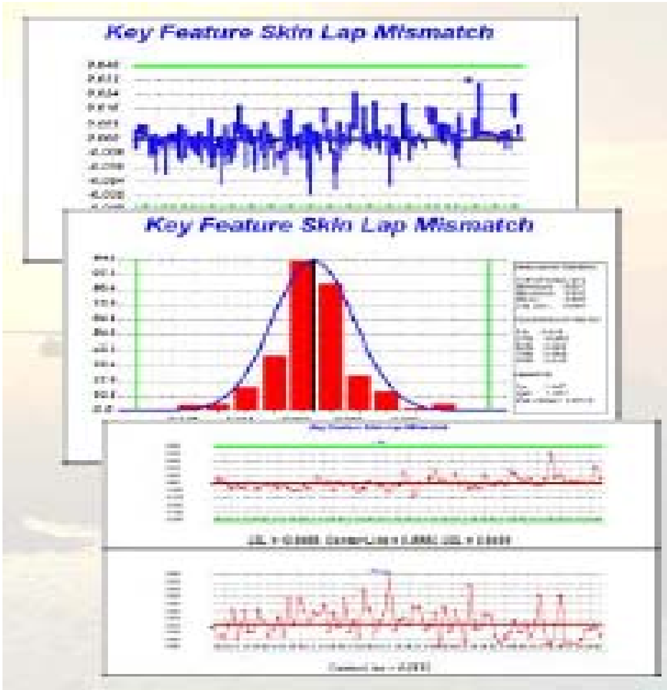


Figure 4.12: Output of a Graphical analysis

4.6.8 Process Scores

The system should be able to evaluate some indices like the process capability indices (Cp, Cpk or Z score) automatically. These engineering related features help the management to interpret the data and results in a very quick and efficient manner.

4.6.9 Process Comparisons

The performance of different tools, processes or machines can be compared by generating process charts or using other comparative methods (Figure 4.13).

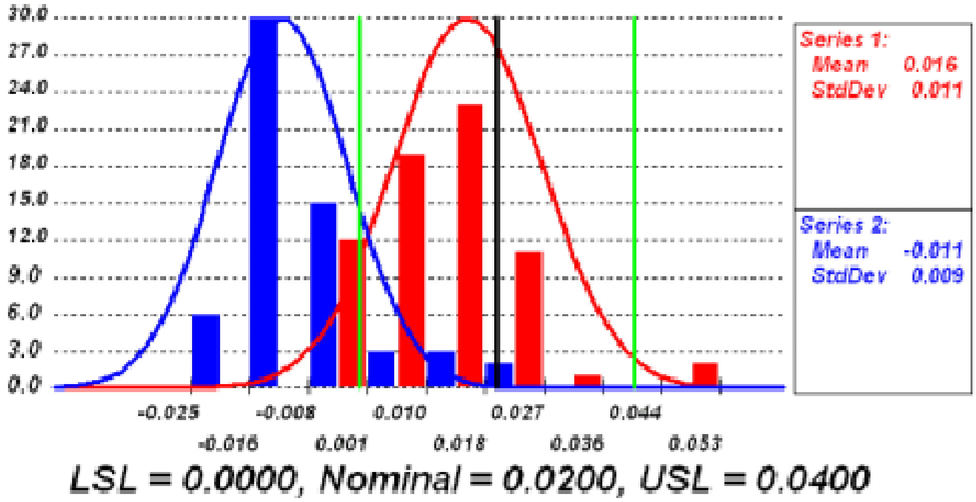


Figure 4.13: Tool A to Tool B process comparison

4.6.10 Laser Tracker 3D Survey

A laser tracker 3D survey system can be used to measure the specific features on an airplane. Data can be collected in different formats like graphical format or data format. Figure 4.14 and 4.15 show the measurement as well as data collection in graphical format.

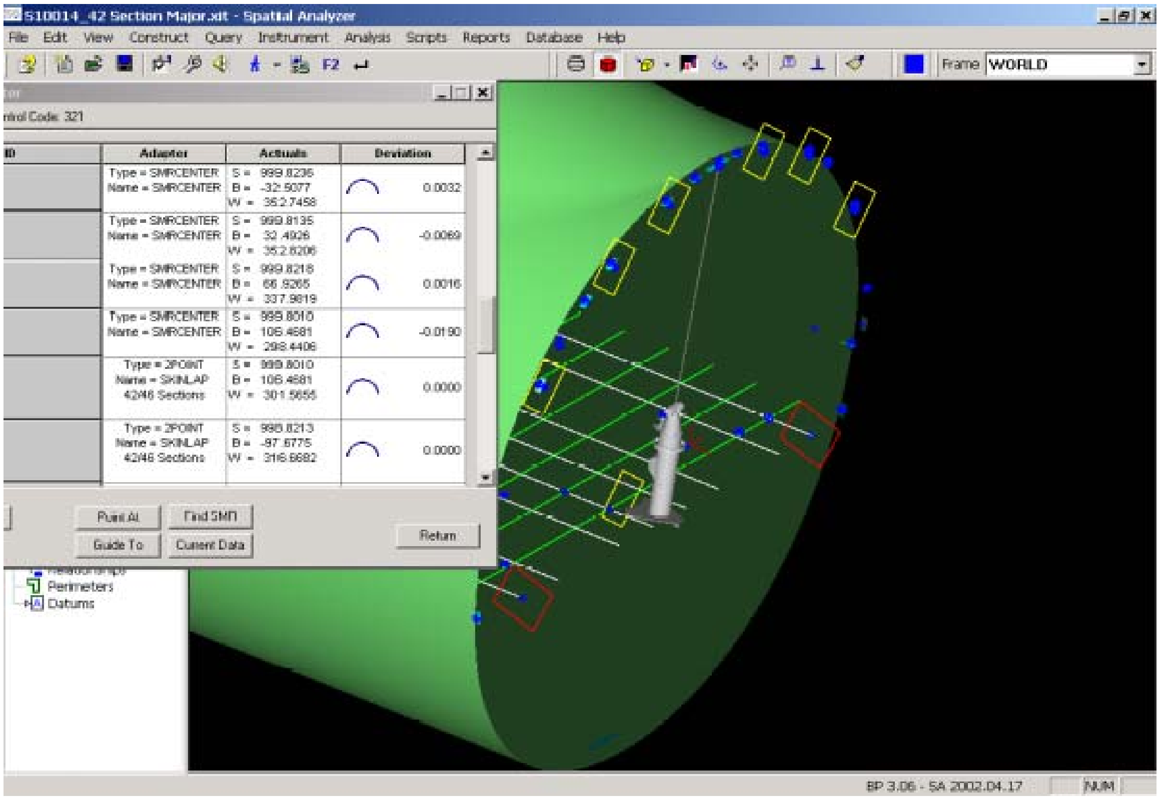


Figure 4.14: Measuring features using Laser Tracker

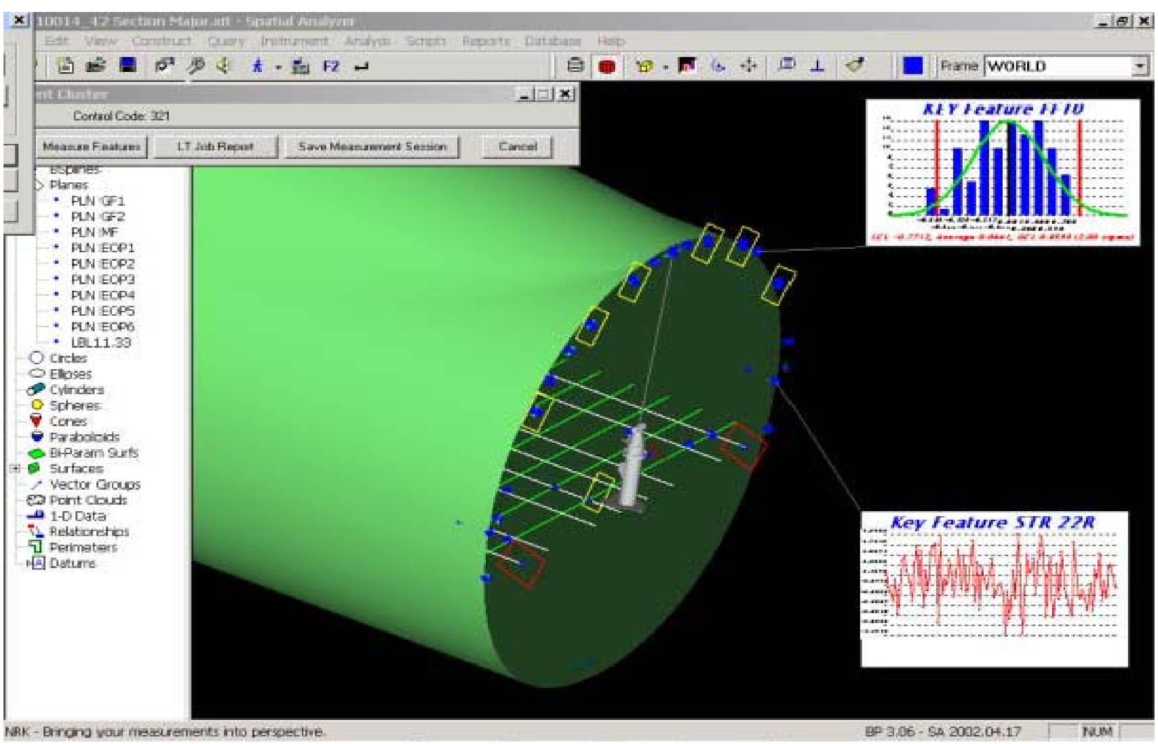


Figure 4.15: Historical reporting using Laser Tracker 3D survey

4.7 Reference

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Chapter 5. Quality Control Hardware

5.1 Introduction

In the shipbuilding industry, a shipbuilding system based on group technology, using a product-oriented work break down structure (PWBS) and integrated hull construction, outfitting and painting, requires that the accuracy of each process and stage be well controlled. Thus, accurate measurements in each stage are needed to ensure accurate and productive final assembly. Conventional measurement tools including plumb bobs and wooden templates are labor intensive and generally not very accurate. During the past twenty years, accurate 3-D coordinate measurement systems (CMS), such as laser tracker and electronic theodolite, have been developed. Due to their high cost and the difficulty in hiring skilled workers, such systems have not been used in all shipyards. However, today more and more shipyards are using 3-D systems to improve the accuracy of shipbuilding and ensure the integration of different processes and stages. A survey conducted at four European shipyards[14] indicates that various optical/electronic devices, digital/electronic devices, Sokkia Digital/ Micrometer Theodolite systems are used in dimensional measurement and accuracy control. There are four types of 3-D CMS, including theodolite systems, industrial total stations, photogrammetry systems and laser tracker systems. In this chapter, these four different systems will be introduced and a small explanation of how they work will be presented.

5.2 3-D Measurement Systems

5.2.1 Theodolite Systems

A theodolite coordinate measurement system is an optical measurement system that is used to measure horizontal and vertical angles to a point.

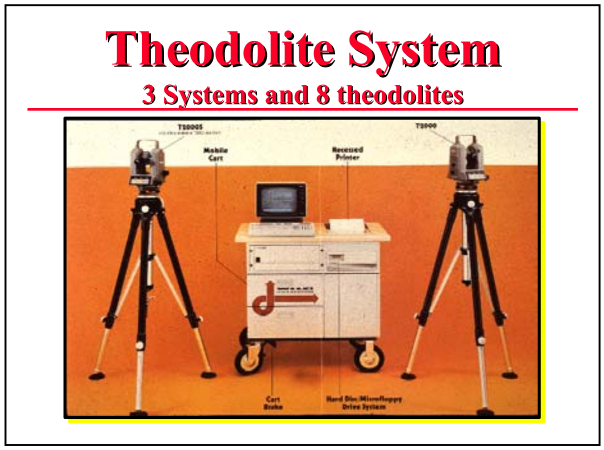

Figure1: Theodolite System[2]

Figure 1 shows a theodolite system that is used at Northrup Grumman Newport News. This system allows operators to map data points and send the data to a personal computer for immediate processing. The system typically uses two or more theodolite heads placed around the object to be measured. A target point is sighted on the object by each scope, yielding the directions of two intersecting lines-of-sight to the point. Triangulation is then done in real time to calculate the three-dimensional coordinates of the point. The true scale for measurements must also be established, which is usually done by measuring reference points on a scale bar with the theodolites.[4]

Advantages:

- If the theodolite system is equipped with laser beams for projecting a dot on the point of interest, there is no need to manually place targets on the object.
- Cost is relatively low compared with other coordinate measurement systems.

Disadvantages:

- Set up time is long
- It needs 2-3 operators measuring the target using the different theodolite heads.
- Measurement rate is slow. The measurement data can be collected at a rate of five points per minute using experienced operators.

Accuracy Capability:

Generally, the electronic theodolite system has an accuracy of 0.001 - 0.005 inches.

Major Product:

Leica Inc. provides a series of theodolite systems that can be used in large-scale assembly and inspection. For example, the Leica TDA 5005 is suitable for any kind of medium to large-scale measurement tasks such as:

- part assemblies
- part inspections
- machine alignment & inspection
- tool inspection
- jig building and inspection

Example:

Northrup Grumman Newport News has three Leica systems with eight electronic theodolites that can be mixed and matched between any of the three systems. Each system is flexible enough to connect all eight theodolites into one network, or as few as two. Currently, these systems are typically used in shop environments. Achievable accuracies are on the order of 0.001 - 0.005 inches. One of the unique capabilities of the theodolite system is the ability to accurately "build" coordinates. In other words, once the theodolite system is loaded into the correct user coordinate system, the operators can instruct the system to point to a desired location very accurately. This capability is used for piping applications to adjust template heads in the shop, or to accurately lay out reference lines or profiles.[2]

5.2.2 Industrial Total Station

Industrial total stations are enhanced electronic theodolites that utilize a near infrared light emitting diode, which is transmitted coaxially with the telescope's line-of-sight. The leading industrial total station products are Sokkia's NET2 and NET2B, and Leica's TDM5000. It is a single station, single operator system intended for industrial, rather than surveying applications.

Accuracy Capability:

Depending on the geometry and work zone of the measurement project, accuracy of 0.1 mm (0.004") to 1.0 mm (0. 039") can be achieved by an industrial total station.

Major Product:

In this section, we will introduce the Sokkia system. (See Figure 2)

Figure 2. Sokkia System

In 1982, the Sokkia Company, Ltd., Ishikawajima-Harima Heavy Industries Company, Ltd. and three other shipyards, together with a working group in the Super Modernization Committee of the Shipbuilders Association of Japan began to develop a new 3-D measurement technique which is able to measure 3-D hull blocks of over 10 m^2 with high accuracy (to several millimeters). In 1989, based on that development, a new measuring instrument for commercial use was introduced to the Japanese market. That early measuring system is an improved electronic theodolite, in which a highly accurate near-infrared distance-measuring sensor is embedded. One year later, this equipment was integrated with an electronic notebook, through which data can be recorded and transferred to a personal computer. Today, over 200 shipbuilders around the world are using such systems.

In 1991, the Sokkia Company introduced this technique to the United States. Beginning in 1994, the IMTEC Group undertook the task of introducing the measuring instrument to the U.S. shipbuilding market.

Application in U.S. shipyards:

In the U.S. shipbuilding industry, the following shipyards own and operate a total station system.

Name of Shipyard	Number (unit)
Alabama Shipyard	1
Atlantic Marine	1
Bath Iron Works	2
Bender Shipbuilding & Repair	1
Carderock Div Nswc	1
Northrup Grumman Ingalls Shipbuilding	1
Metro Machine Corp of Erie PA	1
Northrup Grumman Newport News	7
Tampa Bay Shipbuilding & Repair	1
Todd Pacific Shipyard	2
Kvaerner Philadelphia Shipyard	3

The characteristics of the Sokkia system

The Sokkia 3-D measuring system has been continuously developed and updated. The original instruments were known as NET 2's, and the second generation is NET 2B. The current iteration is named as NET 2100. The NET 2100, together with the optional software NETrology™, has documented and proven precision of 0.1 mm (0.004") to 1.0 mm (0. 039") depending on the geometry and work zone of the measurement project. The NET 2100 is capable of storing up to 3000 data points in its internal memory. This data can be easily downloaded to the PC based NETrology™ for analysis.

The specification parameters are:

Telescope	49 mm Aperture, 30x, erect image, 1° 30' Field of view
Automatic Compensator	2-Axis Tilt Sensor, ± 3' compensation, ON/OFF selectable, <1"
Angle Measurement	Display: 0.5", Resolution: 0.5",
Distance Measurement: Reflective Target Sheets	0.8 mm + (1 ppm X D) up to 100 meters 1.3 mm + (1ppm X D) 100 to 250 meters
CPS 12Prism	2.0 mm + (2 ppm X D) up to 1 Kilometer (1000 meters)
Relative measurement	± 0.1 mm to 0.5 mm depending on workzone and environment

Industrial Application: [6]

The Sokkia system can be used in the following fields:

- Measurement of hull subassembly blocks for pre-trimming of excess material
- Monitoring of structures during welding for dimensional control
- Alignment of manufacturing equipment
- Alignment of shafting

- Alignment of hull erection units
- Verification of patterns and molds
- Dimensional inspection of shell plating with complex curvature.

