Measurement System Analysis for Process Control at Company XYZ

by

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ABSTRACT

Company XYZ is a glass manufacturer located in west central Wisconsin. Founded in 1962, it has led the industry in the development of durable float glass. In order to expand business, satisfy growing customer demands, meet customer expectation and requirements, and to be more effective in the global market, Company XYZ is building a new plant in Washington D.C. Therefore, the plant in Wisconsin has the opportunity to evaluate the possibility to replace current equipment, especially laser inspection system. If this system needs to be replaced at the Wisconsin facility, they will have the option to purchase new equipment for both plants in order to get a better price from suppliers in Europe.

The purpose of this research project is to evaluate the quality of performance of the laser inspection system in a continuous fully automatic and computer controlled production line. A measurement system analysis for process control will be conducted by using process capability, gage reproducibility, and gage repeatability studies to analyze the inspection system.

For this quantitative research, the data collection results were analyzed by using statistical software to evaluate process capability, gage repeatability, and gage reproducibility. The data analysis indicated that the laser inspection system is working satisfactorily under the quality parameters of the Company XYZ.

The study will conclude with recommendations to improve this analysis for future evaluations of the laser inspection system at the Company XYZ and a general recommendation for this company to improve its work environment and business processes.

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Chapter I: Introduction

The growing competition in the current global market is an issue translating into a vast need for the continuing evolution of the industry. Therefore, world business is continually in search for the competitive edge due to the growing demands of customer needs and expectations. Quality has an important role in the business process across the entire organization, to be more efficient and effective in the global market, thus improving productivity and customer loyalty as well as increase market share.

By using quality assurance systems and methodologies to accomplish the requirements for the final product or service, companies can increase performances, profit, employee morale and quality of products, while decreasing the lead-time and costs.

Company XYZ is a glass manufacturer located in west central Wisconsin. Since its founding it has led the industry in the development of durable float glass for the residential market. By using a sophisticated system, Company XYZ is producing float glass in a nonstop environment with capability to produce different thicknesses of glass (from 1.6 to 7mm). The main components use to manufacture float glass the production process are silica sand, calcium oxide, soda and magnesium. First the components are tested, then weighed in the right proportion and then mixed into batches. In this process the recycled glass is added, in order to reduce the utilization of both costs and energy. The batched raw materials pass from a mixing silo into the chambers of the heating system or furnace where they become molten at an average temperature of 1500°C. The inspection system carefully monitors each step in the process. The molten glass is floated onto a bath of molten tin at a temperature of about 1000°C. After the bath of molten tin, the glass temperature cools down which is necessary to pass to an annealing chamber to temper and strengthen the glass. The glass is now hard enough to pass over rollers and is annealed. After cooling, the glass undergoes rigorous quality checks by lasers from the laser inspection system, to detect the defects out of parameters, in order to meet the specifications and requirements of the customers. It is then cut into sheets, to the format of client demands, and then is stacked and stored ready for transport and delivery. The entire production process from the batching of raw materials to cutting and stocking is fully automatic and computer controlled with strict quality regulations (*Float Glass Production*, 2004).

Company XYZ is building a new facility in Washington D.C. to satisfy its growing, both national and international, customers' demands, expectations and requirements. By developing the new facility, the Wisconsin plant will evaluate the opportunities to replace its laser inspection system or continue working with its current equipment. If the system needs to be replaced at the Wisconsin facility, the option exists to purchase new equipment for both plants in order to get a better price from suppliers in Europe.

Statement of the Problem

How can the quality of reading and detecting defects of the lasers at the laser inspection system, by using process capability, and gage reproducibility and repeatability studies, for Company XYZ be analyzed?

Purpose of the Study

The purpose of this research project was to evaluate the quality of performance of the laser inspection system in a fully automatic and computer controlled production line.

Assumptions of the Study

The assumptions of this study included the following:

1. The laser inspection system was in good condition, installed and operated correctly.

2. The laser inspection system could present some variance by reading and detecting defects.
3. The laser inspection system could detect different sizes and defects on the production line.
4. The experience and knowledge of the quality manager to manage this project.
5. All data was collected under normal operation at the facility.
6. The collection of all data for this study was collected by personnel that are experienced and well qualified.

Definition of Terms

The following definitions were included:

Accuracy. Used to describe the degree to which the measurement result reflects reality; accuracy is the statement made withy defines how closely the measured value approximates the true value of a characteristic (Kimber, Greiner and Held, 1997, p. 612).

Analysis of variance (ANOVA). A statistical method for dividing the total variations into components corresponding to several sources of variation in a process. This method is concerned with finding out if averages differ and only uses the variance as a tool to help make a wise decision (Baker, 1994, p. 228). Analysis of the impacts of variances caused by factors. ANOVA is performed after the decomposition of the total sum of square (Taguchi, Chowdhury & Wu, 2005, p. 1618).

Annealing. Under natural conditions, the surface of molten glass will cool more rapidly than the centre. This results in internal stresses which may cause the glass sheet or object to crack, shatter or even explode some time later. The annealing process is designed to eliminate or limit such stresses by submitting the glass to strictly controlled cooling in a special oven known as a "lehr". Inside the lehr, the glass is allowed to cool to a temperature known as the "annealing point". When the glass reaches this point, the lehr temperature is stabilized for a specific length of time (depending on the glass type, its thickness, its coefficient of expansion and the amount of residual stress required) to allow stresses present in the glass to relax. This phase is followed by a period of cooling with a pre-defined temperature gradient (*Glass On line*).

Assignable Causes. A name of resource of variation in a process that is not due to chance and therefore can be identified and eliminated. Also called "special causes" (Bauer, Duffy & Westcott, 2002, p. 148).

Bar graph. Horizontal or vertical bars that summarize and present data in an easily understood manner to describe different situations or scenarios.

Control Charts. An effective tool to monitor and manage a process. A procedure used to track a process with time for the purpose of determining if sporadic or chronic problems (common or special causes) exist (Breyfogle, 2003, p. 1103).

Control Limits. The expected boundaries of a process within specified confidence levels to achieve the quality standards and requirements, expressed as the upper control limit (UCL), and the lower control limit (LCL).

Common Causes. A source of process variation that is inherent to the process and is common to all the data. Also called "chance cause" (Bauer, Duffy & Westcott, 2002, p. 150).

Defect. Nonconformity of a quality characteristic from its parameters. For this study, the defect will be the objects such as sand, stone or bubble on the glass.

Descriptive Statistic. Techniques for displaying and summarizing data. Descriptive statistics help pull useful information from data, whereas probability provides among other things a basis for essential statistics and sampling plan (Breyfogle, 2003, p. 1104).

Factors. Input or output variables involved in the process.

Float Glass. Float glass is produced by floating a continuous stream of molten glass onto a bath of molten tin. The molten glass spreads onto the surface of the metal and produces a high quality, consistently level sheet of glass that is later heat polished. This method gives the glass uniform thickness and flat surface. The glass has no wave or distortion and is now the standard method for glass production and over 90% of the world production of flat glass is float glass (Float Glass Production, 2004).

Gage. A tool used to obtain measurements. Any device used to obtain measurements. The term is frequently used to refer especially too shop floor devices, including go/no-go devices (Breyfogle, 2003, p. 1107).

Gage Repeatability and Reproducibility (Gage R&R) studies: "The evaluation of measuring instruments to determine capability to yield a precise response" (Breyfogle, 2003, p. 1107).

Gage Repeatability. The difference or variation due to the measurement system. It is the difference or variation due to the measurement device. It is the difference observed when the same operator measures the same part repeatedly with the same device (Breyfogle, 2003).

Gage Reproducibility. The difference or variation due to the measurement system. It is the difference observed when different operators measure the same part using the same device. The interactions variance represents the variation in the average part sizes measured by each operator (Breyfogle, 2003).

Histogram. Vertical bar graph that shows the distribution of data in terms of the frequency of occurrence for specific values of data. A frequency diagram in which bars proportional in area to the class frequencies are erected on the horizontal axis. The width of each section corresponds to the class interval of the variate (Breyfogle, 2003, p. 1108).

Inspection System. The process of measuring, analyzing, testing and comparing something with certain requirements or parameters to determine if the product matches with the specifications.

Interaction. A description for the measure of the differential comparison of response for each level of a factor at each of the several levels of one or more other factors (Breyfogle, 2003, p. 1109).

Mean. A measurement of a central tendency. The arithmetic average of all measurements in a data set (Bauer, Duffy & Westcott, 2002, p.158).

Measurement. The process of analyzing the performance or characteristic of an object, represented by nominal or numerical value.

Measurement System. The whole process of acquiring measurements in the manufacturing or service industry. This involves all the factors that are included in the production system.

Median. A measurement of a central tendency. The middle number or center value of a set of data when all the data are arranged in sequence (Bauer, Duffy & Westcott, 2002, p.158).

Mode. A measurement of a central tendency. The value occurring most frequently in a data set (Bauer, Duffy & Westcott, 2002, p.159).

Population. The totality of items under consideration (Breyfogle, 2003, p. 1113).

Precision. The net effect of discrimination, sensitivity, and repeatability over the operating range (size, range, and time) of the measurement system (Breyfogle, 2003, p. 1113).

Process Capability. A statistical measurement of the inherent process variability for a given characteristic (Bauer, Dufy and Westcott, 2002, p. 161).

Quality Assurance. Actions, methodology, or activities taken to meet a service or product requirement that matches costumer expectation and satisfaction.

Quality Tool. An instrument or technique that is used to support and/or improve the activities of process quality management and improvements (Bauer, Duffy and Westcott, 2002, p.163).

Range. A measurement of dispersion. Difference between the maximum or highest value and the minimum or lowest value in a data set.

Sample. A group unit or number of observations taken from a population to analyze in a minor scale to make a decision or tendency. One or more observations drawn from a larger collection of observations, or universe (population) (Adams, Gupta and Wilson, 2003, p.281).

Scatter Diagram. A graph used to determine the relationship between two kinds of data or the tendency in a process.

Standard Deviation. A measurement of dispersion. A compute measurement of variability indicating the spread of the data set around the mean (Bauer, Duffy & Westcott, 2002, p.165).

Statistical Process Control (SPC). Application of statistical techniques in a process to control procedures and avoid undesirable variation.

Variation. A chance in data that may be due to a special cause, a common cause, or tampering; also, the amount a value deviates from that to which it is compared, as in accounting, meteorology, etc (Bauer, Duffy & Westcott, 2002, p.168).

Methodology

For this quantitative research, the methodology used was to conduct a gage repeatability and reproducibility study, and process capability. The population was all the defects with different sizes and features that the laser inspection system can detect and all the workers at the plant. Several types of sampling techniques were used in this study. Stratified sampling was used to obtain a sub-group from the population which was the category of small defects and the workers that work at the process area. Then, the sample was randomized and determined by choosing four defects from the small category of defects and three workers from the process area.

Chapter II: Literature Review

World business is continually in search for the competitive edge due to the growing demands of customer needs and expectations. Therefore, the current market is moving toward the evolution and the innovations of technology, to enhance the quality in the business process by increasing effectiveness, efficiency, service levels, productions, market share, customer loyalty and profit, while reducing costs and lead times.

The purpose of this research project was to evaluate the performance quality of the reading and detecting defects, of the laser inspection system in a fully automatic and computer controlled production line, for Company XYZ. A measurement system analysis for process control was conducted by using process capability, gage reproducibility, and gage repeatability studies to evaluate the inspection system.

Quality

According to Montgomery (2005), quality is one of the most important decision factors in the selection of products and services. Therefore, quality leads to business success, growth, and increases competitiveness, as well as improves the work environment. Additionally, it involves the employee in achieving the corporate goals and brings a substantial return of investment. The study and the analysis of quality must be aimed at understanding, meeting, exceed and surpassing customer needs and expectations (Kolarik, 1995).

Miller and Miller (1995) correlated quality to performance, reliability and maintainability. Performance creates standards by using the same features and capabilities for a product or service. Reliability applies quality consistently during the process or the market product life. Maintainability offers a product or services with minimal repairs or adjustment.

The increasing development of industrial automation has driven today's corporation to assure a stable operation in an automatic control system. In such systems, the process can be monitored and controlled from a central control room to work under the quality parameters or specifications. Therefore, the use of automation in industrial processes improves productivity, product quality, and the corporate environment (Balchen & Mumme, 1988).

Process Control

A process is the adjustment or alteration of raw material into a final product by using labor, instruments, or facilities, according to customer requirements (Oakland, 2003). In each step, monitoring all the procedures involved in the process is essential to produce a quality product which meets customer expectations and requirements.

According to Kirkpatrick (1970), control relates to the use of a restraining or directing influence over a process. Regardless of the process or product that is being directed, control consists of four basic procedures: (1) setting standards, measurement variance from the standards; (2) taking corrective action to minimize the variances; (3) planning for improvements in the standards; and (4) conformance to the standards. Quality control is primarily concerned with product-output conformance to the technical-design specifications.

