Statistical Validation in Process Capability for a

High Pressure Flexible Polyurethane

Foam Pouring Machine

by

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ABSTRACT

Company XYZ is in the process of developing a new product line that will utilize a new piece of equipment. This machine will produce flexible polyurethane foam (FPF) seat fillers. The lack of experience with this type of equipment and the lack of published information about the industry has made it necessary to conduct this statistical study. This exercise in statistical analysis will allow company XYZ to better understand their current process capability. Understanding the processing limitation will allow company XYZ to communicate more effectively with their chemical supplier and their customers. Methods and procedures of this study include a review of literature relevant to FPF production and testing, statistical analysis, and calculating process capability. After completion of the statistical analysis, recommendations for process and equipment improvements were documented.

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Chapter I: Introduction

Introduction

Company XYZ originally started as a tent and awning company serving local markets in Northeastern Wisconsin. Present ownership purchased the company in 1975 and it has grown through acquisition and self-expansion. XYZ, Incorporated produces products directly for Original Equipment Manufactures (OEM), OEM Parts and Accessory (P&A) dealers, and products under their branded names. The company functions within two groups, the 'Marine Products Group' and the 'Powersports Products Group'. The Marine Products Group's focus is on boat covers, tops, and enclosures. The Powersports Products Group's focus is on personal watercraft (PWC), snowmobile, all terrain vehicle (ATV), and motorcycle products.

The largest growth for XYZ, Inc. has been in their power sports products, specifically in motorcycle accessories for OEMs. XYZ, Inc. had unsuccessfully attempted to produce motorcycle seats in the past. This attempt focused only on the cut, sew and upholstery of the seats; purchasing all other components, but the purchase and storage of the foam fillers proved difficult and expensive. However recently, several existing customers have requested quotes for seating projects.

This has prompted the management team to attempt producing motorcycle seats again. This time they have decided to bring in additional engineers to support the business with a task of purchasing a Flexible Polyurethane Foam (FPF) pouring machine and the foam testing equipment. The FPF pouring machine allows seat cushions to be produced just in time for manufacturing. When placed in the Seat Assembly Cell, the bulky seat cushions are not inventoried. They are poured, upholstered and shipped.

For poured foam products to be produced and shipped in this manner, XYZ's Quality Control and Engineering teams will need to validate the machines repeatability and the foam filler's quality within the customer's specifications. The cost of each product is directly affected by the amount of labor that is required to test and inspect the quality of the FPF filler. In order to control costs, it is important for XYZ, Inc. to communicate their processing capabilities to their customers and to communicate the needs of the customer to the foam chemical supplier.

While many types of additives can be added to the chemical make-up of a FPF product, XYZ, Inc. will only use the two basic chemical components. These components are a polyol and an isocyanate with water (Polyurethane Foam Association, 1991). These are mixed together vigorously in high intensity mixers in specific amounts for immediate reaction of the foam. Figure 1 displays the layout of a typical high-pressure foam machine (Crawford, 2007). Bubbles are formed, and the mixture expands (Polyurethane Foam Association, 1991). It has been compared to bread rising. In a matter of minutes the reaction is complete. While most foam forms can be removed from the die within eight minutes, full cure will occur over the next 24 to 48 hours.

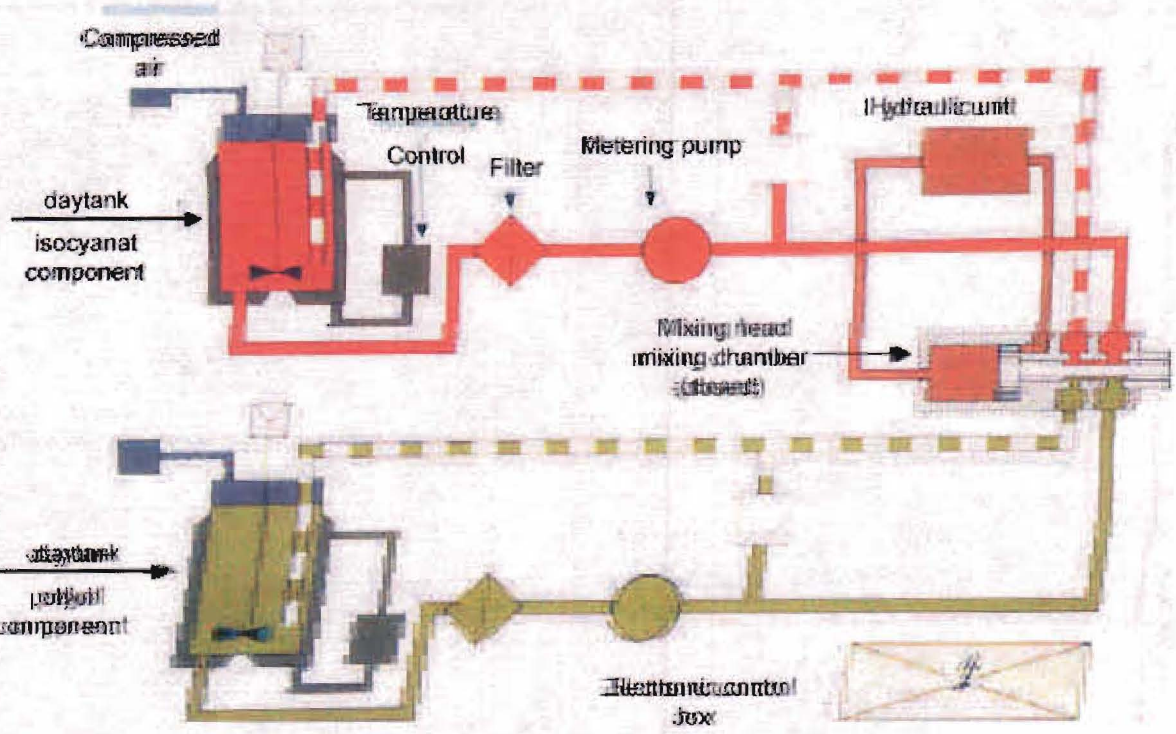

Figure 1. High Pressure Foam Pouring Machine

Source: Crawford, 2007

The remainder of this chapter will explain the inherent problems with validating FPF production and explaining the limitations with the end-user. This chapter will also cover the objectives and significance of the study as it relates to company XYZ, Inc. and its customers.

Statement of the Problem

If XYZ, Inc. is to satisfy their customer's expectations; they will need to satisfy two requirements. First, they need to successfully communicate their FPF processing capabilities to the customer. Secondly, they will have to create mutually acceptable testing requirements and sampling plans.

Foam performance consistency has historically been a controversial subject between foam producers and end-users (Polyurethane Foam Association, 1994). The key issue behind the controversy has been a lack of agreement on foam performance. OEM's are typically unsure of what can be produced, measured, and controlled by suppliers.

In many cases, performance properties cannot be controlled as tightly as end-users desire (Polyurethane Foam Association, 1994). Discrepancies are compounded by variations in test results even under ideal laboratory conditions. For example, foam firmness measured at the supplier can vary from 28 pounds to 34 pounds when measured at the end-user's laboratory. Such an apparent variance can be frustrating for both parties.

Purpose of the Study

This study used statistical methods to identify the company's FPF processing capabilities, and to validate the daily 'Standard' measurement limitations. When complete, XYZ, Inc. will have a greater understanding of its foam processing abilities, the costs associated with in-process testing and the assumed financial risks of sampling plans. XYZ's customers will be assured of consistent quality products produced in a statistically controlled process.

The objectives of this study are to:

1. Validate the processing capabilities of the FPF pouring machine using a five-pound per cubic foot (pcf) density foam mixture.
2. Confirm the hypothesis of the correlation between weight and Indentation Force Deflection (IFD).
3. Create a statistical study of a poured foam 'Standard' 15" x 15" x 4" using the 5 pcf density foam mixture.

4. Develop a material and labor usage estimate associated with creating and testing poured foam 'Standards'.

Assumptions of the Study

The assumptions of this Study are:

1. Normal seasonal changes in humidity and temperature will not greatly affect the results of the statistical results.
2. XYZ, Inc. will not change their chemical supplier or foam density requirement.
3. The mold release material and application device will not adversely affect the finished FPF filler.
4. All sensors and controls on the foam pouring equipment will function properly.

Definition of Terms

Definitions were taken from the Flexible Polyurethane Foam Association Glossary (n.d.) and FPF: A Primer in Comfort (n.d.).

American Society of Testing and Materials (ASTM) - An organization devoted to the establishment of standard methods and procedures for testing materials.