5.2.3 Photogrammetry

Photogrammetry employs photographs (or digital imagery) for measurements. There are two typical methods of photogrammetry that are used in the shipbuilding industry called convergent photogrammetry and stereo photogrammetry respectively.

Advantages

Photogrammetry offers users a number of attractive and unique advantages over conventional measurement techniques.

- The single camera E3 system is capable of producing accuracies of the order of 1:60,000 of the object size.
- The measurement process is totally non-contact. This makes it ideal to measure delicate items that deform when touched.
- Immune to temperature fluctuations and vibrations.

Disadvantages

- Not fast, as it takes time to develop the pictures
- Awkward in tight areas trying to set up the equipment.

Convergent photogrammetry

In the technique of convergent photogrammetry, retro-reflective targets must be placed on the surface of the object, and then a special camera is used to photograph those targets from several locations, at several angles. Three-dimensional coordinate data are determined from the two dimensional photographs via optical triangulation.

The JFK/Leica system was the first analog photogrammetric system developed for shipbuilding. Due to the relatively long process time and high labor cost, analog photogrammetry has been largely replaced by digital photogrammetry.

Accuracy Capability:

Generally digital photogrammetry can achieve an accuracy of 1:100,000 of the major dimension of the object.

Primary Product

One current industry leader in providing the digital photogrammetry systems is Geodetic Services, Inc. (GSI). The GSI V-STARS system includes the photogrammetric camera, strobe, notebook computer, and proprietary software. The whole system is fast, portable, accurate, and immune to vibration.

The following figure shows the components of the V-STARS system.[5]

Figure 3. V-STARS System

Typically, the operator first uses the digital camera to photograph the targets on the object from several locations and several angles, and then these photographs can be directly recorded onto a hard disk and easily transferred to a desktop or notebook computer. Furthermore, the photographs will be measured and processed in order to calculate the three-dimensional coordinates of each target. Since the V-STARS system contains the computer and proprietary software, the entire photogrammetry job that includes measuring and data processing can be completed on site. This is a notable advantage of the V-STARS system.

According to GSI inc., its single camera V-STARS/S system is capable of producing accuracies of the order of 1:120,000 of the object size (0.08mm on a 10m object). The dual camera V-STARS/M system is capable of producing accuracies of the order of 1:60,000 of the object size (0.17mm on a 10m object). [5]

According to the characteristics of the GSI V-STARS system, it can be used in the following stage or process in shipbuilding: [5]

- Steel plate measurement
- Surface measurement
- Deformation measurement
- Pipe measurement
- Temperature deformation
- Repeatability check
- Component alignment
- Shape analysis
- Transportation check

  (Check of built components after transportation to customer or from suppliers)
- Ship block measurement
- Hull circularity checks
- Vibration studies

Vexcel Corporation also plays a role in the industrial photogrammetry market. Their software FotoG-FMS allows users to get accurate 3D models of the object by taking the photographs and processing them. The Photomodeler software, provided by Eos System Inc. can also create 3-D models from digitized photos.

Vexcel Corporation and Midcoast Metrology are performing an NSRP project employing and demonstrating the photogrammetric process with Bath Iron Works. The goal of this project is to adapt and expand an existing close-range photogrammetric process, currently in use by aerospace, automotive, military, and process plant designers, to the unique applications of shipbuilding construction. The process will allow for highly accurate 3D measurements and 3D models to be extracted from digital photography. Currently these requirements are handled using labor intensive applications, reducing production efficiency through costly downtime, fabrication interference, and incomplete data. This NSRP project is supposed to be finished in 2003.[7]

Examples of the use of photogrammetry at Bath Iron Works are shown below. Figure 4 is of a bearing foundation, where photogrammetry is used to permit a one time shipboard cut, versus multiple scribe and cut operations.

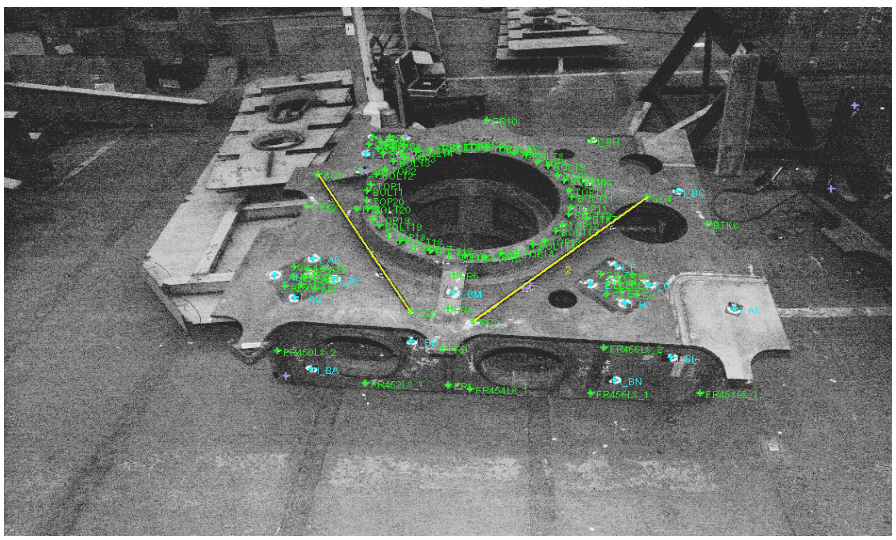

Figure 4a – Bearing foundation measurements using photogrammetry

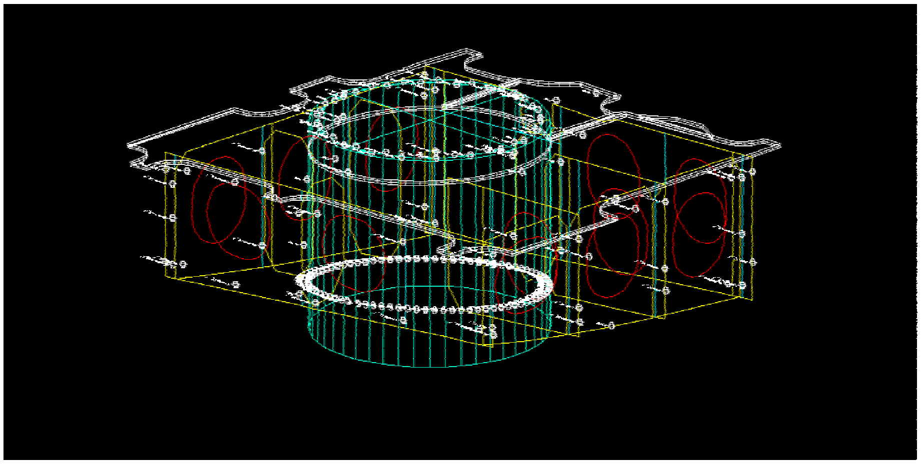

Fig 4b – CAD drawing of bearing foundation

Figure 5a – Unit end measurements to determine unit make-up alignment accuracy

Figure 5b – Unit end measurements to determine unit make-up alignment accuracy

Stereo photogrammetry:

Compared with the multiple camera locations and angles of convergent photogrammetry, stereo photogrammetry uses only two camera locations with the camera axes parallel. The principle of stereo photogrammetry is similar to normal stereoscopic vision. When an observer views an object with both eyes, the object's position can be determined in all three dimensions, because each eye will see the object from a different position and hence the object will appear to be different in each eye. These differences in images seen by the observer's two eyes are used by the person's brain to determine the location of the object in three dimensions. So with stereo photogrammetry, two photographs (stereo pair) with overlapping imagery can be measured with little or no need for targeting. The camera axes of the stereo pair are maintained nominally parallel to one another, within ±10 degrees. Using an analytical compiler, the stereo pair is presented to the observer's eyes, creating the perception of a three-dimensional rendition or stereo model. The analytical compiler is fitted with a measuring mark that the operator can freely move around to measure any given point of interest.

Accuracy Capability:

Generally, digital photogrammetry can achieve an accuracy of 0.003-0.005 of an inch. However, the accuracies vary depending on several factors such as the distance from the camera to the object, clarity of the photographs and the skill level of the operator.

Compared with digital photogrammetry, the accuracy of stereo photogrammetry is relatively low. However, stereo measurement can be used in some situations where digital photogrammetry cannot be used appropriately. For example, in a situation where a required point of interest was not targeted or when targets are impractical to place in an area to be measured, stereo pairs can be used for verification. Thus stereo measurements are most beneficial when used in a combination with a convergent survey.

5.2.4 Laser Tracker

The laser tracker is a very popular measurement tool used to measure large objects in many manufacturing industries. It is often used for reverse engineering and inspection, alignment, testing and maintenance in the shipbuilding, aircraft manufacturing and other manufacturing industries. A laser tracker can provide fast and accurate 3-D measurement of a mobile target. Unlike the distance measuring methods applied in the photogrammetry and theodolite systems, laser tracker uses a laser interferometer to measure relative distance, and optical encoders to measure azimuth and elevation of a beam-steering mirror. [1] (See Figure 6)

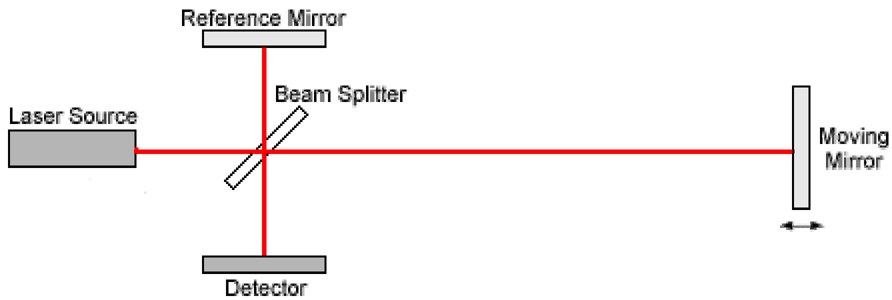

Figure 6. Standard interferometer

The system emits a laser beam from the laser source to the moving mirror. When the beam passes through the beam splitter, it is divided into two beams. One beam is used as a reference while the other beam is reflected back from a mirror or retro-reflector at some distance. It is then merged with the reference beam, producing interference. Using that data, the relative distance can be measured. The laser tracker can be used for dynamic and static object measurement.

Accuracy Capability:

The laser tracker has an accuracy of 1:1,000,000 of the major dimension of the object (limited to between 1 and 90 feet) or 0.0002 of an inch at 20 feet. Although the actual accuracy of a laser tracker system depends on the configuration used and measurement conditions, a typical achievable accuracy using a single beam tracker is 0.001 of an inch at 20 feet. Laser tracker systems are generally capable of higher accuracies than electronic theodolite-based systems, while offering the same advantage of real-time coordinate measurement. [2]

Advantage of the laser tracker

Intuitive: operator places the target anywhere a coordinate is required

Single user: one device and operator can record points working alone

Range: typically tens of meters, creating a large working volume; also it is portable.

Compatibility: the 3-D information created by the system can be input into another computer system to generate seamless CAD and tooling data.

Disadvantage of the laser tracker

Occlusion: can only operate in line of sight; breaking the beam requires resetting the coordinate system

Contact: target must physically touch the measured point

Offset: recorded coordinates are offset from the actual surface

Target size: size of the retro-reflector limits the minimum radius of curvature measurable

Static scene: scene must remain static as the points are measured

Environment: changes in air temperature, pressure and humidity affect measurements [1]

Example:

Boeing Helicopter, Philadelphia is responsible for producing wings and other components that are for Boeing's commercial helicopters and for military aircraft. In the past years, the quality engineers used digital theodolites to verify the surface contours. Generally, two or three people are needed to set up the theodolite system, and only one measurement can be made in a minute. When this plant introduced the laser tracker system, the productivity improved dramatically. The laser system can be used by one operator and can make 60,000 measurements in one minute.

Primary Product

SMX Laser Tracker

Figure 7. SMX laser tracker

The SMX laser tracker is a portable coordinate measuring machine (CMM) that makes three-dimensional measurements. The SMX Laser tracker is used in automotive, aerospace, and many other industries. Its clients include the Boeing Co., General Electric Co., General Motors Corp., Westinghouse Electric Corp. and Northrup Grumman Newport News.

The SMX laser tracker is connected to a PC (or laptop) on the shop floor, where SMXInsight® software displays results, including interactive graphics and 3D images. The coordinate data the tracker collects can be "fit" by software to geometrical entities such as points, planes, spheres, or cylinders.

System features:

Work range: 0-35m

Accuracy: 10 µm + 0.8 µm/m

Acquisition rate: Up to 1000 measurements/sec

In order to offset the environmental effect on the measurements, the SMX laser Tracker has a NIST-traceable integrated barometer and thermistor mounted close to the beam to monitor temperature and barometric pressure and automatically adjust for measurement deviations caused by atmospheric conditions. [3]

5.2.5 Conoscopic Holography[1]

Optimet (Optical Metrology Ltd.) has developed radically new non-contact 3-dimensional measurement sensors and systems using a unique technology called Conoscopic Holography.

A single beam from an object is divided into ordinary and extraordinary components using a polarizer. These beams then traverse the uni-axial crystal individually but along the same path. This produces holograms--even with incoherent light--with fringe periods that can be measured precisely to determine the exact distance to the point measured, as shown in figure 8.

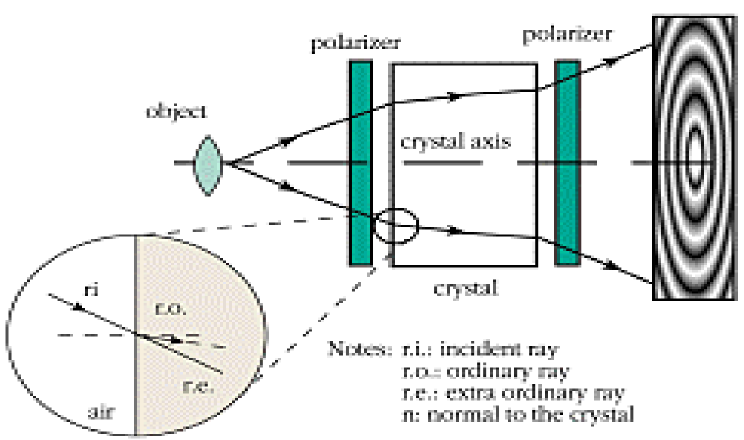

Figure 8: Basic Principle of Conoscopic Holography

Industrial Product and applications

The product ConoProbe (Figure 9) is a non-contact single-point measuring sensor. It is built with interchangeable lenses for a large variety of working and precision ranges. This general-purpose measuring device is designed primarily for OEM customers for integration into different measuring and control applications. The ConoProbe can be used in the shipbuilding industry to measure very complex geometries. This instrument combines co-linearity with bending/relay optics to measure deep, narrow grooves and holes.

Figure 9: ConoProbe System

Advantages

- High precision and repeatability over a wide working range. The repeatability is better than 1/8000th of the working range, and the precision is better than 1/2000th.

- Outstanding versatility in the working range and standoffs
  No need to change sensors, only a simple change of the front lens varies the measurement range and standoff of the probe.
- Multiple dimensions (from sub-microns to meters) can be measured by using a single ConoProbe head and by changing the objective lens.

5.2.6 3D Confocal Microscopy[2]

In white light, confocal microscopes emit light from a point source, which is imaged into the object focal plane of the microscope objective. The reflected light is detected by a photo diode behind a pinhole and it leads to a part suppression of light from the defocused planes. Combined with CCD image processing, the rotating Nipkow disc, which consists of a spiral-shaped multiple pinhole mask, affects the xy-scan of the object field in real-time video. An additional z-scan is used for the evaluation of highly precise height data.

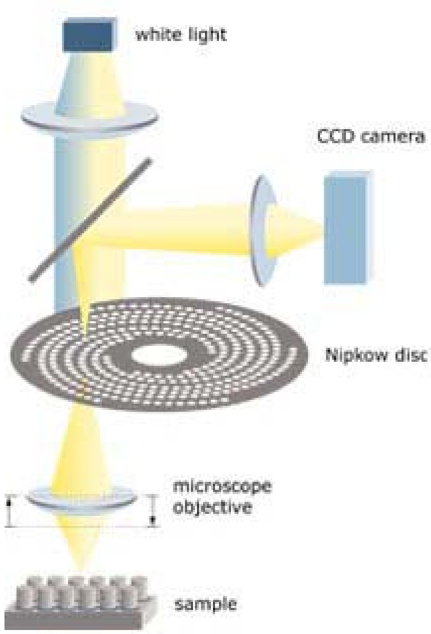

Figure: 10 Diagram of the Confocal Microscope Nanosurf

Advantages

- High vertical and lateral resolution: An increase of nearly 20% lateral diffraction limited resolution compared to conventional microscopy is achieved through the physical pinhole filtering.
- Ability to measure steep edges, complex structures or transparent coatings.