Ensuring that an aspect of a product conforms to quality specifications is the goal of measurement (Kimber, Grenier, & Heldt, 1997). Incorrectly rejecting products that are compliant with specifications or accepting products that are not compliant is both costly and has a negative effect on a company's reputation. Therefore, the equipment used to make measurements must be accurate to a level higher than the tolerance of the measurement.

Measurement System

Measurement systems for process control are used to reduce defects and make the production process more efficient and effective. "A measurement is a series of manipulations of physical objects, or systems according to a defined protocol, which results in a number" (Benbow, Berger, Elshennawym, & Walker, 2002, p. 174). The number represents the range defined by the specification limits compliant to customer requirements by using process control.

Breyfogle (1999) found "the purpose of a measurement system is to better understand the sources of variation that can influence the results produced by the system" (p. 224).

The elements of a measurement system are all the instrumentations and human factors used in the manufacturing or service processes, to reduce the variability in process, products, and services. Measurement systems indicate the sources of variations that can affect the results or outputs produced by the system and make decisions to improve the processes in an organization. Montgomery (2005) found that determining the capability of the measurement system is an important aspect of many quality and process improvement activities.

Measurement systems can quantify and evaluate the accuracy, precision, repeatability, and reproducibility of any process (Evans & Lindsay, 2002). To measure the accuracy of a process, the observed average of a set of measurements is compared to the true value of a reference standard. A good measurement system will present a very small standard deviation or variation from its data collected. To determine repeatability and reproducibility, a study of variation is required through statistical analysis.

Wang (2004) determine the following:

> *Repeatability* is the measurement variation of the same device caused by one operator several times in measuring the same part or characteristic. To get an accurate and

precise repeatability measurement in any process the specific conditions of measurement shall be defined and fixed factors as:

- Standards or parameters to establish the acceptable range of repeated measurements.
- Operator by considering experience, technique and physical conditions.
- The part or device to measurement (shape, surface, weight).
- The part in the measurement system (position, location).
- The measurement system (conditions, maintenance, clean).
- Methodology: establish the same technique to measure the same device.
- Assumptions and environment (temperature, humidity, atmospheric pressure, lighting, cleanliness, vibration).

Reproducibility is the average measurement variation of the same part on the same device observed by different operators. This average of variations determines the variations between conditions or systems of measurement. An adequate reproducibility in a measurement system should be defined by the following factors:

- Average between instruments by using the same operator, technique, part and environment.
- Average between parts by using the same instrument, methodology and operator.
- Average between methods.
- Average between operators by considering the skills, techniques, training and experience.
- Average between environments. (p. 8-10)

Statistical Tools

Statistical tools allow measurement and evaluation of the performance in a process to improve its quality. The tools frequently used to support decision making. According to Montgomery (2005), statistical tools can be helpful in developing activities previous to manufacturing, in measuring process variability, in analyzing this variability relative to product requirements or specifications, and in eliminating or greatly reducing variability in process. These tools allow the interpretation of the process by detecting when the variables change and experimentation by knowing how the variables can change by experimental designs (Ott, Schilling & Neubauer, 2000).

Statistical application in process control is very important to establish stability in the manufacturing process and maintain a state of control over an extended period. It provides the measurements of the central tendency: mean, median, mode; the measurement of dispersion: standard deviation, variance, range; and the maximum and the minimum to analyze and measure the variation in a process or product features or characteristics (Mitra, 1993).

Good statistical control of research results indicates good control of the process. Therefore, it is very useful for the analysis and enhancement of a production process (Burr, 2005).

Control Charts

Control charts are very useful to monitor the process which involves detection of out of specification products already produced. When unusual sources of variability are present, the sample average will plot outside the control limits. This tool helps to apply corrective action on the process in the product specifications or in the range of acceptance. Therefore, control charts are also very useful for the analysis and enhancement of a production process, and allow incorporation of the process into the specifications to obtain a good process control and improvement in quality (Burr, 2005).

Ott, Schilling & Neubauer (2000) found that control charts provide a graphical time sequence of data from the process itself. This then allows the use of analysis to evaluate the behavior and performance of a process.

According to Griffith (1996), control charts are the best tool for process control to ensure the detection of special causes of variation during the process and gauging the natural tolerance orientated for normal variation. It helps to make the process capable under the specification limits or tolerance; detect the presence of special causes; and take corrective actions before nonconforming or defecting units are manufactured (Benbow, Berger, Elshennawy & Walker, 2002).

The principal uses of control charts are to help the process operator monitor and identify the existence sources of "variability (special causes) from stable variability" (Stamatis, 2004, p. 61), in a select variable for monitoring, analyze the process, and take appropriate actions to obtain the process inside the control limits. These control limits are calculated from the data collected of the process. (Benbow & Kubiak, 2005).

Control charts allow obtaining a means to check statistical control and to analyze process capability. (Kotz and Lovelace, 1998).

Process Capability

DeGarmo, Black, & Kohser (1999) noted the following:

> The objective of the process capability study is to determine the variability of the process to the desired specifications. The variability may have assignable causes and may be correctable if the causes can be found and eliminated. That variability to which no

cause can be assigned and which cannot be eliminated is inherent in the process and is therefore nature. (p.317)

According to Evans and Lindsay (2002), a process capability establishes the range over which variability is expected to occur in a process that is in control and meets the standards and specifications. It determines if a process can meet the standards and specifications to identify the equipment and control levels required to satisfy the customer demand. This process allows the establishment of new standards or adjustment of existing standards.

Kotz and Lovelace (1998) found that systematic study of a process by means of statistical control charts is necessary in order to discover whether it is a behaving naturally or unnaturally; plus investigation of any behavior to determine its causes; plus actions to determine any of the unnatural behavior which is desirable to eliminate for economic or quality reasons. (p. 230). They suggest the purpose of a process capability is to determine the capability of the entire process to produce quality products. Also they note different scenarios that may occur in the analysis of the process in a production system: process on control and under specification limits; process not in control but under specifications limits; process in control but not under specifications; and process without both not in control and not under specifications limits.

To quantify process capability and represent it in a number some capability indices have been developed. Two of the most common indices are Cpk and Cp. The Cpk index represent where the tendency of the process and indicates the nearest specification limit that it could be; the Cp index does not consider whether the process is centered within the tolerance limits. Historically, these indices value are more than or equal to 1 were considered capable. The value indicates the process is within tolerance limits (Benbok & Kubiak, 2005).

The intent of a process capability study is to determine the capability of the entire process to produce quality products.

Gage Repeatability and Reproducibility

Breyfogle (2003) found that "Traditionally, the tool to address the appraiser/operator consistency is a gage repeatability and reproducibility study, which is the evaluation of measurement instruments to determine capability to yield a precise response" (p. 307).

The objective of a gage repeatability and reproducibility study is to obtain the amount of variation in a measurement system and to allocate that variation to the two categories, repeatability and reproducibility (Benbow & Kubiak, 2005). The measurement variation can be divided into two categories: repeatability and reproducibility (Mitra 1998). Gage repeatability refers to the difference or variation due to the measurement device. It is the difference observed when the same operator measures the same part repeatedly with the same device. Gage reproducibility refers to the difference or variation due to the measurement system. It is the difference observed when different operators measure the same part using the same device. The interactions variance represents the variation in the average part sizes measured by each operator (Mitra, 1998).

Various methods have been developed to conduct a gage repeatability and reproducibility study. Two of the most common methods are the ANOVA method and the average and range method. The ANOVA method is useful to determine the reproducibility variation due to the iteration between the gage and the operators. The average and range method are useful to determine the variability caused by reproducibility and repeatability. It is composed for the following variations: part-to-part, repeatability and reproducibility (Wang, 2004).

The following was taken from *User's Guide 2: Data Analysis and Quality Tools* by MINITAB Statistical Software (p. 11-4). The figure shows the components of total variability of measurements observations:

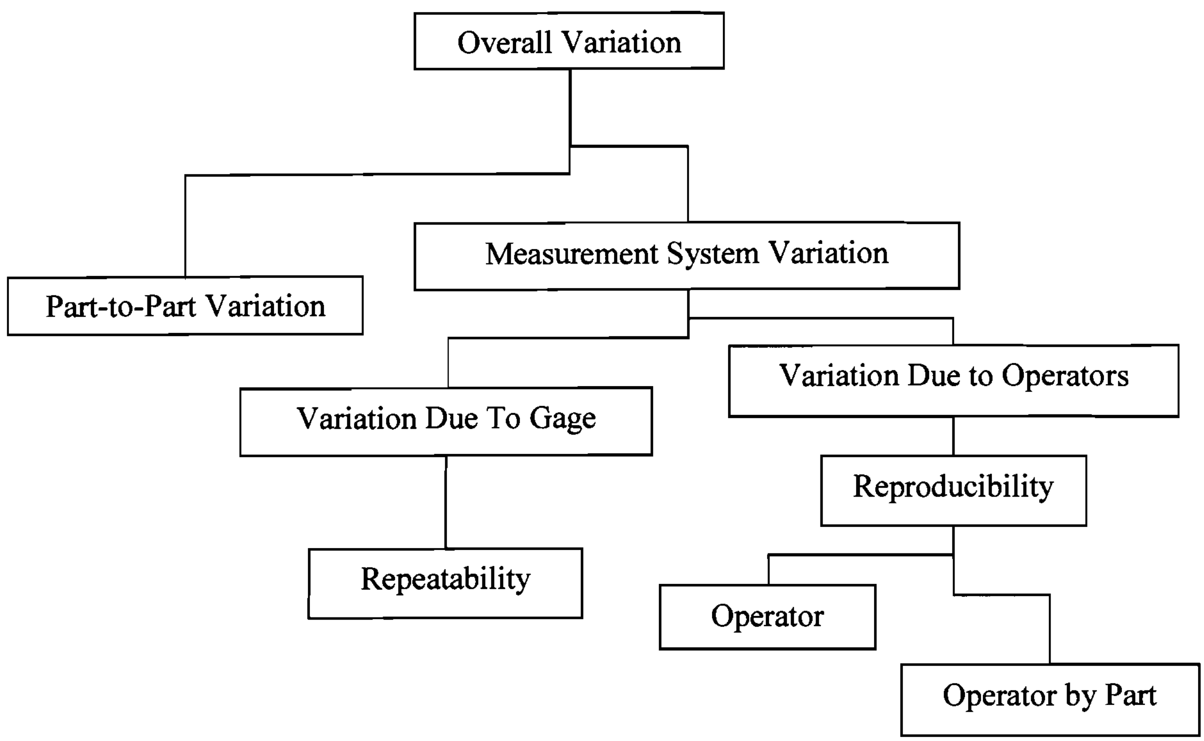

Figure 1. Components of Total Variability of Measurements Observations.

Stamatis (2004) has noted the following:

> Stability and linearity are also measures of measurement and integral part of the repeatability and reproducibility (R & R). Repeatability and reproducibility are indices of measurement error based on relativity short periods of time. Stability describes the consistency of the measurement system over a long period. The additional time period allow further opportunities for the sources of repeatability and reproducibility error to change and add errors to the measurement system. All

> measurement systems should be able to demonstrate stability over time. A control chart made from repeat measurement of the same items documents the level of the system's stability. On the other hand, linearity is the difference in bias errors over the expected operating range of the measurement system. (p. 91)

To conduct a gage R & R study it is important to considerer the following factors: the measurement must be in statistical control or process with common causes of variation; the process to analyze must have a small variation of the measurement system; and the process variation and the specification limits must be in the rage of the increments of measurement (Breyfogle, 1999).

In manufacturing and services industries the quality of the final product or service is very important to increase market demand and match with the customer requirements and expectations. Therefore, by using technology, quality tools, quality control and more emphasis on the philosophy of doing the right thing the first time, variability and errors are reduced in the production system and in all procedures to process the raw materials into outputs.

Chapter III: Methodology

The purpose of this research project was to evaluate the quality performance, of the laser inspection system in a fully automatic, computer controlled production line. A measurement system analysis for process control was conducted by using process capability, gage repeatability, and gage reproducibility studies to analyze the inspection system.

The objectives of this study were: (1) to acquire accurate and realistic information about the performance of the laser inspection system; (2) to conduct a measurement system analysis for process control by using gage repeatability and gage reproducibility studies for this inspection system; (3) to compare the capabilities of reading and detecting defects in each laser and between both lasers in this inspection system; and (4) to analyze the results and to provide Company XYZ a realistic scenario of the opportunities to replace the current laser inspection system.

This chapter will discuss the methodology used for this research study, as well some limitations that it presented.