Bottom Out – Lack of support under full weight load.

Cell – The cavity remaining in the structure of FPF surrounded by polymer membranes or the polymer skeleton after blowing is complete.

Comfort – The ability of the cushioning structure to deflect at the surface and to conform to body shape, preventing a concentration of pressure on the body.

Compression Modulus – Ratio of an FPF's ability to support force at different indentation (or compression) levels. It is determined by taking the ratio of the FPF's Indentation Force Deflection (IFD) at 25% indentation and 65% indentation.

Density – A measure of the mass per unit volume. For this study we will use pounds per cubic foot (pcf).

Durability – How well an FPF retains its comfort, support, and shape with use.

FPF – An acronym for Flexible Polyurethane Foam.

Hand – The feel of the FPF as the hand is rubbed lightly over the surface.

Indentation Force Deflection (IFD) – This is a laboratory deflection test that measures the force required to deflect a standard sized FPF to a specific percentage of its thickness. This test is usually done at 25% and 65% of initial height. Previously call "ILD (Indentation Load Deflection)".

Recovery – The amount of return to original dimension and properties of an FPF sample after a deforming force is removed.

Surface Firmness – The number of pounds of force required to indent a FPF sample by 25% of its original height.

Universal Test Frame (As it applies to this study) – A testing apparatus that allows for several variations in test set-ups allowing one piece of equipment to do the necessary physical tests to validate foam filler samples.

Limitations of the Study

1. The results of this study are limited to XYZ, Inc.

2. The study did not create quality requirements for individual products. Quality standards for individual products are determined by the OEM and approved by XYZ Inc. Engineering and Quality Control based partially on the findings of this study, and FPF pouring machine processing capabilities.
3. The results are limited to a single supplier of both polyol and isocyanate chemicals.
4. Density, IFD and Compression Modulus test results are limited to those taken from the 15" x 15' x 4" 'Standard' mold form.

Methodology

Chapter Two discusses the latest techniques and industry concerns with proper testing. It also reviews the statistical methods utilized in creating the analysis and making conclusions. Chapter Three outlines the research methods used in this study. Chapter Four presents the results from the Statistical Process Control (SPC) data analysis. Chapter Five presents the conclusions and recommendations drawn from the process analysis. Chapter Five also presents recommendations for future research.

Chapter II: Literature Review

Flexible Polyurethane Foam

Flexible polyurethane foam is one of the most versatile materials ever created and over 1.7 billion pounds of foam are produced and used every year in the United States (Polyurethane Foam Association, 1991). Foam has become extremely popular because of its unique combination of form and function since it can be molded or cut into nearly any shape. It is also light, resistant to mildew, and does not aggravate common allergies, like other natural cushioning materials.

Flexible polyurethane foam appears to be a simple product, but in reality it is very complex and can be produced to have nearly infinite variations in properties. While two foams may look identical, they can have very different performance properties. These properties can be identified and specified very precisely. The foam industry utilizes several measurements and tests to select the right foam for the right application.

The three key ingredients to all foam applications are support, comfort, and durability. The foam needs to support the proper amount of weight to properly cushion an object or person. Foam cushions must 'feel' good to the user and provide not just cushioning but also comfortable use. Finally, the foam must hold up through use without losing its original properties. If these basics are understood about the product, it is possible to accurately select the flexible polyurethane foam.

The basic FPF is produced from a chemical reaction between two key components, a polyol and an isocyanate with water. These two chemicals are mixed together vigorously in high intensity mixers. The ratio of the two chemicals and the temperature at which they are mixed is critical to fulfilling the requirements of support, comfort and durability. The chemical reaction which begins almost immediately creates bubbles to expand the mixture.

The foam production process can be controlled through changes in the foam chemical mixture. In addition to the polyol, isocyanate and water used to produce the foam, a variety of other additives and chemicals can be used to change the properties of the foam. Auxiliary blowing agents are added to enhance the normal production of carbon dioxide producing lighter or softer foam. Catalysts are also used to accelerate the reaction to speed production while surfactants are added to aid in the formation of foam cells, and flame-retardants are often added to foam to meet state and federal fire requirements. Solid Fillers are also added to the foam to add weight. Unfortunately, these additives often have a negative effect on comfort, support, and durability.

The two common production processes for Flexible Polyurethane Foam are Slabstock and Molded foam. Most foam for furniture and bedding are produced as Slabstock. Pouring the foam mixture onto a moving conveyor with sides allowing the foam to 'free rise' two to four feet produces Slabstock. The continuous slab is cut, stored and then fabricated into useful shapes.

The Molded foam process is typically used in the production of automotive seats and some custom furniture applications. In this process, the foam mixture is poured into a specially shaped mold where the foam expands to fill the cavity. Molds must be properly designed to withstand internal pressure and allow gases to escape. The Molded foam process allows for even more opportunity to manipulate support and comfort characteristics.

There are several physical properties used when specifying foam for a particular application (Polyurethane Foam Association, 1991). The following characteristics are used when describing or specifying a motorcycle seat:

Density is a measure of the mass per unit volume and expressed in pounds per cubic foot (pcf) or kilograms per cubic meter (kg/m^3). It is the most important of all foam properties. Density is a function of the chemistry used to produce the foam and can be manipulated without adjusting the ratio of polyol and isocyanate when molded under pressures above normal 'free pour'. It affects foam durability and support. Typically, the higher the polymer density, the better the foam will retain its original properties.

Indentation Force Deflection (IFD) is a measure of foam firmness (Tan, 1998). Firmness is independent of foam density, although it is often thought that higher density foams are firmer. IFD specification relates to comfort. It is a measure of the surface feel of the foam and is measured by indenting the foam 25% of its original height.

A second IFD measurement is sometimes taken by indenting the foam to 65% of its original height. This is used to help determine the ability of the foam to provide deep down support. Typically, the higher the difference between the 25% and 65% IFD, the more ability the foam has to support weight. By dividing the 65% IFD by the 25% IFD, we get the 'Compression Modulus'. The Compression Modulus is sometimes referred to as the 'Support Factor'. The higher the modulus, the better the ability of the foam when providing support.

Flex Fatigue or Dynamic Fatigue is one of several tests designed to measure foam durability. Durability is a measure of how well foam retains its original firmness properties or height (Polyurethane Foam Association, 1991). There are several methods used to measure the durability of an FPF. Most methods are mechanical means of flexing or compressing the material a specified number of times and measuring the foam firmness and height before and after testing.

Many manufactures will test the tear strength of FPF samples (Polyurethane Foam Association, 1991). The tests used to determine these factors are tensile strength, tear resistance and elongation. They determine the foam's ability to be stretched or flexed without tearing. These tests are particularly important for foams with additives for fire retardation and fillers.

Polyurethane Foam Testing Standards

The ASTM Standard Test Methods for Flexible Cellular Materials-Slab, Bonded, and Molded Urethane Foams, D 3574 – 05, describes the methodology for how these materials are to be tested. Specifically, the designation D 5672 – 03, the Standard Test Method for Testing Flexible Cellular Materials Measurement of Indentation Force

Deflection Using a 25-mm [1-in] Deflection Technique, covers the apparatus to be used, the conditioning of the foam block, and the procedure to be followed for testing these materials. The 25% IFD test is traditionally used on a 100-mm [4-in] thick sample. It is important to note that ISO 2439 is a similar test, but there are technical differences. This test method is intended to provide a quick and simple method to screen flexible polyurethane foams for determination of its firmness grade and therefore should not be used on foam samples less than 75-mm [3-in] thick.

Section 4 of the Joint Industry Foam Standards and Guidelines, published in July of 1994, discusses the history, use, and variability within the Indentation Force Deflection (IFD) Standards and Guidelines (Polyurethane Foam Association, 1994). Variability within test samples can come from many factors. Some of these factors are variations in foam block size (15-in x 15-in minimum) or thickness (typically 4-in), measuring equipment, and changes in temperature and/or humidity.

The IFD is typically run at 25% and 65% of the foam block thickness (Polyurethane Foam Association, 1994). The 25% IFD value is used in determining the foam grade. In the United States, the 65% IFD is commonly measured but not used to specify grade. The ratio between the 65% and 25% IFD is commonly called the support factor. For example, a foam block measuring 100 lbf at 65% and 50 lbf at 25% would have a support factor of two. The support factor provides an indication of support characteristics not correlated with any other foam property.

