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EMPLOYMENT REPORT

Sources of Variation of Treated Wood

performed at the course of studies
Forest Products Technology and Management
Salzburg University of Applied Sciences/Kuchl Campus

submitted by
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Abstract

Previous work has shown that statistical process control (SPC) can be a successful method to minimize variation within production processes. In this report, sources of variation for pressure treated wood are analysed.
In this research SPC and root cause analyses were assessed at a production facility. Other statistical techniques were applied to study the significant differences in retention values versus several process parameters for pressured treated wood. Comparisons of mean retention values revealed a statistically significant difference in association and industry retention means. Multivariate analyses were also conducted to correlate process parameters with retention test values. Long term variation was quantified using control charts for one year at the production test site. Natural variation was quantified and special-cause variations were detected at the production test site.

Key words: Statistical process control, pressure treated wood, root cause analysis, sources of variation

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1. Introduction

The scarcity of raw materials requires companies from the 21st century to improve quality, increase productivity and lower manufacturing costs (Young & Winistorfer, 1999). The wood preservation industry offers a wide variety of products for many consumers applications, while also conserving natural resources by relying on a renewable resource (Cheremisinoff, Rosenfield, & Davletshin, 2013). Pressure treated lumber is widely used for a range of outdoor construction applications, including those that are structurally critical. To evaluate the quality, standard practise in commercial wood treatment operations is to analyse wood cores, after the treatment process is complete. This is determined by removing 20 core samples from each charge.

The AWPA (2016) (American Wood Protection Association) is a commonly used standard in the industry which specifies wood species, preservative types, commodity details and the following three additional factors:

- assay zone, the analysis zone that extends from the surface 5 to 100 mm into the wood. This is depending on the type of woof product and treatment type. The assay zone is cut from the cores after they are removed from the treated wood.
- penetration is the distance from the surface of the wood that the chemical is present in the assay zone
- retention is the amount of chemical that is present in the assay zone (Lebow, Taylor, & Young, 2015).

In every kind of manufacturing no two things are alike. Just the recognition of variation is not satisfactory. It is only possible to produce a uniform product, when the sources of variation in a product are well understood. Today's management task should be to know as much as possible about the sources of variation which are affecting their product and take the right steps to reduce it (Wheeler & Chambers, 1992).

1.1. Objectives

This research study supported a 24-month research project titled 'A Statistical Analysis of the Quality Control Testing Protocol for Penetration and Retention Values of Residential Treated Lumber'. Two of the four research objectives (or questions) during my three-month internship of this longer term 24-month research project were completed which addressed two key research questions: 2) recommendations on data quality (for wood treatment tests conducted by the quality control lab at treatment mills; 3) recommendations on root cause analysis for reducing variability based on several mill tours.

The long-term objectives of this project are to find sources of variation in the treatment process to help the industry to improve their production with the goal of recommendations to minimize the variation, a statistical control of the process and a possible tool to predict the process. Primary goal of this study is to analyze the data quality, to characterize the variability expected in retention values when treated wood charges are measured multiple times and to look for statistical evidence how process parameters are influencing the retention.

1.2. Problem Definition

The durability of this treated lumber or treated poles is dependent of the retention of the preservative in the wood. For every charge of lumber or poles a certain number of samples is drilled and measured. The measured value can differ if the same batch is measured a second or a third time (Lebow et al., 2015). The extent of the variability has been quantified by Juriga (2016). Juriga also recommended to apply statistical process control for treatment plants. With this tools the mills could predict and have their process better under control.

1.3. Research Hypothesis

This research is investigating sources of variation in treated wood. The hypotheses in this study are:

1. Is there statistical significant correlation of process parameters on the retention of pressure treated poles and pressure treated lumber?
2. What are sources of variation in treated wood? For this a root cause analysis will be generated.
3. Would statistical process control be a suitable continuous improvement tool for the wood treating industry?

1.4. Report Organization

The main part describes the pressure treatment process and the sampling of the treated wood. Also, the statistical tools which are used to analyse the data are explained. In the following a short introduction of statistical process control is given. Then the results of the statistical analysis are presented and discussed. In the end, the work which was done is concluded and recommendations for the future are given.

Main Part

2. Materials and Method

2.1. Pressure Treatment Process

Several methods for the preservation of timber have been developed over the last years. The amount of available wood preservatives is still increasing and everyone has its own characteristic properties (Kollmann & Côté, 1968).

The treating process, which is commonly used, is a controlled vacuum/pressure process. White wood is loaded onto rail/tram cars (Figure 1) and pushed into a horizontal treating cylinder. At the Langdale Forest Products in Sweetwater rails are used for this, as show in Figure 1.

Figure 1: Rail cars loaded with poles

Figure 2: Loaded treatment cylinder

The cylinder door is sealed and a vaccum is applied to remove most of the air out of the cylinder and the wood cells. The following step is the filling of the cylinder with vacuum. During this process the vacuum should be maintained until the pressure is applied.
At the plant of Langdale Forest Products the pressure for poles is aproximately 150 psi and for lumber around 120 psi to force the preservative into the wood.
Also, for the poles treating process 2 vacuum pumps are used as for the lumber treating pump just 1 pump is in use. When the target retention is achieved, the pressure is slowly released and the remaining solution is returned to a work tank for reuse. A second vacuum step is applied to extract excess solution from the wood. Positive effects of this step are, it removes surplus liquid weigt, minimizes potential post treatment dripping, and helps to optimize preservative retention.
At the end of the process the door is opened and the treated wood is pulled out. After this, the poles or the treated lumber is stored on a chemical containment drip pad. This area should be made from sealed concrete that allows the liquid to flow to a steel lined process pit.

2.2. Mixing of the solution

The mixing of the solution for treated poles is different than for treated lumber. The solution for CCA treated poles is mixed in the work tank and the solution for MCA treated wood is mixed in the combo tank.

2.3. Sampling of the treated wood

At the Langdale forest products plant 2 different products are produced. The first product is copper chrome arsenate (CCA) impregnated poles. The second product is micronized copper azole (MCA) treated lumber with and without ground contact. Te sampling procedure is performed according to the AWPA standard M2 20. After the treatment cycle, the treated wood is removed from the treatment cylinder (Figure 3) and stored on dripping pads (Figure 4)
.

Figure 3: Poles after the treatment cycle

Figure 4: Poles on drip pad

After this step, the core samples are drilled with a borer with an inner diameter of 0.2 inches (Figure 5). Treated wood plugs are used to close the drilling holes afterwards.

Figure 5: Drilling of the samples

Figure 6: Core samples from treated poles

As the heartwood is difficult to treat, a heartwood indicator is used according to (AWPA M2 – 4.3.1.1). For this a O-anisidine hydrochloride or a 10 percent sodium nitride solution is used. The heartwood turns red after the indicator is applied (Figure 7). To determine the penetration of the chemical, an indicator for copper is sprayed on the samples. As an indicator a mixture of chrome azurol and sodium acetate is used. As seen in Figure 8 the indicator turns the treated part of the core samples into a dark color.

Figure 7: Samples with applied heartwood indicator

Figure 8: samples with penetration indicator

This test shows the core samples which are insufficiently penetrated by the preservative. According to AWPA T1-section, at least 85 % of the entire samples need to pass this test. In the following step, the samples are dried with a microwave to a moisture content of 0 % (Figure 9).

Figure 9: Drying of the samples in the microwave

Figure 10:Grinding of the core samples with a grinder

After drying the samples are grinded with a grinder as displayed in Figure 10 to a size of 20 mesh (0.0331 inch) and compressed inside a small cup (Figure 11).