Subject Selection and Description

For this quantitative research, the population was all the defects with different sizes and features that the laser inspection system can detect and all the workers at the plant. Several types of sampling techniques were used in the study. Stratified sampling was used to obtain a sub-group from the population, which was the category of small defects and the workers in the process area. Then, the sample was randomized and determined by choosing four defects from the small category of defects and three workers from the process area.

The laser inspection system consists of Laser 1 (L1) and Laser 2 (L2). Both lasers are located parallel to each other and are situated after the glass was tempered and strengthened and before the cutting machine on the production line. Both lasers have the same features, calibration, and specifications.

To test the laser inspection system four samples were developed. They labeled as: Defect 1 (D1), Defect 2 (D2), Defect (D3), and Defect 4 (D4). These defects were stratified and randomized from the category of small defects, basically originated for small particles of sand or stone. This category is in the range of defects between 0.080-0.210 mm.

The operators were called: Operator A (A), Operator B (B), and Operator C (C). Each of these operators are skilled, qualified, and knowledgeable for the methods that they need to apply to evaluate the laser inspection system.

This experimental research was conducted in the process area in April 2005 under normal conditions for the production process.

Instrumentation

The equipment used to collect the data were the lasers at the laser inspection system and the quality control system at the control tower to detect and read all the features of the defects. The equipment also checked the performance of the lasers by using an automatic and computer controlled system.

A check sheet was used to compile the data for this study. The data colleted was analyzed by using MINITAB Statistical Software, version 14, to (1) acquire the maximum, minimum, mean and the standard deviation of the reading for each laser (L1 and L2) and for each defect (D1, D2, D3, and D4); (2) to measure the variation of the reading defects at the laser inspection system; and (3) to obtain the capability of this system to read the defects and the gage reproducibility and repeatability by using the operators. The MINITAB software enabled a better and more realistic scenario of this inspection system.

Data Collection Procedures

Once the quality manager of Company XYZ chose the category of the size and the defects to analyze and the three operators, the data could begin to be collected. The gage repeatability and reproducibility study consisted of the operators (A, B, and C) measuring each of the four defects (D1, D2, D3, and D4) 10 times to be read for each laser (Laser 1 and Laser 2). With this information the study was obtained the data (240 outputs) to analyze by using statistical software. In other words, these values were represented the size of each defect (D1, D2, D3 and D4), by reading each defect 10 times in each laser (L1 and L2), by each operator (A, B and C).

Data Analysis

This study analyzed the data by using MINITAB Statistical Software to evaluate the gage repeatability study, gage reproducibility study, and process capability. From interpretation of the control charts, bar graphs, histograms, and scatter diagram, the results of the performance of the laser inspections system and the parameters to make the right recommendations and suggestions have been determined.

Limitations

This study presented some possible limitations on the data collected. The defects selected have irregular shape. Also, the results were considered assuming that the operators put the sample on the production line at the same location, to evaluate the reproducibility and repeatability methodologies.

Another limitation was the probability that the glass on the production line has a defect at the same location that the sample has the defect to examine or where the operator set the sample on the production line. This possibility might influence in the results or the reading of the laser.

The last limitation was the accuracy of the lasers, software, and equipment used in this research study.

Chapter IV: Results

As stated in Chapter 1, the statement of the problem was: How can the quality of reading and detecting defects of the lasers at the laser inspection system, by using process capability, and gage reproducibility and repeatability studies, for Company XYZ be analyzed? And the purpose of this research project was to evaluate the quality performance, of the laser inspection system in a fully automatic, computer controlled production line. A measurement system analysis for process control was conducted by using process capability, gage repeatability, and gage reproducibility studies to analyze the inspection system.

The objectives of this study were: (1) to acquire accurate and realistic information about the performance of the laser inspection system; (2) to conduct a measurement system analysis for process control by using gage repeatability and gage reproducibility studies for this inspection system; (3) to compare the capabilities of reading and detecting defects in each laser and between both lasers in this inspection system; and (4) to analyze the results and to provide Company XYZ a realistic scenario of the opportunities to replace the current laser inspection system.

Item Analysis

Appendix A illustrates the data collected. These values represent the size of each defect (D1, D2, D3 and D4) at the laser inspection system, by reading each defect 10 times in each laser (Laser 1 and Laser 2) by each operator (A, B and C). Also, this table shows both the maximum and the minimum values, with the frequency and the percentage that it represents over the total of 30 readings for each defect in Laser 1 and Laser 2.

Table 1 indicates the maximum and the minimum values of 10 ten times reading of each defect, in each laser by each operator. These values show the variability of repeated measurement of the same defect, by the same operator, in each laser.

Table 1

Maximum and Minimum of Each Defect

Operator		Laser 1 (Left) Defects				Laser 2 (Right) Defects			
		D1 L1	D2 L2	D3 L1	D4 L1	D1 L2	D2 L2	D3 L2	D4 L2
A	Maximum	0.122	0.173	0.215	0.144	0.118	0.167	0.193	0.138
A	Minimum	0.100	0.142	0.177	0.122	0.100	0.148	0.148	0.122
B	Maximum	0.122	0.167	0.213	0.142	0.120	0.167	0.187	0.136
B	Minimum	0.100	0.156	0.179	0.122	0.106	0.152	0.167	0.122
C	Maximum	0.122	0.167	0.217	0.138	0.116	0.163	0.189	0.138
C	Minimum	0.100	0.144	0.177	0.122	0.102	0.146	0.162	0.122

The values on Table 2 display the range of the readings between each laser (Laser 1 and Laser 2) of each defect by each operator. In other words, it shows the variability of reproducibility measurement between the Laser 1 and Laser 2 by using the same defect and same operator. The maximum and the minimum values showed on Table 1 were used to obtain these range values.

Table 2

Difference Between Laser 1 and Laser 2

		Defects			
Operator		D1	D2	D3	D4
A	Maximum	0.004	0.006	0.022	0.006
A	Minimum	0.000	0.006	0.029	0.000
B	Maximum	0.002	0.000	0.026	0.006
B	Minimum	0.006	0.004	0.012	0.000
C	Maximum	0.006	0.004	0.028	0.000
C	Minimum	0.002	0.002	0.015	0.000

As the above tables have shown, there are some variations of the reading defects in each laser and also between lasers, that may contained or caused for assignable causes or common causes.

MINITAB 14 statistical software was used to calculate the mean, standard deviation and the specification limits (upper specification limit [USL] and lower specification limit [LSL]) to analyze the process capability, gage reproducibility, and gage repeatability for each defect in each laser and between both lasers. This data is shown in Table 3. The upper specification limit and lower specification limit also are called the upper and lower tolerance limits (DeGarmo, Black, & Kohser, 1997).

Table 3

Statistical Information and Control Limits

	Laser 1 (Left) Defects				Laser 2 (Right) Defects			
	D1 L1	D2 L1	D3 L1	D4 L1	D1 L2	D2 L2	D3 L2	D4 L2
Mean	0.11133	0.15877	0.19337	0.13253	0.11040	0.15793	0.17910	0.12907
Sta Dev	0.00783	0.00839	0.01117	0.00724	0.00552	0.00539	0.00939	0.00495
LSL	0.08784	0.13360	0.15986	0.11081	0.09384	0.14176	0.15093	0.11422
USL	0.13482	0.18394	0.22688	0.15425	0.12696	0.17410	0.20727	0.14392

Table 4 indicates the difference of the statistical information between each defect for each laser. This table shows a very low variation of the reading of the defects between the lasers. Also, the difference between the means of the defect obtained from Laser 1 and Laser 2 is very close to zero. That could represent that the laser inspection system was working in a good condition and was providing accurate information. But, the gage reproducibility and gage repeatability provides a more realistic scenario.

Table 4

Statistical Information by Analyzing all the Reading defects in each, Laser 1 and Laser 2, at the Laser Inspection System.

	Defects			
	D1	D2	D3	D4
Mean	0.00093	0.00084	0.01427	0.00346
St. Dev.	0.00231	0.00300	0.00178	0.00229
LSL	0.00600	0.00816	0.00893	0.00341
USL	0.00786	0.00984	0.01961	0.01033

Table 5 provides information of the process capability for each defect in each laser. When the Cp and the Cpk are more than or equal to one, the process is in control and meets the design specifications. In other words, the process is capable. This table shows that defect 4 (D4) is not capable with its specifications for Laser 1 and Laser 2 because the value in both indices are below one. It indicated that this process cannot meet the requirements of the experimental design. The complete information for the process capability is in Appendix B.

Table 5

Process Capability

	Laser 1 (Left)				Laser 2 (Right)			
	Defects				Defects			
	D1 L1	D2 L1	D3 L1	D4 L1	D1 L2	D2 L2	D3 L2	D4 L2
Cp	1.03	1.12	1.01	0.99	1.04	1.10	1.04	0.95
Cpk	1.03	1.12	1.01	0.99	1.04	1.09	1.04	0.95

Tables 6 to 8, show the analysis of variance with different scenarios between the operator, defects and lasers as the results of the gage repeatability and reproducibility for the dimension defect in Laser 1, Laser 2 and for both lasers.

The "p value" is the smallest level of significance. It represents the statistical significance or relationship between the analyzed parts. According to the quality parameters from Company XYZ when the "p value" is less than 0.25, by using ANOVA method, it represents a very accurate process and MINITAB statistical software would use the full model with all interaction. But, when this value is more than 0.25 the software would reduce the model without interaction.

Table 6 and Table 7 show the analysis of variance with operator and the part interaction, in other words the relation between each operator with each defect on Laser 1 and Laser 2 respectively. The readings of the defects at the Laser 1 present a better performance (p=0.057) than the Laser 2 (p=0.98). Laser 1 is more precise by reading defects and has smaller variation. However, when the "p value" is more than 0.25, MINITAB statistical software would run the model with no iteration. The "p value" in Laser 2 is equal 0.980, which represents that it has a poor interaction between the dimensions of each defect and each operator and then the model calculates a new "p value" without interactions. Table 8 shows the new "p value" for Laser 2 equal 0.128.

Table 6

*Analysis of Variance Table with Operator*Part Interaction – Laser 1*

Source	DF	SS	MS	F	P
Part Num Las	3	0.112612	0.0375372	240.003	0.000
Operator Las	2	0.000042	0.0000212	0.136	0.876
Part Num Las * Operator Las	6	0.000938	0.0001564	2.116	*0.057*
Repeatability	108	0.007982	0.0000739		
Total	119	0.121574			

Table 7

*Analysis of Variance Table with Operator*Part Interaction – Laser 2*

Source	DF	SS	MS	F	P
Part Num Las	3	0.0833415	0.0277805	3392.46	0.00
Operator Las	2	0.0001766	0.0000883	10.78	0.01
Part Num Las * Operator Las	6	0.0000491	0.0000082	0.19	*0.98*
Repeatability	108	0.0047659	0.0000441		
Total	119	0.0883331			

Table 8

*Analysis of Variance Table with Operator*Part Without Interaction – Laser 2*

Source	DF	SS	MS	F	P
Part Num Las	3	0.0833415	0.0277805	657.727	0.00
Operator Las	2	0.0001766	0.0000883	2.091	*0.128*
Repeatability	114	0.0048150	0.0000422		
Total	119	0.0883331			

The guidelines for acceptance of the total gage repeatability and reproducibility value for the measurement system are: (1) under 10% is acceptable satisfactory; (2) 10% to 30% error may be acceptable and its rejection will be consider by analyzing other factors such costs; and (3) over 30% error is not satisfactory (Wang, 2004).

Table 9 and Table 10 provide the variance component given by each source for the total gage repeatability and reproducibility of Laser 1 and Laser 2, respectively. At Laser 1, the total gage repeatability and reproducibility is equal to 6.19% and for the Laser 2, it is equal to 4.42%. This indicated that the Laser 1 and Laser 2 were reading the dimension of each defect with high precision and satisfactory. It was determined by adding the percentage obtained from the repeatability plus the variance between each operator, which was very low for both lasers and it reflected the reproducibility. The high percentage in the part-to-part, at laser 1 equals 93.81% and 95.52% for Laser 2, meaning that each defect did not have any relations or approximations between each dimension of each defect. The sum of the percentage of the total gage repeatability and reproducibility and the percentage of the part-to-part was the total variation of the analysis for each laser at the laser inspection system.

Table 9

Gage Repeatability and Reproducibility Laser 1

Source	VarComp	% Contribution (Of VarComp)
Total Gage R & R	0.0000822	*6.19*
Repeatability	0.0000739	5.56
Reproducibility	0.0000082	0.62
Operator Las	0.0000000	0.00
Operator Las*Part Num Las	0.0000082	0.62
Part-To-Part	0.0012460	93.81
Total Variation	0.0013282	100.00

Table 10

Gage Repeatability and Reproducibility Laser 2

Source	VarComp	% Contribution (Of VarComp)
Total Gage R & R	0.0000434	*4.48*
Repeatability	0.0000422	4.36
Reproducibility	0.0000012	0.12
Operator Las	0.0000012	0.12
Part-To-Part	0.0009246	95.52
Total Variation	0.000968	100

Table 11 and Table 12 provide the variation of gage reproducibility and the gage repeatability at Laser 1 and at Laser 2, respectively. Other important information from this table is the "number of distinct categories" that according to AIAG (Automobile Industry Action Group, 2002) more than five represents an acceptable measurement system.

