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Structural Design for Production: A Human Factors Viewpoint

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Abstract

Structural design for production can be approached in a number of ways. In looking at the world's most competitive shipyards, especially those involved in building double hulled tankers, it is possible to identify the connection between productivity, accuracy, and safety. Assuming this model is correct, a plan for U.S. shipyards can be recommended. Specifically, the initial goal is to achieve high accuracy. This is achieved by applying the principles of statistical accuracy control, including the use of small group activities. Next, the use of automation and robotics can provide the next improvement in safety, accuracy, and productivity. Finally, the use of a product organization is very helpful in obtaining the best results from small group activities.

1. Introduction

Effective design for production can be achieved in many ways. These can vary from libraries of preferred design details to shipyard organization and practice. Experience in the world"s most competitive shipyards can be used to provide insight into which of the many possible approaches is most likely to achieve success. In addressing this issue, this paper will start with some basic assumptions and use those, with a review of worldwide shipbuilding practice and results, to propose a plan for achieving the best possible improvement in structural design for improved safety and productivity.

2. Assumptions/Theory

In order to address the concept of structural design for production, a brief statement of a model of the issues is required. This model will be based on a few assumptions, and presented in the context of a Product Work Breakdown Structure (PWBS), which has clearly been shown to be the most productive way to build ships in the absence of large series production. The intent of improved design for production is improved productivity. Although productivity improvement is required in an overall shipbuilding context, that is including the major categories of work of structure, outfit, and surface preparation and coating (see Figure 1), structural design for production for double hull tankers can be viewed somewhat independent is essentially that more productive work is easier to perform, that is work that is accomplished by working smarter, not harder, is more productive. Thus, for example, more productive downhand work is easier to perform, and it is therefore safer and more accurate. Compare work positions shown for similar work in Figures 2 and 3 to further understand this idea. Figure 2 shows sub-assembly work prepared for downhand welding, with easy and safe access provided. Figure 3 shows substantial quantities of overhead welding of bulkheads and frames, in an enclosed area. This work will be harder, less productive, and less safe.

One of the basic productivity improvement concepts in a PWBS is to move work to earlier stages as much as possible. Thus, as shown in Figure 4, a goal is to perform more work in the sub-assembly stage (sub-block zone in the figure), rather than saving it for the block assembly or erection stages. [1] One of the reasons for this is smaller parts are easier to handle and work on than larger ones. Additionally, work positions in erection are substantially more difficult and more dangerous than similar work in the sub-assembly stage. Figure 5 shows typically difficult fitting and welding work at erection (compare Figures 2 and 5). Thus, moving work to earlier production stages improves productivity and safety simultaneously.

There is also a similar direct relationship between accuracy and productivity. Improved accuracy results in both less and easier work at later work stages. Predictable and repeatable accuracy results in less and easier shipfitting and welding at erection and block assembly. Especially for double hull tankers, these are potentially dangerous work areas. Figure 6 shows erection of very accurate hull blocks, requiring no staging. Because these blocks are extremely accurate, shipfitting and welding can be done using man-lifts rather than staging, and automatic or semiautomatic welding is also facilitated. Compare the erection work shown in Figures 6 and 7 with that shown in Figure 5. Also, note in Figure 7, how painting work is also improved from the perspective of both productivity and safety.

3. Current Safety Status

Safety data are reported somewhat differently in different countries. Despite this, it is possible to provide a reasonable picture of the status of shipyard safety around the world. The typical measure is day-off incidents. U.S. data can be obtained from the Survey of Occupational Injuries and Illnesses, 1993, published by the U.S. Department of Labor, Bureau of Labor Statistics, in February 1995. [2] The number of incidents of injuries resulting in days away from work for the Standard Industrial Classification 3731, ship building and repairing, for 1993 was 7,700. These incidents came from a work force that had an average size of 111,000 in 1993. Similar data are available for the seven major Japanese shipbuilding companies, which includes 20 shipyards. This data is reported by the Shipbuilders Association of Japan. For those 20 shipyards, a total of 42 incidents that resulted in days away from work were reported for 1995. [3] This is reported as a frequency rate of 0.23 incidents per million work hours. Assuming an average of 2000 work hours per year for U.S. workers, with an average work force of 111,000 workers, there were 222 million work hours in 1993. This is a frequency rate of 34.7 incidents per million work hours, or about a rate 150 times higher than the seven major Japanese shipbuilding companies.

Clearly these statistics should be viewed in a context beyond just the numbers. The U.S. data include all shipbuilders and repairers. It is likely that the major U.S. shipyards have safety records that are better than the industry averages. Nevertheless, there is a substantial disparity. I believe the approach to ship production, and organizational issues contribute to this disparity.

4. Model for Improving U.S. Shipyards

Based on the theory of productive shipbuilding, the assumptions of the direct relationship between safety, accuracy, and productivity, and a review of safety data and current practice in the world's most competitive shipyards, a model for U.S. shipyards can be developed, especially considering yards entering the market for double hull tankers.

Assuming that a shipyard has already begun implementation of a PWBS, two primary approaches have been used to in the world"s most competitive shipyards to achieve dominance in the market for double hull tankers. These techniques are the application of statistical accuracy control and the use of automation and robotics, in that order. These two techniques are not independent. In fact, successful implementation of automation and robotics depends first on successful use of statistical accuracy control. Shipyards, such as Odense, Lindo, Hitachi Zosen, Ariake, and more recently IHI, Kure, that have demonstrated successful implementation of automation and robotics, all had mature accuracy control systems in place prior to the use of automation.

Thus the recommended model for simultaneously improving productivity, accuracy, and safety is the implementation of a statistical accuracy control program, the use of appropriate automation and robotics, and the installation of the organizational structure necessary to foster an environment of continuous improvement.

Accuracy control is based on the use of statistical techniques to determine process capability for typical parts manufacturing, sub-assembly, block assembly and erection. Although accuracy control techniques are applicable to outfitting products and processes, this paper will concentrate on it's application to structure. Appropriate automation and robotics is very much a function of the existing facility, and the proposed market for the shipyard. To be successful, automation and robotics must be flexible enough to allow the shipyard to offer a range of vessels to prospective owners. This implies computer controlled welding robots that can be quickly programmed, and a mix of human and machine work. The final part of this system is small group activities to determine, monitor, and control accuracy and effectiveness of processes. These small group activities are used to define and stabilize processes, as well as to provide continuous improvement. The same small group activities that are used as a part of an accuracy control system are also employed as a part of a safety system. There is considerable experience to show that issues relating to accuracy and productivity can be directly tied to safety through these small group activities. The organizational structure of the shipyard must support these activities, which implies a product organization.

5. Accuracy Control

Accuracy control is based on the principles of control chart theory, as developed by Dr. Walter Shewhart of Bell labs in the 1930's. This theory, which is in turn based on the central limit theorem, states that the means of random samples from any population follow a normal distribution, with mean and standard deviation directly related to the mean and standard deviation of the original population. [4] Figure 8 shows the distribution of a population (in this case assumed to be a normal population) and the corresponding distribution of means of random samples from that population. [5] Since plus or minus three standard deviations from the mean of a normally distributed variable contains 99.73% of all the values from that distribution, control chart theory is based on using control limits of plus or minus three standard deviations to determine stability of a variable.

For an industrial process, such as parts cutting, parts welding, sub-assembly, etc., Shewhart type control charts can be used to monitor processes for stability and to determine the capability of the process in terms of mean and standard deviation of outputs. Figure 9 shows a typical variables control chart pair for a shipbuilding process (parts cutting). The control chart pair is used to monitor mean and standard deviation of outputs from this process, based on random sampling of parts produced by a cutting machine. [6] These charts can be used to develop a normal distribution of outputs from that process. By adding statistically all the variability produced by manufacturing and assembly processes (using variation merging equations), it is possible to predict the distribution of outputs at the final assembly work station, or at erection for shipbuilding. [7] This ability to control and predict final process accuracy permits neat cutting of parts and assemblies, while still producing accurate interim and final products. The neat fit of hull blocks, providing a substantially safer work environment (Figures 6 and 7), is the result of the application of a mature accuracy control system.

There are a number of prerequisites to the establishment of an accuracy control system. First, the use of a PWBS is required, so that repeatable interim products are used. This permits application of the principles of short run statistical process control, which is essential given the one of a kind nature of commercial shipbuilding. Next, the use of repeatable work processes is required. Finally, data collection and analysis, to achieve stability of processes is essential. Stable processes are those that produce results that are normally distributed, with a known mean and standard deviation. The use of small group activities and a product organization can greatly facilitate the development of a data base defining stable processes.

6. Robotics

A number of the world's most competitive shipbuilders have implemented automation and robotics for structural work for double hulled tankers. Examples of the use of robots are shown in Figures 10 and 11. Figure 10 is a picture of Hirobo robots welding a structural block for double hulled VLCCs at Odense, Lindo. [8] Note that multiple robots are used simultaneously. Also note the structural details, including neat cut tees that require no cover plates or brackets. Clearly, accuracy of these cutouts and the structural tees must be very good. This shipyard has spent considerable effort to develop and perfect this robotic welding system, including consideration of design details, computer and robot programming, and welding distortion control. Figure 11 shows one of a group of three welding robots controlled by one on-site worker, at the Hitachi Ariake shipyard. [9] Robotic welding at that shipyard accounts for about 90% of all primary panel welding work. Here again, design details and a total commitment to accuracy are essential to the successful application of robotics.

Design details nearly identical to those used by Odense and Hitachi are shown in Figure 12, from IHI, Kure. This figure is a picture taken prior to that shipyard"s recent implementation of automation in welding for double hull tankers. The picture shows "accuracy control" offset measuring marks. These lines, marked inside the edges of the plates, permit measurements of dimensions to be taken as the part progresses through the production process, through sub-assembly, block assembly and erection. Thus, the normal variation produced by each of these processes has been monitored, subjected to statistical analysis, and controlled using control charts.