The support factor has often been called a comfort ratio. The Polyurethane Foam Association (PFA) has been cautious not to confuse support with comfort. Comfort is too subjective a term across an entire industry. Although in some instances, particularly in the furniture industry, the support factor can be related to comfort. Foams with a higher support factor are often considered more appropriate for comfortable seat cushions. They provide more load bearing at higher deflection values.

Statistical Analysis in Process Capability

All Processes are subject to variability (Rauwendaal, 1993). Shewhart distinguished two basic causes of variability. The first being common causes. Common causes are those sources of variation that are inherent to the process under normal conditions. The second cause of variability is assignable causes. Assignable causes are those that are not inherent to the process. Common causes of variation are often slight and cannot be traced back to a single common cause. Assignable causes on the other hand are often sporadic, chaotic or unnatural. Their effect can be strong.

Variable Control Charts. A variable control chart is created within a systematic method of plotting process data over time. To create control charts for variables, samples, arranged into subgroups, are taken during the process (Summers, 2006). The averages of the subgroups are plotted on the control chart. The centerline shows where the process average for that attribute is centered. The upper and lower control limits (UCL, LCL) are calculated based on $\pm 3\sigma$ limits 99.73% of the time, provided the process does not change and is under control. Figure 2 shows a typical control chart with centerline and control limits. While Figure 3 shows one of the mathematical formulas for calculating sigma of a population, most statistical software packages will automatically calculate sigma for a population or sample group.

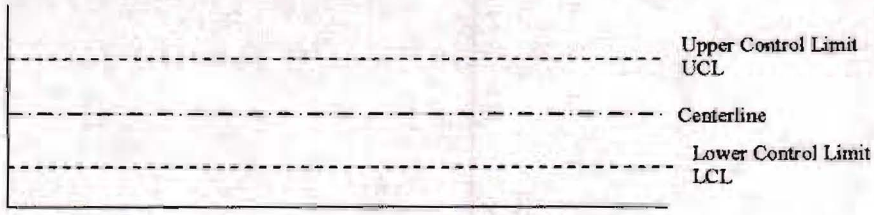

Figure 2. Typical Control Chart

Source: Summers, 2006, p. 224

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \mu)^2}{n}}$$

σ = standard deviation of the population
μ = mean value of the series of measurements
X_i = $X_1, X_2, \ldots, X_n$ = values of each reading
N = number of readings

Figure 3. Sigma Calculation – Population

Source: Summers, 2006, p.176

Individual and Moving-Range Charts. Individual and moving-range charts are often used when the data collected occurs either once a day or on a week-to-week basis (Summers, 2006). These charts are created when the measurements are single values or when the number of products produced is too small to form traditional X-Bar and R charts. Moving Ranges are calculated by plotting the absolute value difference between individual data points. R-bar or the centerline is the calculated average and the UCL is the calculated +3σ of the data points (range).

Moving-Average Charts. Rather than plotting individual points, it is also possible to combine *n* number of individual values to create an average (Summers, 2006). The average is calculated by taking the *n* number of individual values, dropping off the first, replacing it with the next n^{th} value and calculating the new average for the data point. The control limits are calculated using the same method as with X-Bar and R charts. By combining individual values over time, moving averages smooth out short term variation allowing the study of trends in the data.

Control Limits versus Specification Limits. A process is only in control when the process centering and variation present within the process remains constant over time (Summers, 2006). A process under control will exhibit the following six characteristics:

1. Two-thirds of the points are near the center value.
2. A few of the points are close to the center value.
3. The points float back and forth across the centerline.
4. The points are balanced on both sides of the centerline.
5. There are no points beyond the control limits.
6. There are no patterns or trends on the chart.

It is important to note the difference between the control limits and the specification limits (Summers, 2006). Specification limits are determined during the design of a product while control limits are calculated based on the data set. It is important to note that a process can be in control and still not meet the set specifications. At the same token it is possible for a measured variable to be within specification, but not have been produced within a process under control.

Statistical Correlation. In Dietrich and McClave's (1988) book Statistics they state, "A numerical descriptive measurement of the correlation between two variables x and y is provided by the Pearson product moment coefficient of correlation, *r*" (p. 710).

Figure 4 gives the mathematical formula for calculating *r* of Pearson product moment coefficient of correlation. The correlation is one of the most common and most useful statistics (Correlation, n.d.). Correlation *r* is a single number that describes the relationship between two variables. The square of *r* or r^2 is equal to the magnitude or strength of the relationship (StatSoft, 2003).

$$r = \frac{N\Sigma xy-(\Sigma x)(\Sigma y)}{\sqrt{[N\Sigma x^2-(\Sigma x)^2][N\Sigma y^2-(\Sigma y)^2]}}$$

Where:
N = number of samples
Σxy = sum of the products
Σx = sum of x
Σy = sum of y
Σx^2 = sum of squared x
Σy^2 = sum of squared y

Figure 4. Calculation Formula for Correlation *r*

Source: Correlation, n.d.

The next step in evaluating a correlation with two variables is to determine the significance of the calculated correlation (StatSoft, 2003). The significance level calculated for each correlation is a primary source of information about the reliability of the correlation. The level of significance can be gathered from a table of critical values of *r* (Correlation, n.d.). Before this value can be located within the table, the user will need to calculate the degrees of freedom (df) or *N*-2, the significance level of alpha (alpha = .05 = 95%), and the type of test, one-tailed or two-tailed. A two-tailed test would be typical for variables with little or no known history.

Process Capability Indexes. In order to determine process capability and performance indexes, the user must go through the following three phases (Grant & Leavenworth, 1996):

1. *Establish control over the process*. A process out of control may skew subsequent calculation for estimates of the parameters of the distribution.
2. *Analyze process data*. Estimates are made of the process average, dispersion, and frequency histograms may be plotted to get the form of the distribution.
3. *Analyze sources of variation*. Knowledge of the process becomes extremely important at this phase. Studying the sources of variation and their magnitude can be extremely complicated experimental designs over long periods of time.

Calculating performance indexes are relatively easy once the standard deviation (σ) is calculated and the specification limits (USL & LSL) are set (Grant & Leavenworth, 1996). Figure 5 shows the calculation for C_p, and C_{pk}. The process index C_p, is best described as the process capability potential. It describes the precision rather than the accuracy of the variable's data set. Precision describes the grouping of the data without relationship to a set point, while accuracy describes the data set about a nominal specification value. The process index C_{pk}, on the other hand does consider the accuracy of the data set about a nominal specification value, and the upper and lower specification values.

$$C_p = \frac{U - L}{6\sigma} \qquad C_{pL} = \frac{\mu - L}{3\sigma} \qquad C_{pU} = \frac{U - \mu}{3\sigma}$$

$$C_{pk} = \min(C_{pL}, C_{pU})$$

Where:
C_p = capability potential
C_{pL} = lower capability current
C_{pU} = upper capability current
U = upper specification limit
L = lower specification limit
μ = average , process center
σ = standard deviation

Figure 5. Calculations for C_p and C_{pk}

Source: Grant & Leavenworth, 1996, p. 325-326

The process index of C_{pk} can be correlated to the number of standard deviations from nominal and to quantity of parts per million (ppm) defective (C_{pk} Vs ppm, 2001). Figure 6 shows the histogram variation between different C_p values (Netherwood, 2007). Table 1 shows the correlation between C_{pk}, Standard deviation, and ppm.

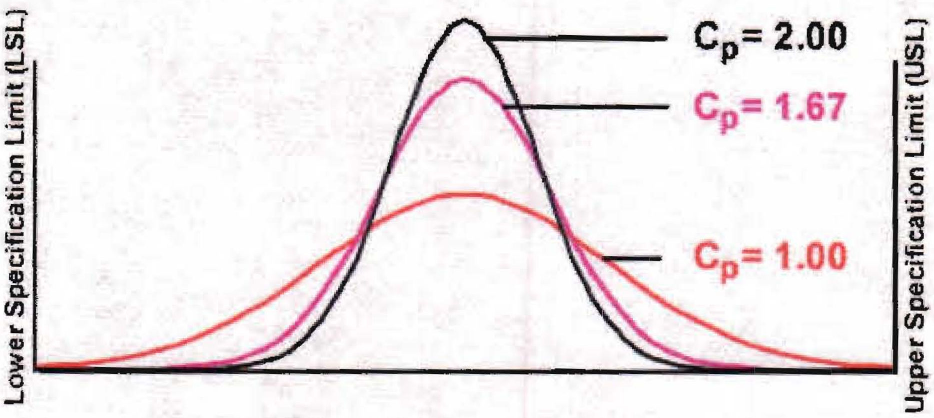

Figure 6. Histograms for C_p

Source: Netherwood, 2007

Cpk	Standard Deviations	Parts per Million (ppm)
1.00	±3	2,700
1.33	±4	64
1.66	±5	0.50
2.00	±6	0.002

Note: Summarized form C_{pk} Vs ppm Table (2001)
http://www.siliconfareast.com/cpkppm.html

Table 1. Comparison of C_{pk}, Standard Deviation, and ppm

Source: C_{pk} Vs ppm Table, 2001

Chapter III: Methodology

Introduction

The purpose of this study is to assist company XYZ in producing quality seating products that meet their customers' specifications. The objectives of the study are to validate the processing capabilities of the FPF pouring machine, determine if there is a correlation between weight and IFD, create a statistical study and analysis the data on a foam standard block. This chapter will detail the methods to be used for creating the specimens to be measured, collecting the data to be analyzed, and analyzing the graphical and empirical information.