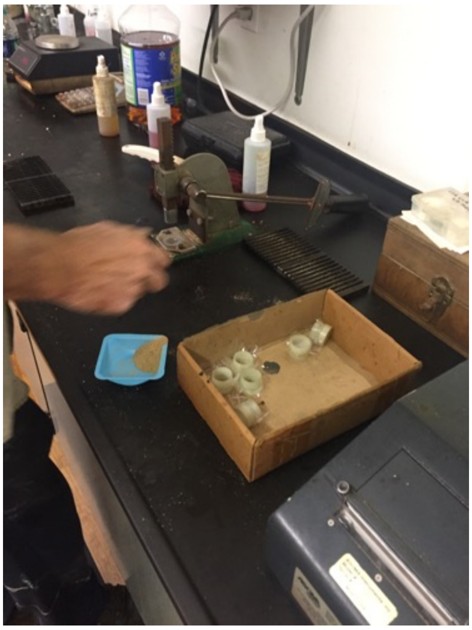

Figure 11: Compressing of the drilled samples

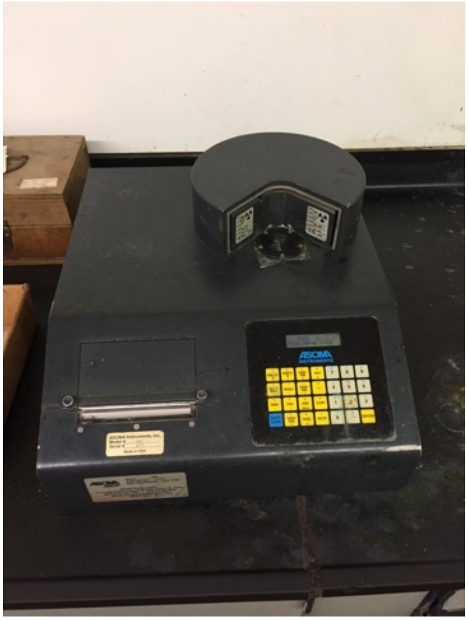

Figure 12: X-ray measurement device

The small cup with the compressed samples is then placed in the X-ray device (Figure 12), which is measuring the concentration of chemical in lb/ft^3. For every charge the retention values have to be reported . When the sample doesn't pass the required retention and penetration values, it is possible to retest the charge up to 3 times before it has to be retreated. The following table shows the minimum preservative retention requirementsby its end use (Table 1).

End Use	Minimum Active Retention lf/ft^3			
	CA-B	CA-C	µCA-B (MCA-B)	µCA-BC (MCA-C)
Above ground – general use	0.10	0.06	0.06	0.05
Species listed in Section 3.3 (primarily sapwood)	0.08	0.06	0.06	0.05
Species listed in Section 3.3 (primarily heartwood)	0.21	0.15	0.15	0.14
Ground contact – general use	0.21	0.15	0.15	0.14
Ground contact – heavy duty	0.31	0.25	0.23	0.23
Ground contact – wood fountain systems	0.31	0.25	0.23	0.23
Ground contact – extreme duty	0.41	0.35	0.33	0.33

Table 1: Minimum preservative retention requirements (ICC Evaluation Service 2016)

2.4. Statistical analysis

The aim of statistical process control is to improve the process and to understand the tools and techniques of statistical process control (Wheeler & Chambers, 1992). For the statistical analysis of the data, the treatment program JMP Pro 13 was used. Process data from one year, including CCA treated poles, MCA treated lumber above gound and MCA treated lumber with ground contact was collected and analysed. The following process data was available in the datasets.

- Retention
- Initial vacuum time(min)
- Initial vacuum pressure (psi)

- Pressure time (min)
- Pressure (psi)
- Pressure injection (gal/f^3)
- Pressure release
- Final vacuum (min)
- Final vacuum pressure (psi)
- Final injection (gal/f^3)
- Start solution

2.4.1. Summary of descriptive statistics

In Table 2 descriptive statistics, which is used later in the results and discusiion, is described briefly.

Value	Explanation	Formula
Mean/Average	The average identifies the center of the mass for the values in the dataset	$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} = \frac{X_1 + X_2 + \lambda + X_n}{n}$
Median	The sample of a set of n measurements is the middle value (50th percentile) when the measurements are arranged fro smallest to largest	
Min	Smallest value of the dataset	
Max	Biggest value of the dataset	
Mode	The mode is the value which occurs the most often	
Standard deviation	A quantity calculate to indicate the extent of deviation for a group as a whole.	$s = \sqrt{\frac{\sum(x - \bar{x})^2}{n - 1}}$
CV/Coefficient of Variation	Is a standardized measure of dispersion of a probability distribution or a frequency distribution	$CV = \frac{s}{\bar{x}} \times 100$
Variance	Is the squared deviation of a random variable from its means	$S^2 = \frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}$
Range	The range is defined as the maximum minus the minimum	
N	Number of samples	

Table 2: Summary of descriptive statistics (Wheeler & Chambers, 1992)

2.4.2. Histograms and Q-Q plots

The first step is always to look at the quality of your data. For this histograms are used, as they reveal data problems. Also you can use histograms to detect and remove outliers. A histogram is a plot of the data which has possible values one axis and frequencies of those values on the other axis. Another important tool is the quantile quantile or Q-Q plot. This is a graphical tool which helps to asess if the data is normally distributed. (Young, 2017b). The QQ Plot is a scatterplot created by plotting two sets of quantiles against one another. If both sets of quantiles came from the same population, we should normally see the points forming a line which is roughly straight. The greater the departure from the reference line, the higher the evidence that the two data sets have come from populations with different distributions (Young, 2017a).

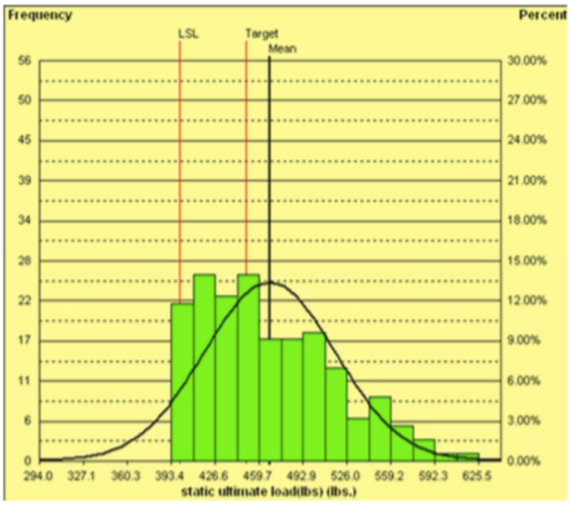

Figure 13: Histogram (Young, 2017b)

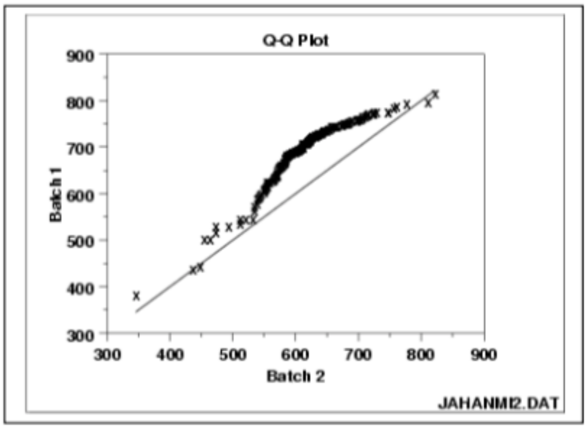

Figure 14: Q-Q Plot (Young, 2017a)

2.4.3. Box Plots

Box Plots are also known as box and whiskers plots and summarize the distribution of points at each factor level. The end of the box represent the 25th and 75th percentiles (1st and 3rd quartiles). The difference between the quartiles is the interquartile range. The line across the middle of the box identifies the median (50th percentile) sample value. Each box has lines called whiskers, that extend from each end. The whiskers extend from the ends of the box to the outermost data point that falls within the distances computed. The upper quartile is + 1.5*(interquartile range) ad the lower lower quartileis - 1.5*(interquartile range). Any points outside the whiskers are considered outliers. Box Plots can also be used for data quality asessment (Young, 2017a).