A high degree of accuracy is required to support the use of robotic welders. These high accuracy levels are obtained in a number of ways. For example, dimensional accuracy of cut details and part dimensions, like structural tees, are obtained through use of mechanical planers or careful monitoring of cutting and welding to minimize heat input. Competed structural blocks for double hulled tankers, manufactured with extensive use of robotics, are shown in Figures 13 and 14, representing work practice at Odense, Lindo and Hitachi Zosen, Maizuru. [8]

Evidence has shown that good housekeeping has a positive effect on both productivity and safety. Compare the good housekeeping evident in Figure 15 with the disorganized situation shown in Figure 16. As seen in Figure 17, the use of robotics and automation can provide the opportunity for maintaining good housekeeping. In this figure, a worker at IHI, Kure sweeps while monitoring gravity-feed welders. [10]

7. Small Group Activities

Accuracy control and the use of control charts forms one part of a Total Quality Management (TQM) system. There are many ways to achieve these systems, and a number of styles of TQM, including those based on the work of Deming, Juran, Crosby, Feigenbaum, and others. All these systems attempt to achieve the same goal, the establishment of a system of continuous improvement in quality and productivity. Whichever system is employed, a key part is the positive involvement of the work force.

Here again, there a many ways to achieve this input from the work force. One approach that has proven successful in many applications around the world is the use of small group activities. Small group activities have been known as quality circles, productivity improvement teams, and other names. Successful application of this approach requires adequate training of team members and the use of analytical techniques. While there are a variety of analytical tools that can be employed as a part of these small group activities, a number of authors have referred to “the magnificent seven.” [4] These seven tools are:

- process flow charts,
- cause and effect diagrams, or fishbone charts,
- check sheets,
- Pareto diagrams,
- histograms,
- scatter diagrams, and,
- control charts.

In addition to these seven tools, experiment design can be used to develop and test improvement suggestions. Figure 18 summarizes these eight tools. Figures 19, 20, 21, and 22 are examples of fishbone charts, check sheets, Pareto diagrams, and histograms, respectively. [11]

The small groups are made up of those people most directly involved in the problem and with the ability to analyze the problem, propose solutions, implement solutions, and verify the results of the effort. This is equivalent to the PDCA cycle (plan, do, check, act), proposed and used initially by Deming and Juran. Figure 23 shows the cycle. This never-ending cycle of activities, performed by small groups, applies to productivity, accuracy and safety improvements. The group members can be from a single work station, but in most cases, since problems are related to many functional areas, representatives from different functions are required on the team. In a product organization, functional activities are organized around interim products, represented by any one combination of zone, area and stage in Figure 4. Thus, in addition to the workers, structural design engineers, process engineers, welding engineers, material handling personnel, human resource personnel, training personnel, and others could be involved in the activities. Because they focus on the interim product, each brings their specific knowledge and background to the group, aiding in the development of improvements that satisfy the requirements of all functions..

Figure 24 outlines a system of operation for small group activities in the context of the overall organization. [10] The small group activities, utilizing the PDCA cycle and analytical tools, result in improvement suggestions that are part of an overall improvement strategy.

8. Conclusion

Shipyards that hope to be successful in the emerging market for double hull tankers must consider the related topics of design for production, productivity, safety, and accuracy. Anecdotal evidence suggests there is a direct relationship between accuracy, productivity, and safety. A number of factors are driving shipyards in the double hull tanker market to increasing use of automation and robotics. While this will improve safety, an important prerequisite is the use of statistical accuracy control. Product organization and small group activities greatly facilitate a statistical accuracy control system. Thus, a recommended model for U.S. shipyards entering the double hull tanker market involves:

1. the application of a product organization and small group activities to deal with issues of accuracy, productivity, and safety,
2. implementation of statistical accuracy control, and
3. appropriate development and implementation of automation and robotics.

References

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3. Shipbuilders Association of Japan, “Monthly Safety Report,” 1995 (as transmitted by Mr. Shuji Sato, IHI, AMTEC).
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10. National Shipbuilding Research Program, “Product Oriented Safety and Health Management,” U.S. Department of Transportation, 1986.
11. National Shipbuilding Research Program, “Analytical Quality Circles,” U.S. Department of Transportation, 1986.