Industrial Product and applications

NanoFocus Inc. is a manufacturer of non-contact surface measurement solutions. Its automated and semi-automated profilometers and confocal microscopes are based on laser and optical inspection technologies. The NanoFocus NanoSurf scanning confocal microscope was especially designed for R&D and industrial quality assurance as an independent 3D optical measurement system. As such, its application in the shipbuilding industry is feasible.

The NanoSurf can measure optically complex surface structures while maintaining high vertical and lateral resolution. The confocal physical filtering principle leads to a significant reduction of optical artifacts and a robust & predictable height signal in cases where other optical methods fail. Measuring results using surface roughness standards show a good correlation to the most accurate tactile instruments. The NanoSurf (Figure 11) consists of a compact confocal module that is mounted to a solid stand and can be moved in a vertical direction. The sample is placed on an x-y precision slide. Because of the precise motion control, extended measurement areas can be measured by combining basic fields via stitching. The NanoSurf confocal microscope is controlled by software working under MS Windows® NT; the surface topography data can be presented and analyzed in various ways.

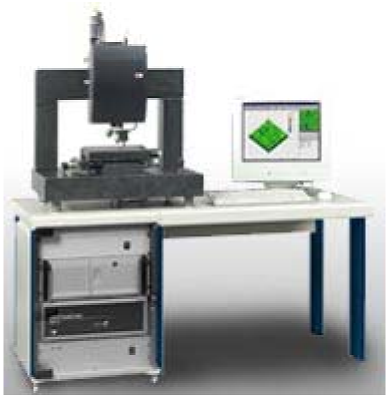

Figure 11: NanoSurf System

Standard components

- Confocal image sensor (measurement principle: whitelight confocal microscopy)
- Vertical measurement range: limited by working distance of objectives
- Lateral resolution: 512 x 512 pixel in the basic field
- MS Windows (NT)

5.2.7 Intelligent Pipe Measurement System (IPMS)[3]

Ship repair involves, to a very large extent, the replacement of old worn pipes. It requires accurately measuring flanged pipes in 3D co-ordinates, including straight sections, toroidal bends and reducers, and the relative positions of the end flanges with respect to the centerline orientation of the pipes. The current procedure used in many shipyards in performing both measurement and fabrication is primarily a slow and tedious manual process. It involves placing the worn-out pipe onto a large steel base, fixing mating flanges onto all the end flanges of the worn-out pipe, and manually welding these mating flanges onto the base to produce a fixture for subsequent fabrication, as shown in Figure 12. Additional supports are fabricated and installed as necessary to firmly fix the pipe to the steel base.

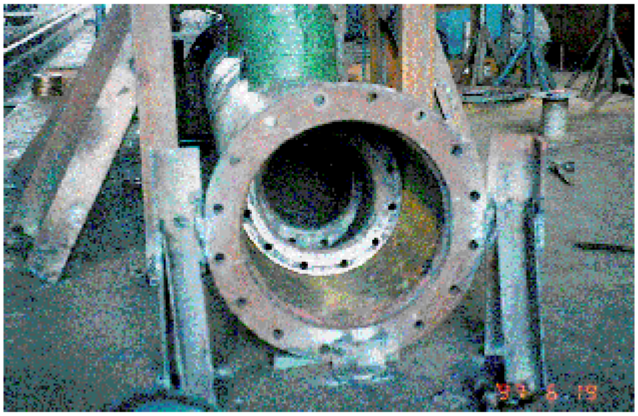

Figure 1: Fixturing of Pipes for Measurement.

Figure 12: Manual pipe repair measurement

A research project undertaken in the Department of Mechanical & Production Engineering, National University of Singapore aims at the development of an automated Intelligent Pipe Measurement System (IPMS). In the IPMS system, a computer-controlled robotic fixturing system is used to hold, and at the same time, measure the relative coordinates of the end flanges of the old pipes. This is illustrated in Figure 13.

Figure 13: Computer-controlled Pipe Fixturing System

A laser ranging system, together with a machine vision system, mounted on an instrumented two-degree-of-freedom gimbal system (see Figure 14) is then used to measure the co-ordinates of a specified number of points on the surface of the pipe. The vision system is first used to determine the outlines of the pipe and, from this, the approximate locations of the points to measure. The computer-controlled laser ranger is then moved to target these points one at a time and their co-ordinates in 3D space measured. From these measurements, the diameter of the pipe, and the 3D coordinates of the centerline of the pipe are determined. The robotic fixturing system is also instrumented with sensors which allows the computer to determine the type of flanges used.

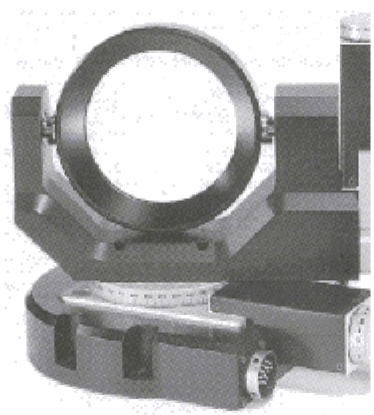

Figure 14: Computer-controlled Two-axis Gimbal for Camera and Laser.

With all this information, the complete geometry of the pipe is thus obtained and production drawings can then be produced to facilitate the fabrication process. Data on the pipe measured, and its identification, are stored in the computer for subsequent retrieval when needed.

5.2.8 Vexcel Photogrammetry Software[4]

Vexcel Corporation, founded in 1985, is an internationally recognized remote sensing company. The corporation provides engineering services, hardware, and software in the areas of

Aerial and Close-Range Photogrammetry, Radar (SAR) Technologies, and Remote Sensing Ground Systems.

FotoG(TM) is advanced close range photogrammetry software. The software provides an in-house capability to obtain accurate measurements and create 3D as built CAD models, direct from photographs. Upgraded photogrammetry software FotoG(TM) 5.2 is used to make measurements and create 3D CAD models of real world structures and objects from digital photos. Vexcel's 3D point cloud feature of FotoG 5.2 turns the task of creating a CAD surface element from manually clicking points in digital images into a one-step process. FotoG 5.2 creates a 3D representation of a given area using the point cloud data it automatically generates from digital photos. Not only does the point cloud feature reduce the time it takes to create the 3D image, it also creates a more accurate representation of complex curves.

Applications and Features

Industry application areas include shipbuilding, process and manufacturing, petrochemical, architectural, automotive, pulp and paper, equipment design and installation, construction, and forensic.

- FotoG(TM) integrates directly with AutoCAD, Microstation, Mechanical Desktop, PASCE, SDRC, Pro/ENGINEER.
- Automated image matching removes the tedious task of identifying common points in images for photogrammetric processing.
- Automated collection routines reduce time required for taking measurements and producing models.
- Choice of Photography input feature provides the user with the flexibility to use a variety of imaging technologies – e.g., digital cameras and videos.

- FotoG(TM) can run on standard hardware, windows and UNIX versions.
- The reporting and error checking software provides feedback that permits evaluation of the quality of results, and quantifying the measurement accuracies to be expected.
- Minimal control information is required
- Only four control points are needed in each block (up to 50 photos) of photographs.

5.2.9 Scanning Moiré Interferometry™ (SMI)[5]

Scanning Moiré Interferometry™ (SMI) is a recently patented 3D technology that enables the use of the traditional, well-proven moiré interferometry technique in a high speed, scanning mode. This technology has its advantages over the traditional Moire' Interferometry.

In traditional Moire' Interferometry, the object is illuminated with the moiré light pattern (projected by placing a fine grating in front of a light source) and images are captured with a high resolution CCD camera. The light pattern is shifted very precisely by a few microns and the second image is captured. Then, a third image is captured by shifting the light pattern slightly by the same distance. 3D topography of the object is calculated by inserting all the intensity readings from the three images into a formula.

Some of the inherent problems associated with Traditional Moire' Interferometry includes ultra-precise positioning control, complex mechanical fixturing, high costs and time-consuming shift-and-acquire procedure. However, in the SMI implementation, the Moiré pattern projection remains largely unchanged. Instead of the high-resolution 2D CCD array, SMI uses a tri-linear CCD (triple-line scan.). Now the acquisition process takes place as follows:

- A tri-linear CCD and moiré light pattern are fixed with respect to each other and are referred to as an SMI sensor.

- An object is moved past the SMI sensor (or vise versa) and 3 intensity points are acquired for every scanned point.

- The 3D topography of the object is calculated by inserting the intensity readings for each point into a formula.

- The scanning is continuous, with range calculations made on-the-fly.

This new process offers the following improvements over traditional moiré interferometry. First, the inherent internal precision of the silicon die eliminates the need for the precise handling mechanism and positioning control. Second, the three CCD lines eliminate the need for three consecutive full field image captures. Third, the three CCD lines, together with the scanning motion, also provide continuous 3D data acquisition at video rates. The net result is a compact, rigid sensor that achieves the same accurate results of the traditional approach, but with much higher speeds, simpler design and lower costs.

Industrial Product: Impact™ machine vision micro-system

The IMPACT™ machine vision micro-system provides a new level of performance for OEM's, system integrators and end-users of automated inspection equipment. PPT's patented, high-speed Digital Vision cameras and advanced lighting components allow IMPACT to capture high quality images at production speeds. The system is linked to a high-speed processor running inspection algorithms to generate inspection and quality results. In addition, IMPACT's Ethernet connectivity provides a tool for data collection and analysis as well as remote monitoring and control.

IMPACT provides the flexibility to meet the inspection requirements of a variety of different applications. Moreover, IMPACT's software provides a simple, intuitive graphical user interface that enables inspection programs and operator interfaces to be set up in just minutes.

Figure 15: IMPACT™ machine vision micro-system

5.2.10 Geodelta's 3D geometric image processing[6]

3D geometric image processing is Geodelta's main field of expertise. This is the technique with which the spatial dimensions of objects can be determined from digital photo images. This measurement system has been built by the integration of image processing and the principles of photogrammetry and statistics. Typical applications of 3D geometric image processing include shipbuilding and repair, space engineering, medical science, and the automotive industry. Geodelta has developed number of techniques in the field of geometric image processing over the last few years.

Phoxy technology

Geodelta's phoxy technology, which is the heart of the measurement system, gives flexibility in the building of applications (from measuring faces to measuring of piping installations) that are based on clients needs. This technology is used in almost every application in which the determination of shape, size and position are important.

Due to its capacity to reference external data sources, Phoxy technology can be used in Intranet and Internet applications. Types of applications of Phoxy technology include space industry, medical world, offshore industry and steel building production etc.

PHAST (Flexibility and accuracy in strain measurement)

Phast is a vision based measurement system for determination of surface strain on sheet metal. This system is capable of detecting the smallest measurements errors. It can measure millions of surface points simultaneously. This technique guarantees homogenous results as the complete surface is expressed in one coordinate system.

This technique consists of following steps:

- Image acquisition;
- Creating a new Phast project;
- Measure barcode targets and orientation of command;
- Detect and identify grid;
- Calculations;
- Analysis of results.

Specifications and features of Phast

- Measuring accuracy: $\pm 0.5\%$ strain.
- Portable system, fits in a shoebox.
- Graphical sheet metal deformation analysis with FLD, major and minor strain.
- 3D measurement of strain data.
- Sophisticated quality control of all measurements, control points and calculated 3D co-ordinates.
- Unparalleled image acquisition and processing speed.
- Windows graphical user interface.
- Measurement of complete surface at once.
- Automatic strain calculation.
- Export facilities to industry standard document processors and spreadsheets.
- Unlimited number of images.
- Real-time integrated system calibration with state-of-the-art modelling techniques.
- Automated measurement of millions of surface points.

Vision Systems (Versatile 3D measurement systems)

Geodelta has designed, constructed, tested and delivered 3D vision measurement systems to a variety of customers. Its versatile processing software can be used to make 3D surface reconstruction of arbitrary shaped objects. Basically, an object is photographed from several sides. The images are imported into the measurement system which determines the locations of the images and calculates the complete surface in one run. The main advantage of a vision system is that the system can be taken to shop floor instead of bringing the components to a heavy coordinate measuring machine.

5.3 References

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Chapter 6. Real-Time SPC Software

6.1 Introduction

Although statistical process control was developed before computer use was common, statistical process control (SPC) software can play a valuable role in implementation. It allows operators to avoid tedious computations and can augment the system capabilities. It can also interact with various databases off line to extend the usefulness of the data and to provide input to other types of analysis.

In today's software market, hundreds of SPC software packages are available. Each of them can implement the most basic SPC functions such as control charts and process capability analysis. So, selecting the appropriate software can be a daunting problem for quality control managers in the shipbuilding industry.

Before we introduce some typical SPC software packages, let's define some rules for selecting SPC software. [1]

- **Real-Time**

  Once special causes appear in the manufacturing process, we need to detect their presence and remove the special causes ASAP. Thus "real-time" capability is one of the important factors that should be considered when purchasing the SPC software. Actually, for most SPC software packages, the time used in computing and plotting the charts and in performing basic analysis will be much shorter when compared with the time used in data collection. So, when selecting SPC software, the user needs to pay more attention to the data collection and exchange part of the package, which will have a great effect on the "real-time" function.

- **Ease of Use**

Ease of use is critical, since the quality and production management workload is continuously increasing, while there is constant pressure to reduce the overhead expense. If the operators must learn additional computer skills to perform the necessary functions, the time and cost for performing the SPC functions will increase.

- **Robust communication**

It is very important that the SPC software is flexible to import and export common files to and from the existing systems in the shipyard. For example, if the SPC software does not interface with existing systems easily, the manager must consider the potential cost of purchasing other software. Furthermore, the SPC software may need to query data from the current database of the shipyard. Thus it important that the SPC software have a robust communication functions to match with different types of databases. Also, the SPC software's output should be easily used in other application packages. At least, the control charts and the analysis results should be easily copied to text editors and report generators, such as MS Word.

- **Easy to upgrade**

Considering the short lifetime of software application packages, the selected SPC software should be easy to upgrade in the future.

- **Client-server architecture**

Client-server architecture is helpful for SPC application in large factories. In some instances, the operator at the shop floor level may not be the appropriate person to make decisions once a special cause has been detected. Thus, a client-server architecture may facilitate notification of the problem to appropriate levels of the shipyard management structure. Also, this architecture can provide multitasking capabilities for collecting data on multiple processes simultaneously. Furthermore it is safer with this architecture. If a client is shutdown, the configuration and data can be recovered through the backup files in the server.

- **Cost**

When purchasing the package, the quality control manager should consider buying the most "appropriate" package, not the most expensive or most powerful one. Do not choose a package that is overqualified for the current circumstance. However, since many packages have multiple capabilities, it may be possible to obtain only the needed parts.

In this chapter, we will introduce some popular application packages that can implement most SPC functions, and also introduce some special SPC software, which is recommended in the manufacturing industry.

6.2 SPC Software

6.2.1 General software used for SPC

MINITAB

MINITAB statistical software, provided by Minitab Inc., is a very popular product in statistics and quality improvement. MINITAB is used around the world by thousands of distinguished companies such as GE, 3M, Ford Motor Company, Paccar Inc., the leading Six Sigma consulting firms, and in more than 4,000 colleges and universities. [2]

MINITAB 13 is the current version of Minitab statistical software. It has the following features:

System Requirements

Processor:	Personal computer with a 486 or higher processor
Memory:	16 MB of RAM
Disk Space:	40 MB hard disk space
Operating System:	Windows 95/98/2000/Me, or Windows NT 4.0
Display:	VGA or SVGA monitor, minimum 800x600 recommended

The standard version of MINITAB 13 is for PC and Windows operation system. Also, a user can ask Minitab Inc. to provide a "customized" package, i.e. a package for other platforms.

Functions for SPC

Although Minitab 13 is not specially designed for SPC, there are enough modules for SPC in this all-in-one software.

The following picture shows the basic functions for SPC in Minitab 13.