Table 11

Variation Gage Repeatability and Reproducibility Study Laser 1

Source	St. Dev. (SD)	Study Var. % Study Var (6 * SD)	% Study Var (%SV)
Total Gage R & R	0.0090639	0.054383	24.87
Repeatability	0.0085967	0.051580	23.59
Reproducibility	0.0028723	0.017234	7.88
Operator Las	0.0000000	0.000000	0.00
Operator Las*Part	0.0028723	0.017234	7.88
Num Las			
Part-To-Part	0.0352991	0.211795	96.86
Total Variation	0.0364442	0.218665	100

Number of Distinct Categories = 5

Table 12

Variation Gage Repeatability and Reproducibility Study Laser 2

Source	St. Dev. (SD)	Study Var. % Study Var (6 * SD)	% Study Var (%SV)
Total Gage R & R	0.0065870	0.039522	21.17
Repeatability	0.0064990	0.038994	20.89
Reproducibility	0.0010731	0.006439	3.45
Operator Las	0.0010731	0.006439	3.45
Part-To-Part	0.0304074	0.182444	97.73
Total Variation	0.0311127	0.186676	100

Number of Distinct Categories = *6*

Table 13 and 14 show a summary of the results of the gage repeatability and gage reproducibility study in Laser 1 and Laser 2 at the laser inspection system.

Table 13

Gage Repeatability and Reproducibility for Dimension Defect in Laser 1

	Variance Component
P Value	0.057
Total Gage R & R	6.19%
Repeatability	5.56%
Reproducibility	0.62%
Part to Part	93.81%
Number of Distinct Categories	5

Table 14

Gage Repeatability and Reproducibility for Dimension Defect in Laser 2

	Variance Component
P Value (with interactions)	0.980
P Value (without interactions)	0.128
Total Gage R & R	4.48%
Repeatability	4.36%
Reproducibility	0.12%
Part to Part	95.52%
Number of Distinct Categories	6

The detailed information and graphs of the gage repeatability and reproducibility study for Laser 1 and Laser 2, are located in Appendix C.

The following tables show the results of the gage repeatability and reproducibility studies to analyze the accuracy at the laser inspection system between Laser 1 and Laser 2. To assure both Laser 1 and Laser 2 were measuring and reading the same defect with a very low variation between readings. This information determined the accuracy and precision of the laser inspection system at Company XYZ. In others words, it gave a better information about the reproducibility of the laser inspection system.

Table 15 indicates that the "p value" for the gage repeatability and reproducibility study between the Laser 1 and the Laser 2 is equal 0.231 which is less than 0.25 and represent an accuracy process by using ANOVA method. Therefore, MINITAB software calculated this study with iterations.

Table 15

*Analysis of Variance Table with Operator*Part Interaction – L1 and L2*

Source	DF	SS	MS	F	P
Part Num L1/	3	0.194122	0.0647074	656.604	0.000
Operator L1/	2	0.000116	0.5880000	0.588	0.584
Part Num L1/ * Operator L1	6	0.000591	1.3610000	1.361	*0.231*
Repeatability	228	0.016504	0.0000724		
Total	239	0.211333			

Table 16 provides percentage of contribution of the variation of this analysis. The total gage repeatability and reproducibility percentage of variation is equal 6.41 which is the sum of the variation percentage of repeatability and the variation percentage of reproducibility. The value represented a good measurement system for this study. Laser 1 and Laser 2 were measuring and reading the defects with high accuracy and precision by giving readings with a very low variation.

Table 16

Gage Repeatability and Reproducibility Between Laser 1 and Laser 2

Source	VarComp	% Contribution (Of VarComp)
Total Gage R&R	0.0000737	*6.41*
Repeatability	0.0000724	6.29
Reproducibility	0.0000013	0.11
Operator L1/	0.0000000	0.00
Operator L1/*Part Num L1/	0.0000013	0.11
Part-To-Part	0.0010768	*93.59*
Total Variation	0.0011505	100

Table 17 shows the variation of gage repeatability and reproducibility between the Laser 1 and Laser 2. Also it shows the "number of distinct categories" which is equal to five. According to AIAG (Automobile Industry Action Group, 2002) this value represents an acceptable measurement system.

Table 17

Variation Gage Repeatability and Reproducibility Between Laser 1 and Laser 2

Source	St. Dev. (SD)	Study Var. % Study Var (6 * SD)	% Study Var (%SV)
Total Gage R & R	0.0085844	0.051507	25.31
Repeatability	0.0085079	0.051047	25.08
Reproducibility	0.0011438	0.006863	3.37
Operator L1/	0.0000000	0.000000	0.00
Operator L1/*Part	0.0011438	0.006863	0.37
Num L1/			
Part-To-Part	0.0328148	0.196889	96.74
Total Variation	0.0339191	0.203515	100

Number of Distinct Categories = 5

Table 18 shows a summary of the results of the gage repeatability and reproducibility study between Laser 1 and Laser 2 at the laser inspection system.

Table 18

Gage Repeatability and Reproducibility for Dimension Defect Between Laser 1 and Laser 2

	Variance Component (%)
P Value	0.231
Total Gage R & R	6.41%
Repeatability	6.29%
Reproducibility	0.11%
Part to Part	93.59%
Number of Distinct Categories	5

The detailed information and graphs of the gage repeatability and reproducibility study for Laser 1 and Laser 2, are located in Appendix D.

Chapter V: Discussion

Company XYZ is a glass manufacturer located in west central Wisconsin. Since it was founded it has led the industry in the development of durable float glass. To expand its business, satisfy its growing customer demands, meet customer expectation and requirements, and to be more effective in the global market, Company XYZ is building a new plant in Washington D.C. Therefore, the plant in Wisconsin has the opportunity to evaluate the possibility to update its current equipment, especially its laser inspection system. If it does not work under the quality parameters the company will update the laser inspection system, and will complete the order with the new equipment for the new plant, in order to get a better price from its suppliers in Europe.

The purpose of this research project was to evaluate the quality of performance of the laser inspection system in a fully automatic and computer controlled production line. A measurement system analysis for process control was conducted by using process capability analysis, gage reproducibility and gage repeatability studies to analyze the laser inspection system.

The statement of the problem for this research project was: How can the quality of reading and detecting defects at the lasers of the laser inspection system, by using process capability, and gage reproducibility and repeatability studies, for Company XYZ be analyzed?

For this quantitative research, to conduct a gage repeatability and reproducibility study, and process capability, the population was all the defects with different sizes and features that the laser inspection system could detect and all the workers in the plant. Several types of sampling techniques were used in this study. Stratified sampling was used to obtain a sub-group from the population, which was the category of small defects and the workers that work at the process area. Then the sample was randomized and determined by choosing four defects from the small category of defects and three workers from the process area.

The equipment used to collect the data were the lasers of the laser inspection system and the quality control system at the control tower to detect and read the dimension of the defects, choose the samples, and check the performance of the lasers by using an automatic and computer controlled system. A check sheet was used to assemble and compile the data concerned for this study; the data colleted was analyzed and charted by using statistical software to study the trends of the variations of the reading defects at the laser inspection system.

Data was collected after the quality assurance manager of Company XYZ chose the category of the size of the defects to analyze and the three operators. The gage repeatability and reproducibility study consisted of three operators (A, B, and C) who measured each of the four defects (D1, D2, D3, and D4) ten times for each laser (Laser 1 and Laser 2).

Limitations

The limitations of this study were:

1. The analysis was limited to information provided directly by the Company XYZ.
2. This analysis did not investigate other factors or procedures that influence the quality of the final product.
3. This analysis did not conduct experimental designs to reduce defects on the production system for Company XYZ.
4. This analysis evaluated process capability, gage repeatability, and gage reproducibility by using three standard deviation or 3-sigma for its statistical study.
5. This analysis did not consider financial impacts for the Company XYZ.

Conclusions

This study analyzed the data (240 outputs) by using MINITAB statistical software. From interpretation of the control charts, bar graphs, histograms, scatter diagrams it was determined that the performance of lasers in the laser inspections system was very satisfactory. However the quality assurance manager expected to see lower standard deviations of the data collected for the defects that were reading for Laser 1 and Laser 2. With this study Company XYZ knows that its laser inspection system was giving accurate information regarding the dimensions of the defects for the small category. Therefore, Company XYZ does not need to replace their current laser inspection system.

Recommendations

The recommendation for future research on this topic, or if Company XYZ wants to complete a similar study in the future, is to ensure that the operators put the defects on the production line before the laser inspection system all in the same way to ensure that the lasers are reading the defects similarly. It was noticed through observations that the operators were not putting the defects on the production line in the same manner, resulting in variation in the data collection. This could be a reason why the standard deviation was not at the level that the quality assurance manager was expecting. In future studies, the operator should put each defect in with the same angle in each repetition, in each reproduction, by using the same defect for each Laser (1 and 2) at the laser inspection system, in order to reduce the variation for the data collection and to get more realistic information about the features of each defect.

A general recommendation for Company XYZ is that continuous improvement for any process in all the business process is very important. Therefore, it is very important to train, educate and add value to people, take leadership actions, create and share the corporate vision, align the organization to priorities, empower people to accomplish their work, and reward people when the projects are done. These factors will provide capabilities to the organization in order to be more efficient and effective in the global market, thus improving productivity and increasing market share.

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Appendix A: Data Collected

Operator	Sample	Laser 1 (Left) Defects D1 L1	D2 L1	D3 L1	D4 L1	Laser 2 (Right) Defects D1 L2	D2 L2	D3 L2	D4 L2
A	1	0.100	0.148	0.193	0.142	0.102	0.148	0.173	0.132
	2	0.106	0.144	0.189	0.144	0.108	0.159	0.177	0.128
	3	0.112	0.167	0.195	0.122	0.118	0.154	0.189	0.138
	4	0.102	0.167	0.215	0.136	0.114	0.167	0.183	0.128
	5	0.122	0.142	0.183	0.138	0.118	0.157	0.148	0.132
	6	0.106	0.173	0.177	0.142	0.100	0.157	0.189	0.138
	7	0.106	0.167	0.179	0.138	0.118	0.157	0.189	0.132
	8	0.108	0.159	0.185	0.128	0.116	0.163	0.173	0.128
	9	0.108	0.167	0.193	0.138	0.112	0.167	0.189	0.128
	10	0.106	0.163	0.187	0.138	0.106	0.157	0.193	0.122
B	1	0.106	0.157	0.213	0.142	0.112	0.157	0.173	0.126
	2	0.122	0.157	0.193	0.128	0.110	0.157	0.183	0.122
	3	0.122	0.161	0.204	0.132	0.112	0.157	0.177	0.132
	4	0.102	0.167	0.193	0.138	0.112	0.157	0.177	0.136
	5	0.116	0.157	0.197	0.122	0.120	0.161	0.181	0.128
	6	0.112	0.161	0.199	0.136	0.110	0.152	0.187	0.132
	7	0.106	0.157	0.189	0.126	0.106	0.167	0.183	0.126
	8	0.112	0.167	0.187	0.136	0.106	0.161	0.177	0.136
	9	0.100	0.156	0.183	0.126	0.118	0.167	0.183	0.132
	10	0.122	0.167	0.179	0.142	0.106	0.163	0.167	0.122
C	1	0.122	0.167	0.193	0.126	0.116	0.146	0.169	0.126
	2	0.116	0.163	0.177	0.132	0.110	0.157	0.174	0.126
	3	0.100	0.167	0.207	0.126	0.106	0.157	0.183	0.138
	4	0.112	0.158	0.193	0.122	0.102	0.157	0.189	0.126
	5	0.102	0.152	0.217	0.126	0.102	0.157	0.162	0.122
	6	0.122	0.148	0.187	0.122	0.110	0.163	0.179	0.132
	7	0.116	0.157	0.193	0.138	0.110	0.148	0.187	0.128
	8	0.120	0.146	0.193	0.138	0.106	0.154	0.179	0.126
	9	0.122	0.157	0.215	0.126	0.110	0.157	0.179	0.128
	10	0.112	0.144	0.193	0.126	0.116	0.157	0.181	0.122
Maximum		0.122	0.173	0.217	0.144	0.120	0.167	0.193	0.138
Frequency		7	1	1	1	1	4	1	3
Percentage		23%	3%	3%	3%	3%	13%	3%	10%
Minimum		0.100	0.142	0.177	0.122	0.100	0.146	0.148	0.122
Frequency		3	1	2	4	1	1	1	5
Percentage		10%	3%	7%	13%	3%	3%	3%	17%