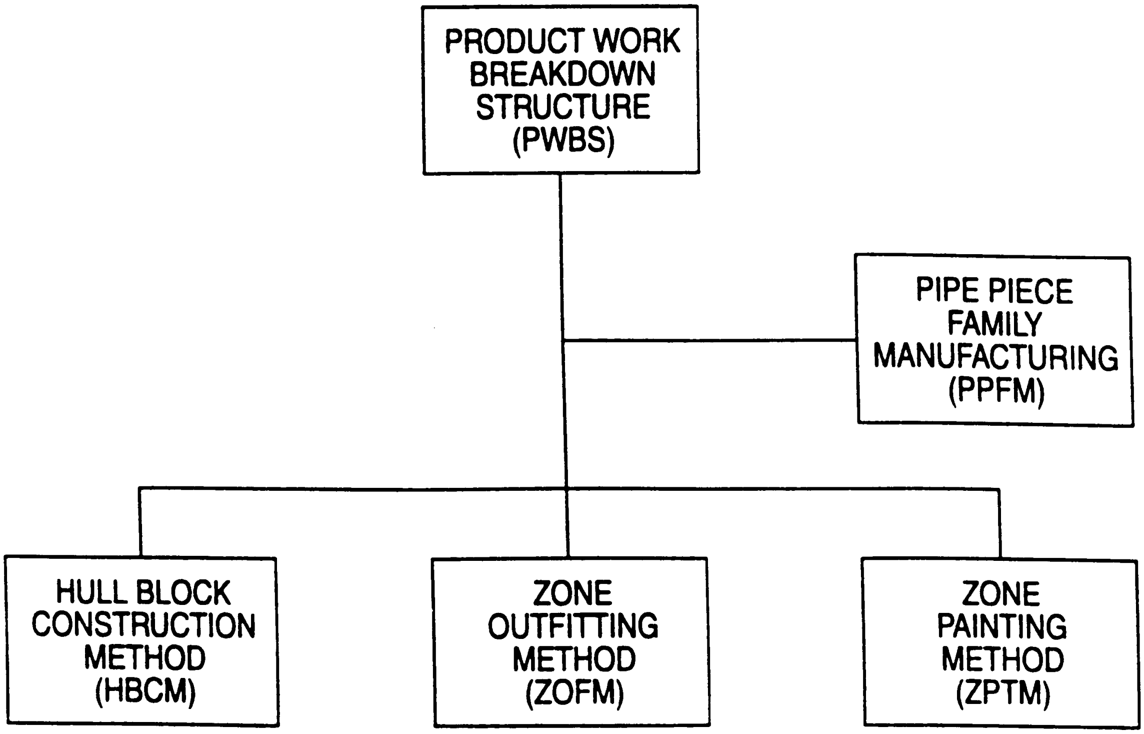


Figure 1
Components of a Product Work Breakdown Structure

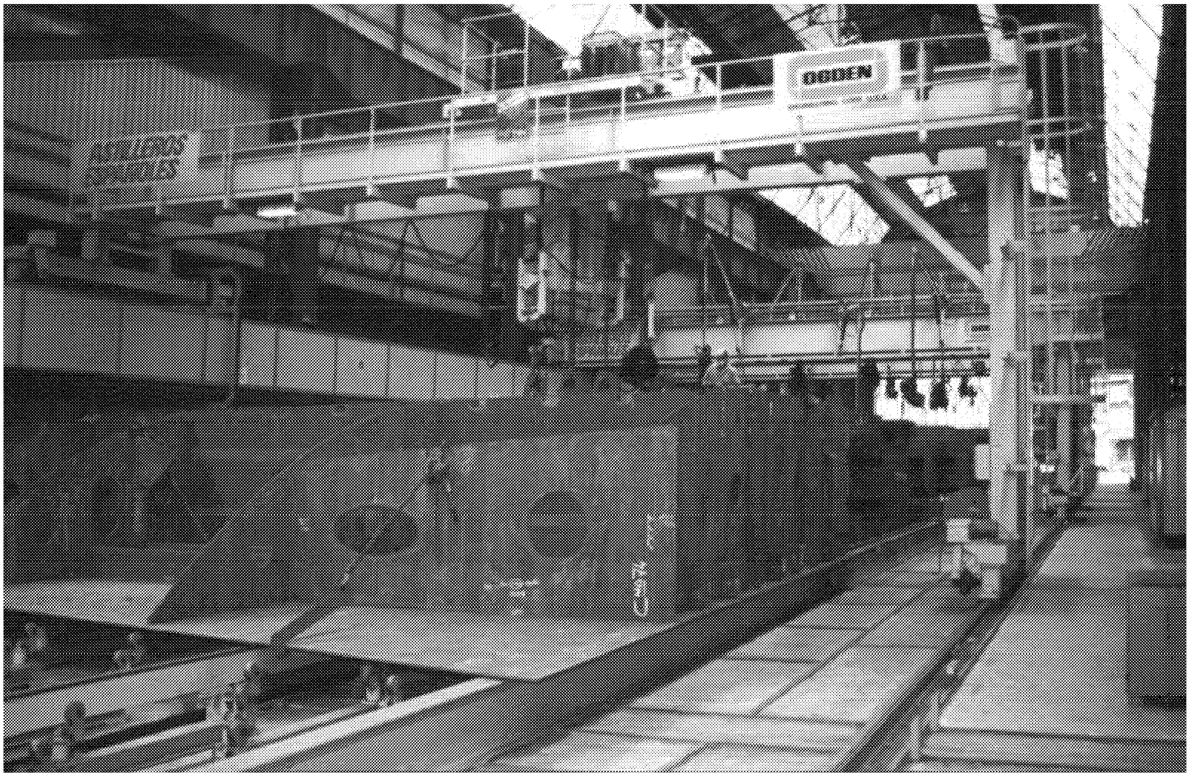


Figure 2
Sub-assembly Work, Downhand and With Easy Access

Figure 3
Assembly Work Requiring Overhead Welding

<table>
<tr><th rowspan="2">PLAN'G LEVEL</th><th rowspan="2">MFG LEVEL</th><th colspan="5">PRODUCT ASPECTS</th></tr>
<tr><th colspan="2">ZONE</th><th>AREA</th><th colspan="2">STAGE</th></tr>
<tr><td rowspan="2">1</td><td rowspan="2">7</td><td colspan="2" rowspan="2">SHIP</td><td rowspan="2">FORE HULL
CARGO HOLD
ENGINE ROOM
AFT HULL
SUPERSTRUCTURE</td><td colspan="2">TEST</td></tr>
<tr><td colspan="2">ERECTION</td></tr>
<tr><td rowspan="3">2</td><td rowspan="3">6</td><td rowspan="10">BLOCK</td><td rowspan="3"></td><td rowspan="3">FLAT PANEL
CURVED PANEL
SUPERSTRUCTURE</td><td>BACK PRE-ERECTION</td><td>NIL</td></tr>
<tr><td>PRE-ERECTION</td><td>NIL</td></tr>
<tr><td>JOINING</td><td>NIL</td></tr>
<tr><td rowspan="4">3</td><td rowspan="4">5</td><td rowspan="7">NIL</td><td rowspan="4">FLAT
SPECIAL FLAT
CURVED
SPECIAL CURVED
SUPERSTRUCTURE</td><td>BACK ASSEMBLY</td><td>NIL</td></tr>
<tr><td colspan="2">ASSEMBLY</td></tr>
<tr><td>FRAMING</td><td>NIL</td></tr>
<tr><td>PLATE JOINING</td><td>NIL</td></tr>
<tr><td rowspan="3">4</td><td rowspan="3">4</td><td rowspan="5">SIMILAR SIZE IN A LARGE QUANTITY
SIMILAR SIZE IN A SMALL QUANTITY</td><td>BACK ASSEMBLY</td><td>NIL</td></tr>
<tr><td colspan="2">ASSEMBLY</td></tr>
<tr><td>PLATE JOINING</td><td>NIL</td></tr>
<tr><td rowspan="2">5</td><td rowspan="2">3</td><td rowspan="4">SUB-BLOCK</td><td rowspan="2">NIL</td><td>BACK ASSEMBLY</td><td>NIL</td></tr>
<tr><td colspan="2">ASSEMBLY</td></tr>
<tr><td rowspan="2">6</td><td rowspan="2">2</td><td rowspan="2"></td><td rowspan="2">SUB-BLOCK PART
BUILT-UP PART</td><td>BENDING</td><td>NIL</td></tr>
<tr><td colspan="2">ASSEMBLY</td></tr>
<tr><td rowspan="3">7</td><td rowspan="3">1</td><td colspan="2" rowspan="3">PART</td><td rowspan="3">PARALLEL PART FROM PLATE
NON-PARALLEL PART FROM PLATE
INTERNAL PART FROM PLATE
PART FROM ROLLED SHAPE
OTHER</td><td>BENDING</td><td>NIL</td></tr>
<tr><td colspan="2">MARKING & CUTTING</td></tr>
<tr><td>PLATE JOINING</td><td>NIL</td></tr>
</table>

Figure 4
Hull Block Construction Method Showing Product Aspects

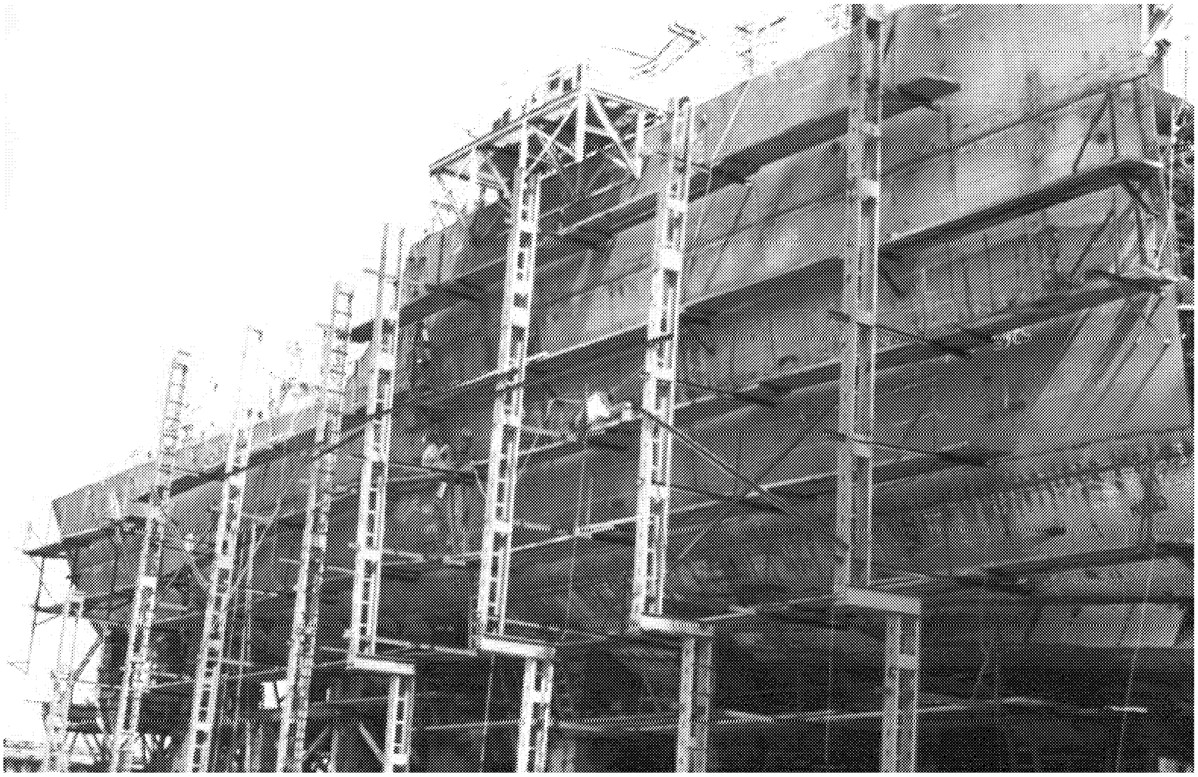


Figure 5
Erection Work, Involving Difficult Fitting and Welding

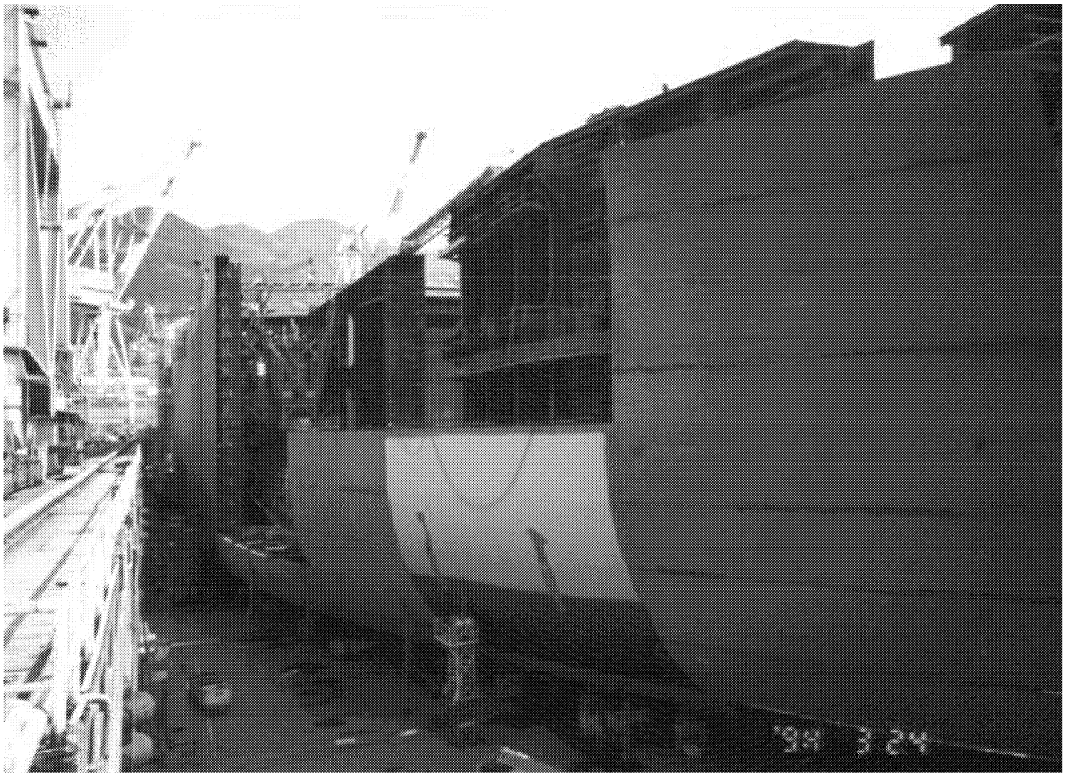


Figure 6
Hull Block Accuracy Improves Fitting and Welding Productivity and Safety