Specimen Selection and Description

A 15" x 15" x 4" poured foam block was selected for the study. The ASTM D3574-05 Standard Test Methods for Flexible Cellular Materials requires a minimum test block sample 15" wide by 15" long along with a recommendation of a 3" minimum for thickness. While the specification does recommend a larger block for testing, it was determined to be both cost prohibitive and unnecessary to exceed the minimum width and length. However, it was determined to use a 4" thickness as described in the ASTM D5672-03 Standard Test Method for Testing Flexible Cellular Materials – Indentation Force Deflection.

As the foam blocks have no value other than for data collection, it was critical to select the most prudent quantity for the population. The study will consist of 150 samples, produced at a minimum of 30 per shift. All specimens were measured and logged for analysis. Any specimen suspected of being outside of the normal process were identified with the observed assignable cause. These specimens were evaluated after the data collection.

Measuring Equipment

Each specimen created was measured for thickness and physically tested using an MTS Insight™ electromechanical testing system. The specimens were then compressed to 25% and 65% of its measured thickness using a 50 in^2 disc as described in the ASTM standards. The MTS TestWorks®4 software comes preprogrammed to perform the IFD test including the preflex. This assures that each of the samples were tested in a consistent manner. All feed speeds and crosshead positions are controlled internal to the test apparatus and software. A calibrated 2.5kN load cell was electronically connected to the test software to accurately record the force curve and identify the 25% and 65% IFD values.

Data Collection Procedures

The study consists of a 150-specimen population with a minimum of 30 specimens run per shift. Each specimen was identified 1 thru 150, with its weight, and placed on a rack for a 24-hour minimum cure. The daily average temperature and relative humidity was recorded for comparison with future studies. The specimens were then placed into the test frame. They were then tested using the preflex and test program for the ASTM 25% and 65% IFD. After the test cycle was complete, the program queried the operator for the specimen weight in grams. The operator was required to enter the weight for that specimen. Each shift's test results were saved within the system's sample file folder. All observations from the machine operator were recorded within the specimen 'Notes' area of the sample file.

There was no machine setting adjustments once the study began.

Statistical Data Analysis

Several statistical analysis tools were used to evaluate the data set. The data was formatted into three types of control charts. The study charted individual, moving-range, and moving-averages. The study calculated correlation values between IFD and weight. Finally, process indexes were calculated for C_{pk} on the 25% IFD, 65% IFD and weight variables. These indexes were calculated on the adjusted data.

Limitations

The primary limitations for this study are as follows:

- The study is limited to company XYZ, Inc.
- The results are limited to a poured foam filler of 5-pcf density foam from a specific supplier.
- The calculations for process capability were calculated at the current process capability; not necessarily on an in control process.

Chapter IV: Results

The purpose of this study is to give company XYZ, Incorporated a better understanding of their foam pouring process. The study will confirm the relationship between the IFD and the measured weight of the foam filler. The evaluation of control charts and the expertise of the manufacturing engineering group will identify and evaluate variability and the causes of the variability.

Statistical Correlation

The first analysis tool used was the individual run chart. The entire 151 data points for 25% IFD and 65% IFD were plotted with the weight values for each of the foam fillers. Figure 7 shows the graphical correlation between the 25% IFD on the right *y-axis* and weight on the left *y-axis*. Figure 8 shows the graphical correlation between the 65% IFD on the right *y-axis* and weight on the left *y-axis*.

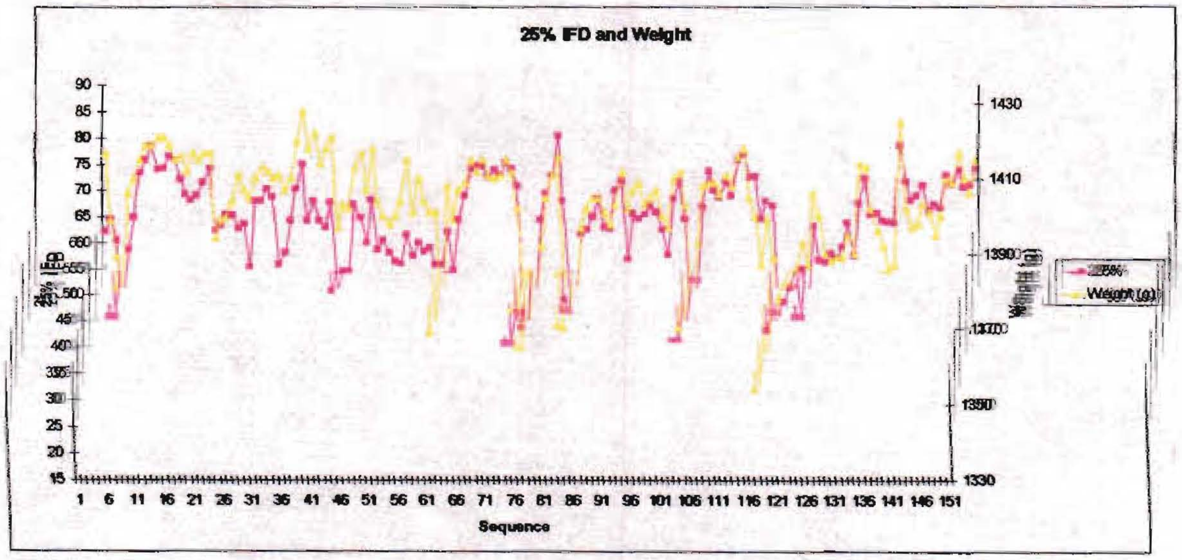

Figure 7. Graph of 25% IFD and Weight

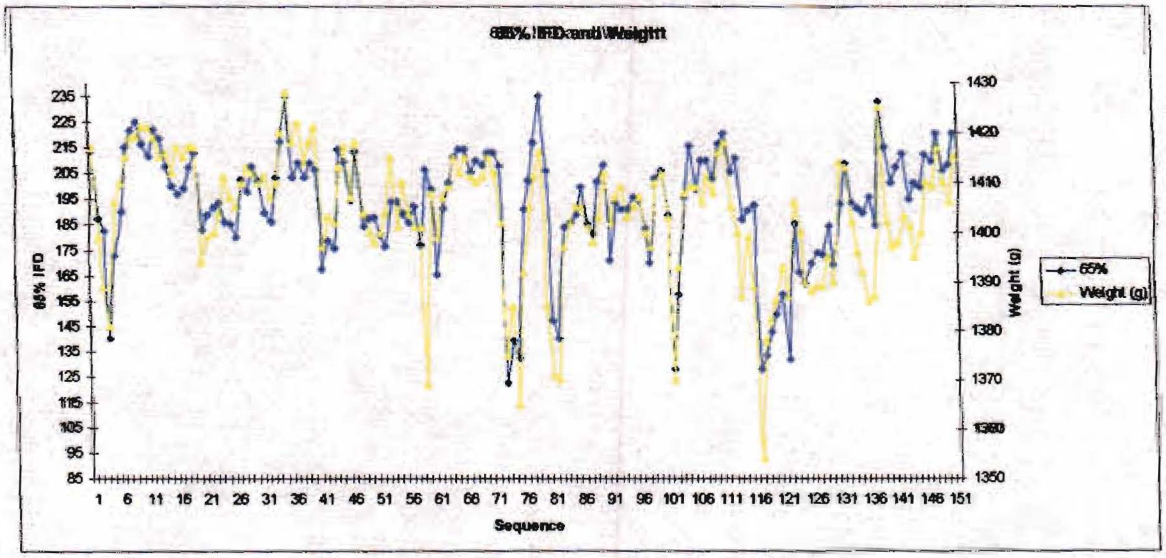

Figure 8. Graph of 65% IFD and Weight

Along with the graphical depiction of the IFD to weight correlation, the data was processed using the Pearson product moment coefficient of correlation, *r*. The correlation, *r* value for 25% IFD to weight was .77 and .81 for the 65% IFD to weight. These strong correlation, *r* values confirm the positive correlation between IFD and weight.