2.4.4. Students t-Test

The students t-test is a statistical hypothesis test to determine if two sets of data ar significantly different from each other. The test statistics followas a Student's t-distribution under the null hypothesis. It was first introduced by William Sealy Gosset, a chemist which was working for the Guiness brewery and "Student" was his pen name. He was hired by Guiness to apply statistics to the industrial processes of the Guiness brewery. He devised the t-test of as ab economical way to monitor the quality of stout. The most frequently used t-tests are the one sample location test and the two sample location test of the null hypothesis (Heumann, 2017).

2.4.5. Welch's Test

In statistics, the Welch Test or Unequal Variance Test is a two sample location test which is used to determine if two populations have equal means. The Welch's test is designed for unequal variances but still assumes that the populations are normal.

2.4.6. Analysis of Variance (ANOVA)

ANOVA is a statistical design which helps to allow to determine if the means of two or more distributions are significantly different. The technique of ANOVA was invented by Sir Ronald Fisher (Heumann, 2017). Variance of group means around a central tendency (grand mean) tells us, on average, how much each group is different from another. The distribution which is used in Analysis of Variance is the F-distribution. The F-distribution is a continous right skewed distribution. (Young, 2017a).

There are two main types of tests:

- One-way ANOVA between groups: used when you want to test two groups to see if there's a difference between them.
- Two way ANOVA without replication: used when you have one group and you're double-testing that same group. For example, you're testing one set of individuals before and after they take a medication to see if it works or not.
- Two way ANOVA with replication: Two groups, and the members of those groups are doing more than one thing. For example, two groups of patients from different hospitals trying two different therapies (Heumann, 2017).

There is also a difference between ANOVA and student's t-test- A Student's t-test will tell you if there is a significant variation between groups. A t-test compares means, while the ANOVA compares variances between populations (Heumann, 2017).

2.4.7. Tukey-HSD (Honestly Significant Difference)

The Tukey-Kramer test allows the comparison of all pairs of means and controls the experimentwise error rate. However, when used with unequal sample sizes, the procedure yields a conservative estimate of a Type 1 Error (jmp, 2017).

2.4.8. Multivariate Analysis

You can use the multivariate analysis to see how many variables relate to each other. Multivariate just means invloving many variables than just one or two (univariate, bivariate) (jmp, 2017).

2.4.9. Quantifying Variation with Control Charts

One of many statistical tools which can be used to prevent the manufacture of defective or off grade products is the Shewhart Control chart. Excessive process variation can be detected earlier, that would have otherwise occurred under inspection-only processes. The control chart is used to distinguish between special cause and common cause variation (Figure 15).
Control charts should be used to:

- Identify critical process variables of great importance
- Estimate natural process variation
- Proactive thinking or prevention viewpoint
- Promotes data driven thinking and decision making
- Identifies events
- Initiates Root Cause Analysis (Young, 2017b).

Individuals and moving range charts (Figure 16) are used to monitor individual values and the variation of a process. To produce the control limits, the mean and standard deviation are used. Once the control limits have been established, these limits can be used to monitor the variation of the process.

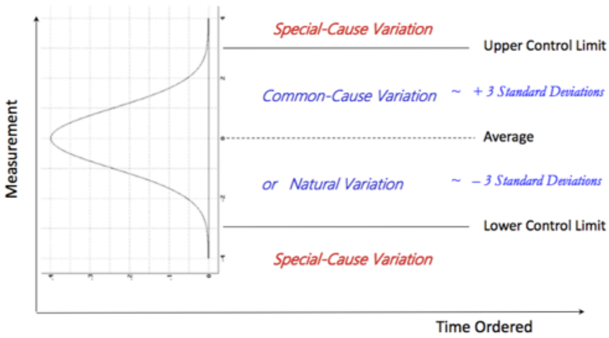

Figure 15: Estimating Special Cause and Common Cause Variation (Young & Winistorfer, 1999)

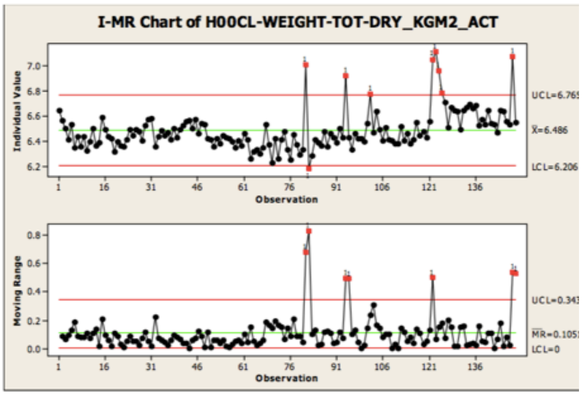

Figure 16: Example for Individual and Moving Range Chart (Young, 2017b)

The process behaviour charts seeks to determine if a sequence of data may be used for predictions. As most statistical procedures assume that data are homogenous, process behaviour charts examine the data for a evidence of a lack of homogeneity. The process may be predictable if the values are all within the limits. If the process continues to stay within the calculated limits it is the ultimate proof of a predictable process. If the values are inconsistent with the limits, the process is unpredictable. Evidence of exceptional variation can be safely use to act and change something in the process. The process should not be changed until indicates that a change has occurred (Wheeler & Chambers, 1992).

2.4.10. Hypothesis Testing

A statistical hypothesis, is a hypothesis which is testable on the basis of observing a process which is modeled via a set of random variables. Very common is, that two statistical data sets are compared. Also very common is that data which is obtained by sampling is compared against a synthetic data set from an idealized model. Whatever you want to detect in a research is the alternative or research hypothesis. Since the research or alternative hypothesis is H_1, it is hoped that the evidence leads us to reject H_0 and support our H_1 (Young, 2017a).

	Real Situation	
Decision Resulting from Data Analysis	Null Hypothesis Test ("In Reality True")	Research (Alternative) Hypothesis Test ("In Reality True")
Research Hypothesis Supported (Reject Null)	α Error (Type I) *"False Positive"*	Correct Decision
Study is Inconclusive (Do Not Reject Null)	Correct Decision	β Error (Type II) *"False Negative"*

Figure 17: Decision resulting from Data Analysis (Young, 2017a)

- A Type I error is an error that is made when the null hypothesis is rejected when, in fact, it is true. The probability of committing a Type I error is called the level of significance of the test and is denoted by the Greek letter alpha.
- A Type II error is an error that is made when the null hypothesis is not rejected when, in fact, H1 is true. The probability of committing a Type II error is called the level of significance of the test and is denoted by the Greek Letter Beta.

- p-value is the exact probability of a Type I error (Young, 2017a).

2.5. Continuous Improvement and Variation Reduction

A state of a virtually uniform product can only be achieved through the precise study of the sources of variation in the process, which are affecting the product. By reducing production variation you can reduce waste, manufacture a consistent product, have less claims and complaints. If a process displays routine variation, it is normally predictable and consistent. To reduce variation present in the process, the process itself must be changed (Wheeler & Chambers, 1992).Process variation can include for example moving the target, running higher targets or moisture variation etc. By reducing the weight target in particle board plants by just 0.5 % it is possible to save up to $300000 per year. Cost for process variation include low efficiency, rework, scrap or reruns or overfill. If you want to improve something continuously the management has to start to strongly support continuous improvement efforts. The roles of the supervisors and operators have to be clearly defined. Also, the senior management, supervisors and operators must develop a good working knowledge of key statistical methods. A very important point is to develop a cross functional communication between teams and departments (Young, 2017b).

2.6. Statistical Process Control

The word 'statistical' implies the collection, representation and interpretation of data. Statistical methods provide a means of assessing risks and predicting results. SPC involves understanding basic chart and being capable to handle data. The technique can be understood by anyone but needs training to various levels of competence (Owen, 2013). SPC is first and foremost a way of thinking, which happens to have some tools attached. Wheeler (1992) says, that there is always a framework of ideas which make the statistical ideas relevant. Without this framework the tools and techniques can’t be used effectively. As the aim of SPC is to improve the underlying process, it requires to understand the process and the way to use the tools and techniques for continual improvement of the system.