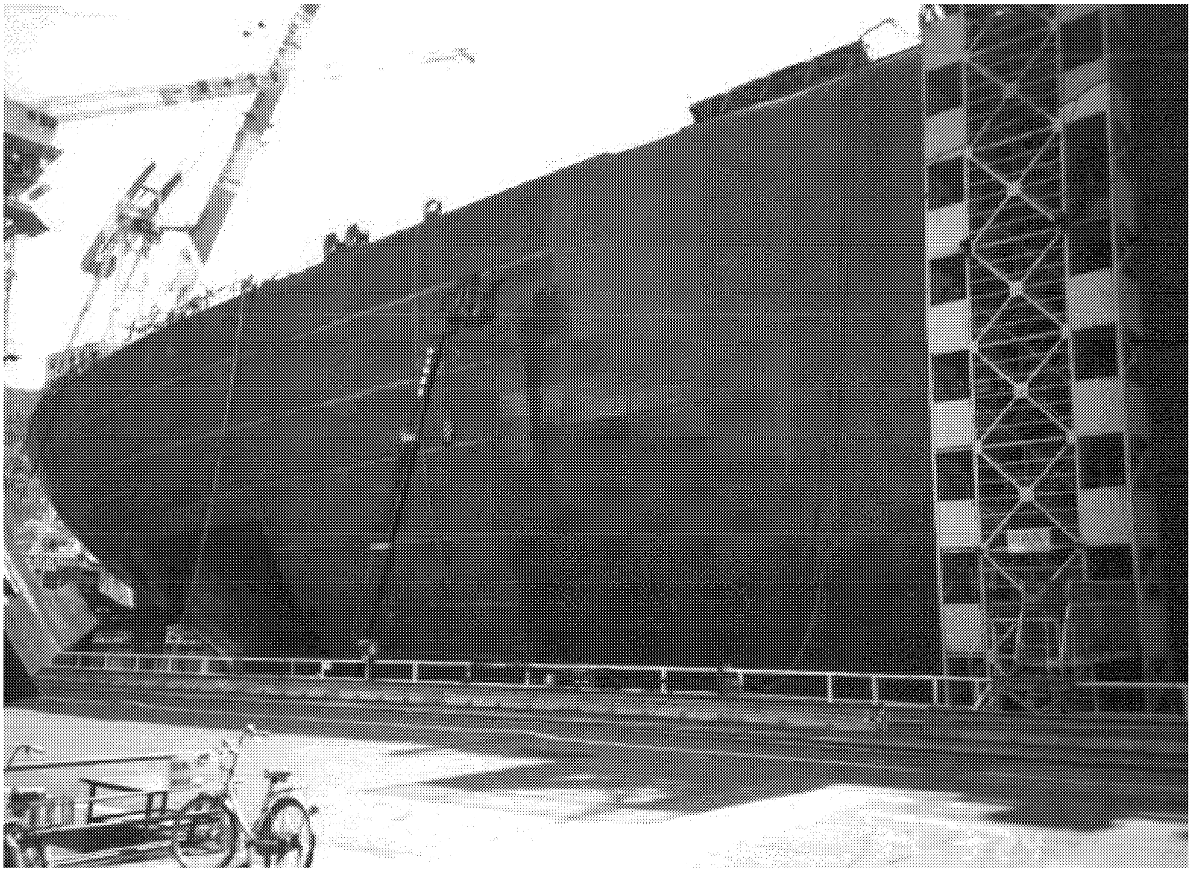


Figure 7
Hull Block Accuracy Improves Painting Productivity and Safety

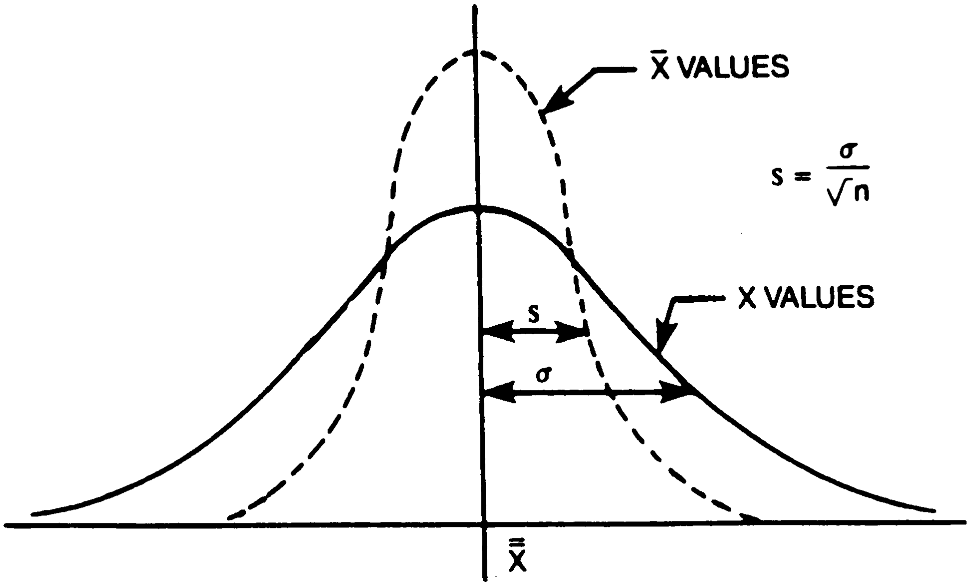
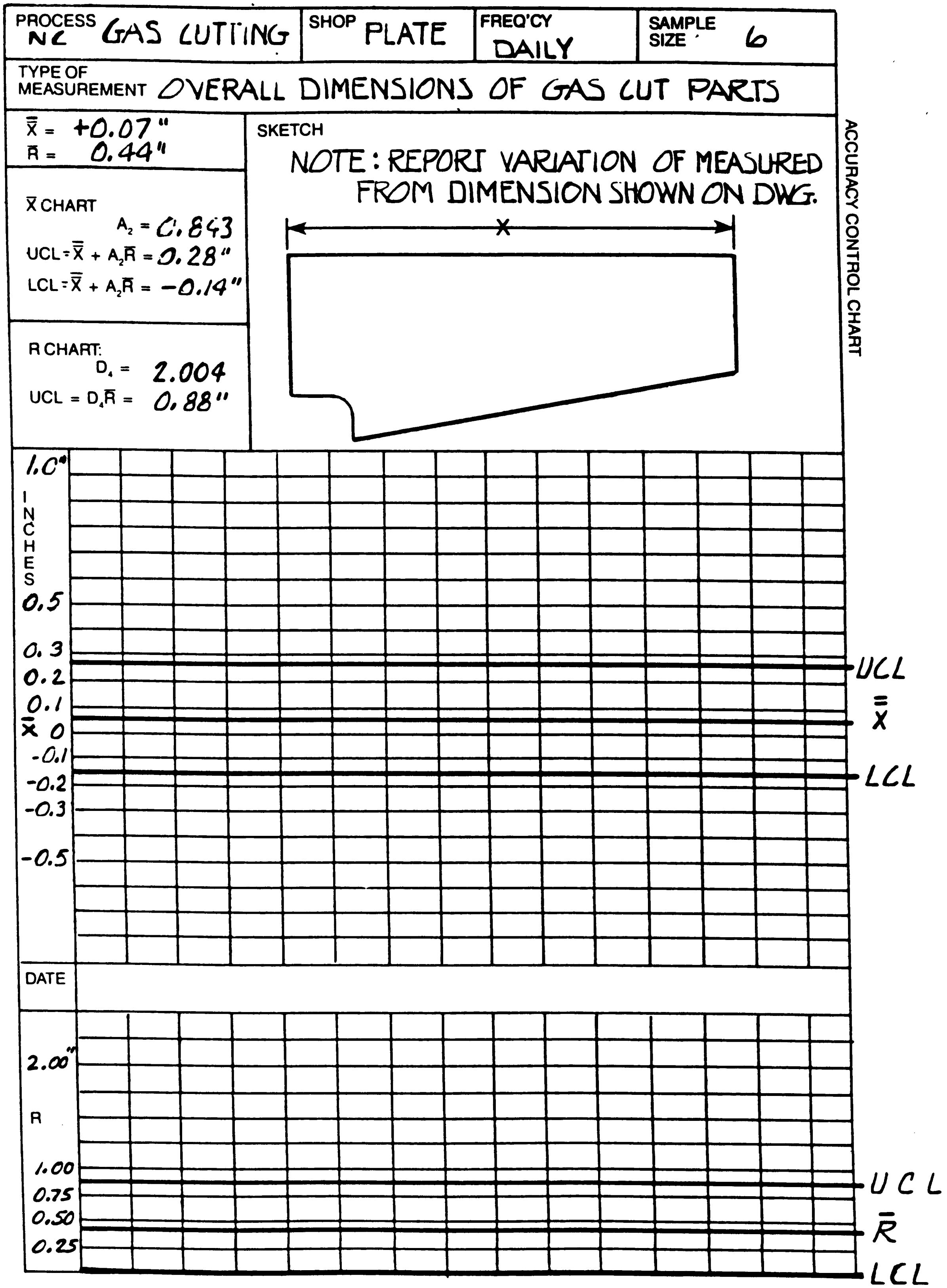


Figure 8
Relationship Between a Population Distribution and The Distribution of Means From Random Samples From the Population



PROCESS NC GAS CUTTING

SHOP PLATE

FREQ'CY DAILY

SAMPLE SIZE 6

TYPE OF MEASUREMENT OVERALL DIMENSIONS OF GAS CUT PARTS

$\bar{\bar{X}}$ = +0.07"

$\bar{R}$ = 0.44"

$\bar{X}$ CHART

A_2 = 0.843

UCL = $\bar{\bar{X}} + A_2\bar{R}$ = 0.28"

LCL = $\bar{\bar{X}} + A_2\bar{R}$ = −0.14"

R CHART:

D_4 = 2.004

UCL = $D_4\bar{R}$ = 0.88"

SKETCH

NOTE: REPORT VARIATION OF MEASURED FROM DIMENSION SHOWN ON DWG.