Control Charts

After the correlation was confirmed, the study focused on the variation within the population. Data points with confirmed assignable causes such as initial start-up, low head-pressure, low chemical warnings, incorrect mold temperature, and incorrect nitrogen blanket pressure were removed from the data sets. Most of these conditions were confirmed through the IFD to weight correlation. When weight varied by about 2% of the average it coincided directly with an insufficient IFD value. Once these values were pulled from the data set, control charts were created for moving-average and moving-range. The data set was reduced from 151 to 133 points. Figure 9 shows the graphical representation of the 25% IFD and Figure 10 shows the graphical representation of the 65% IFD.

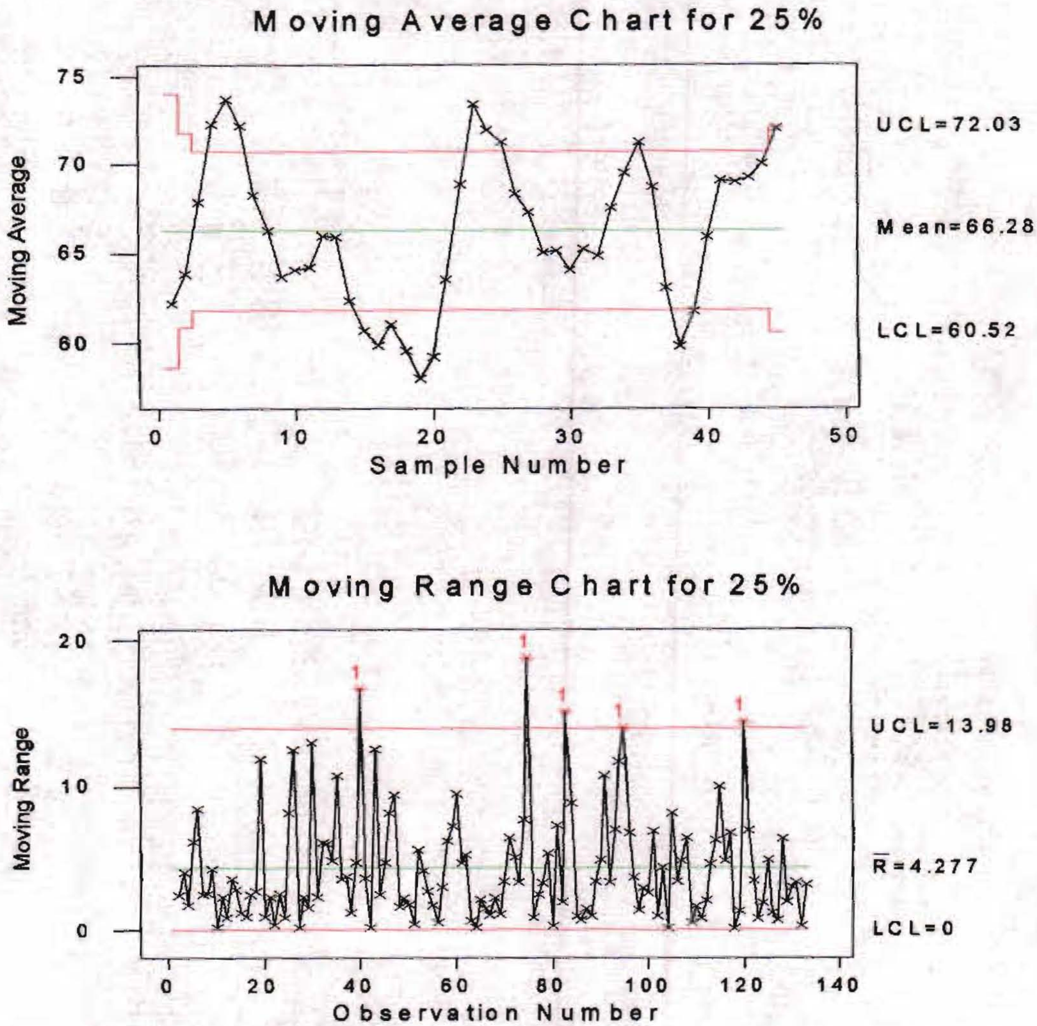

Figure 9. 25% IFD Moving-Average and Moving-Range

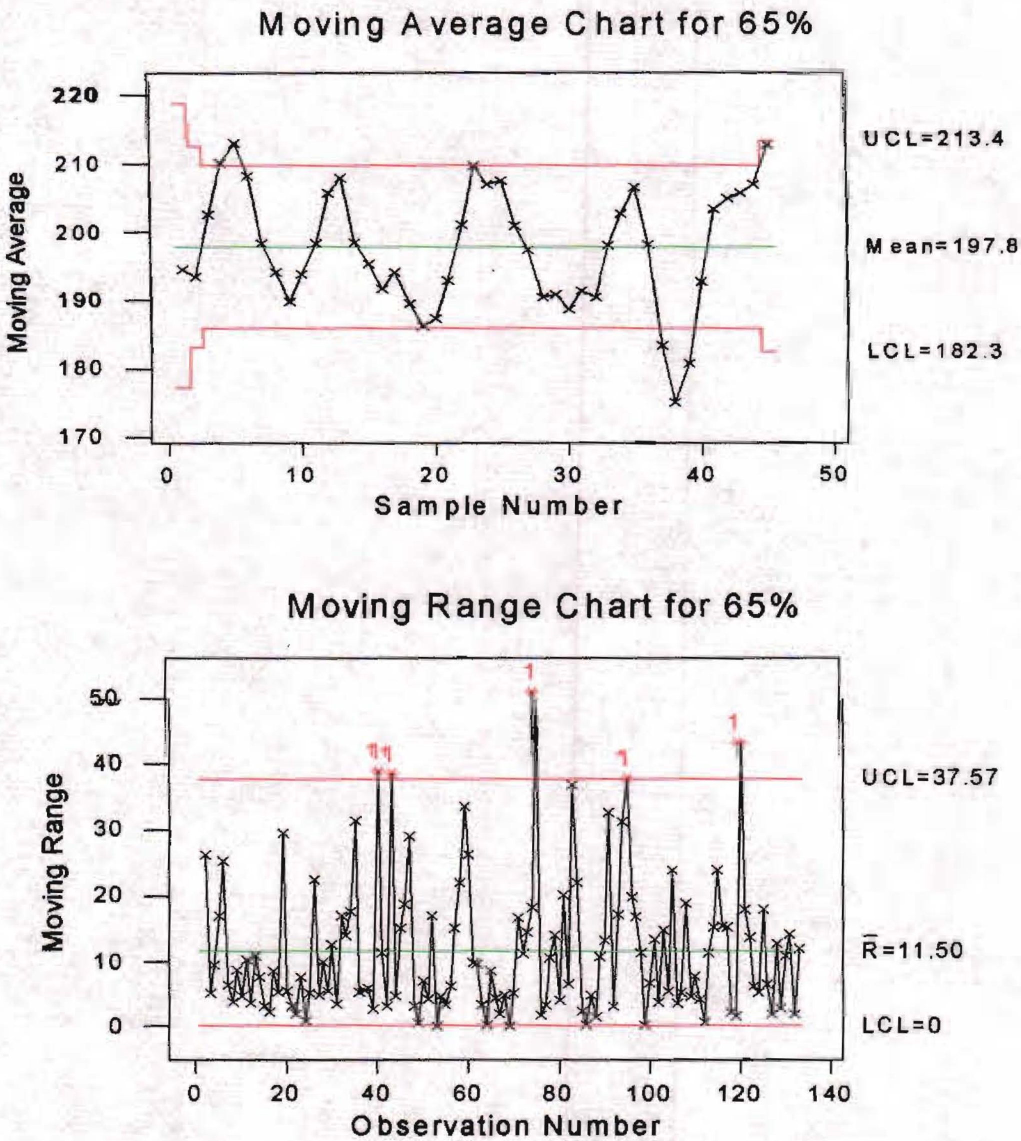

Figure 10, 65% IFD Moving-Average and Moving-Range

The number of data points outside of the upper and lower control limits on the moving-average and moving-range control charts gives an indication of additional causes of variation that are moving the current process out of control. Based on this information it would not be pertinent and may cause inaccurate assumptions about the process capability to calculate process indexes such as C_p or C_{pk} on the data set.