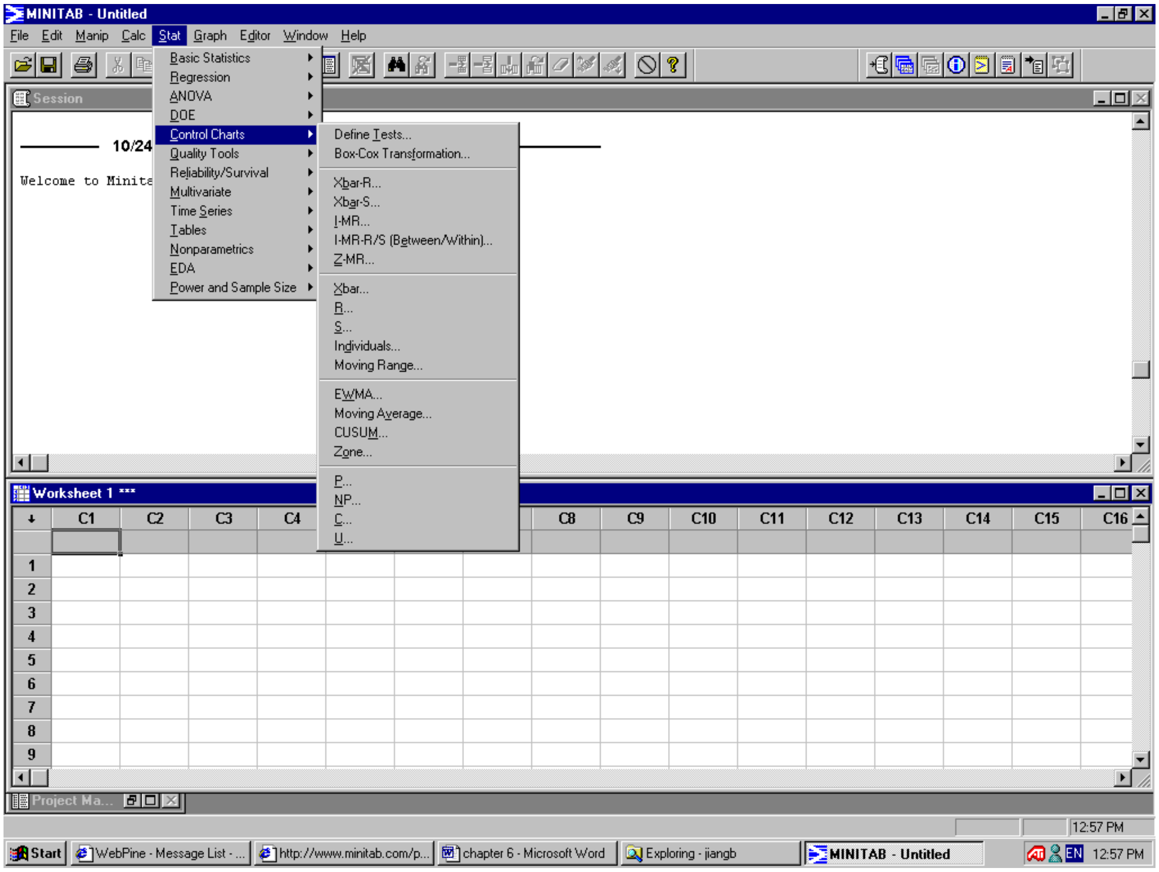

Figure 1. SPC function in MINITAB

In fact, Minitab 13 can perform the following SPC functions:

- Run chart
- Pareto chart
- Fishbone diagram
- Control charts: XBar, R, S, XBar-R, XBar-S, I, MR, I-MR, I-MR-R/S, MA, EWMA, CUSUM, zone, short run, p, np, c, u
- Custom tests for special causes
- Normal or non-normal data
- Box-Cox transformation

- Historical/shift-in-process charts
- Process capability: normal, non-normal, attribute and batch
- Normal and Weibull plots
- Gage R&R: ANOVA and XBar-R methods, gage linearity and accuracy; gage run chart; nested

In these functions, Fishbone and Pareto charts are used to identify the special causes of process variability. Control Charts are used to monitor the process. MINITAB includes charts for variables and attributes data, handles non-normal data, and includes specialized charts like CUSUM, EWMA, and Zone Control. If a process is being changed, the user can use the Historical/Shift-in-Process Chart to compare results before and after the change. The user can also employ Process Capability for batch data when process variation exists both within subgroups and between subgroups.

Ease of use

Minitab 13 has very user friendly interface. The user can define each data analysis task as one project. When the user runs one project, there will be three windows open at the same time. Project manager is the summary of the whole project, which includes all components of the project such as the data sheet, the graphics and the history of the project. Work sheets are used to import the raw data with the size of the worksheet being unlimited. The session window shows the text of the result and the process of the task.

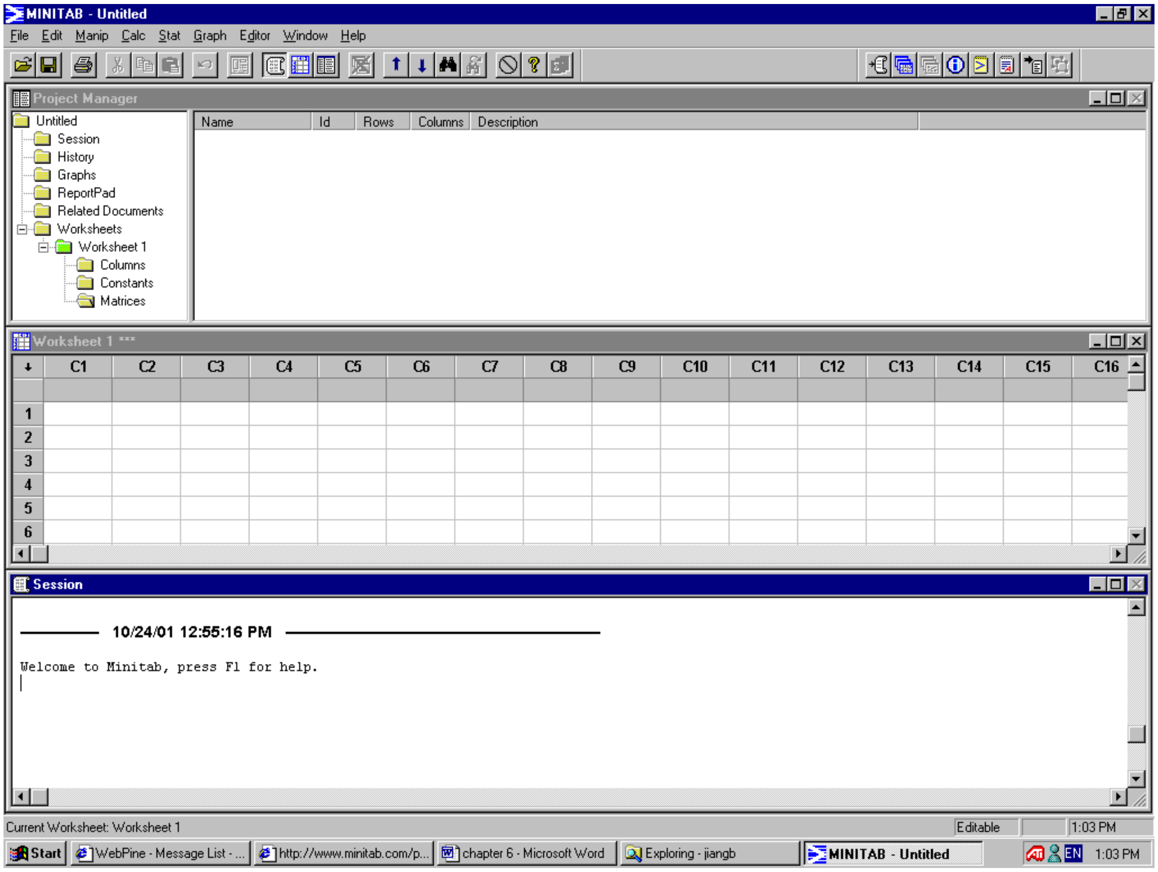

Figure 2. Graphical interface in MINITAB

Figure 3 shows an example of using X bar and R control charts for process control. The worksheet contains the raw data collected directly from the manufacturing process. Using this data, we can plot the x-bar and R control charts. The graphics is the control charts. In these two charts, we find some points are beyond the control limits. And the session window on the left tells us the result of running control charts. If the process is out of control, then it points out which data are beyond the control limits.

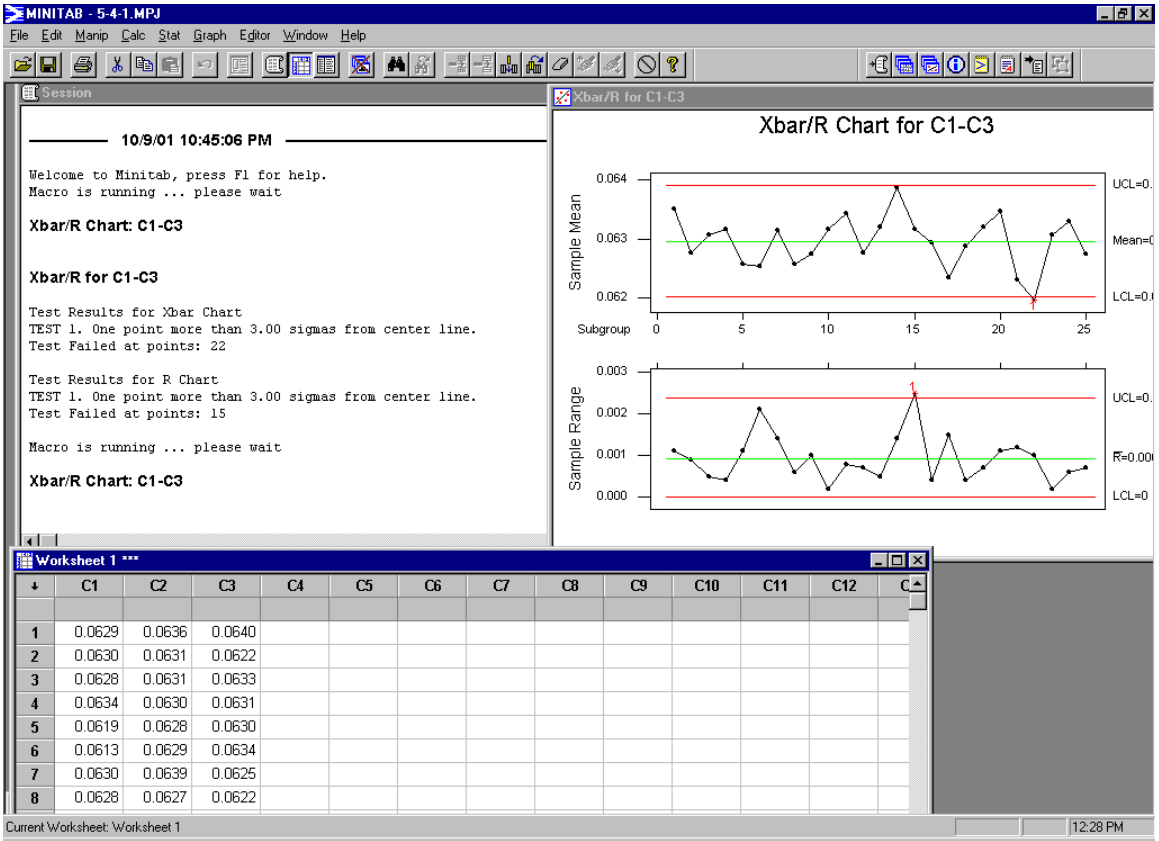

Figure 3. X bar / R charts in MINITAB

Compatible with other applications

Minitab 13 can import and export all common file types including EXCEL and text files. Also, the output graphics and text can be easily used in other general application files.

If a user needs to get data from the databases, he must use ODBC to query data from databases. ODBC stands for Open Database Connectivity. ODBC lets the user import data from database files. ODBC is a protocol shared by many applications. To use ODBC in Minitab, the user may have to first install ODBC software on the system. Once ODBC is set up correctly in Minitab, the user can use the Query Database command to connect to the database file that the user wants and import subsets of data.

Estimated Cost

According to the information provided by Minitab Inc., the current price for Minitab 13 is $1195.

Advantage and Disadvantage

Since Minitab 13 is an all-in-one software, it also can implement other statistical functions besides the SPC function. However, because of its generality, Minitab 13 seems not as powerful as other special real-time SPC software.

EXCEL

Although using Excel for Statistical Process Control is not as easy as specialty SPC software, considering the commonality of MS office package, it is feasible for a company to implement the basic SPC functions using EXCEL, rather than purchasing expensive SPC software.

System Requirements

Since EXCEL is one component of MS Office, it is most easily used in the Windows operating system. There are no other special limitations for EXCEL. In fact, since MS Office is very popular, EXCEL is probably already available in most companies.

Functions for SPC

By using EXCEL, the following SPC functions can be implemented: [3]

- X bar and R control chart
- X bar and S control chart
- p and np control charts
- c and u control charts
- Process capability

- Pareto and Fishbone Diagrams
- Moving range control charts

Also using Excel, one can perform regression analysis and develop ANOVA tables. Although EXCEL can only implement the basic SPC functions, such as control charts and process capability, it may be enough for some manufacturing applications.

Ease of use

Since EXCEL is not designed for SPC, it is not easy for the beginner to implement SPC functions. First the user should be very familiar with EXCEL, especially with the computing function and the plotting function. Furthermore, the user needs to be very clear with the basic concepts of these SPC functions. Unlike the hidden equations inside the Minitab or other SPC software, with Excel, the user needs to make the decision on which equations to use. However, after the sheets have been developed for SPC functions, it will be much easier for later users.

Another problem with using EXCEL is flexibility. Since the user needs to define the equations in the worksheet, if parameters such as the sample size change, the user would need to find the new constants and define the equations again.

Thus, for the simple manufacturing process with fixed sample size, EXCEL may be a good choice; otherwise, using EXCEL for SPC would be very complex for the user.

Figure 4 shows an example of X bar and R chart made by EXCEL.

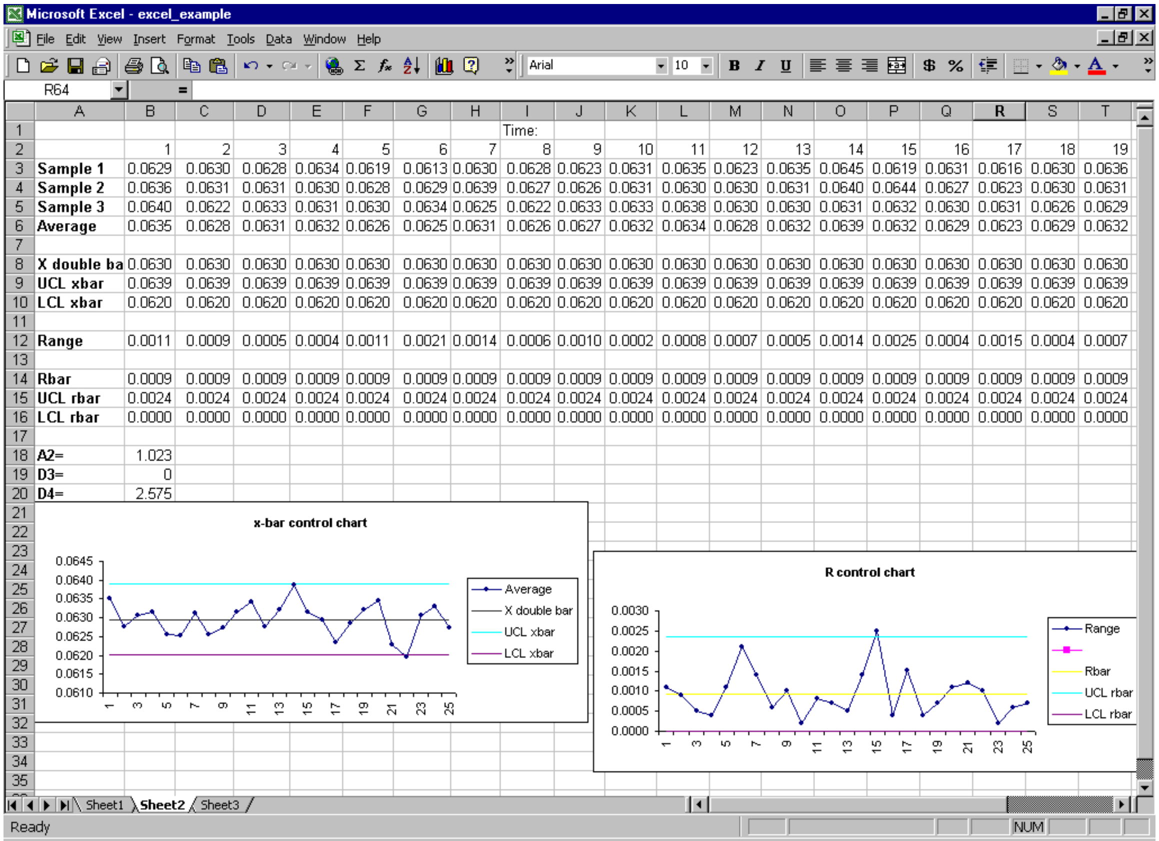

Figure 4. X bar/R chart in EXCEL

Compatible with other applications

Excel can accept the data input directly, and also the external data from a database. Similar to MINITAB, EXCEL can use ODBC to query data from databases.

For Excel, the output graphics, data and text can be easily used in other general application files.

Estimated Cost

No additional cost since most companies own the MS Office packages.

Advantage and Disadvantage

Since Excel is not a special SPC package, it is not easy to use and it is not suitable to online analysis. Also, the flexibility of EXCEL for SPC is poor. However, considering its cost, it is feasible for the company to use Excel to finish basic off-line analysis and predict the production trend.