2.6.1. Deming’s 14 points

Variation was seen by Deming as the disease that threatened US manufacturing. The more variation, the more waste. For this premise, he set out his 14 points for management.

1. “Create constancy of purpose towards improvement.” Replace short-term reaction with long-term planning.
2. “Adopt the new philosophy.” The implication is that management should actually adopt his philosophy, rather than merely expect the workforce to do so.
3. “Cease dependence on inspection.” If variation is reduced, there is no need to inspect manufactured items for defects, because there won’t be any.
4. “Move towards a single supplier for any one item.” Mulitple suppliers mean variation between feedstocks.
5. “Improve constantly and forever”. Constantly strive to reduce variation.
6. “Institute training on the job”. If people are inadequately trained, they will not all work the same way, and this will introduce variation.
7. “Institute leadership”. Deming makes a distinction between leadership and mere supervision. The latter is quota- and target-based.
8. “Drive out fear”. Deming sees management by fear as counter-productive in the long-term, because it prevents workeres from acting in the organizations’s best interest.
9. “Break down barriers between departments.” Another idea central to total quality management is the concept of the ‘internal customer’, that each department serves not the management, but the other departments that use its outputs.

10. “Eliminate slogans”. Another central TQM idea is that it’s not people who make most mistakes – it’s the process they are working within. Harassing the workforce without improving the processes they use is counter-productive.
11. “Eliminate management by objectives”. Deming saw productin targets as encouraging the delivery of poor quality goods.
12. “Remove barriers to pride of workmanship”. Many other problems outlined reduce worker satisfaction.
13. “Institute education and self improvement.”
14. “The transformation is everyone’s job” (Young, 2017b).

3. Results and Discussion

In this chapter, the results of the statistical analysis of the data are presented and interpreted. The datasets of CCA treated poles, MCA treated lumber with ground contact and MCA treated without ground contact were used.

3.1. Cause and effect diagram

The cause and effect diagram was first invented by Dr. Kaoru Ishikawa. Very often in some plants, employees are overwhelmed with the number of factors which could be influencing a problem. The data’s are organized using a fault tree. It can be used as an enhanced tool that caputres problems and solutions visually. Because of its versatility, the Cause and Effect diagram can be employed in every area of manufacturing and service industries to organize and solve problems. The procedure to make this diagram is divided into 5 parts (Wheeler & Chambers, 1992).

1. Choose the effect to be studied and write it at the end of a horizontal arrow.
2. List all the factors that influence the effect under consideration.
3. Arrange and stratify these factors. Choose the principal factors and subdivisions of activity. This will form th the major branches of the horizontal arrow.
4. Draw the sub-branches for the various sub-factors. This process is continued till all variables are included on the diagram.
5. Check the diagram to make sure all relevant variable are on the chart (Wheeler & Chambers, 1992).

The diagram should reflect the perspective of many individuals who are experts with the process.

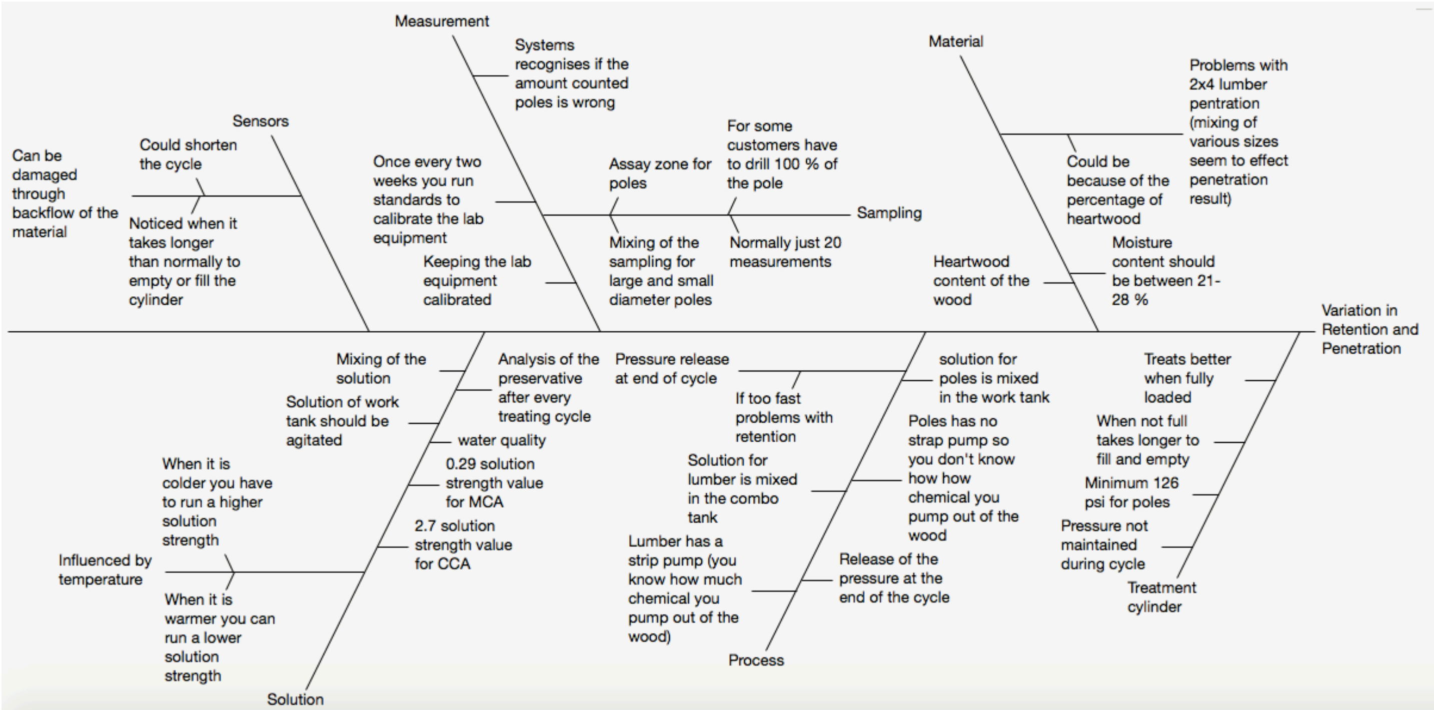

Figure 18: Cause and Effect Diagram for "Variation of Retention and Penetration of Treated Wood"

As displayed in Figure 18, a cause and effect diagram for the variation and penetration of treated wood was developed. For this, the treatment operator and the operators which are responsible for the sampling and testing were interviewed. Also the treatment manual for the treatment cylinders was used to develop the diagram. The diagram was divided in to the following six parts: Sensors, Measurement, Material, Solution, Process and Treatment cylinder.

The sensors are very important to regulate the treatment cycle. They can be damaged through the backflow of the material, which can contaminated by wood residues. As a result of this, the impregnation cycle can be shortened. It is usually noticed by the operator, when it takes longer than normally to empty or fill the cylinder.

There is a very big variation in the sampling and measurement process by itself, as large and small diameter logs are mixed. Because of the age of the trees and the different amount of heartwood, there is always different values in retention and penetration. Normally lab equipment is calibrated once every 2 weeks by running standards.

Also a very important factor influencing the treating result is the solution of the chemical. The operators indicated, that the solution strength is highly dependent on the outside temperature. When it is colder, they normally have to run a higher solution strength to meet the specification limits. After every treatment cycle, the solution strength is analysed to know the remaining percentage of chemical in the work tank. This is important for the mixing of the solution for the impregnation cycle. According to the operator, the quality of the water which is added to the solution is important. Bad quality of water, can influence the treatment result negatively. As the chemical is stored in a big tank, it needs to be agitated to reduce variation. The treatment plant in Langdale has installed agitators in their tanks to mix the chemical better.