Process Capability

However, for the purpose of the study, C_{pk} values for the 25% IFD, 65% IFD and weight were calculated. Figure 11, 12 and 13 respectively show the graphical representation of each of the modified data sets with both the specification limits and control limits. Table 2 shows the C_{pk}, upper, lower and nominal specifications along with the control limits for each of the variables.

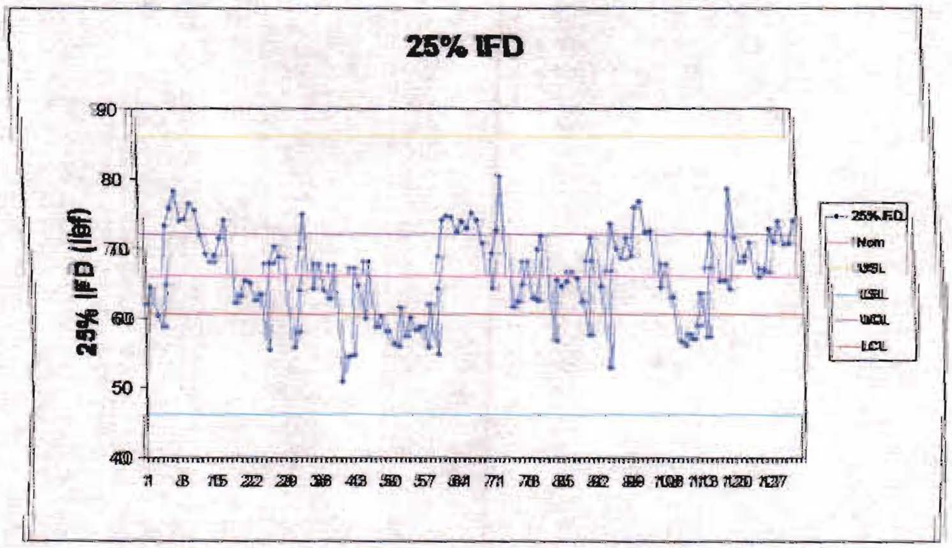

Figure 11. 25% IFD Graph

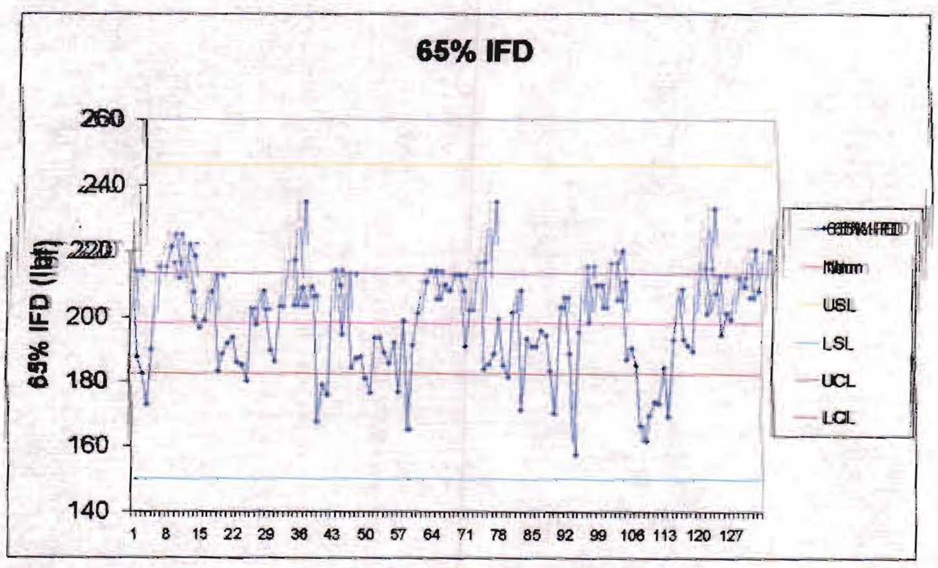

Figure 12. 65% IFD Graph

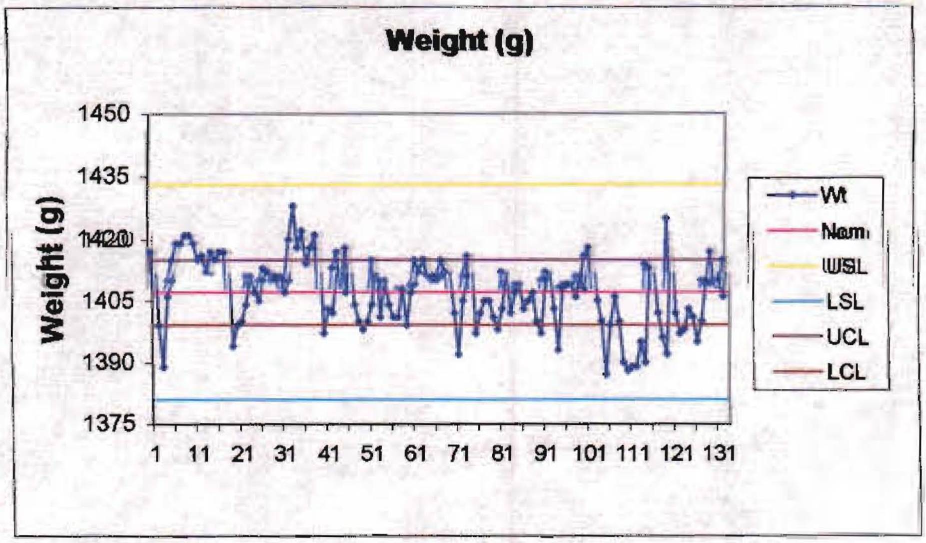

Figure 13. Foam Filler Weight Graph

	25% IFD	65% IFD	Weight (g)
Cpk	1.020	1.016	1.002
USL	86	246	1433
Nominal	66	198	1407
LSL	46	150	1381
UCL	72.03	213.40	1415
LCL	60.52	182.30	1399

Table 2. Cpk, Control, and Specification Limits

Summary

From these graphs and the statistical output from MiniTab, we have concluded that there is significant process variation. While the process variation did not produce specimens outside of the acceptable specification limits, we do feel that it is necessary to create a series of suggestions for process improvement. Chapter five will give a detailed explanation of the proposed process changes and potential equipment modifications.

Chapter V: Conclusions and Recommendations

Introduction

This chapter will cover conclusions and recommendations for company XYZ Incorporated. They are specific to the observations and statistical analysis in regard to all stated limitations.

Summary

The purpose of this study was to give company XYZ, Inc. a detailed picture of their current foam pouring process and to make recommendations for improvement. The objectives of this study were to:

1. Validate the processing capabilities of the FPF pouring machine using a 5-pcf density foam mixture.
2. Confirm the hypothesis of the correlation between weight and Indentation Force Deflection (IFD).
3. Create a statistical study of a poured foam 'Standard' 15" x 15" x 4" using the 5-pcf density foam mixture.

Limitations

The primary limitations for this study are as follows:

- The study is limited to company XYZ, Inc.
- The results are limited to a poured foam filler of 5 pcf-density foam from a specific supplier.
- The calculations for process capability were calculated at the current process capability; not necessarily on an in control process.

Conclusions

Objective 1. Validate the processing capabilities of the FPF pouring machine using a 5-pcf density foam mixture. The study was able to show that the process is capable of meeting the specification limits. It was also shown that the process lacks control. It is this lack of control that will require additional steps within the process and sufficient operator training to detect unacceptable variations in weight and IFD.

Objective 2. Confirm the hypothesis of the correlation between weight and Indentation Force Deflection (IFD). The confirmation of the strong correlation between IFD measurements and weight will allow for a much less expensive option for in-process inspection. The weight of the foam fillers can be measured in seconds, while IFD measurements take eight to ten minutes. It is important to note that while the correlation between IFD and weight were significant; the significance is only accurate as long as the ratio of the chemical mix (Isocyanate and Polyol) remains consistent.

Objective 3. Create a statistical study of a poured foam 'Standard' 15" x 15" x 4" using the 5-pcf density foam mixture. A study, along with sufficient analysis, was conducted producing the following recommendations for improvement. The completed statistical study allowed for the satisfactory completion of the first two objectives.

Process improvement Recommendations

The following initial recommendations should be implemented immediately:

1. Based on the strong correlation of weight to IFD, all foam fillers should be weighed prior to further processing, and suspect material should be set aside for further review.
2. Operators need to be trained in identifying suspect parts based on the 'hand'.