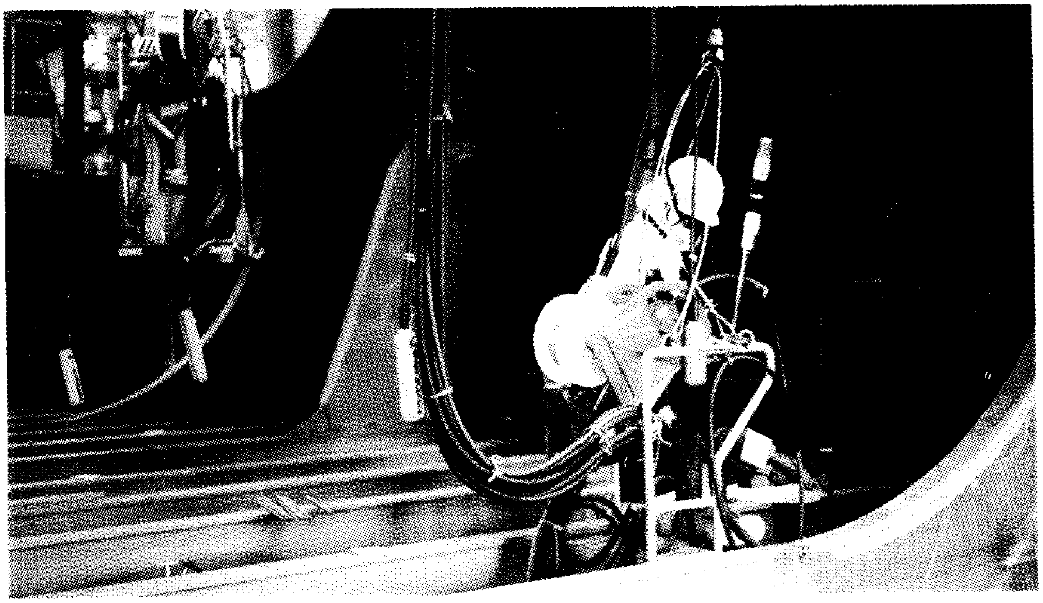
ACCURACY CONTROL CHART

DATE

Figure 9

Typical Variables Control Chart Pair, For Parts Cutting

Figure 10
Structural Block For Double Hulled VLCC Being Welded
Using Hirobo Robots At Odense, Lindo



NOVEMBER 1990

Figure 11
One of Three Welding Robots Controlled By One Worker At Hitachi, Ariake

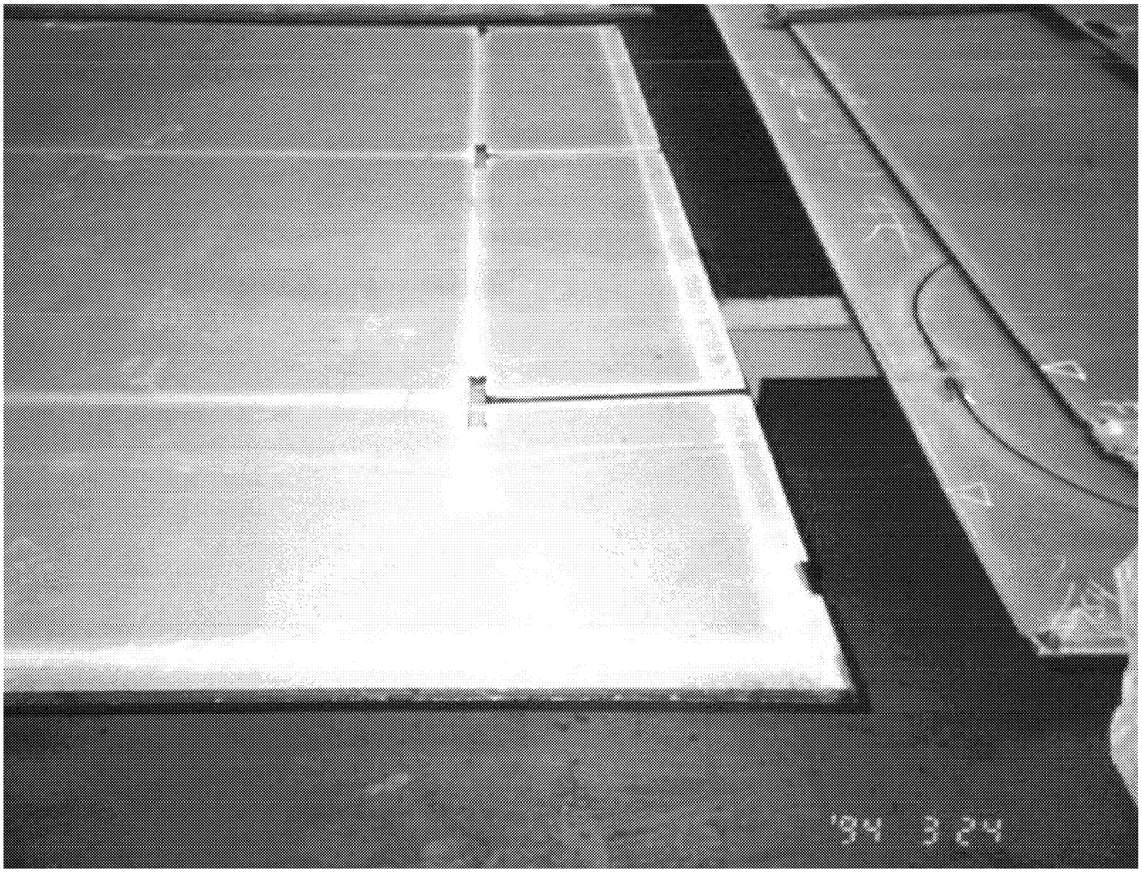


Figure 12
Slots For Tee Bars in Oil Tight Bulkhead Plating at IHI, Kure

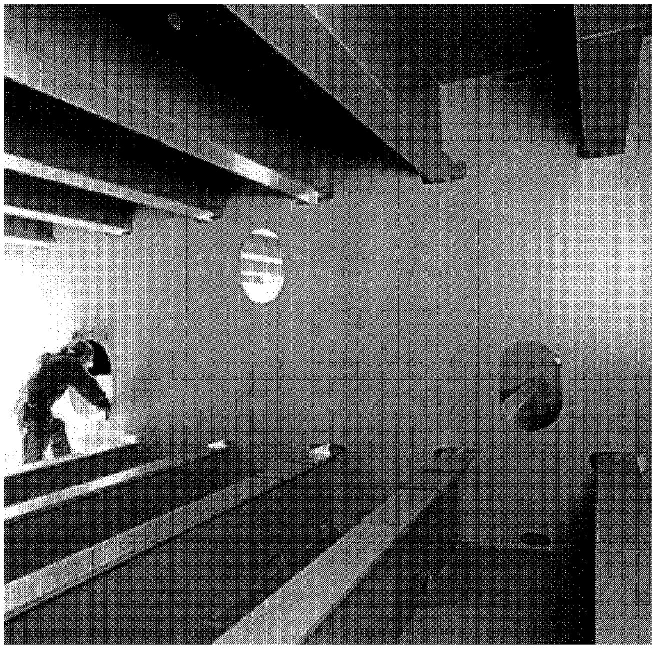


Figure 13
Completed Structural Block For Double Hulled VLCC
Welded by Robots at Odense, Lindo