As previously mentioned in measurement, as wood is inhomogenous, the material by itself has a lot of variation. Especially for the mixing of different sizes of lumber leads penetration and retention issues. A reason for this could be the percentage of the heartwood of the lumber. Bigger lumber sizes, normally have a higher heartwood content.

One of the most important factors is the treating process. As there are a separate treating cylinders, tanks and pumps, there is variation the process. As explained by the treatment operators, the pressure release at the of the cycle has a high influence on the retention. Problems may occur when the pressure is released too fast. The main difference in the process for lumber and poles is, that for poles the solution is mixed in the work tank and for lumber, the solution is mixed in the combo tank. An advantage in the treatment process for lumber is the

strip pump. With this pump, you always know how much chemical you pump out of the wood at the end of the cycle.
There are also some important factors regarding the performance of the treating cylinder. The best treating results can be obtained with a full treating cylinder. When the cylinder is not full, it takes much longer to full and empty the cylinder. The minimum pressure which has to be obtained for the pressure cycle for poles should 126 psi. Also problems in retention can occur, when the pressure is not maintained during the treating cycle.

3.2. Histograms of the process parameters for treated poles

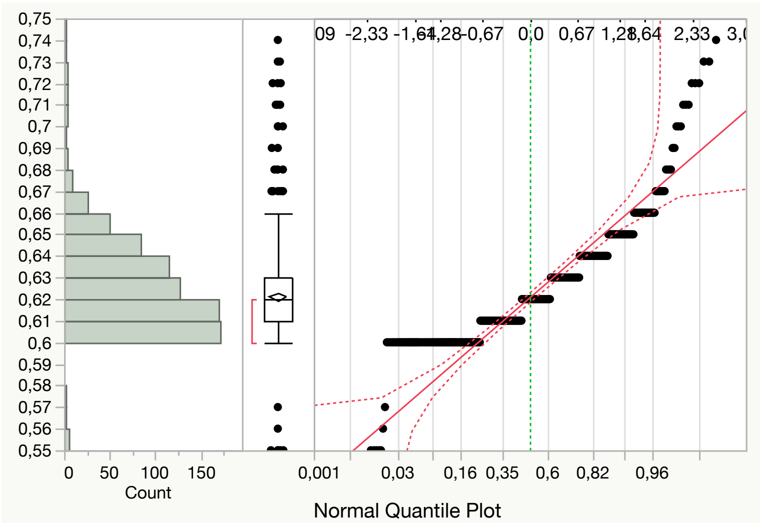

Figure 19: Histogram and Q-Q plot for the retention of treated poles

Mean	0,6212005
Std Dev	0,0279768
Std Err Mean	0,0009998
Upper 95% Mean	0,6231631
Lower 95% Mean	0,6192379
N	783
Variance	0,0007827
CV	4,5036632
Median	0,62

Table 3: Descriptive statistics for the retention of treated poles

Figure 19 shows the retention values for CCA treated poles over a one year period. The y-axis of the graph shows the retention values and the x-axis shows how often every value is occuring. The lower specification retention value is 0,6. As displayed in the Q-Q plot, the data seems to be normally distributed till the lower specification limit. The red line shows the line where data should be if it is normally distributed. This looks like this because, if a batch fails they are allowed to retest the charge up to 3 times. If it still fails, they have to retreat the charge. Retreated charges were removed from the dataset, because they possibly show very high retention values and are a different product. As there is a natural variation in the treatment process and the sampling by itself, the data should be normally distributed. Still there is a lot of variation in the process and a high range. If the treatment company can lower the variation in the retention, they can save money, by example using less chemical and still meet the specification limits. The mean and the median show nearly the same value which means, that the mean is not influenced by any strong outliers.

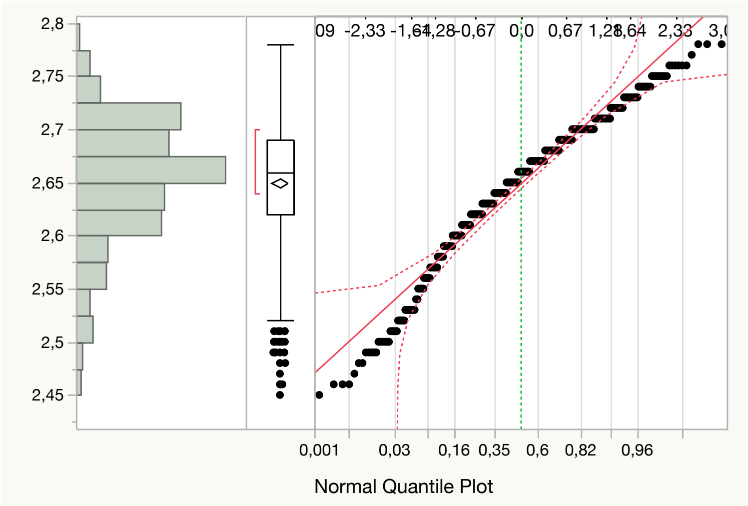

Figure 20:Histogram and Q-Q plot for the start solution of CCA treated poles

Mean	2,6493982
Std Dev	0,0575239
Std Err Mean	0,0020584
Upper 95% Mean	2,6534388
Lower 95% Mean	2,6453576
N	781
Variance	0,003309
CV	2,1712054
Minimum	2,45
Maximum	2,78
Range	0,33

Table 4: Descriptive statistics fort the start solution of treated poles

In Figure 20 the Histogram and Q-Q plot for the start solution of CCA treated poles are displayed. The amount of chemical in the start solution is very important, as it strongly influences the retention of the treated poles. Looking at the Q-Q plot the data seems to be normally distributed. With a minimum value of 2,45 and a maximum value of 2,78 the range is 0,33, which could be optimised to reduce variation in the retention.

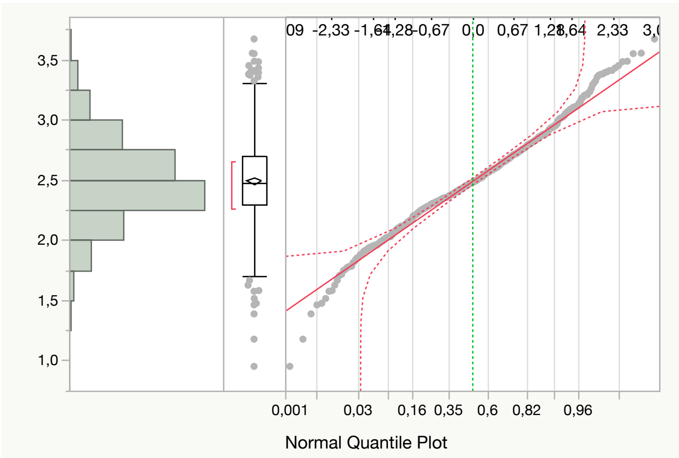

Figure 21: Histogram and Q-Q plot for the final injection (gal/f^3) of CCA treated poles

Mean	2,4911714
Std Dev	0,3484648
Std Err Mean	0,0125092
Upper 95% Mean	2,5157272
Lower 95% Mean	2,4666155
N	776
CV	13,987989
Minimum	0,948
Maximum	3,669
Range	2,721

Table 5: Descriptive statistics fort the final injection (gal/f^3) of treated poles

Also for the distribution of the data for the final injection of treated poles as shown in Figure 21 seems to be normally distributed. Also with this dataset there is a problem with the high range of 2,721. The coefficient of variation is with 13,98 fairly high. The final injection rate is an important process parameter, as it gives information about how much chemical remains in the wood after the treatment cycle.