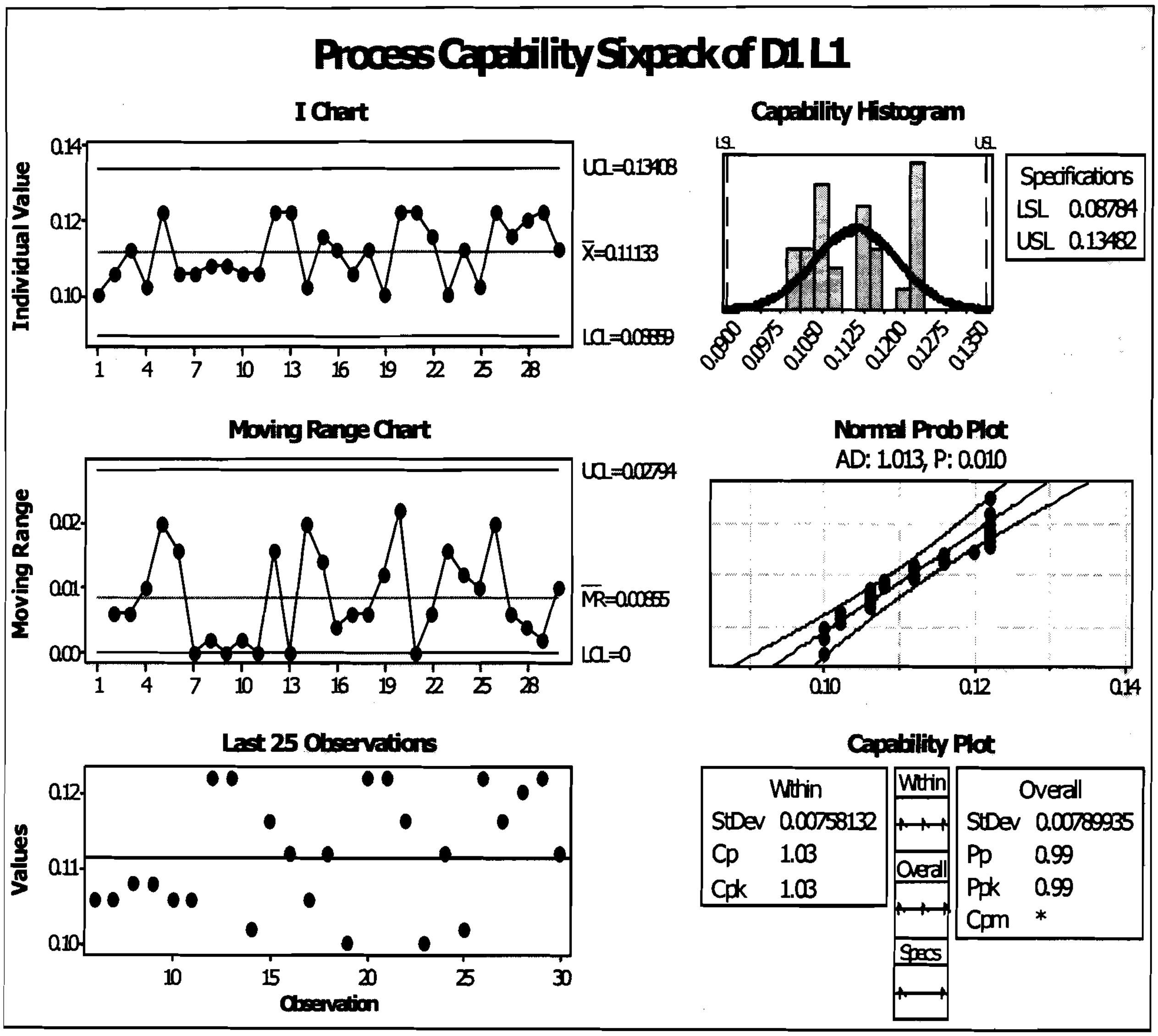
Appendix B: Process Capability for each Defect in each Laser

Descriptive Statistics: Defect 1 in Laser 1 (D1 L1)

Variable	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3
D1 L1	30	0	0.11133	0.00143	0.00783	0.10000	0.10600	0.11200	0.12050

Variable	Maximum
D1 L1	0.12200

LSL = 0.08784 USL = 0.13482

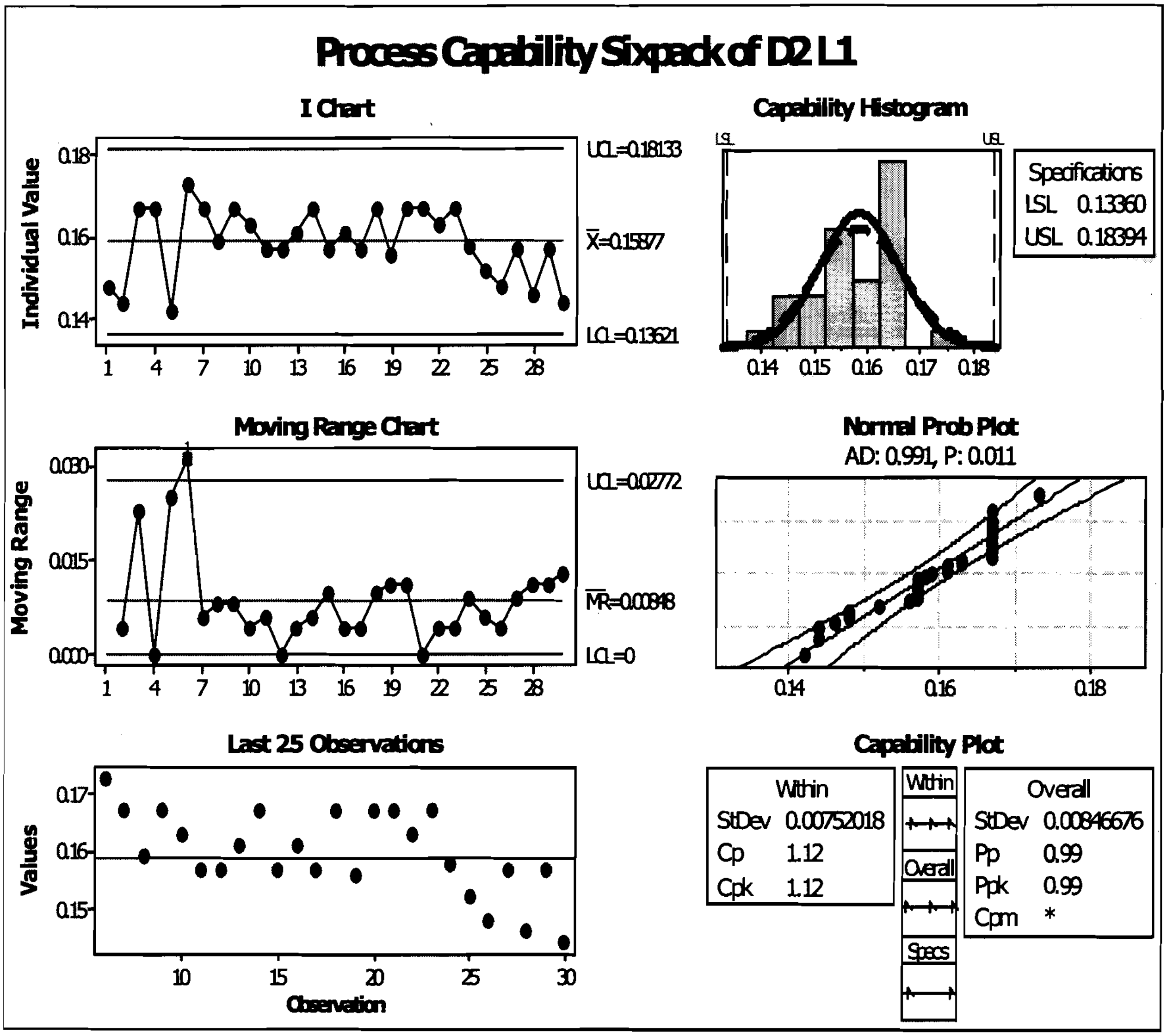


Descriptive Statistics: Defect 2 in Laser 1 (D2 L1)

Variable	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3
D2 L1	30	0	0.15877	0.00153	0.00839	0.14200	0.15500	0.15850	0.16700

Variable	Maximum
D2 L1	0.17300

LSL = 0.13360 USL = 0.18394



Test Results for MR Chart of D2 L1

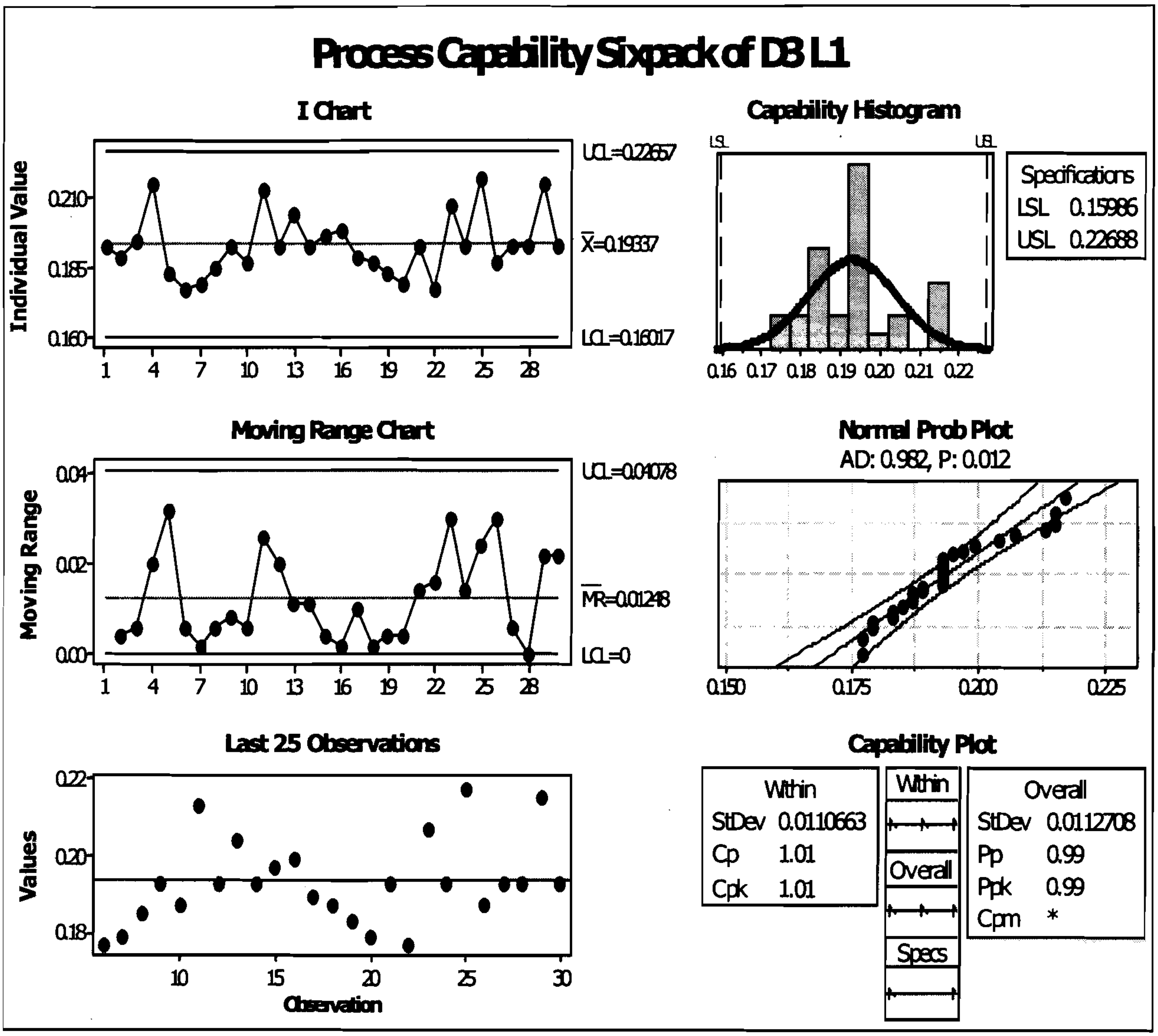
TEST 1. One point more than 3.00 standard deviations from center line.
Test Failed at points: 6

Descriptive Statistics: Defect 3 in Laser 1 (D3 L1)

Variable	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3
D3 L1	30	0	0.19337	0.00204	0.01117	0.17700	0.18650	0.19300	0.19750