6.2.2 Special SPC Software

In the August 1999 issue of "Manufacturing Engineering" magazine, four SPC software packages are recommended. They are: [5]

- VisualSPC:

  (Supplied by CimWorks GageTalker)

- QI Analyst

  (Supplied by SPSS)

- Synergy 2000

  (Supplied by Zontec)

- WinSPC C/S

  (Supplied by DataNet Quality Systems)

These four packages will be introduced in this section.

The competition between SPC suppliers is stiff, and more and more companies pay attention to Real-Time Statistical process control. Different SPC software suppliers have a different understanding of the definition of real-time SPC. Thus, these four SPC software packages have different strengths with regard to SPC.

VisualSPC

VisualSPC, a product from CimWorks GageTalker, can run with packages that perform other manufacturing information functions. The VisualSPC family of data collection software is built from the factory floor up to reflect the whole work process. This Windows-based software incorporates several modules in its software package. [6]

- VisualSPC ShopFloor
- VisualSPC MSA
- VisualSPC Importer
- VisualSPC Monitor
- VisualSPC Analyst
- VisualSPC Reports
- VisualSPC Wizard
- VisualSPC Designer

System Requirements

- Windows 95, Windows 98 or Windows NT 4.x
- Pentium class processor or higher
- 32 MB RAM
- VGA Monitor
- 640x480 or higher resolution monitor
- Keyboard and pointing device
- Access to CD-ROM drive

Enough functions for SPC

In VisualSPC, the module VisualSPC Analyst is for data analysis. VisualSPC Analyst offers comprehensive and flexible analysis on the data collected by VisualSPC ShopFloor. In this module, several kinds of charts can be produced.

- Histograms

Histograms show the frequency distribution relative to the upper and lower tolerance and sigma (±3, ±6 or both) limits

- Variables Control Chart such as Xbar-R and Xbar-S, Individual X and Moving R.
- Attribute Control charts such as p, np, c and u-Charts.
- Pareto charts

One of the most powerful features of VisualSPC Analyst is Group By, which allows the user to look at data grouped by a traceability category across a number of data fields. The user could, for example, group by operator and generate separate reports of the data collected by three different operators for three different characteristics. [6]

Import/Export

Data collection

As was mentioned earlier, the time needed for collecting data in SPC software has a great effect on "real time" function. In VisualSPC, there are two modules for different types of data collection. VisualSPC ShopFloor is designed to collect the variable or attribute data directly. Operators in the shop floor can input the data collected from the process using this module. Also, the data can be tagged with traceable information such as lot number, machine or line, tool, shift, or operator.

VisualSPC Importer is used to accept all available data from all sources. Besides the data collected by VisualSPC ShopFloor, flat ASCII files generated by gages and other measuring systems can also be imported directly into the standard VisualSPC database in VisualSPC Importer. Also, the user can use ODBC to query data in other databases such as SQL Server and Oracle.

Output

VisualSPC Reporter is a collection of standard summary reports. It also provides a full set of the standard reports the user needs for weekly tracking of production performance.

Ease of Use

Generally, only after several hours training, a user could be ready to use the VisualSPC package. For the initial setup, the module VisualSPC Wizard can create the setup automatically. System managers can simply enter a few facts and the VisualSPC Wizard produces the setup automatically.

Real Time

The module VisualSPC Monitor allows the operator to easily monitor the production process from a PC on the network. This on-line process reporting tool for the data collection network monitors all active processes. It lets the operator immediately spot improvement or trouble by providing a summary picture of what is happening on the production floor.

High Flexibility

The module VisualSPC Designer lets the user quickly customize the data collection screen, the statistical calculations, and printed reports that look exactly the way you want them to. This “have-it-your-way” module provides high flexibility to the user.

When compared with MINITAB and EXCEL, VisualSPC is the special SPC package that is much easier to be used in a real manufacturing process. Its comprehensive design and functions help to implement the “real-time” statistical process control.

The following is an example using VisualSPC.[7]

Tecomet, Tempe, AZ, a manufacturer of components for medical orthopedic, turbine engine, aerospace and high-tech commercial markets, installed the VisualSPC system for statistical process control. Tecomet used the “client-sever” architecture for the SPC implementation. It has 10 Computer workstations on the factory floor, strategically located near the critical process. These workstations are connected by LAN to the server that runs the VisualSPC package. Predetermined sample quantities from the production line are automatically sent to the VisualSPC application, and the software can analyze the data and give instant feedback to the operators. If the process is out of control, the QC system can notice the QC staff immediately through a network monitor, and the process can be stopped right away so that no more poor quality parts are produced.

VisualSPC package works well with Tecomet’s existing hardware and software, which keeps integration costs low. Also, after four hours training, operators are ready to use this system.

Using this system, the scrap rate of Tecomet decreased dramatically, from 7 percent to around 1 percent.

Synergy 2000

Zontec Inc. offers the series of Synergy 2000 Statistical Process Control software. It is designed for networked plant computing environments that want an enterprise-wide approach to quality management. The software includes complete facilities for real-time data collection, charting, monitoring, analysis, messaging and reporting across geographically distributed facilities. This powerful SPC system is easy to understand, maintain and support from the plant floor to the executive suite.

System Requirement:

- Pentium-processor-based PC with CD-ROM drive
- Super VGA monitor
- Pentium-class network server with CD-ROM capability and hard drive
- Windows NT Server, Windows 2000 Server, Windows XP Server or Novell Netware
- Microsoft Windows 95, Windows 98, Windows ME, Windows NT, Windows 2000
- Any printer supported by the Windows operating system

Architecture:

Synergy 2000 makes full use of the network functions. Any networked user can check on the current status of any process at any workstation in any department, at any plant, across town or around the globe. Synergy 2000 optimizes the highly successful three-level architecture pioneered by Zontec a number of years ago with exclusive program functions and security dependent on the type of user (Operator, Engineer or Manager).

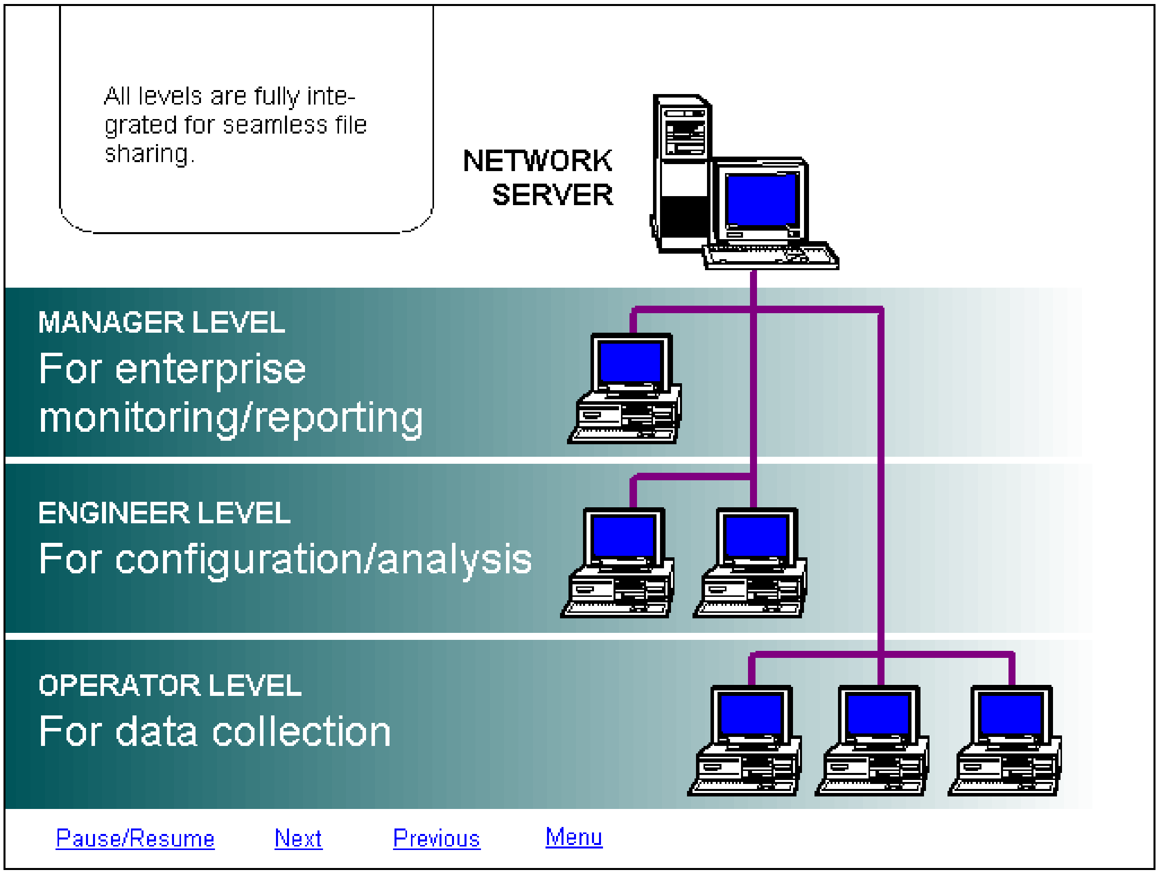

Figure 5. Architecture of Synergy 2000

Ease of Use

The design of the Synergy 2000 package presents the idea of "Total Quality Management", i.e. all people in the company should take part in the quality movement. The three levels of Synergy 2000 make it easier for users.

For the operators, their task is to input the raw data via keyboard or gage. Also they can view the drawing of the part and work instructions stored in the software, which makes the data collection task clearer.

For the engineers, they will focus on:

- Create and manage SPC data files
- Calculate control limits
- Set up specification limits
- Change sample sizes
- Analyze data
- Import and export data

For the manager, the responsibility is:

- Monitor production at all facilities at the same time
- Create global summary report
- Communicate on-line with engineers & operators

Database Compatibility:

For bi-directional direct data access between Synergy 2000 and the other databases, Zontec has developed the AnyBase Connectivity Modules to work specifically with the user's databases. These are optional software components supporting more than 125 of the most popular data base management systems in use today. There are separate AnyBase modules for data import and data export.

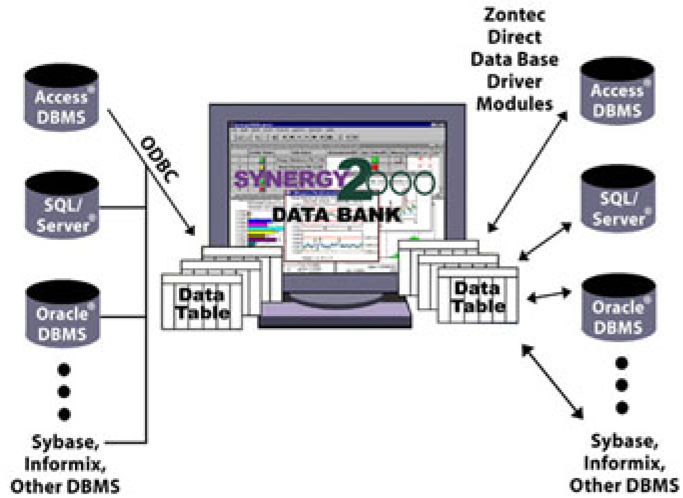

Figure 6. Connectivity with other databases in Synergy 2000

Since Synergy 2000 is based on a network, and thus it requires that the plant must have good network infrastructure. Before buying this package, the user must evaluate the existing network environment in the plant. Otherwise, the integration cost of the package will be quite high.

QI Analyst Enterprise

QI Analyst Enterprise is a complete SPC software that is also easy to use. The characteristics of its powerful analytical techniques, real-time communication, and comprehensive process capability analysis allows the user to be well informed in real time. With critical information, operators can make the right changes to the process at the right time.

QI Analyst Enterprise allows the user to access data immediately and analyze it accurately to identify, monitor and react to situations when they occur. Thus, by improving process performance, the user can reduce costs and increase productivity to produce better products and obtain more market share. [9]

System Requirements

- 586 or higher based computer
- Microsoft Windows 95, 98 or NT
- 32MB RAM for Windows® 95/98 minimum
- 64MB RAM for Windows NT minimum
- 30MB of hard drive space
- VGA monitor
- PCs connected through network operating system

QI Analyst Enterprise consists of:

- QI Analyst Controller - a full version of the software, with complete functionality for setup, monitoring and analysis.
- QI Analyst Workstation - typically used on the shop floor, the Workstation enables local data entry and viewing.

The following diagram shows how QI Analyst can improve communication of shop floor SPC data in one plant or across multiple plant sites:

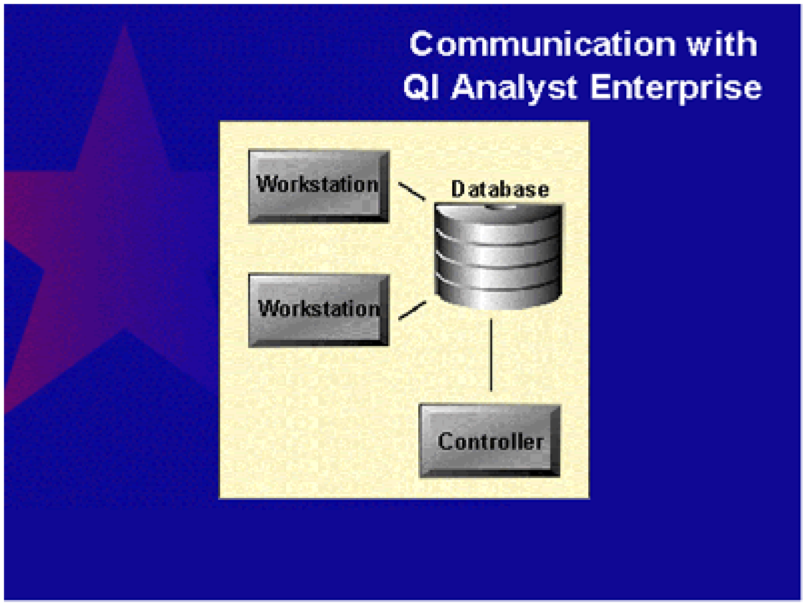

Figure 7. Communication with QI Analyst Enterprise

Enough Functions for SPC

QI Analyst can create a lot of different types of control:

- X-bar and R control charts, X-bar and S control charts
- Individuals and moving range
- Moving average and range, Moving average and sigma
- EWMA (means & individuals)
- CUSUM (means & individuals)
- p chart an np chart
- c and u chart
- DPMO (defects per million opportunities)
- Run chart

- Run chart with median line
- Histogram
- Pareto of nonconformities
- Pareto of assignable causes
- Pareto of actions
- Pareto of rule violations

Statistics

- Process capability statistics: Cp, Cpk, CR, CpM, CpU, CpL, K
- Process performance statistics: Pp, Ppk, PR, PpM, PpU, PpL
- Descriptive/distribution statistics: Z-max, Z-min, Z-upper, Z-lower, percentage out of spec (actual and estimated), skewness, Kurtosis
- Descriptive process and point statistics: total, mean, upper control limit, lower control limit, number of rows, standard deviation, estimated sigma, sigma type, trend, standard error, median, range, minimum, maximum, upper specification limit, target, lower specification limit
- Descriptive scatter plot statistics: intercept, slope, correlation, standard error, t, p-value, degrees of freedom, predicted Y

Database compatibility

- Oracle®
- Microsoft® SQL Server®

- Microsoft Access®
- Flexibility for custom solutions that provide real-time access to any database
- Access to historical data in any ODBC-compliant database System requirements

Import/export and device support

- Data acquisition from any OPC server
- Provide OPC server support for numerous measuring devices including Mitutoyo, CIM Works/GageTalker, Starrett Multiplexers, Fowler Gages and more
- Supports RS-232 gage interface
- Static data import from ODBC-compliant database
- User-defined time intervals for polling data from OPC servers

WINSPC C/S

DataNet Quality System Inc. provides WinSPC C/S Enterprise statistical process control and data analysis system. It has the following features: [10]

Web publishing

Publish reports for web viewing by customers, suppliers and management no matter where they are in the world. Customizable security restricts access to appropriate information. Customers and suppliers, or local, divisional and corporate management can view reports with a common Web browser.

Query specific information

WinSPC's query tools can filter data sets by user ID, station, date and time range, or by user-defined tags such as lot number, machine, shift or customer. This built-in flexibility enables fast response to data requests from customers or management. WinSPC helps the user "slice-and-dice" the data. Users can look at the data by shift, operator, machine, batch or mold.

Control the control limits

Control limits can be generated at specific machines or analyzed across all. It can also calculate part or process control limits by batch or across data collected at multiple stations.

Random data collection

Some processes require flexibility for the order and/or frequency in which data is collected. WinSPC's "random" mode accepts data in any order and distributes it to the appropriate characteristic.