3.3. Histograms of the process parameters for treated lumber with ground contact

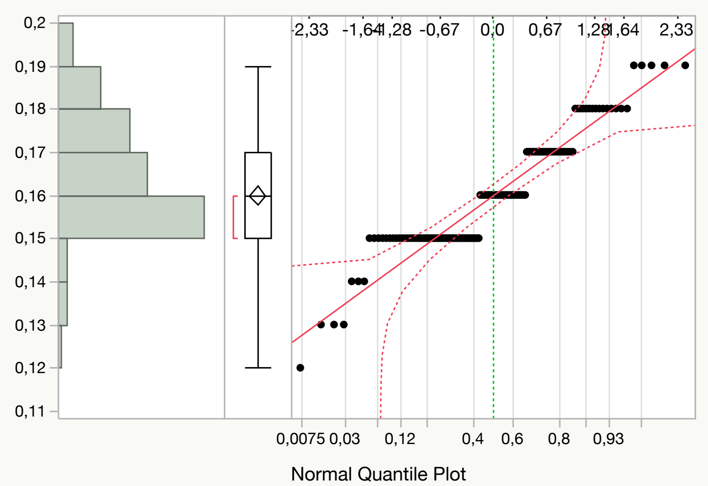

Figure 22: Histogram and Q-Q plot for the retention of treated lumber with ground contact

Mean	0,16
Std Dev	0,0133208
Std Err Mean	0,0011507
Upper 95% Mean	0,1622761
Lower 95% Mean	0,1577239
N	134
Variance	0,0001774
CV	8,3254976
Minimum	0,12
Maximum	0,19
Median	0,16
Range	0,07

Table 6: Descriptive statistics for the retention of treated lumber with ground contact

Similar to the histograms for poles, Figure 22 displays the same data problem for lumber. The lower specification limit is 0,15 and the distribution of the data stops at this point. The range, which amounts 0,07 is very high which is also displayed by the coeffiecient of variation with 8,32.

3.4. t-test and ANOVA for CCA treated poles

3.4.1. Comparison of Means and Variances for Treated Poles IV Vacuum Pressure vs Retention

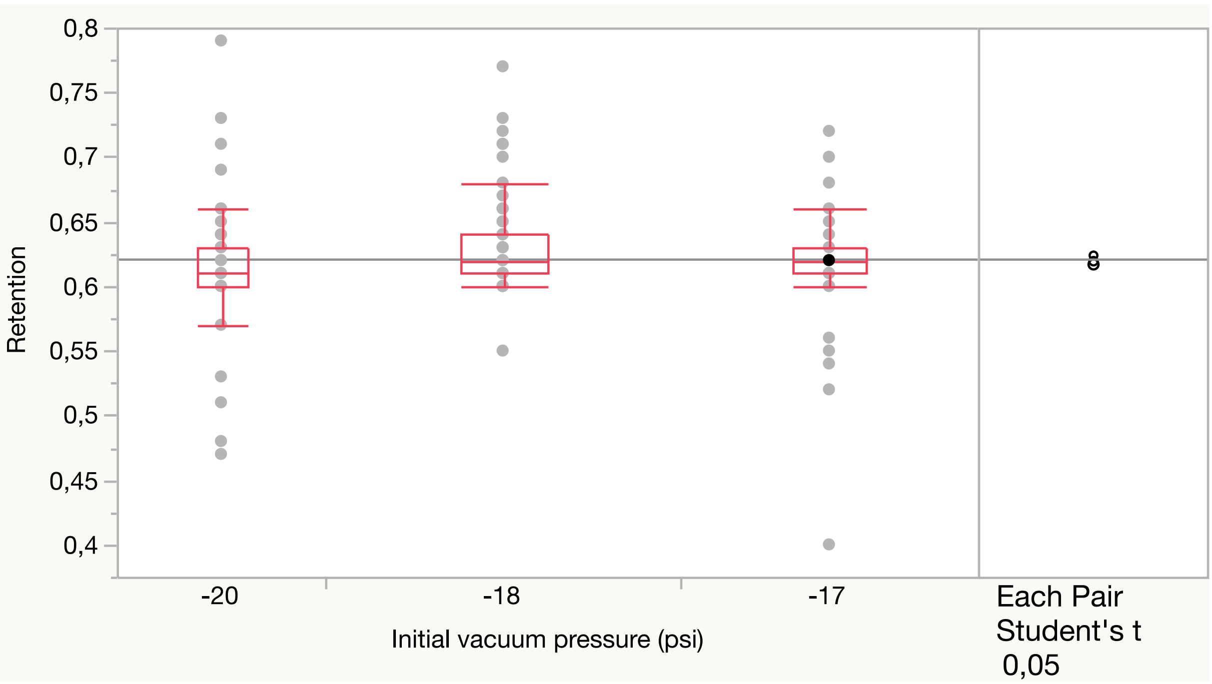

Figure 23: Box Plots of Treated Poles of Retention by IV Pressure

Figure 24 displays box plots of treated poles retention values by initial vacuum pressure. A student's t-test was applied to see if there is a significant difference between the means of the retention values with different initial vacuum pressures. The p-value shows the exact probability of a type 1 error. Which means, that you reject the null hypothesis when in fact it is true. As shown in Table 7, with a p-value of 0,0052 there is high statistical evidence that you get higher retention results when you apply an initial vacuum pressure of -18. With a p-value of 0,0463, there is also statistical evidence that you get different retention results, when you apply an initial vacuum pressure of -17 instead of -18.

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
-18	-20	0,0069567	0,0024802	0,002088	0,0118256	0,0052*
-18	-17	0,0044594	0,0022340	0,000074	0,0088449	0,0463*
-17	-20	0,0024973	0,0025664	-0,002541	0,0075354	0,3308

Table 7: Comparison for each pair using Student's t for Treated Poles IV Vacuum Pressure vs Retention

Level			Mean
-18	A		0,62449686
-17		B	0,62003745
-20		B	0,61754011

Table 8: Connecting Letters Report for each pair using Student's t for Treated Poles IV Vacuum Pressure vs Retention

In Table 9 the comparisons of all pairs for treated poles initial vacuum pressure is displayed using Tukey-Kramer HSD (honestly significant difference test). This test is an exact alpha-level test if the sample sizes are the same, and conservative if the sample sizes are different (Hayter, 1984). Same as the student's t-test, the p-value with 0,0143 for the initial vacuum level shows significance that the mean retention levels for -18 and -20 are different. There is sufficient evidence to reject the null hypothesis the means are equal

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
-18	-20	0,0069567	0,0024802	0,001133	0,0127809	0,0143*
-18	-17	0,0044594	0,0022340	-0,000787	0,0097055	0,1138
-17	-20	0,0024973	0,0025664	-0,003529	0,0085240	0,5941

Table 9: Comparisons of all pairs using Tukey-Kramer HSD for Treated Poles IV Pressure vs Retention

3.5. Students t-test and ANOVA for MCA treated lumber with ground contact

3.5.1. Comparison of Means and Variances for Treated lumber with ground contact IV Vacuum Pressure vs Retention

Figure 24 shows Box Plots for the process parameter Initial Vacuum pressure with -18 psi and -20 psi. According to the ANOVA in Table 10 there is statistical evidence with a p-value of 0,0465 that the mean of the retention value is different. Which means that with an initial vacuum pressure of -20, a higher retention value with 0,161 gal/f^3 can be obtained.