3. Engineering will need to create the acceptable weight ranges for each product.
4. The area supervisor will need to create a schedule for rolling breaks to eliminate fall-out due to unnecessary start-ups.
5. Tools should be preheated prior to shooting foam. This will minimize defects at start-up.

The secondary recommendations will require some capital expense. The following recommendations are for minor equipment and future tooling enhancements:

1. The addition of auto fill pumps and programmable logic controller to the foam machine will substantially reduce the likelihood of failures due to day tank pressure loss.
2. The addition of flow meters with digital readout to the isocyanate and polyol lines will give the operator additional information to identify short shots. These flow meters will also be necessary to do further modifications to the machine function and reliability.
3. Changing the equipment's pumping systems from gear pumps to axial piston pumps may increase flow accuracy, and increase process capability.
4. Future foam filler dies should be purchased with water heating lines to regulate mold cavity temperatures.

The final recommendation is for a major machine modification that may be necessary if future foam fillers require tighter IFD specifications. The machine modification will require the addition of the flow meters as stated earlier. The existing gear pumps would be replaced with axial piston pumps with higher flow accuracy. In addition to the component modifications and additions, the programmable logic controller (PLC) logic would have to be rewritten. These changes would allow for the foam pouring system to have a closed-loop. The closed-loop logic will allow the variable speed motors to adjust pump volume during the pour time. This adjustability should increase process capability.

Recommendations for future studies

As process changes are implemented, it is recommended that this study be repeated. Because of the cost implications, I recommend reducing the sample population to a single shifts production. However, if the major machine modifications are found to be necessary, the recommendation is to reproduce the study in its entirety with a sample population of 150 foam fillers. This will allow for a direct comparison with this study for confirming the new process capability.

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Appendix A: Raw Statistical Data Table

#	Length	Width	Date	Humidity ((Rel)	Pour Time	Temp	Weight (g)	Specimen Height	Load @ 25% (b)	Load @ 65% (d)	Support Factor
	in	in			s	F		in	lbf	lbf	65%/25%
1	15	15	4/2/2007	35	3.5	74	1417	3.79	61.921	213.722	3.452
2	15	15	4/2/2007	35	3.5	74	1399	3.96	64.328	187.537	2.915
3	15	15	4/2/2007	35	3.5	74	1389	3.95	60.328	182.395	3.023
4	15	15	4/2/2007	35	3.5	74	1381	3.91	45.688	140.29	3.071
5	15	15	4/2/2007	35	3.5	74	1406	3.95	58.592	172.829	2.95
6	15	15	4/2/2007	35	3.5	74	1410	3.94	64.762	189.754	2.93
7	15	15	4/2/2007	35	3.5	74	1415	3.95	73.229	214.978	2.936
8	15	15	4/2/2007	35	3.5	74	1419	3.96	75.713	221.281	2.923
9	15	15	4/2/2007	35	3.5	74	1419	3.97	78.236	225.047	2.877
10	15	15	4/2/2007	35	3.5	74	1421	3.98	74.007	216.342	2.923
11	15	15	4/2/2007	35	3.5	74	1421	3.95	74.152	211.675	2.855
12	15	15	4/2/2007	35	3.5	74	1419	3.96	76.417	221.942	2.904
13	15	15	4/2/2007	35	3.5	74	1415	3.96	75.563	218.342	2.89
14	15	15	4/2/2007	35	3.5	74	1416	3.96	71.995	207.429	2.881
15	15	15	4/2/2007	35	3.5	74	1412	3.97	69.184	199.723	2.887
16	15	15	4/2/2007	35	3.5	74	1417	3.94	67.999	196.673	2.892
17	15	15	4/2/2007	35	3.5	74	1415	3.96	68.938	198.88	2.885
18	15	15	4/2/2007	35	3.5	74	1417	3.97	71.422	207.37	2.903
19	15	15	4/2/2007	35	3.5	74	1417	3.96	74.117	212.601	2.868
20	15	15	4/2/2007	35	3.5	74	1394	3.94	62.246	183.15	2.942
21	15	15	4/2/2007	35	3.5	74	1399	3.94	63.172	188.531	2.984
22	15	15	4/2/2007	35	3.5	74	1400	3.94	65.442	191.667	2.929
23	15	15	4/2/2007	35	3.5	74	1404	3.96	65.088	193.551	2.974
24	15	15	4/2/2007	35	3.5	74	1411	3.96	62.575	185.979	2.972
25	15	15	4/2/2007	35	3.5	74	1407	3.95	63.407	185.176	2.92
26	15	15	4/2/2007	35	3.5	74	1405	3.88	55.28	180.092	3.258
27	15	15	4/2/2007	35	3.5	74	1410	3.97	67.776	202.503	2.988
28	15	15	4/2/2007	35	3.5	74	1413	3.95	67.939	197.688	2.91
29	15	15	4/2/2007	35	3.5	74	1412	3.96	70.247	207.627	2.956
30	15	15	4/2/2007	35	3.5	74	1410	3.95	68.726	202.2	2.942
31	15	15	4/3/2007	33	3.5	73	1411	3.85	55.664	189.627	3.407
32	15	15	4/3/2007	33	3.5	73	1407	3.9	57.963	186.211	3.213
33	15	15	4/3/2007	33	3.5	73	1410	3.92	64.047	203.185	3.172
34	15	15	4/3/2007	33	3.5	73	1420	3.93	70.092	217.172	3.098
35	15	15	4/3/2007	33	3.5	73	1428	3.94	74.919	234.81	3.134
36	15	15	4/3/2007	33	3.5	73	1418	3.93	64.178	203.43	3.17

37	15	15	4/3/2007	33	3.5	73	1422	3.92	67.758	208.71	3.08
38	15	15	4/3/2007	33	3.5	73	1414	3.93	64.004	203.14	3.174
39	15	15	4/3/2007	33	3.5	73	1418	3.89	62.817	209.039	3.328
40	15	15	4/3/2007	33	3.5	73	1421	3.92	67.543	206.329	3.055
41	15	15	4/3/2007	33	3.5	73	1397	3.89	50.81	167.451	3.296
42	15	15	4/3/2007	33	3.5	73	1403	3.91	54.403	178.87	3.288
43	15	15	4/3/2007	33	3.5	73	1402	3.9	54.572	175.721	3.22
44	15	15	4/3/2007	33	3.5	73	1413	3.91	67.16	214.201	3.189
45	15	15	4/3/2007	33	3.5	73	1417	3.93	64.682	209.525	3.239
46	15	15	4/3/2007	33	3.5	73	1407	3.86	59.956	194.432	3.243
47	15	15	4/3/2007	33	3.5	73	1418	3.92	68.124	213.105	3.128
48	15	15	4/3/2007	33	3.5	73	1404	3.93	58.693	184.126	3.137
49	15	15	4/3/2007	33	3.5	73	1400	3.91	60.316	187.265	3.105
50	15	15	4/3/2007	33	3.5	73	1398	3.89	58.065	187.737	3.233
51	15	15	4/3/2007	33	3.5	73	1400	3.91	56.268	180.726	3.212
52	15	15	4/3/2007	33	3.5	73	1404	3.88	55.887	176.574	3.159
53	15	15	4/3/2007	33	3.5	73	1415	3.91	61.45	193.627	3.151
54	15	15	4/3/2007	33	3.5	73	1401	3.89	57.326	193.622	3.378
55	15	15	4/3/2007	33	3.5	73	1410	3.89	60.014	188.963	3.149
56	15	15	4/3/2007	33	3.5	73	1404	3.89	58.299	185.732	3.186
57	15	15	4/3/2007	33	3.5	73	1401	3.91	58.782	191.888	3.264
58	15	15	4/3/2007	33	3.5	73	1401	3.88	55.815	176.815	3.168
59	15	15	4/3/2007	33	3.5	73	1369	3.82	55.83	206.271	3.695
60	15	15	4/3/2007	33	3.5	73	1408	3.9	62.029	198.748	3.204
61	15	15	4/4/2007	32	3.5	74	1399	3.91	54.775	165.18	3.016
62	15	15	4/4/2007	32	3.5	74	1407	3.93	64.253	191.351	2.978
63	15	15	4/4/2007	32	3.5	74	1409	3.96	68.89	201.209	2.921
64	15	15	4/4/2007	32	3.5	74	1415	3.95	74.1	210.865	2.846
65	15	15	4/4/2007	32	3.5	74	1412	3.96	74.73	214.048	2.864
66	15	15	4/4/2007	32	3.5	74	1415	3.97	74.55	213.917	2.869
67	15	15	4/4/2007	32	3.5	74	1411	3.96	72.458	205.412	2.835
68	15	15	4/4/2007	32	3.5	74	1410	3.96	73.962	209.821	2.837
69	15	15	4/4/2007	32	3.5	74	1411	3.96	72.929	207.926	2.851
70	15	15	4/4/2007	32	3.5	74	1415	3.96	75.147	212.724	2.831
71	15	15	4/4/2007	32	3.5	74	1412	3.97	74.088	212.692	2.871
72	15	15	4/4/2007	32	3.5	74	1402	3.97	70.71	207.621	2.936
73	15	15	4/4/2007	32	3.5	74	1375	3.91	40.781	122.467	3.003
74	15	15	4/4/2007	32	3.5	74	1385	3.91	46.455	139.327	2.999
75	15	15	4/4/2007	32	3.5	74	1365	3.92	43.639	132.622	3.039