Custom report

WinSPC correlates and combines data from multiple sources for custom report generation. A built-in statistics engine provides analysis of data collected into non-statistical databases or file structures such as machine data, maintenance information, gage management data and more. Users can create "books" of quality reports for production monitoring, management reporting or customer compliance, then print them on demand from anywhere in the enterprise. Reports are available immediately after data entry or for any relative time period, such as yesterday, last week, last month, etc. It includes graphics, machine data, automation data, production yield information, etc., in addition to quality charts and summary reports.

Running Cpk chart corrects problems before they occur

WinSPC automatically calculates and displays the capability (Cpk) index of all parts and processes from inspection data collected throughout the plant. Automatic real-time alarms and feedback prevent potentially decreasing Cpk indexes that can result in non-conformance.

Advanced analysis

Using over 500 advanced analysis functions and charts, WinSPC offers complete real-time normal and non-normal statistics, including all twelve available Pearson and all Johnson analysis curves.

Production document viewing

WinSPC helps the operators enter accurate information by presenting production-level document viewing at the point of entry. Operators view documents right from the WinSPC operator interface, providing fast and efficient access without delay or interruption.

6.3 Reference

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Chapter 7. Organizational Aspects of Accuracy Control Implementation

7.1 Introduction

Accuracy control is not just a technology used to manage the production process. It is a management method that goes through the whole organization. Accuracy control requires a team effort between customer, engineering, planning, production, and quality departments. Thus the organization's structure, culture, and management style will determine if the A/C program can be successful implemented. In this chapter, some key factors in organization aspects of A/C implementation will be described. Also, an example of an A/C department whose function keeps continuously changing is given. At the end, the responsibility matrix of Northrup Grumman Newport News is provided as an example.

7.2 Organizational Aspects of accuracy control implementation

7.2.1 Leadership and management style

Accuracy control emphasizes the involvement of all people within the organization, especially top management. Furthermore, A/C implementation begins with the support of senior managers, and, most important, the CEO's commitment. Thus, the leadership and management style play an extremely important role in the A/C movement.

Accuracy control leadership and management style require a manager to:

- Participate actively in A/C program.
- Be customer focused
- Ensure all employees understand the strategic directions clearly

- Establish objectives or targets and performance indicators.
- Require improvement action plans and a constant review of those plans.
- Share knowledge about company goals and the status of those goals.
- Reward champions of the quality culture and withhold rewards from those who are anti-quality.

The appropriate leadership and management style in an A/C program should be participative. That means, collecting the employee input, tracking it, acting on it in a right way, working with employee's to improve weak suggestions and rewarding employees for improvements that result from their input. [4]

7.2.2 Organizational culture

Generally, A/C needs a different organizational culture to push it forward in the organization. This culture is different from those old definitions of organizational cultures. The following table shows the comparison between the new and old cultures. [1]

New and Old Cultures

Quality Element	Previous State	Accuracy Control
Definition	Product-oriented	Customer-oriented
Decision	Short-term	Long-term
Emphasis	Detection	Prevention
Errors	Operations	System
Responsibility	Quality control	Everyone
Problem Solving	Managers	Teams

Procurement	Price	Lift-cycle costs, partnership
Manager's Role	Plan, assign, control, and enforce	Delegate, coach, facilitate and mentor

Since the culture change is substantial it needs a long time to be implemented. Therefore, small shipyards will be able to make such A/C-oriented culture change faster than big ones.

In real-life practice, most shipyards will find that changing a company's culture to reflect accuracy control is difficult and requires a lot of time. In order to remove this big barrier from A/C implementation, the following steps need to be taken.

The first step is to ensure that the effort to change the organizational culture must be continuous. The administrators and managers must be committed to the cause and be the driving force in the implementation process. A/C principles must be written into the organizational policies and become an integral part of how the organization operates.

Second, managers must support each other. Open communication is critical as everyone works to implement accuracy control. Managers should realize that selling the concept of A/C to the staff and then reverting to its old way of doing business is totally wrong. The right method is to develop the new culture compatible with A/C implementation.

Third, as referred to above, the culture change is a time-consuming process. Management should not be impatient. The focus on fast results will hurt the implementation process, and furthermore, the whole A/C movement.

In actual practice, starting an accuracy control program will likely require the establishment of an A/C group. One of the important functions of this group will be serving a liaison function, especially between design/engineering and production. As the culture change process progresses, a new organizational structure may eventually lead to the elimination of A/C as a separate organizational group as these functions are migrated throughout the organization.

7.2.3 Supplier/Customer partnership

In A/C theory, one single-source supplier is encouraged. Moreover, the supplier/customer partnership is developed to enhance the quality and reduce the variation.

The advantages of having a single-source supplier are:

- All incoming parts are from the same supplier, thus, it will be simpler and easier to control the variation of the incoming parts.
- By building this relationship, the supplier is considered as part of the whole process. Such integration will be helpful in improving the process and quality.
- For the supplier, it has the opportunity to learn the business of the organization, respond to the potential needs, and help the organization improve the processes.

In the shipbuilding industry, the task of building a ship usually involves numerous different processes, where each process can be seen as the supplier to its next process, and the customer of its previous process. The relationship with the internal supplier and with the internal customer becomes extremely important in the accuracy control program.

The relationship with the internal supplier

In the shipbuilding industry, the supplier is the one who supplies the inputs to the current process. After getting the input, we can complete the work in this stage. The input could be engineering providing data for cutting the piece parts, or could be the actual cutting by the fabrication workshop that will be eventually be joined together to make a subassembly. Thus it is very important to know who our suppliers are, what products they produce and how they are doing with respect to the accuracy standard.

Due to the importance of this relationship, two-way communication is needed. The manager of the supplying process must inform his customer--- the next process, of any change to the dimensions or tolerance conditions. The manager of the current process should provide feedback to the supplier when problems happen. If the current process is out of control, a resolution to this condition should be written on the work center sketch and signed by both managers.[3]

The relationship with the internal customer

The parts that are currently being manufactured are delivered to the internal customer, which is the next process. Also, it is very important to know who our customers are, what products they need and what is the accuracy standard they are using. Similarly, two-way communication is also very important. One reason for that is to avoid the higher cost when problems happen. For example, assume it is discovered that for some reason, the frames were cut shorter than specifications allow. If the manager of the current process could identify this problem to the internal customer ahead of time, both parties could sit together to find the most cost-effective way to solve the problem. The solution of changing some other dimensions may be acceptable to the customer rather than replacing all the frames. Otherwise, if the manager did not tell his customer about the problem in time, and the customer just built the assembly as planned, then there could be excessive root gap in the assembly. As these defective parts continue to go along down stream, more waste would be produced.[3] Meetings that permit face to face communication between internal suppliers and customers will likely be required, especially during startup of the A/C process. These meetings should permit direct communication of actual quality needs from the perspective of the internal customer.

7.2.4 Continuous changing A/C department function

The function of the A/C department changes as time goes by. One reason for that is the A/C department needs to keep absorbing the new A/C theory and then adjusting its function to implement its goal----improve the quality and the competition advantage.

Accuracy control in shipbuilding originated in the 1960's. During the several decades since, the goal of accuracy control, the responsibility of accuracy control implementation and the structure of accuracy control groups in shipbuilding keep changing. Such changes also reflect the development of the A/C theory. The example of Sakaide Shipyard of Kawasaki Heavy Industry, Ltd. shows such functional changes in the past thirty years.[2]

Period	Development of A/C department
1967-1971	**The A/C group in Sakaide shipyard was set up and belonged to hull construction department. Four staff from fabrication, assembly and production engineering consisted of the group. The result of the A/C program was great that in parallel part of the ship, block edge was neat cut.**
1972-1977	**This A/C group was consisted of nine people and belonged to hull yard work section. The result of accuracy control implementation included establishing edge surplus of the blocks and neat cutting at fabrication stage, and standardizing the blocks procedure.**
1978-1986	**In these depression days of shipbuilding, the A/C group was reduced and the focus of the accuracy control was transferred to process control. As the**

	result, all of blocks of non-parallel part were neat cut at shop works process. Another notable change in this shipyard was that each section has taken the responsibility on accuracy control.
1987-present	**In this period, A/C group has been reduced to two members. Each section has taken the responsibility on accuracy control. A/C group has taken the responsibility to plan accuracy control and to investigate in accuracy problems and feedback them. The purpose of the accuracy control in this shipyard is defined as: Target dimensions for ship, Wastes caused by inaccuracy to be reduced and Uniform accuracy for automation utilization**

In the Northrup Grumman Newport News accuracy control manual, the current responsibility of the various functional departments for A/C activities is given. It is a very good example to illustrate the distribution of A/C function and responsibility in all the departments in a shipyard. The following responsibility matrix is directly from the Northrup Grumman Newport News A/C manual. [3]

RESPONSIBILITY MATRIX									
Legend: P = primary A = assist	**Activity**	Dimensional Control	Engineering	Planning	Manufacturing/ Assembly/Trades	Quality & Technical	Production Engineering	Programs
Plan	Define Customer Requirements – Pre-contract activity	A	P		A			A
	Define Requirements – Contract Design and Planning Activity	A	P	A			A	A
	Define Requirements – Detail Design Activity	A	P					

	Assembly and Welding Sequences	A	A	A	P	A	A	
	Accuracy Standards	P			A			
	Control Plans	P			A			
	Reaction Plans	P			A			
	Check Points, Lines and Planes	P			A			
	Design Data	A	P		A			
	Surplus, Excess. And Leave-Loose Designation	A	A	A	P		A	
	Shrinkage Allowance Designation	P	A		A		A	
	Reference Points and Lines	P			A			
	Data Precision	P			A			
	Measurement Methods	P			A			
	Measurement Tools	P			A			
	Check Sheets	P		A				
	Work Package Records	A	P		A		A	
	Data Systems	P						
	Graphic File Library	P						
	Digital control and Measured Database	P						
	Analysis and Reporting Information systems	P						
	Establish Cross Functional Team Structure	A	A	A	A	A	P	
	Perform Cross Functional Team Activities	A	A	A	A	A	P	
	Prepare to Build	A	A	A	P		A	
	Build Narratives	A	A	A	A	A	P	
	Procedures/documents	P						
	Train Personnel	P						
	Verify External Supplier Compliance	P			A	A	A	
Do	Build Product				P			
	Collect A/C Data	A			P			
	Supplier Responsibilities	A	P					
	Customer Responsibilities	A						
Check	Build Strategy Being Followed	P			A			
	Revise Build Strategy	P			A			
	Enforce Existing Build Strategy	P			A			
	SPC Charts	P			A			
	A/C Reporting	P			A			
	A/C Analysis	P			A			
	Process Meet Accuracy Requirements	P			A			
	Customer Satisfaction	A			P			
Act	Develop Improvement Plan	A			P			
	Confirm Process Acceptance	P			A			

In a series of interviews conducted at four European shipyards, [5] it was found that the primary responsibility for each specific functional activity for different shipyards is different. Responsibility primarily depends on each shipyard's organization structure. In two of the shipyards, two groups are responsible for dimensional control, each having a different responsibility. The first group essentially works in formulating strategic level quality related policies, developing procedures to assure compliance with standards prescribed by the classification societies, and performing overall systems audit. The second group is primarily responsible for ensuring accuracy at the shop floor – performing inspection, ensuring conformance of individual parts and assemblies to tolerance specifications, etc. The following table shows the functional activities relating to accuracy control and the group(s) that are primarily responsibility for each specific activity. It should be noted that in the other two shipyards, the production-engineering department is more actively involved for ensuring quality as compared to the first two shipyards.

Activity	Responsibility			
Detail design activity	Engineering Department	Drawing Office, Engineering Department	Basic design is perform by headquarters technology department; the shipyard's technology department performs detailed design	Design office
Assembly and welding sequences	Production Department	Drawing Office, Engineering Department	Methods Department and Production Engineering	Production Engineering
Accuracy standards	Accuracy Control staff	Drawing Office, Engineering Department	Methods Department and Production Engineering	Production Engineering
Control plans	Accuracy Control staff	Production Office and Classification Society	Quality Audit of shipyard	Production Engineering
Reaction plans	Accuracy Control staff	Quality Audit and Classification Society	Methods Department and Production Engineering	Production Engineering
Check points, lines, and planes	Design Department and Accuracy Control staff	Quality Control	Quality Audit and Production Engineering	Dimensional Control staff, Production Engineering
Surplus, excess, and leave-loose planning	Quality Control staff	Design Office and Production	Production Engineering	Dimensional Control staff, Production Engineering
Shrinkage allowance calculations and designation	Quality Control staff	Quality Control	Production Engineering	Dimensional Control staff, Production Engineering

Reference points and lines	Quality Control staff	Quality Control	Production Engineering	Dimensional Control staff, Production Engineering
Data precision	Quality Control staff	Quality Audit, Quality Control, Production	Methods Department and Quality Audit	Dimensional Control staff, Production Engineering
Measurement methods	Quality Control staff	Quality Audit	Methods Department and Quality Audit	Dimensional Control staff, Production Engineering
Measurement tools	Quality Control staff	Quality Audit	Quality Audit and Production Shops	Dimensional Control staff, Production Engineering
Check sheets	Quality Control staff	Quality Control	Quality Audit	Dimensional Control staff, Production Engineering
Work package planning and records	Production and General Manager	Production, Technical	Methods Department and Production Engineering	Production Engineering
Digital control and measured databases	Quality Control staff	Quality Control	Methods Department and Production Engineering	Dimensional Control staff, Production Engineering
Analysis and reporting information systems	Accuracy Control staff	Quality Audit, Quality Control	Quality Audit	Dimensional Control staff, Production Engineering
Collecting A/C data	Accuracy Control	Quality Control	Quality Audit	Dimensional Control staff, Production Engineering
Supplier A/C	Accuracy Control	Quality Control and Quality Audit	Production Shops and Quality Audit	Dimensional Control staff, Production Engineering
Developing and enforcing build strategy	Production, Planning, and Design	Production, Technical	Production Director	Production Engineering
SPC charts	Accuracy Control	Quality Control	Don't use	Production [only used in steel shops]
A/C reporting	Accuracy Control	Quality Control	Don't use	Steel Production, only
A/C analysis	Accuracy Control	Quality Control	Don't use	Steel Production, only

7.3 Summary

A successful A/C program needs strong support from the top management and also the structure of the organization. Based on the characteristics of the shipbuilding industry, the relationship between internal supplier and internal customer plays an important role in accuracy control. Communication between the internal supplier and customer is encouraged, for it can solve possible problems quickly and avoid further damage. Moreover, the responsibility matrix in NNS represents the basic idea of an A/C program: quality control is everyone's job.

7.4 Reference

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Chapter 8. Human Resource Aspects of Accuracy Control Implementation

In the accuracy control movement, the involvement of all workers and processes within the shipyard is the key to successful A/C implementation. Thus, how to make full use of all resources, especially human resources, will directly determine the fate of the A/C program in a shipyard, and will be discussed in this chapter. An introduction of some necessary human resource preparations need to be considered in order for successful implementation of A/C.

8.1 Human resource in accuracy control implementation

8.1.1 Employee involvement

Employee involvement is an essential aspect to improving quality and productivity. Japanese companies first utilized the contribution of employee involvement to the success of the whole organization. Later, this concept was introduced to the U.S. industry. Employee involvement is not a replacement for management but a means to better meet the organization's goal for quality and productivity.[1]

According to Peter Grazier, author of "Before It's Too Late: Employee Involvement… An Idea Whose Time Has Come," employee involvement is a management tool of engaging employees at all levels in the thinking processes within an organization. By successful employee involvement, many decisions made in an organization can be made better after soliciting the employees' suggestion. Employee involvement theory believes that people at all levels of an organization possess unique talents, skills and creativity that are very significant to the organization if allowed to be expressed. [2]

The core of an A/C program is to provide high quality products, satisfy the customer, while minimizing the total cost. By using employee involvement, the decision makers could make better decisions that will optimize the total cost and resource assignment within the organization. Furthermore, employee involvement revokes employees' euthenics to push the A/C movement forward. Their released skills and creativity will construct the foundation of the continuous improvement of the process.

There are several management tools that help to encourage the employee in participating in the process improvement.

Brainstorming

Brainstorming is a method for developing creative solutions to problems. Participants in brainstorming sessions are encouraged to share any idea that comes to mind. During the brainstorming session no criticism of ideas is allowed. All of the ideas are considered valid and recorded. When the brainstorming is completed, the evaluation process begins. After comparing the relative merits of each idea, participants select 3-5 of the best ones and hand them in to the decision-maker.

The following steps show a general procedure for brainstorming:

1. At the beginning, select the group members for the brainstorming process. A manager can do this job. Also a leader and a recorder (they may be the same person) should be determined. A leader should take control of the session. Usually the manager is the leader of a brainstorming session

2. Define the problem to be brainstormed. Make sure every participant is clear on what the problem is.

3. Set up the rules. Some key rules need to be defined at the beginning of the session such as forbidding any criticism, setting a time limit and recording each idea.
4. Start the brainstorming. Every response is written down on the board to let every one see it. During the brainstorming process, no criticism is allowed in order to encourage the free flow of ideas.
5. After the brainstorming is finished, the evaluation process begins. First, similar answers will be deleted and like concepts will be grouped together. Also, the responses that definitely do not fit will be eliminated. Then group members go through the remaining ideas and evaluate the responses one by one.
6. After comparing the relative merits of each idea, participants select several of the best ones and turn them in to the decision maker.