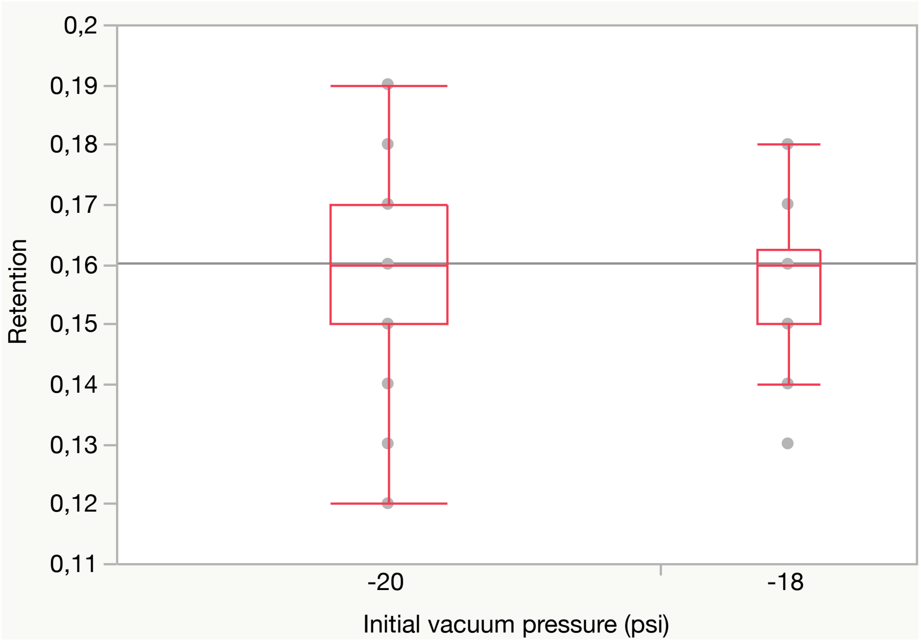

Figure 24: Box Plots of Treated lumber with Ground Contact of Retention by IV Pressure

The null hypothesis is that there is no difference between the means of the retention by applying different initial vacuum pressure. Since the Prob>F is less than 0,05 Table 10 the null hypothesis can be rejected. Which means that there is statistical evidence, that the retention values are different for initial vacuum pressures of -20 and -18. When running the initial vacuum pressure by -20, a mean of 0,161 can be obtained, compared to 0,156 for an initial vacuum pressure of -18 (Table 11).

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Initial vacuum pressure (psi)	1	0,00068315	0,000683	4,0407	0,0465*
Error	129	0,02180998	0,000169		
C. Total	130	0,02249313			

Table 10: ANOVA of Treated Lumber with Ground Contact of Retention by IV Pressure

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
-20	89	0,161798	0,00138	0,15907	0,16452
-18	42	0,156905	0,00201	0,15294	0,16087

Table 11: Means for ANOVA of Treated Lumber with Ground Contact of Retention by IV Pressure

3.6. Comparison of Means and Variances of CCA Treated poles for the retention by month over a one year period

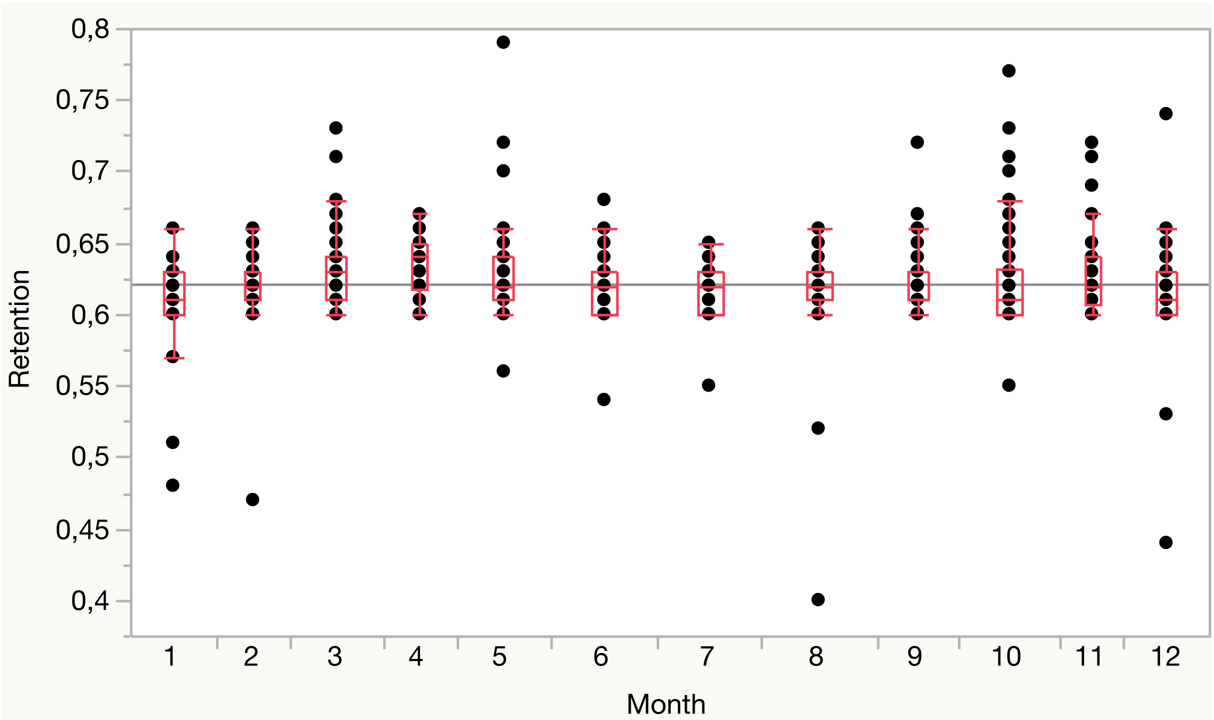

Figure 25: Box Plots of Treated Poles of Retention by month

In Figure 25 Box Plots of the retention values for treated poles by month are displayed. To see if the means are significantly different a student's t-test was applied as seen in Table 12. There is statistical evidence that especially month number 4 (April) has a significant different mean than the other months. Also retention from the month January is significant different to the rest of the year. The months in the warmer period, starting May till October have equal means and don't. It can bes possible that during this time the process is better under control, due to the climatic conditions.

Level	- Level	Differ-ence	Std Err Dif	Lower CL	Upper CL	p-Value
4	1	0,0222760	0,0051161	0,012233	0,0323192	<,0001*
4	12	0,0198566	0,0051161	0,009813	0,0298998	0,0001*
3	1	0,0183871	0,0048436	0,008879	0,0278953	0,0002*
4	2	0,0168519	0,0052896	0,006468	0,0272356	0,0015*
11	1	0,0162132	0,0053486	0,005714	0,0267128	0,0025*
4	9	0,0160923	0,0051763	0,005931	0,0262536	0,0019*
3	12	0,0159677	0,0048436	0,006460	0,0254759	0,0010*
4	8	0,0157712	0,0047831	0,006382	0,0251606	0,0010*
5	1	0,0148577	0,0048264	0,005383	0,0243322	0,0022*

Level						Mean
4	A					0,63388889
3	A	B				0,63000000
11	A	B	C			0,62782609
5	A	B	C			0,62647059
10		B	C	D		0,62189189
7			C	D	E	0,61986486
6			C	D	E	0,61910256
8			C	D	E	0,61811765
9			C	D	E	0,61779661
2			C	D	E	0,61703704

4	6	0,0147863	0,0048657	0,005235	0,0243380	0,0025*
4	7	0,0140240	0,0049192	0,004367	0,0236807	0,0045*
11	12	0,0137938	0,0053486	0,003294	0,0242934	0,0101*
3	2	0,0129630	0,0050265	0,003096	0,0228302	0,0101*
5	12	0,0124383	0,0048264	0,002964	0,0219128	0,0101*
3	9	0,0122034	0,0049071	0,002570	0,0218363	0,0131*
4	10	0,0119970	0,0049192	0,002340	0,0216537	0,0150*
3	8	0,0118824	0,0044904	0,003068	0,0206971	0,0083*
3	6	0,0108974	0,0045783	0,001910	0,0198849	0,0175*
11	2	0,0107890	0,0055148	-0,000037	0,0216149	0,0508
10	1	0,0102790	0,0047322	0,000989	0,0195685	0,0301*
3	7	0,0101351	0,0046351	0,001036	0,0192341	0,0291*
11	9	0,0100295	0,0054062	-0,000583	0,0206422	0,0640
11	8	0,0097084	0,0050310	-0,000168	0,0195845	0,0540
5	2	0,0094336	0,0050100	-0,000401	0,0192683	0,0601
11	6	0,0087235	0,0051096	-0,001307	0,0187540	0,0882
5	9	0,0086740	0,0048902	-0,000926	0,0182737	0,0765
5	8	0,0083529	0,0044718	-0,000426	0,0171314	0,0622
7	1	0,0082520	0,0047322	-0,001038	0,0175415	0,0816

Table 12: Comparison for each pair using students t-test for Treated Poles of Retention by month

12				D	E	0,61403226
1					E	0,61161290

Table 13: Connecting Letters Report for each pair using Student's t-test for Treated Poles of the Retention by month

3.7. Multivariate Analysis for treated poles

First a multivariate analysis was applied to the whole data set to see if there is any significant correlation between the process paramaters and retention values. This didn't show any correlation. Then, the dataset was divided by month and the multivariate analysis was applied again. When you look at at the data monthly, some significant results can be obtained with the multivariate analysis.
The null hypothesis is that there is no significant correlation between the retention and the start solution. As shown in Table 14 with a p-value of 0,0377 between the start solution and the retention, there is statistical significance that they are correlated with each other. This means that the null hypothesis can be rejected.