76	15	15	4/4/2007	32	3.5	74	1392	3.94	64.304	190.883	2.968
77	15	15	4/4/2007	32	3.5	74	1405	3.95	69.362	202.04	2.913
78	15	15	4/4/2007	32	3.5	74	1411	3.94	72.688	216.581	2.98
79	15	15	4/4/2007	32	3.5	74	1416	3.95	80.377	234.828	2.922
80	15	15	4/4/2007	32	3.5	74	1385	3.95	67.915	206.042	3.034
81	15	15	4/4/2007	32	3.5	74	1371	3.93	48.999	147.32	3.007
82	15	15	4/4/2007	32	3.5	74	1370	3.9	46.949	140.292	2.988
83	15	15	4/4/2007	32	3.5	74	1397	3.93	61.598	183.817	2.984
84	15	15	4/4/2007	32	3.5	74	1402	3.96	62.47	185.447	2.969
85	15	15	4/4/2007	32	3.5	74	1405	3.94	64.948	188.717	2.906
86	15	15	4/4/2007	32	3.5	74	1405	3.96	68.205	199.322	2.922
87	15	15	4/4/2007	32	3.5	74	1401	3.97	62.863	185.269	2.947
88	15	15	4/4/2007	32	3.5	74	1398	3.93	62.608	181.268	2.895
89	15	15	4/4/2007	35	3.5	74	1403	3.95	69.914	201.402	2.881
90	15	15	4/4/2007	35	3.5	74	1412	3.97	71.847	207.947	2.894
91	15	15	4/5/2007	35	3.5	74	1402	3.89	56.715	171.113	3.017
92	15	15	4/5/2007	35	3.5	74	1407	3.94	65.584	193.16	2.945
93	15	15	4/5/2007	35	3.5	74	1409	3.95	64.609	190.795	2.953
94	15	15	4/5/2007	35	3.5	74	1403	3.95	65.279	190.923	2.925
95	15	15	4/5/2007	35	3.5	74	1405	3.94	66.776	195.715	2.931
96	15	15	4/5/2007	35	3.5	74	1407	3.98	65.816	194.255	2.951
97	15	15	4/5/2007	35	3.5	74	1400	3.93	62.451	183.478	2.938
98	15	15	4/5/2007	35	3.5	74	1397	3.92	57.546	170.26	2.959
99	15	15	4/5/2007	35	3.5	74	1410	3.94	68.267	202.834	2.971
100	15	15	4/5/2007	35	3.5	74	1412	3.95	71.581	205.871	2.876
101	15	15	4/5/2007	35	3.5	74	1403	3.95	64.583	188.775	2.923
102	15	15	4/5/2007	35	3.5	74	1370	3.91	41.25	127.969	3.102
103	15	15	4/5/2007	35	3.5	74	1393	3.87	52.854	157.6	2.982
104	15	15	4/5/2007	35	3.5	74	1408	3.96	66.886	195.382	2.921
105	15	15	4/5/2007	35	3.5	74	1409	3.96	73.644	215.266	2.923
106	15	15	4/5/2007	35	3.5	74	1409	3.95	69.993	198.354	2.834
107	15	15	4/5/2007	35	3.5	74	1406	3.94	68.631	209.668	3.055
108	15	15	4/5/2007	35	3.5	74	1411	3.94	71.573	209.741	2.93
109	15	15	4/5/2007	35	3.5	74	1408	3.91	68.975	202.996	2.943
110	15	15	4/5/2007	35	3.5	74	1416	3.94	75.873	216.467	2.853
111	15	15	4/5/2007	35	3.5	74	1418	3.97	76.841	220.16	2.865
112	15	15	4/5/2007	35	3.5	74	1405	3.95	72.455	205.31	2.834
113	15	15	4/5/2007	35	3.5	74	1400	3.94	72.583	210.752	2.904
114	15	15	4/5/2007	35	3.5	74	1387	3.94	64.441	186.925	2.901

115	15	15	4/5/2007	35	3.5	74	1399	3.94	67.841	190.542	2.809
116	15	15	4/5/2007	35	3.5	74	1389	3.95	67.11	192.589	2.87
117	15	15	4/5/2007	35	3.5	74	1354	3.91	43.153	128.071	2.968
118	15	15	4/5/2007	35	3.5	74	1378	3.88	46.49	133.544	2.873
119	15	15	4/5/2007	35	3.5	74	1382	3.88	48.729	142.825	2.931
120	15	15	4/5/2007	35	3.5	74	1386	3.89	51.37	149.964	2.919
121	15	15	4/5/2007	35	3.5	74	1393	3.9	54.91	157.375	2.866
122	15	15	4/6/2007	36	3.5	72	1387	3.86	45.668	132.191	2.895
123	15	15	4/6/2007	36	3.5	72	1406	3.94	63.01	185.184	2.939
124	15	15	4/6/2007	36	3.5	72	1400	3.93	56.586	166.312	2.939
125	15	15	4/6/2007	36	3.5	72	1390	3.9	56.065	161.698	2.884
126	15	15	4/6/2007	36	3.5	72	1388	3.92	57.732	169.551	2.937
127	15	15	4/6/2007	36	3.5	72	1389	3.92	56.958	173.769	3.051
128	15	15	4/6/2007	36	3.5	72	1389	3.89	59.046	173.213	2.934
129	15	15	4/6/2007	36	3.5	72	1395	3.95	63.649	184.519	2.899
130	15	15	4/6/2007	36	3.5	72	1390	3.93	57.374	169.174	2.949
131	15	15	4/6/2007	36	3.5	72	1414	3.93	67.368	193.055	2.866
132	15	15	4/6/2007	36	3.5	72	1413	3.95	72.172	208.471	2.889
133	15	15	4/6/2007	36	3.5	72	1402	3.95	65.418	193.224	2.954
134	15	15	4/6/2007	36	3.5	72	1396	3.92	65.506	191.136	2.918
135	15	15	4/6/2007	36	3.5	72	1392	3.93	64.171	189.554	2.954
136	15	15	4/6/2007	36	3.5	72	1386	3.9	63.976	195.641	3.058
137	15	15	4/6/2007	36	3.5	72	1387	3.93	63.686	184.62	2.899
138	15	15	4/6/2007	36	3.5	72	1425	3.96	78.584	232.816	2.963
139	15	15	4/6/2007	36	3.5	72	1402	3.96	71.623	214.813	2.999
140	15	15	4/6/2007	36	3.5	72	1397	3.92	68.16	201.039	2.95
141	15	15	4/6/2007	36	3.5	72	1398	3.94	68.981	207.33	3.006
142	15	15	4/6/2007	36	3.5	72	1403	3.96	70.897	212.568	2.998
143	15	15	4/6/2007	36	3.5	72	1401	3.91	66.045	194.571	2.946
144	15	15	4/6/2007	36	3.5	72	1395	3.92	67.252	201.153	2.991
145	15	15	4/6/2007	36	3.5	72	1400	3.94	66.588	199.313	2.993
146	15	15	4/6/2007	36	3.5	72	1410	3.93	72.933	212.087	2.908
147	15	15	4/6/2007	36	3.5	72	1409	3.93	70.962	209.372	2.95
148	15	15	4/6/2007	36	3.5	72	1417	3.96	73.94	220.318	2.98
149	15	15	4/6/2007	36	3.5	72	1410	3.91	70.638	206.061	2.917
150	15	15	4/6/2007	36	3.5	72	1406	3.93	70.918	207.87	2.931
151	15	15	4/6/2007	36	3.5	72	1415	3.95	74.072	219.947	2.969
Mean							1403.5	3.9	64.5	192.7	3.0
STD Dev.							12.8	0.0	8.3	22.6	0.1