Variable	Maximum
D3 L1	0.21700

LSL = 0.15986 USL = 0.22688

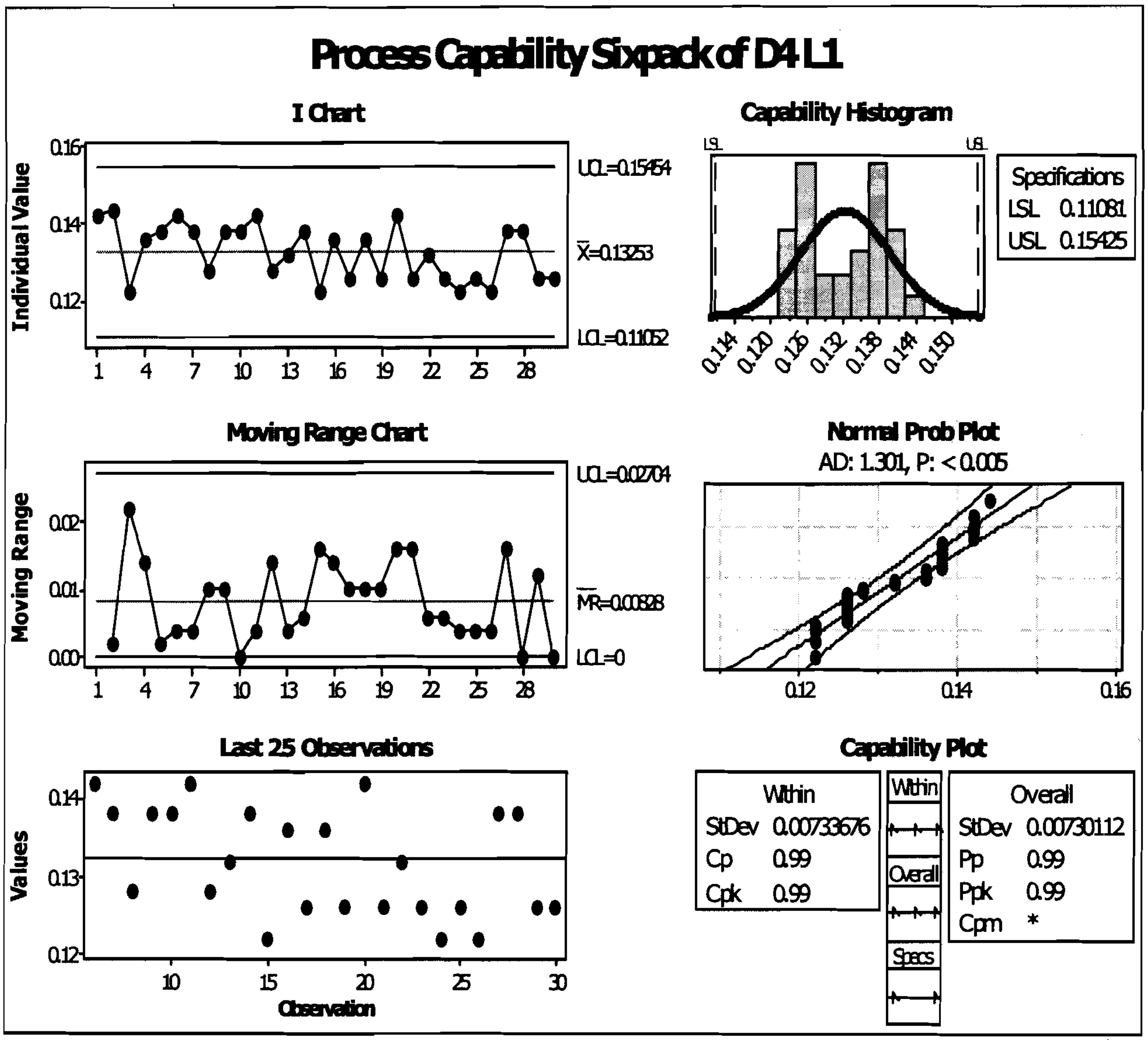


Descriptive Statistics: Defect 4 in Laser 1 (D4 L1)

Variable	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3
D4 L1	30	0	0.13253	0.00132	0.00724	0.12200	0.12600	0.13400	0.13800

Variable	Maximum
D4 L1	0.14400

LSL = 0.11081 USL = 0.15425

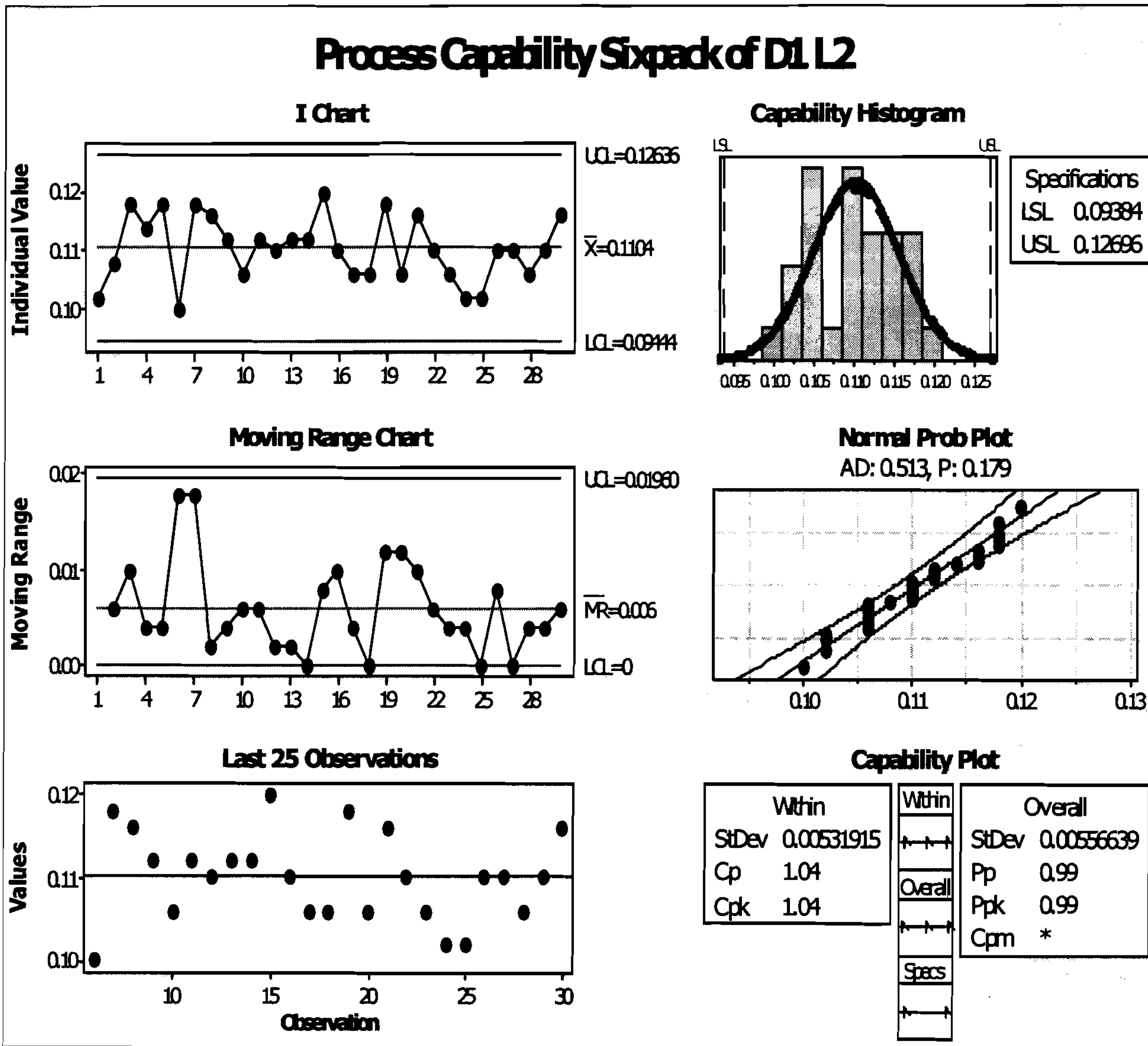


Descriptive Statistics: Defect 1 in Laser 2 (D1 L2)

Variable	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3
D1 L2	30	0	0.11040	0.00101	0.00552	0.10000	0.10600	0.11000	0.11600

Variable	Maximum
D1 L2	0.12000

LSL = 0.09384 USL = 0.12696

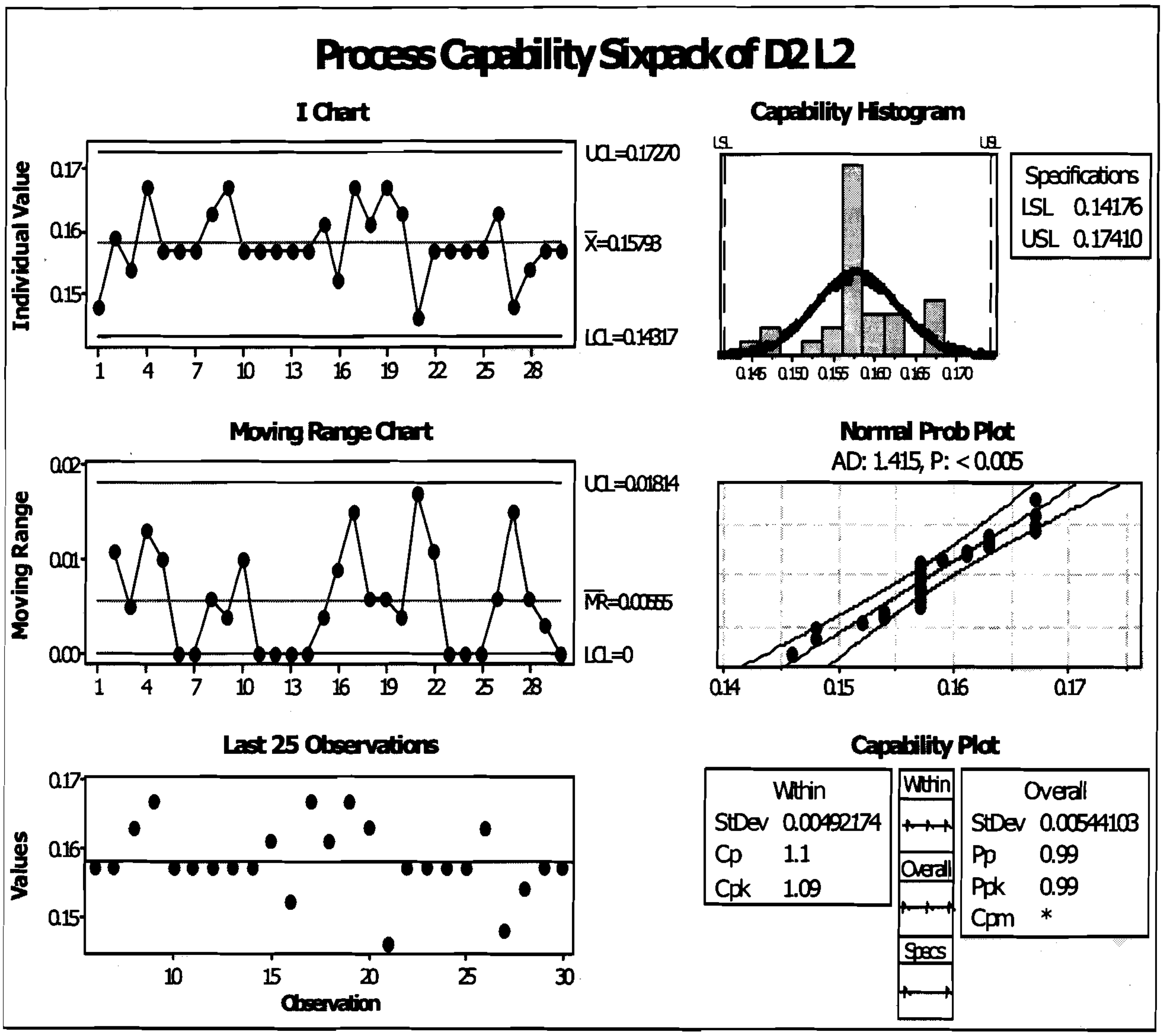


Descriptive Statistics: Defect 2 in Laser 2 (D2 L2)

Variable	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median
D2 L2	30	0	0.15793	0.000985	0.00539	0.14600	0.15700	0.15700