	Reten-tion	**Initial vacuum pressure (psi)**	**Initial vacuum time (min)**	**Start so-lution**	**Final injec-tion (gal/f3)**
Retention	<,0001	0,6075	0,9175	0,0377	0,6047
Initial vacuum pressure (psi)	0,6075	<,0001	0,9422	0,9017	0,6977
Initial vacuum time (min)	0,9175	0,9422	<,0001	0,9445	0,3135
Start solution	0,0377	0,9017	0,9445	<,0001	0,0806
Final injection (gal/f3)	0,6047	0,6977	0,3135	0,0806	<,0001

Table 14:Correlation Probability for some process parameters for Treated Poles for the month of January

Table 15 shows the correation probability for several process parameters for treated poles for the month in february. Different to January, not the start solution seems to have a significant correlation with the retention, but the final injection. With a p-value of 0,0485 the final injection shows significant correlation with the retention.

	Reten-tion	**Initial vacuum pressure (psi)**	**Initial vacuum time (min)**	**Start so-lution**	**Final injec-tion (gal/f3)**
Retention	<,0001	0,7412	0,8920	0,2056	0,0485
Initial vacuum pressure (psi)	0,7412	<,0001	0,1169	0,3631	0,4869
Initial vacuum time (min)	0,8920	0,1169	<,0001	0,1835	0,1842
Start solution	0,2056	0,3631	0,1835	<,0001	0,4165
Final injection (gal/f3)	0,0485	0,4869	0,1842	0,4165	<,0001

Table 15: Correlation Probability for some process parameters for Treated Poles for the month of February

Following Table 16 displays the correlation probability for several process parameters of treated poles. Similar to Table 14, with a p-value of 0,0286 there is significant correlation between the retention of the chemical and the start solution.

	Retention	Initial vacuum pressure (psi)	Initial vacuum time (min)	Start solution	Final injection (gal/f3)
Retention	<,0001	0,6602	0,1213	0,0286	0,8308
Initial vacuum pressure (psi)	0,6602	<,0001	0,2089	0,7538	0,1726
Initial vacuum time (min)	0,1213	0,2089	<,0001	0,6194	0,2868
Start solution	0,0286	0,7538	0,6194	<,0001	0,8459
Final injection (gal/f3)	0,8308	0,1726	0,2868	0,8459	<,0001

Table 16: Correlation Probability for some process parameters for Treated Poles for the month of June

3.8. Control Chart for Treated Poles

Figure 26 displays an individual and moving range chart of the retention of treated poles. The chart is divided into 12 months, starting by january. The green line represents the mean for each month and the red line represents the upper and lower control limit which is 3 standard deviations. Every point outside the control limit, means that the process is not under control anymore. Over the year, the variation seems to be different for every month and in some months the process seems to be less good under control than in others. Also the mean is shifting over the months up and down. The points out of the UCL and LCL are considered as special cause of variation. In this case this could have several resaons. One possible reason is a very high amount of heartwood in the treated wood, which is hard to impregnate. Another reason could be problems in the process by itself. For example damaged sensors or unsuitable impregnation cycle. The goal of every company should be, to keep the variation in the process as small as possible.

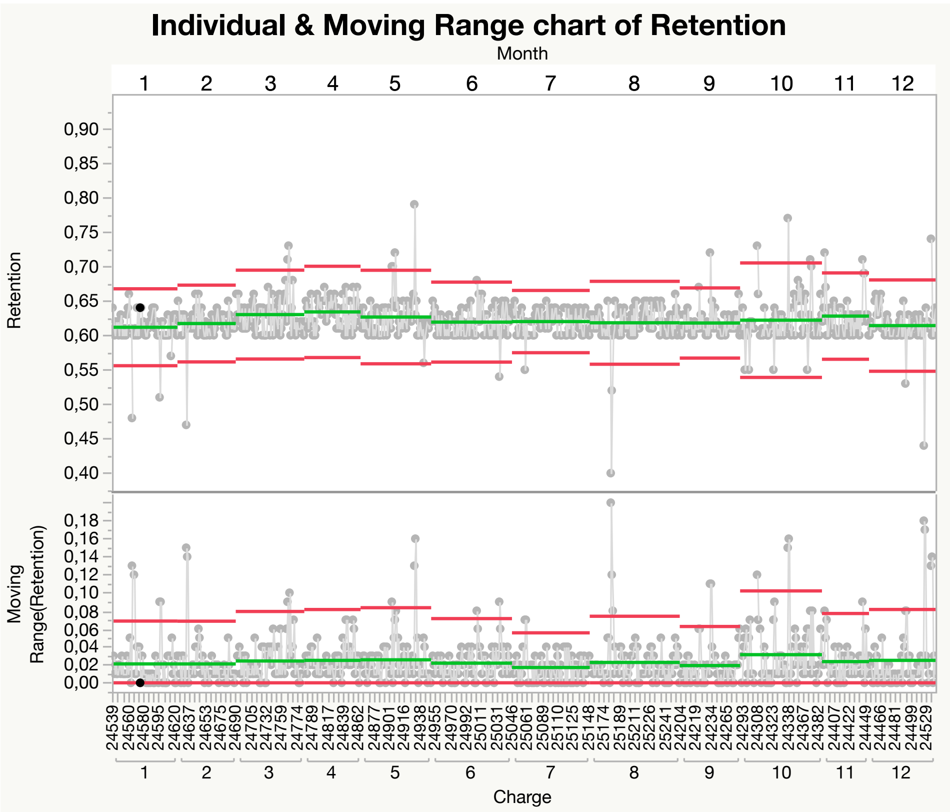

Figure 26: Control chart for treated poles over a 1 year period for the retention values

4. Conclusion

This study investigated recommendations on data quality and recommendations on root cause analysis for reducing variability for the pressure treatment process of lumber and poles. After analyzing the data quality with histograms and Q-Q plots, different statistical methods were applied to see if there is significance in the data. As statistical methods students t-test, Analysis of Variance and Welch's test were performed. Also a multivariate analysis was applied to the dataset of treated poles to look if there is any connection between process parametes and the retention of the wood. As a statistical process tool a control chart of the data for treated poles over a one year period was generated.
When working with the data, the bigggest issue was the data quality. As seen in the histograms (Figure 19, Figure 22) the data seems to be normally distributed till the specfication limit, but under the spec limit there is no more data distribution. This is possible, because the companys are allowed to retest up to 3 times. As there is variation in the sampling of the core borings, the retention and the testing by itself, you will get a satisfactory value the more often you test. The results of this study confirm the hypothesis that there is correlation in several process parameters and the retention of pressure treated wood. Also results of the root cause analysis can be supported by the statistical work which was done. For example the importance of the start solution before the treatment process shows significant correlation on the retention values.
It can be concluded, that it is possbile to use statistical process control for improving the wood pressure treating process. Companies could use tools like control charts to monitor their retention values and improve their variation in the process. Also with statistical techniques like the student's t-test, the process by itself could be optimised to get higher retention values by using less chemical. Future work could be done by using the retention values from the first sampling without retesting and look for correlation with process parameters.

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