Nominal Group Technique

Nominal group technique (NGT) is similar to brainstorming, but it allows for more productive meetings and to balance participation. NGT is best used for small groups. The group size of 7 - 9 people is the ideal size for NGT.

The following steps show a general procedure for NGT[3] :

1. State the problem and make sure all group members understand it.
2. Ask group members to record their ideas independently.

   In this step, each group member writes down his or her ideas on private cards silently. No discussion among group members is encouraged, which is supposed to promote freethinking without judgmental comments or peer pressure.
3. Share each idea among the group members

4. Clarify each idea.

   Make sure that every group member is clear on each idea. If necessary, a group member may be asked to explain an idea. No judgment or criticism is allowed in this step. This step is only used to ensure that all ideas are well understood.

5. Vote for the ideas silently

   Group members are asked to rate each idea from no importance (0) to top priority (10). The leader collects and calculates the ratings and records the cumulative rating for each idea.

The resistance to employee involvement implementation could be from multiple sources.

First, this tool may promote the change of an organizational culture and management style; on the other hand, resistance to change is people's nature. Thus a barrier is produced. This resistance could be from managers or workers.

From the traditional viewpoint, some managers consider employee involvement as an abdication of their power. Then it is incompatible for them to allow and encourage employee involvement. Obviously, lacking support from management will be detrimental for employee involvement. This point cannot be overemphasized. One way to fix this problem is by training managers. Managers should realize that collecting the ideas of all people involved in a process, if done properly, would enhance rather than diminish a manager's power. Managers are still the decision-makers. By stressing employee involvement, decision-makers can have access to more comprehensive and accurate information that directly comes from those closest to the work. Based on such information, their decisions should have fewer errors.

Another barrier lies in employee's reluctance to accept the new management tool. Employees may have seen a lot of short-lived management tools or strategy. WOHCAO is known for this phenomenon. WOHCAO means "Watch Out, Here Comes Another One"[3]. Thus employees could be skeptical of this new method of employee involvement and refuse to change themselves to fit the new method. For this to be successful, managers and employees have to really understand the essence of employee involvement. Another type of barrier we should consider carefully is workforce readiness. If employees are not ready for this management tool, involvement will fail quickly. One key point for the workforce readiness is the education of employees. The better-educated employees are, the easier the workforce readiness is. In order to determine if the workforce is ready for involvement, we need to consider the following three questions. [3]

- Are all employees used to critical thinking?
- Do all employees truly understand the decision making process and their roles with regard to it?
- Are all employees clear on the short term and long term goals of the organization?

Only when these three questions are answered satisfactorily, can we say employees are ready for involvement.

8.1.2. Teamwork

Teamwork is an essential component of the A/C program. It is well known that a good team's ability is more than the sum of the ability of individual members.

Different from the concept of group, a team is a group of people with a common, collective goal. The collective goal is the most important characteristic of a team.

Effective teamwork will push an A/C program. When we build and evaluate teamwork within the A/C program, we need to consider the following aspects:

- Team Tasks
- Team Development

- Team Roles
- Improvement Team Cycle
- Typical Team Challenges
- Team Mission
- Team Project Plan
- Team Ground Rules
- Meeting Guidelines
- Meeting Roles
- Meeting Effectiveness Check
- Consensus Decision Making
- Conflict Management
- Presentations to Management

In order to implement effective teamwork, some necessary steps need to be followed to build, execute, and evaluate the teamwork.

1. Build management conviction using a cost-benefit analysis
2. Decide exactly where teamwork will most help the business
3. Recruit the right skilled and willing team members
4. Structure roles and responsibilities both inside and outside the team
5. Train those involved and affected so they can perform differently
6. Apply only essential tools as needed on a just-in-time basis.

7. Monitor, reinforce, troubleshoot, and support team efforts.

8.1.3 Training

According to David L. Goetsch, (2001), training is an organized, systematic series of activities designed to enhance an individual's work-related knowledge, skills and understanding and/or motivation.[3] A well-trained, skilled and adaptable work force is of importance for a shipyard to be affordable as well as competitive.

There is a direct relationship between reducing the cost of building or repairing ships and training. Some of the return-on-investment calculations suggest that training efforts focused on building or improving technical skills result in a 10-20% improvement in productivity.

Many European and Asian shipyards spend significantly more money to train their workforce than the U.S. shipbuilding industry. They keep their employees on the cutting edge of technology, advancements, and process improvements. A survey conduced at four European shipyards[6] indicated that workers having prior accuracy control background is not a prerequisite in three of the shipyards. In one shipyard, however, this background is required. The workers are generally expected to learn while undergoing on-job training. However, outside consultants are hired when the management feels the need to train the people. Compared with their competitors, U.S. shipyards are lagging behind. So a way to close that training and skills gap is to change the norm, which will eventually increase our competitiveness.[4]

In the NSRP report, "Assist U.S. shipyards to develop and maintain a skilled workforce—Training Program Development Guide," we can find the complete guide of how to design, implement, and profit from a training program.[5]

8.2 Summary

From the above discussion, we can find that a stable and flexible workforce with multiple skills is the key to the success of an accuracy control program. In order to get it, the training program is extremely important to continuously improve the workforce, thus improving productivity and product quality.

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Chapter 9 Action Plans for Advanced Accuracy Control Implementation

9.1 Accuracy Control Theory

Accuracy control is defined as the reduction of variability in processes and products. In the shipbuilding industry, accuracy control means using statistical techniques to monitor, control and continuously improve shipbuilding design details and work methods so as to reduce variation and maximize productivity.[1] Accuracy control in shipbuilding originated in 1960's. During the several decades since, the goal of accuracy control, the responsibility of accuracy control implementation and the structure of accuracy control groups in shipbuilding has changed and evolved.

In accuracy control theory, one of the most important technical tools is statistical process control (SPC). Instead of inspecting quality after production, SPC focuses on online statistical quality control. In fact, SPC not only controls the process, but also has the capability to improve the process as well. Through analyzing data from the process itself, SPC can be used as a powerful tool for reducing process variability and achieving process stability.

SPC employs 7 popular tools, including Flowcharts, Check Sheets, Pareto Diagrams, Cause-and–Effect Diagrams, Scatter Plots, Histograms and Control Charts, where the Control Chart is considered as the most powerful one. There are two types of control charts, i.e., variable control charts and attribute control charts. The former one is used to monitor the quantitative quality characteristics in the process, and the latter one is often used for nonconforming parts or nonconformities. Variable control charts include the $\bar{x}-R$ chart and $x-\overline{MR}$ chart. Attribute control charts include the p chart, np chart, c chart and u chart. Based on the characteristics of the process, an appropriate chart should be chosen to use for the process.

By using the control charts, we can conclude if the process is in control or not. If the process is out of control, then the process should be stopped to avoid further variation and be checked to find the special causes. Once the special causes have been found and removed, the process should return to being in control.

9.2 Basic Shipbuilding Accuracy Control Implementation

Shipbuilding is a make to order industry. The whole process of shipbuilding is very complicated and includes many processes. Some of these are steel work, subassembly and assembly. Thus accuracy control in shipbuilding has its own characteristics. Based on the production arrangement, accuracy control in shipbuilding can be categorized into two groups; one is pre-production control and the other is production control. [2]

Pre-production accuracy control is considered during the designing and planning stage. The basic activities include:

- Design for excess materials
- Simulate the production process
- Predict accuracy problems
- Develop the plan for potential inaccuracy before manufacturing
- Develop check sheets appropriate for each stage of construction

In the phase of production accuracy control, the most important task is to implement accuracy control based on the pre-production A/C planning and design. In order to do that, two tasks need to be executed:

- Define who, when and how to measure
- Take measurements and record data

The objectives of production accuracy control can be summarized as follows:

- Implement the accuracy control plan defined in the previous planning stage
- Provide information to management to facilitate process analysis and improvement

The production accuracy control works through determining that work processes are in a state of statistical control and maintaining that statistical control state.[3]

- **Fabrication**

In this stage, the main enemy of accuracy control is dimensional accuracy and cutting shrinkage. The skills of the workers, the accuracy of the burning machines and cutting robots will definitely affect the dimensions of the parts. Thus, use control charts to monitor the manufacturing process and maintain the machines accordingly. One of the first places to start accuracy control implementation is at the cutting processes for parts fabrication. Even small accuracy problems at this early stage can result in substantial problems throughout the rest of the work and variation minimization and elimination is critical here.

- **Sub Block Assembly**

The main task of accuracy control in the sub-assembly process is to reduce the welding shrinkage and deformations. The alignment of reference control lines and neat edge alignment is of key importance to the process at this and all follow on stages. Monitoring these attributes is a key aspect of the A/C program. Without the establishment of reference control lines, it is not possible to monitor and determine weld shrinkages and deformations. When welding is used to join two parts, the shrinkage caused by welding is difficult to avoid.

The tack welding points, welding procedures, the burning machine and the workers' personal skills can directly affect the welding result.

In this stage, the workers can use the control charts to monitor each process to know if the process is in control and if the process is capable.

- **Block Assembly**

Similar to the subassembly stage, the main task of accuracy control in the assembly process is to reduce the welding shrinkage and deformations. Here again, monitoring and controlling reference control lines and neat edges are important.

- **Erection**

In this stage, accuracy control is more complicated. All inaccuracy caused in the previous stage will be collected together in the erection stage. If the real work has been accomplished at earlier stages, the ultimate goal of easy fit-up for erection will have been achieved and the actual A/C work here will be minimal. In practice, this stage will focus on data collection and problem resolution. Two important decisions will be made in this phase:

- Determine the erection location of each block to be most efficient for setting and welding. The goal is to set the blocks to design locations, so that previous accuracy achievements are carried through here. In particular, this applies to alignment of deck and shell longitudinals and shell and deck plating. Consciously setting the block for a better welding fit, may result in additional work associated with the alignment fit-ups.
- Determine the erection sequence to minimize the possible shrinkage and rework. This work will have been done previously, but here checking for feedback to future work is important.

In the erection stage, A/C personnel need to

- Measure the hull vital points,
- Record the measurement results,
- Compare the results with that in A/C planning,
- Evaluate and analyze the erection process.

9.3 Accuracy Control Hardware

A shipbuilding system based on group technology, using product-oriented work break down structure (PWBS), integrated hull construction, outfitting and painting, requires that the accuracy of each process and stage be well controlled. Thus, accurate measurements in each stage are needed to ensure the quality and productivity of final assembly. Conventional measurement tools including plumb bob and wooden templates are labor intensive and generally not accurate. Despite this, if properly used, conventional measurement tools are simple and can be effective, especially if used in conjunction with more sophisticated tools when required. During the past twenty years, some accurate 3-D coordinate measurement systems (CMS) such as laser tracker and electronic theodolite have been developed. Due to the restriction of the high cost and the need for skilled workers, such systems have not been used in all shipyards, but today more and more shipyards are using 3-D systems to improve the accuracy of shipbuilding and ensure the integration of different processes and stages. Typically, 3-D CMS includes the theodolite system, industrial total station, photogrammetry, and laser tracker.

Theodolite Systems

A theodolite coordinate measurement system is an optical measurement system that is used to measure horizontal and vertical angles to a point.

The advantage of a theodolite system is that there is no need to manually place targets on the object due to the use of laser beams and cost is relative low compared with other coordinate measurement systems. Some of the downsides to this system are a long set up time, multiple operators, and the measure rate is slow. The measurement data can be collected at a rate of five points per minute using experienced operators. Generally, the electronic theodolite system has an accuracy of 0.001 - 0.005 inches. The major product in theodolite systems is the Leica series that can be used in large-scale assembly and inspection. For example, Leica TDA 5005 is perfect for any kind of medium to large-scale measurement tasks such as those in shipbuilding.

Industrial Total Station

Industrial total stations are enhanced electronic theodolites that utilize an infrared light emitting diode, which is transmitted coaxially within the telescopes line-of-sight. The leading products in industrial total station are Sokkia's NET2 and NET2B, and Leica's TDM5000. It is a single station, single operator system intended for industrial, rather than surveying applications. Depending on the geometry and work zone of the measurement project, accuracy of 0.1 mm (0.004") to 1.0 mm (0. 039") can be achieved by industrial total station. The downside is the need for line of sight.

Photogrammetry

Photogrammetry uses photographs (or digital imagery) for measurements. There are two typical methods of photogrammetry that are used in the industry. One is called convergent photogrammetry, which includes film and digital photogrametry. The other is called stereo photogrammetry.

Generally digital photogrammetry can achieve the accuracy of 1:1,000,000 of the major dimension of the object. The current leading product in the digital photogrammetry system is Geodetic Services, Inc. (GSI) V-STARS system.

Compared with digital photogrammetry, the accuracy of stereo photogrammetry is relatively low. However, stereo measurement can be used in some situations where the digital photogrammetry cannot be used appropriately. For example, in a case that a required point of interest was not targeted, or the targets are impractical to place in the measured area, stereo pairs can be used exclusively for insurance.

Laser Tracker

Laser tracker is a very popular measurement tool used to measure large objects in manufacturing industries. It is often used for reverse engineering and inspection, alignment, testing and maintenance in the shipbuilding, aircraft manufacturing and other manufacturing industries.

Laser tracker can provide fast and accurate 3-D measurement of a mobile target. The laser tracker has accuracy of 1:1,000,000 of the major dimension of the object (limited to between 1 and 90 feet) or 0.0002 of an inch at 20 feet. Although the actual accuracy of a laser tracker system depends on the configuration used and measurement conditions, a typically achievable accuracy, using a single beam tracker, is 0.001 of an inch at 20 feet. Laser tracker systems are generally capable of higher accuracies than electronic theodolite-based systems, while offering the same advantage of real-time coordinate measurement.[4] SMX laser tracker is the major product in this area. It is a portable coordinate measuring machine (CMM) that makes three-dimensional measurements. SMX Laser tracker is used in automotive, aerospace, and many other industries. Its clients include Boeing Co., General Electric Co., General Motors Corp., Westinghouse Electric Corp. and Northrup Grumman Newport News.

9.4 Real-Time SPC Software

Statistical process control software plays an important role in process control. It allows operators to avoid undesirable variations in online production. On the other hand, it can interact with various databases off line to plot long-term production trends. Thus, by using statistical process control software, the plant can easily determine if production is stable and predictable, if production costs could be reduced, or if maintenance is needed. We introduced some popular application packages that can implement most SPC functions, and also introduced some specific SPC software, which is recommended for the manufacturing industry.

- **MINITAB**

MINITAB statistical software provided by Minitab Inc. is a very popular product in statistical applications and the quality control and improvement area. MINITAB 13 is the current version of Minitab statistical software. Minitab 13 is all-in-one software; it also can implement other statistical functions besides the SPC function. However, because of its generality, Minitab 13 seems not as powerful as other special real-time SPC software.

- **EXCEL**

Using Excel for Statistical Process control is not as easy as using SPC special software. Considering the commonality of the MS office package, it is feasible for a company to implement the basic SPC functions by EXCEL, rather than purchasing expensive SPC software. However, since Excel is not a special SPC package, it is not easy to use and it is not suitable for online analysis. Also, the flexibility of EXCEL for SPC is poor. However, considering just cost, it is feasible for a company to use Excel to finish basic off-line analysis and predict the production trends since most computers already have Excel installed.

- **Special SPC Software**

In the August 1999 edition of "Manufacturing Engineering" magazine, four types of SPC software are recommended. They are: [5]

- **VisualSPC:**

  (Supplied by CimWorks GageTalker)
- **QI Analyst**

  (Supplied by SPSS)
- **Synergy 2000**

  (Supplied by Zontec)
- **WinSPC C/S**

  (Supplied by DataNet Quality Systems)

The characteristics and supporting information of these four packages are discussed in Chapter 6.

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9.5 Organizational Aspects of Accuracy Control Implementation

Accuracy control is not just a technology used to manage the production process. It is a management method that goes through the whole organization. Accuracy control requires a team effort between customer, engineering, planning, management, production and the quality departments. Thus the organization's structure, culture and management style will determine if the A/C program can be successfully implemented.

Organizational aspects of accuracy control implementation include:

- **Leadership and management style**

Accuracy control leadership and management style require a manager to:

- Participate actively in A/C program
- Be customer focused
- Ensure all employees understand the strategic directions clearly
- Establish objectives or targets and performance indicators
- Require improvement action plans, and a constant review of those plans
- Share knowledge about company plans and status
- Reward champions of the quality culture and withhold rewards from those who are anti-quality

The appropriate leadership and management style in an A/C program should be participative. This means, collecting the employee input, tracking it, acting on it in an appropriate way, working with employee's to improve weak suggestions, and rewarding employees for improvements that result from their input.[6]

- **Organizational culture**

Generally, A/C needs a different organizational culture to push it forward in the organization. This culture is dissimilar from those old definitions of organizational cultures. Since the culture change is substantial, it needs a long time to be implemented. Therefore, small shipyards will be able to make such A/C-oriented culture changes faster than big ones.