Variable	Q3	Maximum
D2 L2	0.16150	0.16700

LSL = 0.14176 USL = 0.17410

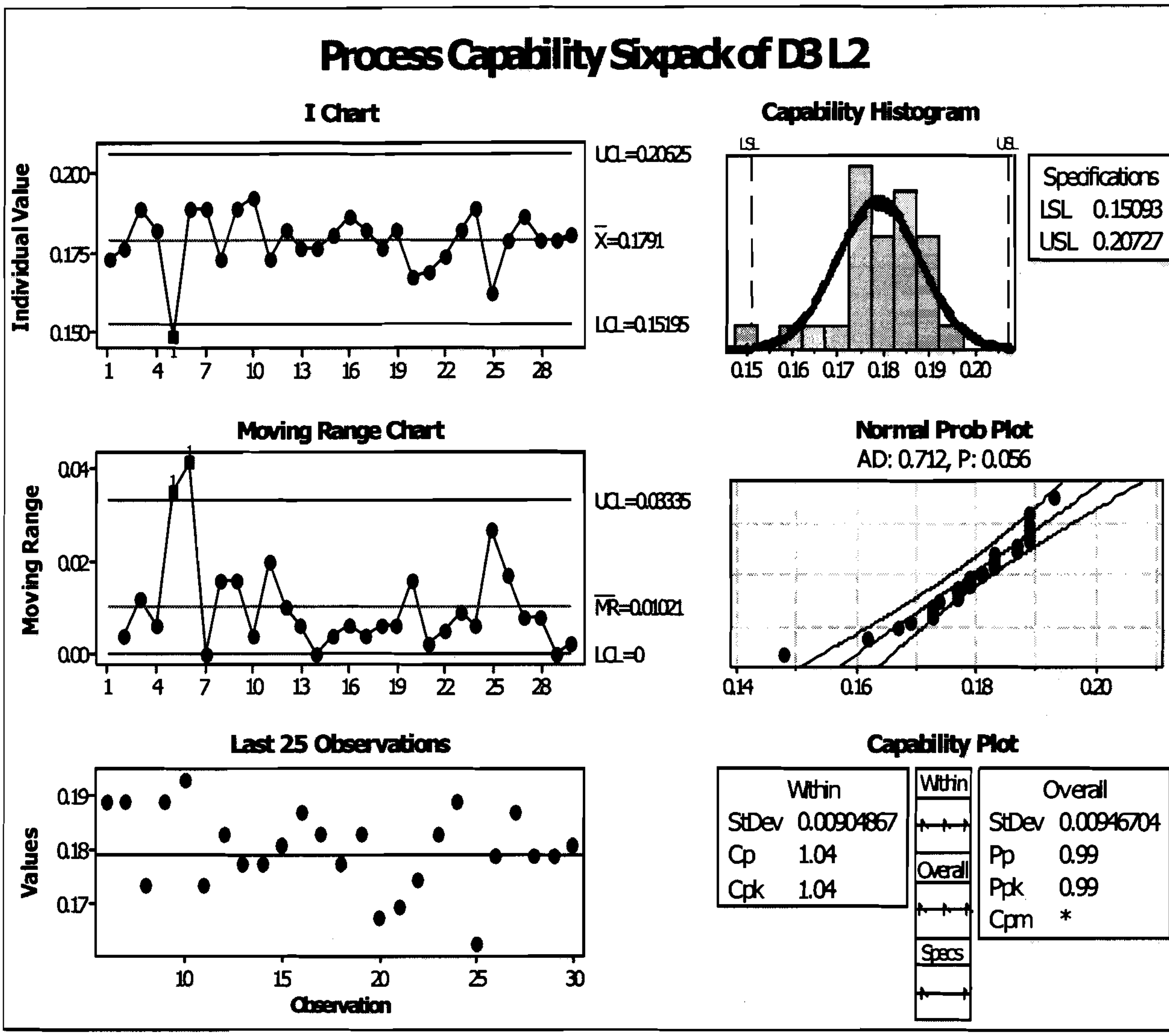


Descriptive Statistics: Defect 3 in Laser 2 (D3 L2)

Variable	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3
D3 L2	30	0	0.17910	0.00171	0.00939	0.14800	0.17375	0.18000	0.18700

Variable	Maximum
D3 L2	0.19300

LSL = 0.15093 USL = 0.20727



Test Results for MR Chart of D3 L2

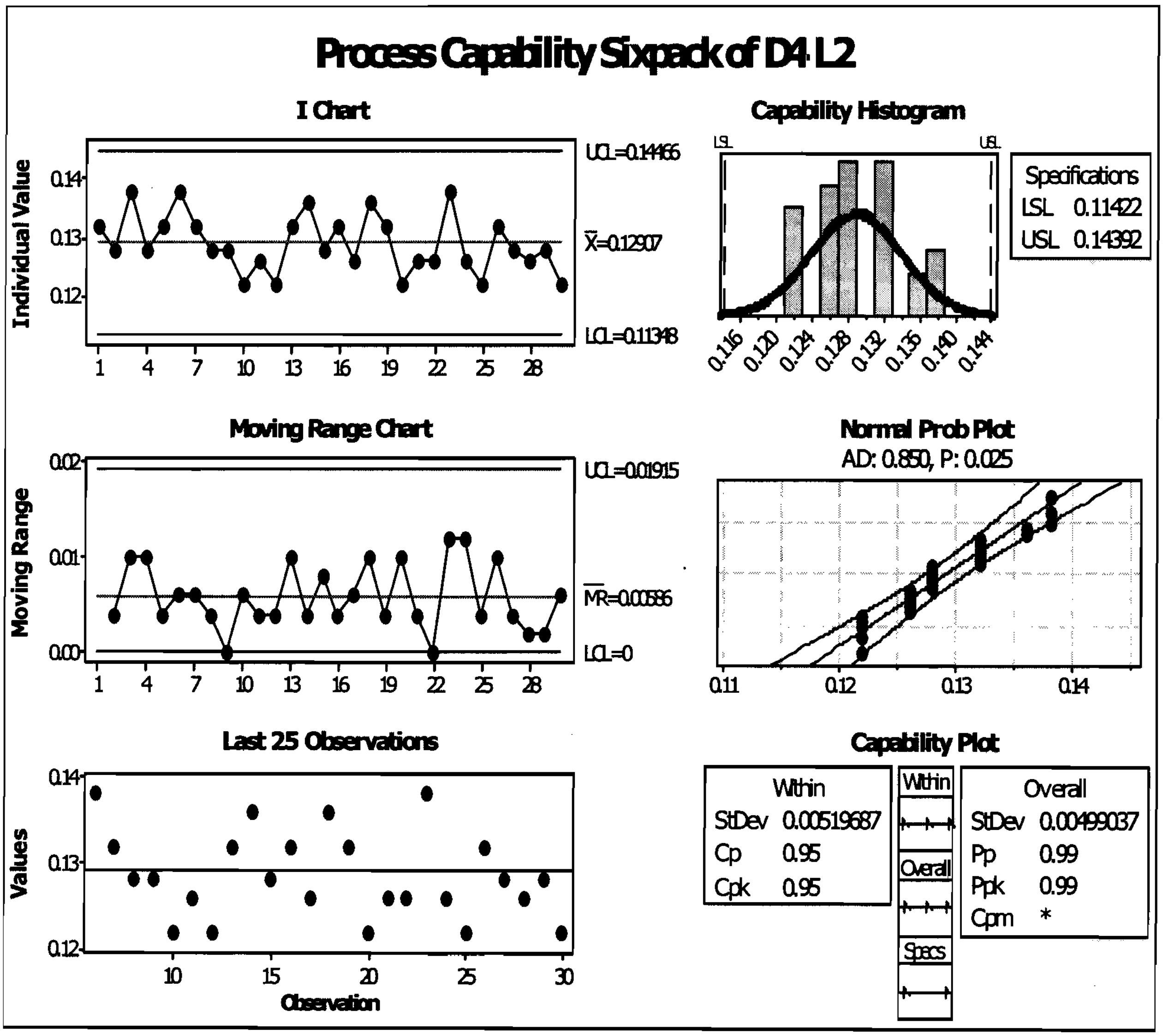
TEST 1. One point more than 3.00 standard deviations from center line.
Test Failed at points: 5, 6

Descriptive Statistics: Defect 4 in Laser (D4 L2)

Variable	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median
D4 L2	30	0	0.12907	0.000903	0.00495	0.12200	0.12600	0.12800

Variable	Q3	Maximum
D4 L2	0.13200	0.13800

LSL = 0.11422 USL = 0.14392



Appendix C: Gage Repeatability and Reproducibility for Dimension Defect in Laser 1 and Laser 2

Gage R&R for Dimension Defect in Laser 1

Gage R&R Study - ANOVA Method

Gage name: Laser 1
Date of study:
Reported by: How Y. Lau M.
Tolerance:
Misc:

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part Num Las	3	0.112612	0.0375372	240.003	0.000
Operator Las	2	0.000042	0.0000212	0.136	0.876
Part Num Las * Operator Las	6	0.000938	0.0001564	2.116	0.057
Repeatability	108	0.007982	0.0000739		
Total	119	0.121574			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000822	6.19
Repeatability	0.0000739	5.56
Reproducibility	0.0000082	0.62
Operator Las	0.0000000	0.00
Operator Las*Part Num Las	0.0000082	0.62
Part-To-Part	0.0012460	93.81
Total Variation	0.0013282	100.00

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	0.0090639	0.054383	24.87
Repeatability	0.0085967	0.051580	23.59
Reproducibility	0.0028723	0.017234	7.88
Operator Las	0.0000000	0.000000	0.00
Operator Las*Part Num Las	0.0028723	0.017234	7.88
Part-To-Part	0.0352991	0.211795	96.86
Total Variation	0.0364442	0.218665	100.00

Number of Distinct Categories = 5

H-GLASS Gage R&R Study

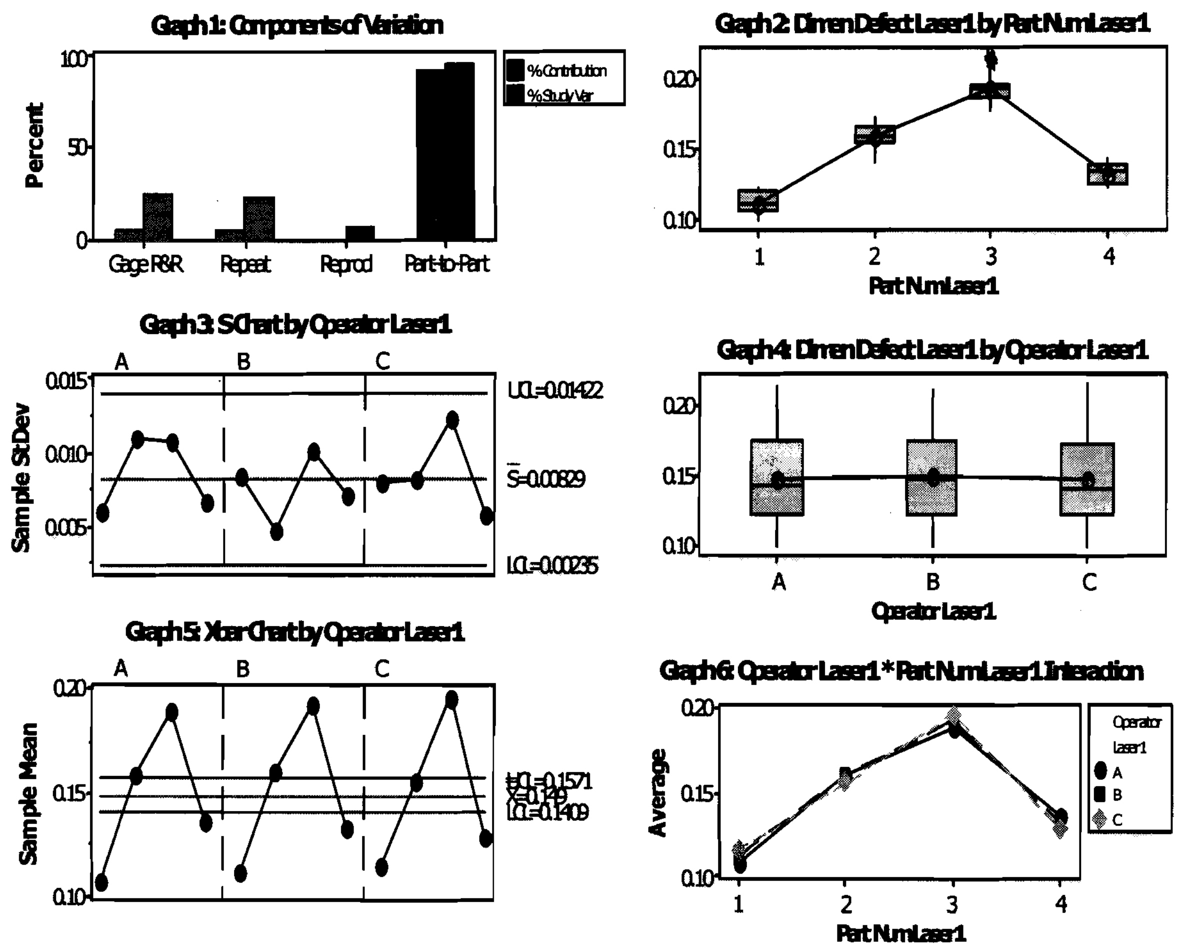
Reported by: How Y. Lau M.