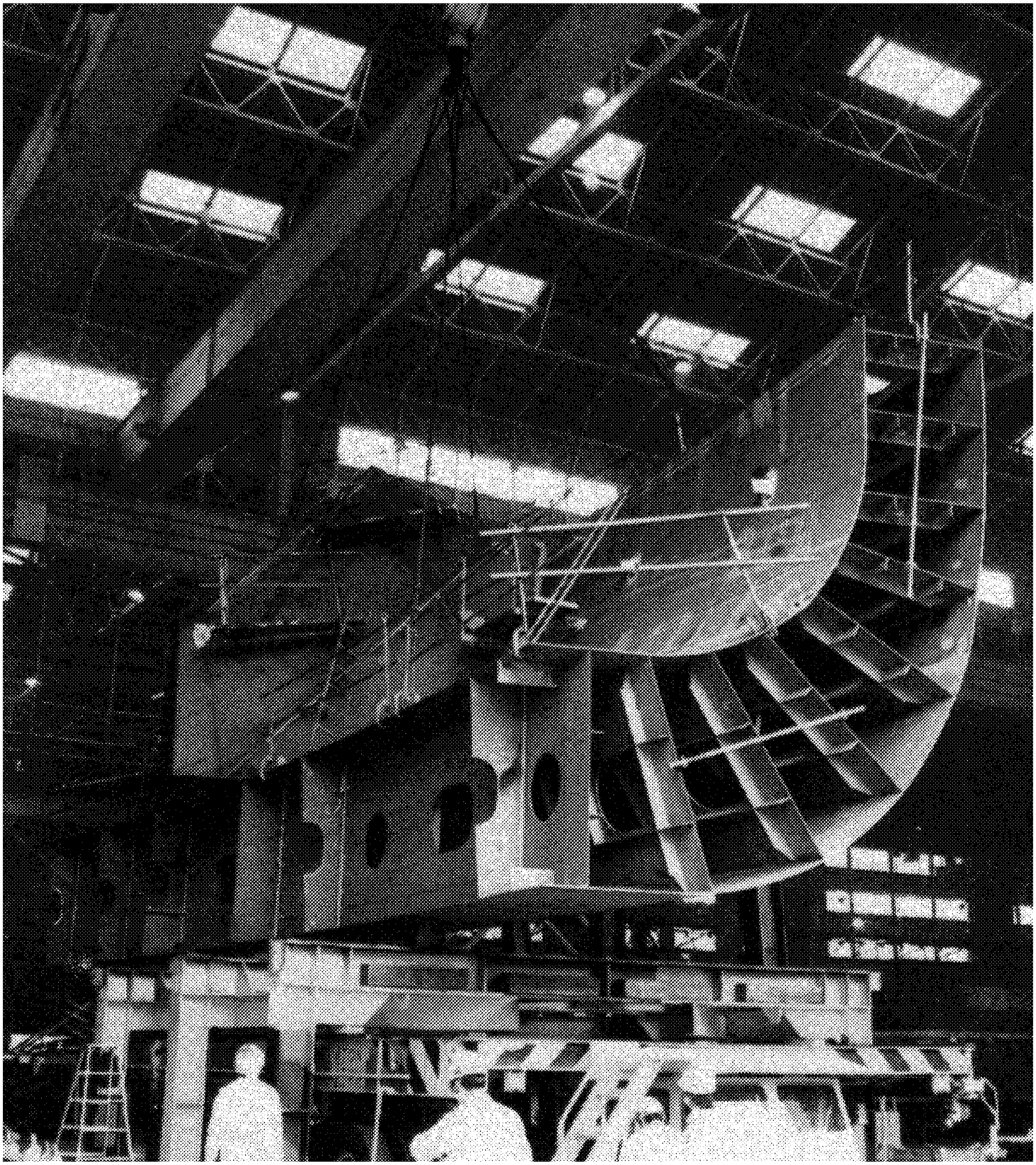


Figure 14
Hull Block of a Double Hull Tanker Built With Extensive
Use of Robots at Hitachi Zosen, Maisuru

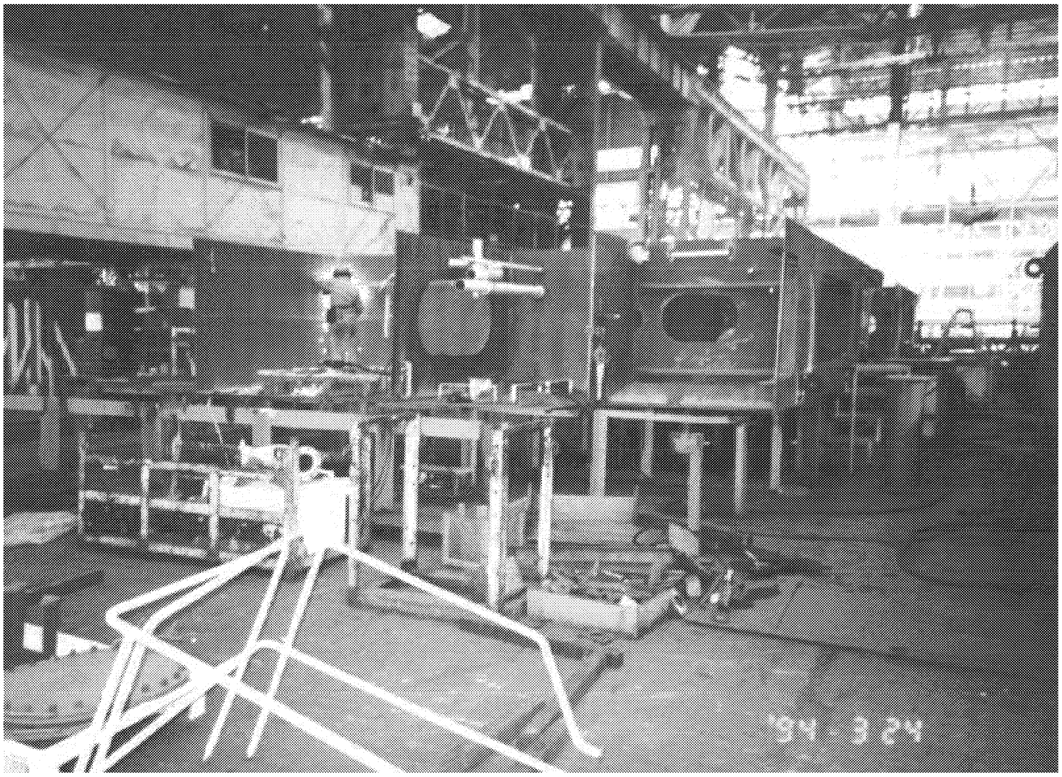


Figure 15
Shipyard Employing Good Housekeeping Practices

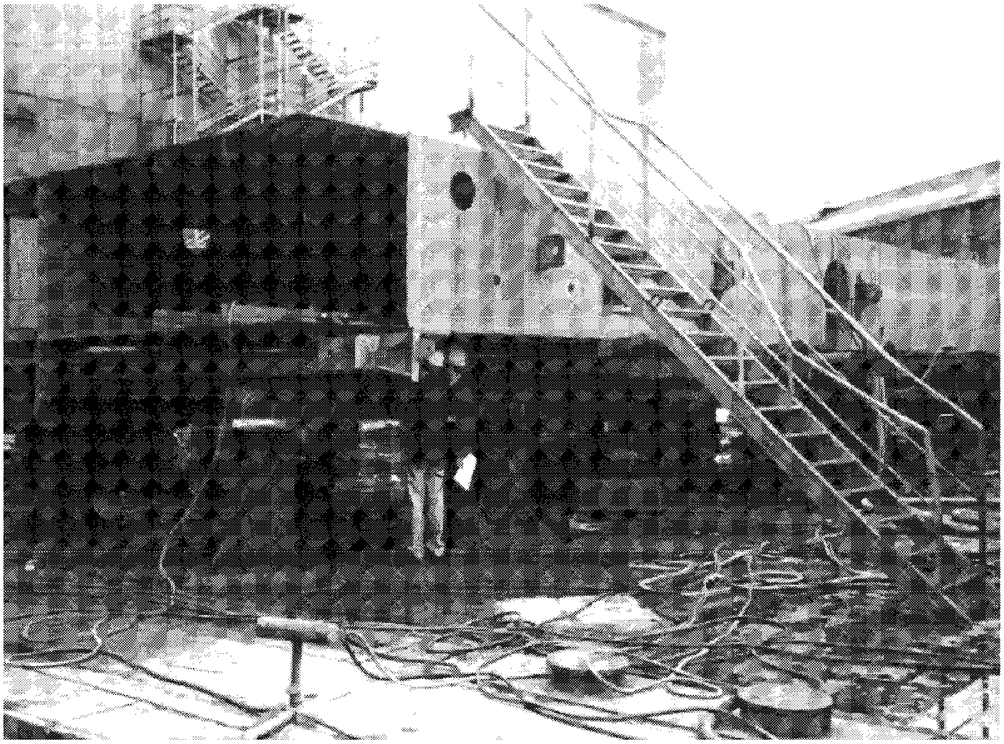


Figure 16
Shipyard With Poor Housekeeping, Disorganized System Runs, and Damaged Access Ladder

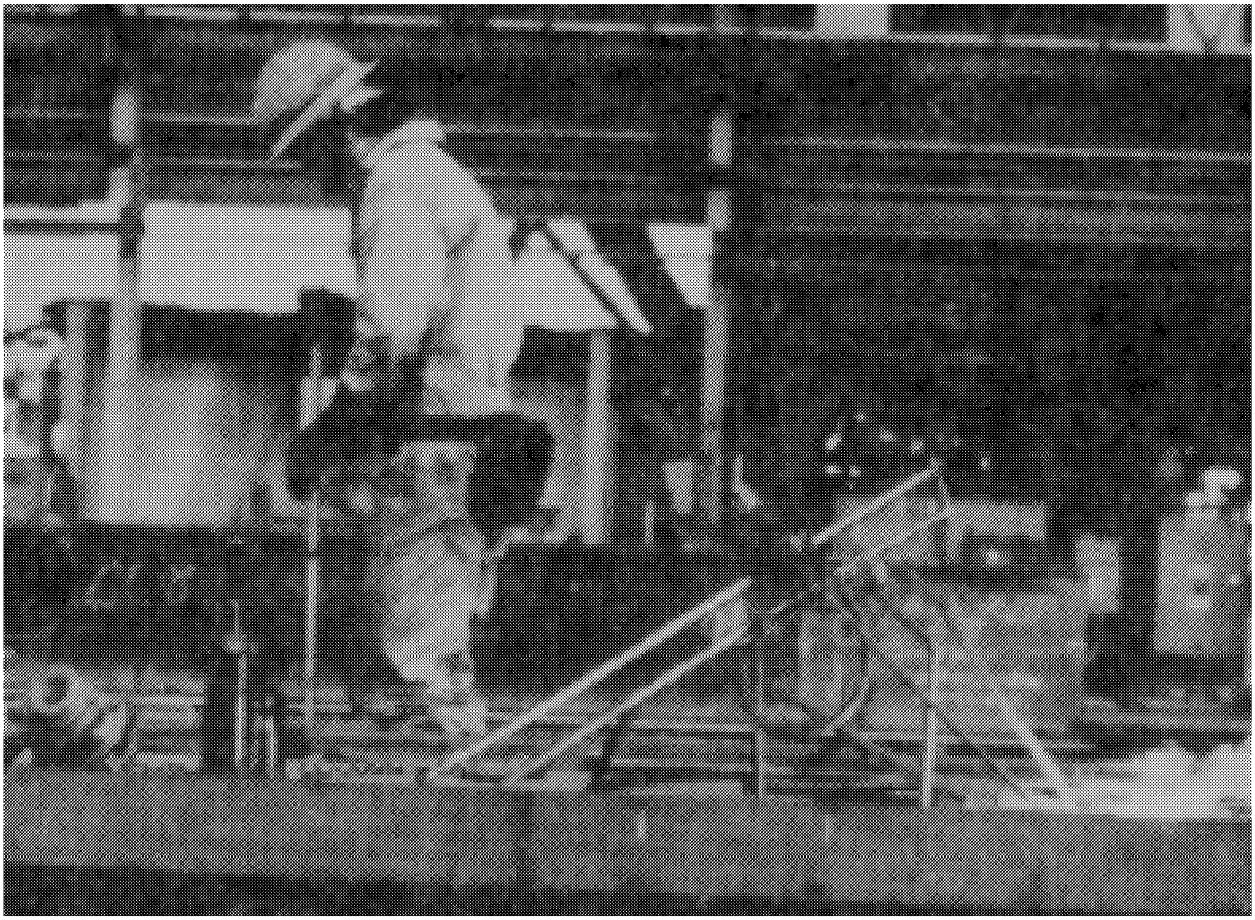
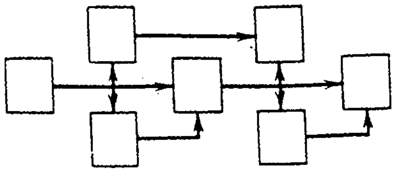