- **Supplier/Customer partnership**

In A/C theory, one single-source supplier is encouraged. Moreover, the supplier/customer partnership is developed to enhance the quality and reduce the variation. In the shipbuilding industry, since the task of building a ship usually involves numerous different processes, each process can be seen as the supplier to its next process, and the customer of its previous process. The relationship with the internal supplier and with the internal customer becomes extremely important in the accuracy control program.

9.6 Human Resource Aspects of Accuracy Control Implementation

In the accuracy control movement, the involvement of all people and processes within the shipyard is the key to successful A/C implementation. This basically means it is imperative that all personnel are involved in this program. The success of the shipyard depends on the implementation of a quality program.

- **Employee involvement**

Employee involvement is a vital approach to improving quality and productivity. Japanese companies first enjoyed the contribution of employee involvement to the success of the whole organization. Later, this concept was introduced to the U.S. Employee involvement is not a replacement for management but a means to better meet the organization's goal for quality and productivity.[7]

- **Teamwork**

Teamwork is an essential component of the A/C program. It is well known that a team's ability is more than the sum of the ability of individual members. Different from the concept of a group, a team is a group of people with a common, collective goal. The collective goal is the most important characteristic of a team.

- **Training**

Training is an organized, systematic series of activities designed to enhance an individual's work-related knowledge, skills and understanding and/or motivation.[6] A well-trained, skilled and adaptable work force is of importance for a shipyard to be affordable as well as competitive. There is a direct relationship between reducing the cost of building or repairing ships and training. Some of return-on-investment calculations suggest that training efforts focused on building or improving technical skills result in a 10-20% improvement in productivity.

9.7 Summary

In this chapter, we reviewed basic accuracy control theory, accuracy control implementation and related knowledge about accuracy control. This chapter can be used as a simple accuracy control guide.

9.8 Reference

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Appendix I: Glossary

Accuracy Control: The use of statistical techniques to monitor, control and continuously improve shipbuilding design details and work methods so as to maximize productivity.

Actual Capability: If the process is running off-center, then according to the definition, C_{pk} should be less than C_p. Typically, if both C_p and C_{pk} are greater than 1, we say that the process is capable.

Attribute: An attribute is defined in quality as those characteristics that conform to specifications or do not conform to specifications

Attributes Data: Qualitative data that can be counted for recording and analysis. Examples include characteristics where the results are recorded in a simple yes/no fashion, such as the acceptability of a hole diameter when measured on a go/no go gage, or the presence of any engineering change on a drawing. Attributes data are usually gathered in the form of nonconforming units or of nonconformities; p, np, c, and u control charts analyze them.

Average: The sum of values divided by the number of values. See mean.

Awareness: Personal understanding of the interrelationship of quality and productivity, directing attention to the requirement for management commitment and statistical thinking to achieve never-ending improvement.

Basic Statistical Methods: Applies the theory of variation through the use of basic problem-solving techniques and statistical process control; includes control chart construction and interpretation (for both variables and attributes data) and capability analysis.

Capability: When the process average plus and minus 3-sigma spread of the distribution of individuals is contained within the specification tolerance, or when at least 99.73% of individuals are within specification, a process is said to be capable. (Can be determined only after process is in statistical control.)

Cause and Effect Diagram: A simple tool for individual or group problem-solving that uses a graphic description of the various process elements to analyze potential sources of process variation. Also called fishbone diagrams or Ishikawa diagrams.

Central Limit Theorem For any random variable w, no matter what distribution it follows, if we take random samples from the distribution and compute the mean of each random sample, then develop a distribution of these means $\overline{w}$, the new distribution will be normally distributed, and the mean of the new distribution is the same as the original distribution,

$$\mu_w = \mu_{\overline{w}}$$

The standard deviation of the new distribution is related to that of the original distribution, by a factor based on the sample size used:

$$\sigma_{\overline{w}} = \sigma_w / \sqrt{n}$$

Central Line: Central line is the line on control charts that presents the average value of sample measurements.

Characteristic: A distinguishing feature of a process or its output on which variables or attributes data ca be collected.

c **Chart:** A *c* chart is used to track the total number of nonconformities in each sample.

np **Chart:** A *np* chart is similar to *p* chart in function, but easier in operation. By *np* we simply mean the number, rather than the fraction, of defective items.

p **Chart:** A *p* chart is used to monitor the parameter of the fraction nonconforming. Fraction nonconforming means the ratio of the number of nonconforming items in a population to the total number of items in that population. For example, suppose we had 30 parts, and among these 30 parts, three did not satisfy the requirement and needed rework. We can say the fraction nonconforming of this sample group is p = 3 / 30 = 0.10.

u **Chart:** A *u* chart is similar to the *c* chart in function. A *u* chart tracks the average number of nonconformities per sample.

Common Causes: In real life, though the process is well designed or carefully maintained, natural variability always exists. If only common causes exist, the process performance will be predictable. In such a situation, we will say, the process is "in statistical control." If this process follows the normal distribution, most data points (99.7%) will fall in the 6σ area.

Consecutive: Units of output produced in succession; a basis for selecting subgroup samples.

Continual Improvement in Quality and Productivity: The operational philosophy that makes best use of the talents with in the company to produce products of increasing quality for our customers I an increasingly efficient way that protects the return on investment to the stockholders. This is a dynamic strategy designed to enhance the strength of the company in the face of present and future market conditions. It contrasts with any static strategy that accepts some particular level of outgoing defects as inevitable.

Control Charts: A graphic representation of a characteristic of a process, showing plotted values of some statistic gathered from that characteristic, a centerline, and one or two control limits. It has two basic uses: as a judgment to determine if a process has been operating in statistical control, and as an operation to aid in maintaining statistical control.

Control Chart for Variables: The control chart used to monitor and control a variable is called a control chart for variables. In practice, variables control charts are posted at individual machines or work centers to control a particular quality characteristic. $\bar{x}$ -R chart is the most popular variable control chart.

Control Chart for Attributes: The control chart used to monitor and control an attribute is called a control chart for attribute. A p chart, np chart, c chart and u chart are the most popular attribute control charts.

Control Limits: Control limits are lines on control charts that are used to judge if the process is in control or out of control. Not to be confused with engineering specifications.

Detection: A past oriented strategy that attempts to identify unacceptable output after it has been produced, and then separate it from the good output.

Distribution: A way of describing the output of a common-cause system of variation, in which individual values are not predictable but in which the outcomes as a group form a pattern that can be described in terms of its location, spread, and shape. Location is commonly expressed by the mean or average, or by the median; spread is expressed in terms of the standard deviation or the range of a sample; shape involves many characteristics such as symmetry and peaked ness.

Dimensional Management: In a large assembly industry such as shipbuilding, each interim process performance could influence the final assembly. Thus, dimensional management becomes one of the most important goals in accuracy control theory.

Excess Allowances: In the shipbuilding industry, since cutting and welding can cause shrinkage, excess allowances are often used to ensure the block assembly in the final stage. However, from the viewpoint of accuracy control, excess allowance is a kind of waste. Although it may be safer for the block with excess allowance in the final assembly, the operator needs to cut the excess allowance at the final assembly station. Such rework increases the production cost and decreases the productivity

Histogram: A pictorial way to display data I frequency form. This provides a visual way to evaluate the form of the data.

Individual: A single unit or a single measurement of a characteristic.

Mean: Mean is the average value for a random sample of size n. If n pieces of parts are measured, and the length of each piece is: $x_1, x_2, x_3 \ldots x_n$. The mean length is:

$$\overline{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

Median: The middle value in a group of measurements, when arranged from lowest to highest; if the number of values is even, by convention the average of the middle two values is used as the median.

Moving Range: The difference between the highest ad lowest value among two or more successive samples such that as each additional data point is obtained, the range associated with that point is computed by adding the new point and deleting the oldest chronological point, so that each range calculation has at least one shared point from the previous range calculation. Typically, the moving range is utilized on control charts for individuals and uses two-point (consecutive points) moving ranges most of the time.

Nonconforming Item: A nonconforming item is a unit of product that does not satisfy one or more of the specifications for that product

Nonconformity: Nonconformity is a different concept from nonconforming item. Nonconformity means each specific point at which a specification is not satisfied. A nonconforming item may contain one or more nonconformities.

Normal Distribution: The Normal distribution is the most important statistical distribution used in accuracy control theory. It is also called the bell-shaped curve or Gaussian distribution. The probability distribution function is

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{x-\mu}{\sigma})^2} \qquad -\infty < x < +\infty$$

The Normal distribution is defined by two parameters: the mean μ and the standard deviation σ. Its curve is perfectly symmetrical (bell shaped) around the mean μ. When the measurements follow the normal distribution, 68.27% of the population values fall in the area between $\mu - \sigma$ and $\mu + \sigma$; 95.46% of the population values fall in the area between $\mu - 2\sigma$ and $\mu + 2\sigma$. 99.73% of the population values fall in the area between $\mu - 3\sigma$ and $\mu + 3\sigma$.

Operational Definition: A means of clearly communicating quality expectations and performance; it consists of (1) a criterion to be applied to an object or to a group, (2) a test of the object or the group, (3) a decision: yes or no- the object or the group did or did not meet the criterion.

Pareto Chart: A simple tool for problem-solving that involves ranking all potential problem areas or sources of variation according to their contribution to cost or to total variation. Typically, a few causes account for most of the cost (or variation), so problem-solving efforts are best prioritized to concentrate on the “vital few” causes, temporarily ignoring the “trivial many.”

Potential Capability: States the maximum manufacturing capability of current process provided that the mean of the process is equal to the target value

Prevention: A future-oriented strategy that improves quality and productivity by directing analysis and action toward correcting the process itself.

Problem-Solving: The process of moving from symptoms to causes (special or common) to actions that improve performance. Among the techniques that can be used are Pareto charts, cause and effect diagrams, and statistical process control techniques.

Process: The combination of people, equipment, materials, methods, and environment that produce output- a given product or service. A process can involve any aspect of our business. A key tool for managing processes is statistical process control.

Process Average: The location of the distribution of measured values of a particular process characteristic usually designated as an overall average, $\bar{\bar{x}}$ (center line).

Process Capability Analysis: The use of statistical techniques to judge if the process is "capable", which means that most of parts produced by the process will satisfy the specification requirements.

Process Performance: The range of a process's total variation.

Process Spread: The extent to which the distribution of individual values of the process characteristic vary; often shown as the process average plus or minus some number of standard deviations.

Randomness: A condition in which individual values are not predictable, although they may come from a definable distribution.

Random Sampling: The process of selecting units as a sample of all products in such manner that every member of the population should have an equal chance of being included in the sample.

Range: The difference between the highest and lowest values in a group.

Rational Subgroup: A subgroup gathered in such a manner as to give the maximum chance for the measurements in each subgroup to be alike and the maximum chance for the subgroups to differ one from the other. This sub-grouping scheme assumes a desire to determine whether or not a process's variation appears to come from a constant system of chance causes.

Run: A consecutive number of points consistently increasing or decreasing, or above or below the centerline. Can be evidence of the existence of special causes of variation.

Run Chart: A simple graphic representation of a characteristic of a process, showing plotted values of some statistic gathered from the process (often individual values) and a central line (often the median of the values), which can be analyzed for runs.

Sample: IN process control applications, a synonym with Subgroup; this use is totally different from this purpose of providing an estimate of a larger group of people, items, etc.

Sigma: The Greek letter used to designate a standard deviation.

Special Causes: If the variability is from some specific source, such as an improperly adjusted machine, defective raw materials or operator errors. If special causes exist, the process performance will not be predictable and repeatable. In this situation, the process is said to be "out of statistical control."

Specification: The engineering requirement for judging acceptability of a particular characteristic. A specification is never to be confused with a control limit.

Spread: The span of values from smallest to largest in a distribution.

Stability: The absence of special causes of variation; the state of being in statistical control.

Stable Process: A process that is in statistical control.

Standard Deviation: Standard deviation describes the spread of the distribution of the observed data around the mean value. Its notation is:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \overline{x})}{n-1}}$$

Statistic: A value calculated from or based upon sample data, used to make inferences about the process that produced the output from which the sample came.

Statistical Control: The condition describing a process from which all special causes of variation have been eliminated and only common causes remain; evidenced on a control chart by the absence of points beyond the control limits and by the absence of non-random patterns or trends within the control limits.

Statistical Process Control: By using statistical techniques such as control charts to analyze data from the process itself, SPC can be applied as a powerful tool for reducing process variability and achieving process stability.

Subgroup: One or more events or measurements used to analyze the performance of a process. Rational subgroups are usually chosen so that the variation represented within each subgroup is as small as feasible for the process, and so that any changes in the process performance will appear as differences between subgroups. Rational subgroups are typically made up of consecutive pieces, although random samples are sometime used.

Type I Error: Rejecting an assumption that is true; e.g., taking action appropriate for a special cause when in fact the process has not changed; over-control.

Type II Error: Failing to reject an assumption that is false; e.g., not taking appropriate action when in fact the process is affected by special causes; under-control.

Upper/Lower Control Limits: UCL/LCL represent the upper/lower control limits for a control chart. These numbers are determined by the process itself such as the skill of operators, the capability of the machines and equipment, etc.

Upper/Lower Natural Tolerance Limits: UNTL/LNTL represent the upper/lower natural tolerance limits for x. The process determines these values. In most cases, we sample from the distribution of x values and develop information about the distribution of sample means. We then use the Central Limit Theorem to determine the distribution of x values. The means are the same.

Upper/Lower Specification Limits: USL/LSL represent the specification requirements on the product. Design engineers often develop these numbers in the design phase. In most cases, USL/LSL also stand for the customer's voice for the product. For example, for a flat bar made in a certain process, the USL/LSL of the length is 5 ± 0.05m. That means, if the length of any flat bar is more than 5.05m or lower than 4.95m, the flat bar will be considered to be unacceptable and in need of rework.

Variable: A quality characteristic measured on a numerical scale is called a variable. Examples include the length of a flat bar or the temperature in the workshop

Variation: The inevitable differences among individual outputs of a process; the sources of variation can be grouped into two major classes: Common Causes and Special Causes.

Variation Merging: A statistical technique often used in large assembly industry. By variation merging, the variation on the final stage could be assigned to each medium stage, and the variation on all stages could be predictable, and thus controllable.

$\bar{x}$ - R chart: A type of variable control chart. The $\bar{x}$ chart is used to control the central tendency and the R chart is used to control the dispersion.

Zone Analysis: This is a method of detailed analysis of a control chart, which divides the X- bar chart between the control limits into three equidistant zones above and below the mean. These zones are usually referred to as "sigma" zones.

Appendix II: Symbols

A_2	A multiplier of R used to calculate the control limits for averages.
C	The number of non-conformities in a sample.
C_p	The capability index for a stable process defined as $\frac{(USL - LSL)}{6\hat{\sigma} = 6(\bar{R}/d_2)}$.
C_{pk}	The capability index defined as the minimum of C_{p_L} and C_{p_U}.
C_{p_L}	The lower capability index defined as $\frac{(\bar{\bar{x}} - LSL)}{3\hat{\sigma} = 3(\bar{R}/d_2)}$
C_{p_U}	The upper capability index defined as $\frac{(USL - \bar{\bar{x}})}{3\hat{\sigma} = 3(\bar{R}/d_2)}$
d_2	A divisor of R used to estimate the process standard deviation.
D_3, D_4	Multipliers of R used to calculate the lower and upper control limits, respectively, for ranges.
k	The number of subgroups being used to calculate control limits.
LCL	The lower control limit.
LSL	The lower engineering specification limit.
MR	The moving range of a series of data points used primarily on a chart for individuals.
n	The number of individuals in a subgroup or the subgroup sample size.
$\bar{n}$	The average subgroup sample size.
np	The number of nonconforming items in a sample size n.
$n\bar{p}$	The average number of nonconforming items in samples of constant size n.

p	The proportion of unit's nonconforming in a sample.
$\bar{p}$	The average proportion of unit's nonconforming in a series of samples.
R	The subgroup range.
$\bar{R}$	The average range of a series of subgroups of constant size.
s	The sample standard deviation.
SL	A unilateral engineering specification limit.
u	The number of nonconformities per unit in a sample, which may contain more than one unit.
$\bar{u}$	The average number of nonconformities per unit in samples not necessarily of the same size.
UCL	The upper control limit.
USL	The upper engineering specification limit.
x	An individual value, upon which other subgroup statistics are based.
$\bar{x}$	The average of values in a subgroup.
$\bar{\bar{x}}$	The average of subgroup averages; the measured process average.
σ	The standard deviation of the distribution of individual values of a process characteristic.
$\hat{\sigma}$	An estimate of the standard deviation of a process characteristic.