Gage name: Laser 1

Tolerance:

Date of study:

Misc:



Gage R&R for Dimension Defect in Laser 2

Gage R&R Study - ANOVA Method

Gage name: Laser 2
Date of study:
Reported by: How Y. Lau M.
Tolerance:
Misc:

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Part Num Las	3	0.0833415	0.0277805	3392.46	0.000
Operator Las	2	0.0001766	0.0000883	10.78	0.010
Part Num Las * Operator Las	6	0.0000491	0.0000082	0.19	0.980
Repeatability	108	0.0047659	0.0000441		
Total	119	0.0883331			

Two-Way ANOVA Table Without Interaction

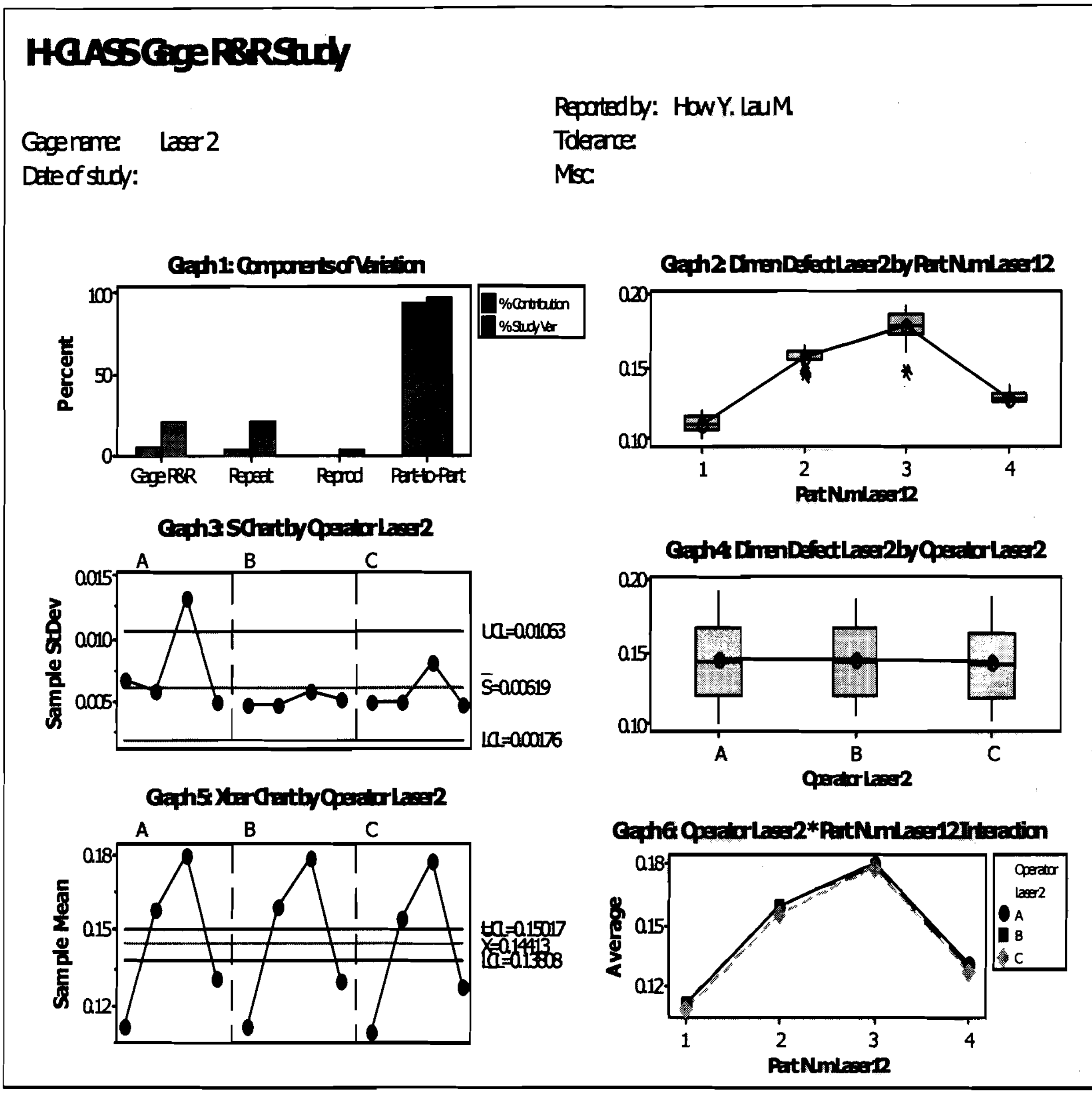
Source	DF	SS	MS	F	P
Part Num Las	3	0.0833415	0.0277805	657.727	0.000
Operator Las	2	0.0001766	0.0000883	2.091	0.128
Repeatability	114	0.0048150	0.0000422		
Total	119	0.0883331			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000434	4.48
Repeatability	0.0000422	4.36
Reproducibility	0.0000012	0.12
Operator Las	0.0000012	0.12
Part-To-Part	0.0009246	95.52
Total Variation	0.0009680	100.00

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	0.0065870	0.039522	21.17
Repeatability	0.0064990	0.038994	20.89
Reproducibility	0.0010731	0.006439	3.45
Operator Las	0.0010731	0.006439	3.45
Part-To-Part	0.0304074	0.182444	97.73
Total Variation	0.0311127	0.186676	100.00

Number of Distinct Categories = 6


H-GLASS Gage R&R Study
Reported by: How Y. Lau M.
Gage name: Laser 2
Tolerance:
Date of study:
Misc:
Graph 1: Components of Variation
Percent
%Contribution
%Study Var
Gage R&R
Repeat
Reprod
Part-to-Part
Graph 2: Dimen Defect Laser2 by Part Num Laser12
Part Num Laser12
Graph 3: S Chart by Operator Laser2
Sample StDev
UCL=0.01063
S=0.00619
LCL=0.00176
Graph 4: Dimen Defect Laser2 by Operator Laser2
Operator Laser2
Graph 5: Xbar Chart by Operator Laser2
Sample Mean
UCL=0.15017
X=0.14413
LCL=0.13808
Graph 6: Operator Laser2 * Part Num Laser12 Interaction
Average
Operator Laser2
Part Num Laser12

Appendix D: Gage Repeatability and Reproducibility for Dimension Defect Between Laser 1 and Laser 2

Gage R&R for Dimension Defect in Laser 1 and Laser 2

Gage R&R Study - ANOVA Method

Gage name: Laser 1 & Laser 2
Date of study:
Reported by: How Y. Lau M.
Tolerance:
Misc:

Two-Way ANOVA Table With Interaction

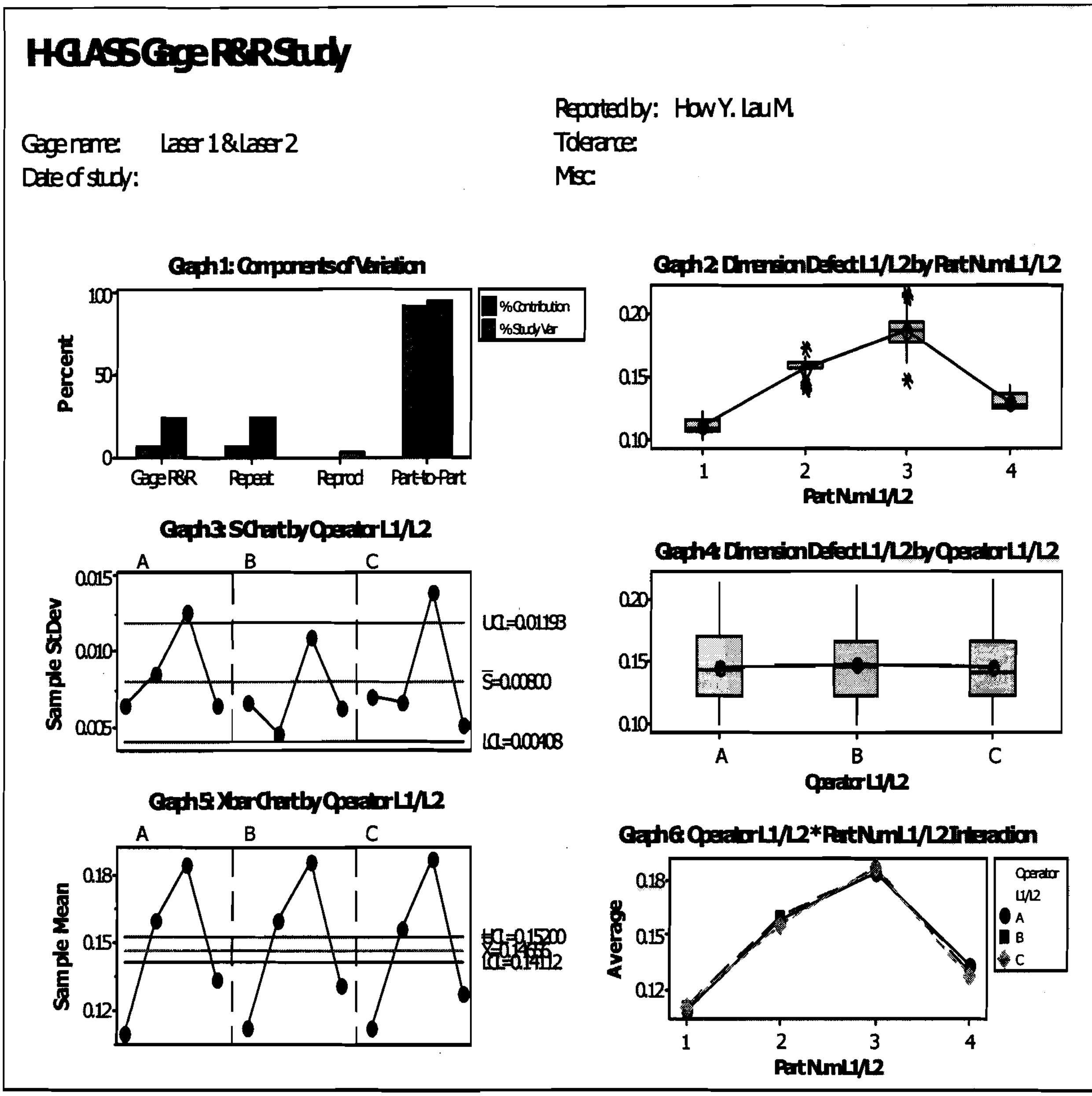
Source	DF	SS	MS	F	P
Part Num L1/	3	0.194122	0.0647074	656.604	0.000
Operator L1/	2	0.000116	0.0000580	0.588	0.584
Part Num L1/ * Operator L1/	6	0.000591	0.0000985	1.361	0.231
Repeatability	228	0.016504	0.0000724		
Total	239	0.211333			

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000737	6.41
Repeatability	0.0000724	6.29
Reproducibility	0.0000013	0.11
Operator L1/	0.0000000	0.00
Operator L1/*Part Num L1/	0.0000013	0.11
Part-To-Part	0.0010768	93.59
Total Variation	0.0011505	100.00

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	0.0085844	0.051507	25.31
Repeatability	0.0085079	0.051047	25.08
Reproducibility	0.0011438	0.006863	3.37
Operator L1/	0.0000000	0.000000	0.00
Operator L1/*Part Num L1/	0.0011438	0.006863	3.37
Part-To-Part	0.0328148	0.196889	96.74
Total Variation	0.0339191	0.203515	100.00

Number of Distinct Categories = 5


H-GLASS Gage R&R Study
Reported by: How Y. Lau M.
Gage name: Laser 1 & Laser 2
Tolerance:
Date of study:
Misc:
Graph 1: Components of Variation
Percent
100
50
0
% Contribution
% Study Var
Gage R&R
Repeat
Reprod
Part-to-Part
Graph 2: Dimension Defect L1/L2 by Part Num L1/L2
0.20
0.15
0.10
1
2
3
4
Part Num L1/L2
Graph 3: S Chart by Operator L1/L2
A
B
C
Sample StDev
0.015
0.010
0.005
UCL=0.01193
S̄=0.00800
LCL=0.00408
Graph 4: Dimension Defect L1/L2 by Operator L1/L2
0.20
0.15
0.10
A
B
C
Operator L1/L2
Graph 5: Xbar Chart by Operator L1/L2
A
B
C
Sample Mean
0.18
0.15
0.12
UCL=0.15200
LCL=0.14112
Graph 6: Operator L1/L2 * Part Num L1/L2 Interaction
Average
0.18
0.15
0.12
1
2
3
4
Part Num L1/L2
Operator L1/L2
A
B
C