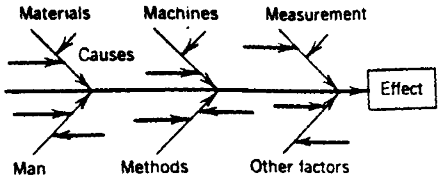
Figure 17
Welder Sweeps While Monitoring Gravity-Feed Welders

Process Flow Diagram



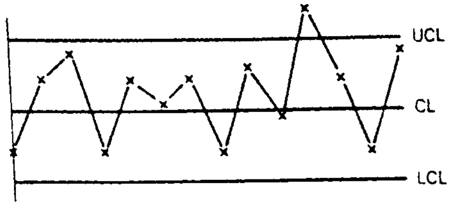
- Expresses detailed knowledge of the process
- Identifies process flow and interaction among the process steps
- Identifies potential control points

Cause and Effect (Fishbone) Diagram



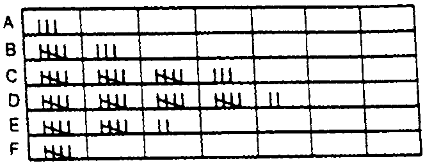
- All contributing factors and their relationship are displayed
- Identifies problem areas where data can be collected and analyzed

Control Chart



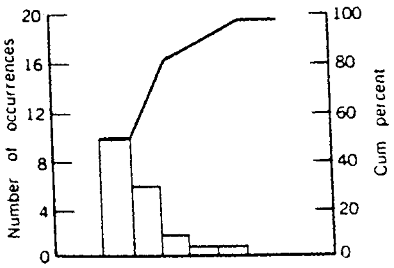
- Helps reduce variability
- Monitors performance over time
- Allows process corrections to prevent rejections
- Trends and out-of-control conditions are immediately detected

Checksheet



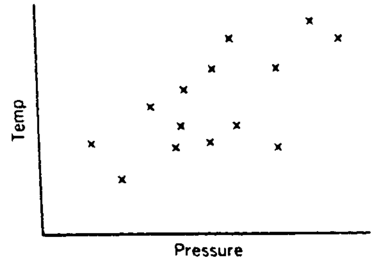
- Simplifies data collection and analysis
- Spots problem areas by frequency of location, type, or cause

Pareto Diagram



- Identifies most significant problems to be worked first
- Historically 80% of the problems are due to 20% of the factors
- Shows the vital few

Scatter Plot

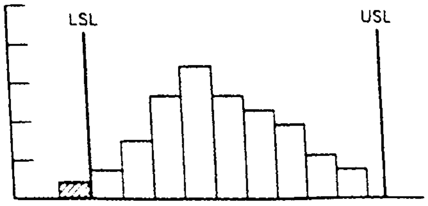


- Identifies the relationship between two variables
- A positive, negative, or no relationship can be easily detected

Design of Experiments (DOE)

- Useful in process development and troubleshooting
- Identifies magnitude and direction of important process variable effects
- Greatly reduces the number of runs required to perform an experiment
- Identifies interaction among process variables
- Useful in engineering design and development
- Focuses on optimizing process performance

Histogram



- The shape shows the nature of the distribution of the data
- The central tendency (average) and variability are easily seen
- Specification limits can be used to display the capability of the process

Figure 18
Eight Tools For Use During Small Group Activities

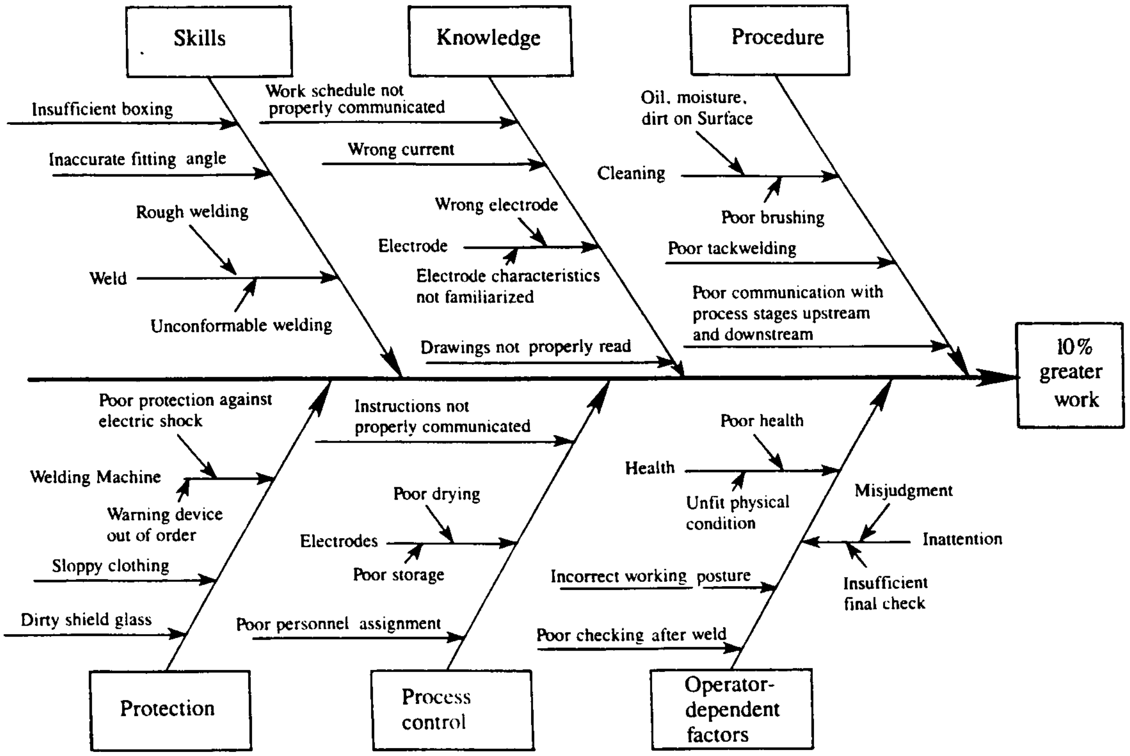
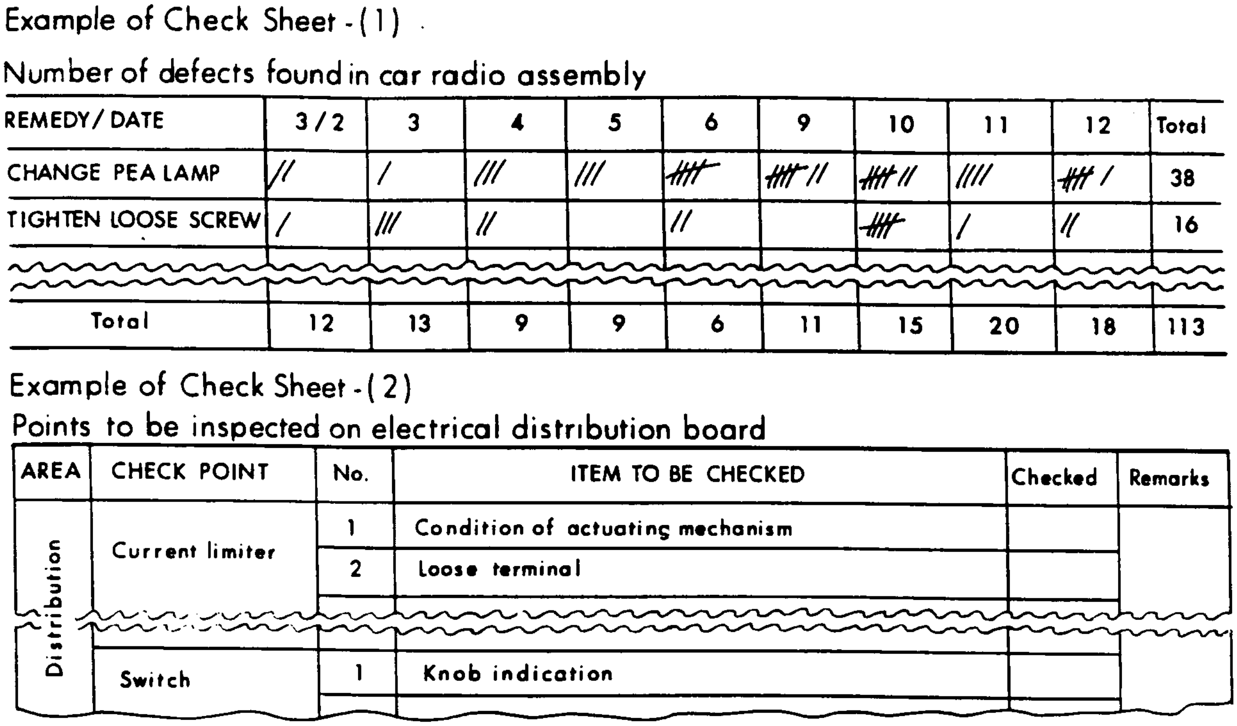


Figure 19
Example of a Cause and Effect Diagram



Example of Check Sheet - (1)

Number of defects found in car radio assembly

REMEDY/ DATE	3/2	3	4	5	6	9	10	11	12	Total
CHANGE PEA LAMP	//	/	///	///	𝍸	𝍸//	𝍸//	////	𝍸/	38
TIGHTEN LOOSE SCREW	/	///	//		//		𝍸	/	//	16
Total	12	13	9	9	6	11	15	20	18	113

Example of Check Sheet - (2)

Points to be inspected on electrical distribution board

AREA	CHECK POINT	No.	ITEM TO BE CHECKED	Checked	Remarks
Distribution	Current limiter	1	Condition of actuating mechanism		
		2	Loose terminal		
	Switch	1	Knob indication		

Figure 20
Examples of Check Sheets From the Auto Industry

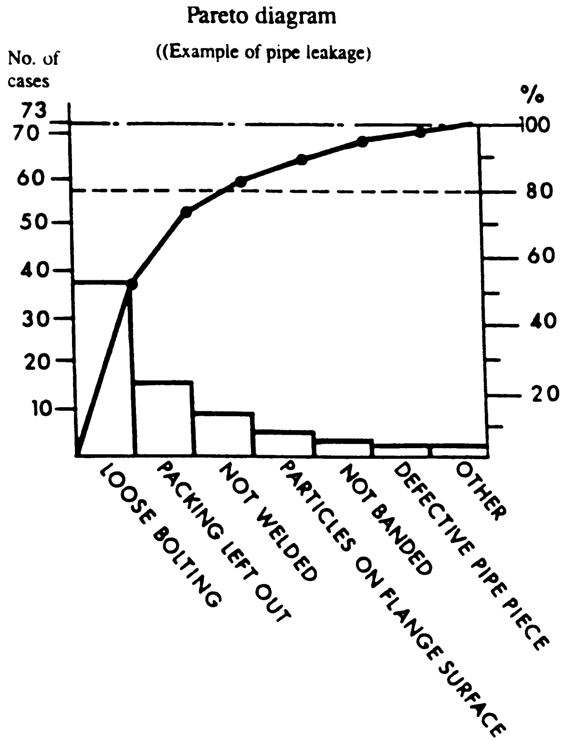


Figure 21
Example of a Pareto Diagram

Frequency distribution table

CLASS	BOUNDARIES BETWEEN CLASSES	CLASS MARK	TALLIES	FREQUENCY OF OCCURRENCE	%	CUMULATIVE %
1	259.5-272.5	271	/	1	1.25	1.25
2	272.5-275.5	274	///	3	3.75	5.00
3	275.5-278.5	277	𝍸/	6	7.50	12.50
4	278.5-281.5	280	𝍸𝍸//	12	15.00	27.50
5	281.5-284.5	283	𝍸𝍸𝍸𝍸/	21	25.25	53.75
6	284.5-287.5	286	𝍸𝍸𝍸////	19	23.75	77.50
7	287.5-290.5	289	𝍸𝍸//	12	15.00	92.50
8	290.5-293.5	292	///	3	3.75	96.25
9	293.5-296.5	295	//	2	2.50	98.75
10	296.5-299.5	298	/	1	1.25	100.00
	Total or Average			80	100.00	

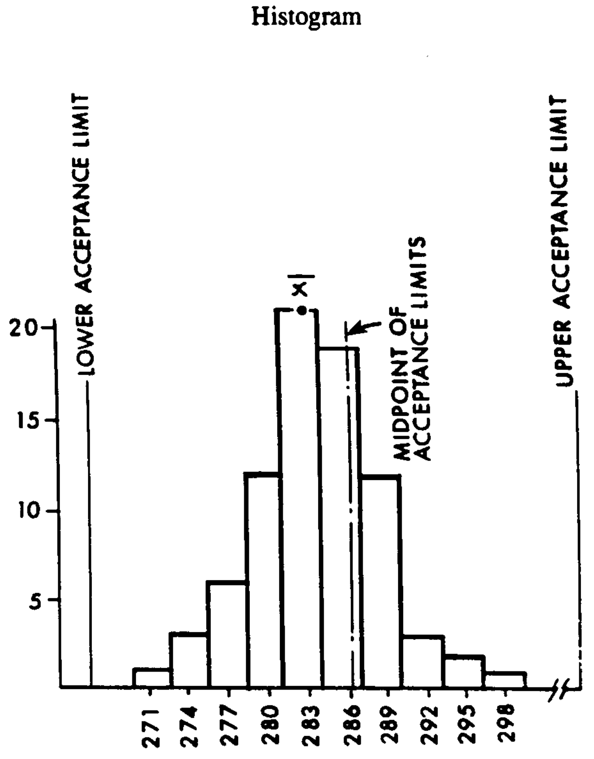


Figure 22
Example of a Histogram

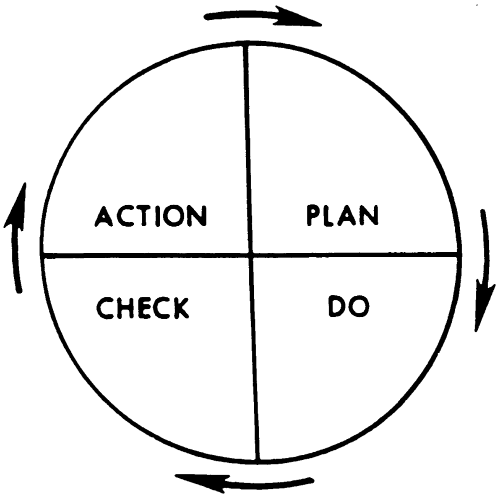


Figure 23
The PDCA Cycle

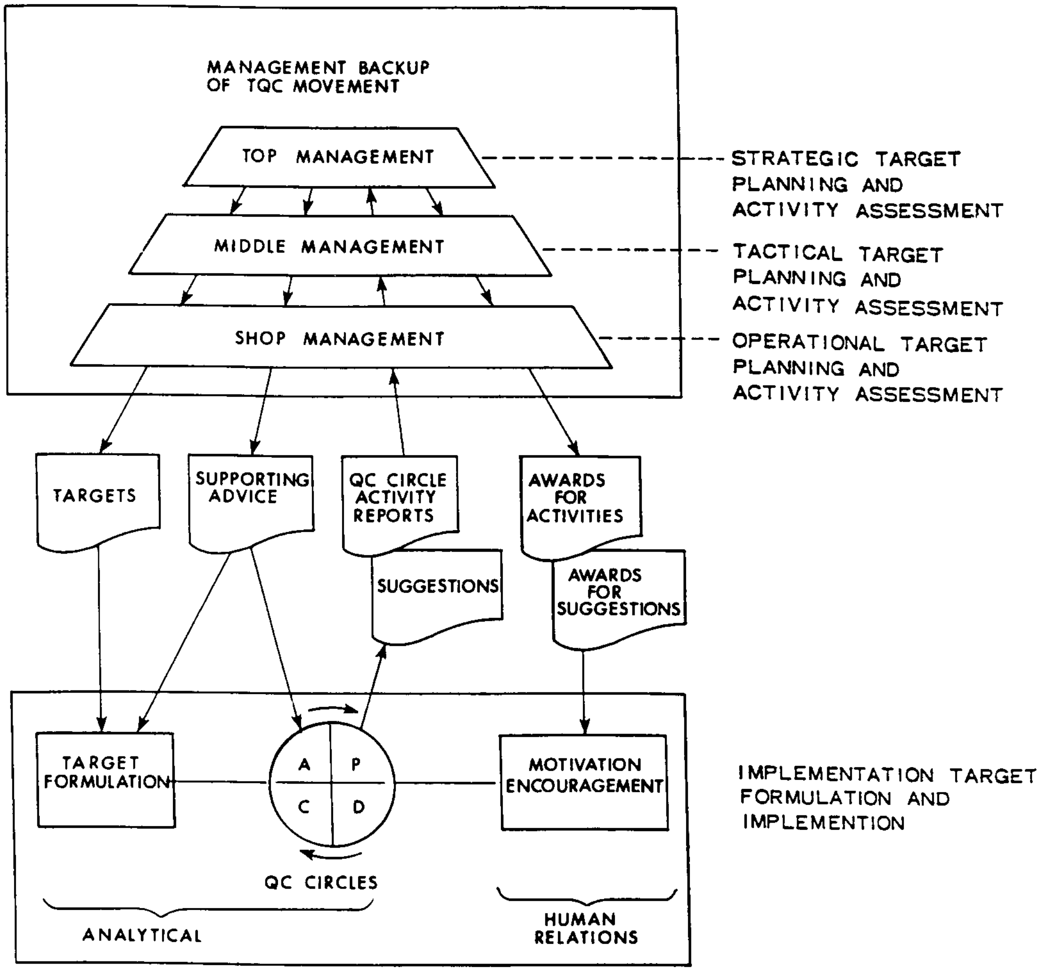


Figure 24
Relationship of Small Group Activities to Organizational Goals