The application of statistical process control (SPC) during feed manufacturing improves product quality and reduces manufacturing costs. Consequently, quality improvement using SPC offers the feed industry a valuable business strategy. This strategy includes quality planning, analysis, and control to ensure that the quality assurance program contributes positively to cash flow, return on investment, and overall business profitability.

SPC is the application of statistical principles and techniques in all stages of production directed toward the most economical manufacturing of a product. The economic benefits associated with SPC include increased product uniformity, less rework and material waste, increased production and plant operating efficiency, increased customer satisfaction resulting in repeat business, less money invested in finished product inspection, and fewer product recalls. These financial benefits should exceed the costs of implementing an SPC quality program, thus resulting in a positive return on investment.

Quality costs are often categorized as follows:
- **Prevention Costs**, or the costs of doing something right the first time.
- **Appraisal Costs**, or the costs associated with measuring, evaluating, or auditing products or services.
- **Internal Failure Costs**, which are costs resulting from a product failing to meet quality requirements.
- **External Failure Costs**, which are costs resulting from a product failing to meet customer expectations.

The application of SPC usually does not increase prevention and appraisal costs; rather, it is a way to better utilize existing data to reduce internal and external failure costs. Examples presented in this bulletin highlight internal and external failure costs and how those can be reduced through the application of SPC tools.

**SPC Application**

Feed manufacturing primarily is a batch manufacturing process. The adaptation of SPC may be difficult at first, particularly if only a few batches of a ration are manufactured each week. To assist feed manufacturers in incorporating SPC in their quality program, a list of potential control points by cost center are presented below:

- **Receiving**: Incoming ingredient moisture content, protein content, temperature, and bulk density.
- **Grinding**: Particle size, grinding rate (tons/hr), and kWh electrical usage per ton.
- **Batching**: Batches per hour, target weight versus actual weight (may be collected via automated systems or production records).
- **Conditioning**: Mash moisture content and temperature before and after the conditioner.
- **Pelleting**: Pellet durability, tons per hour, kilowatt hour per ton, pellet temperature post die, finished pellet moisture content, and pellet temperature post cooler.
- **Bagging**: Bag weight.
- **Feed Product**: Moisture and protein content.

**SPC Tools**

Four of the major SPC tools presented in this publication include the frequency histogram, control chart, Pareto chart, and the cause and effect diagram.

The frequency histogram shows how a process is operating in a summary format. It helps answer four important questions:
Is there a normal distribution for the process or products?
Where is the process centered?
Is the process capable of meeting the engineering or product specification?
What is the economic loss associated with not meeting product specifications?

The frequency histogram does not show when the variation occurred nor does it diagnose why the variation occurred. To answer the question “When did the variability occur?” one applies the control chart.

The control chart is popular in many industries for the following reasons:
• Control charts are a proven technique for improving productivity.
• Control charts are effective in defect prevention.
• Control charts prevent unnecessary process adjustments.
• Control charts provide diagnostic information.
• Control charts provide information about process capability.

The application of the control chart relies on the Central Limit Theorem. This theorem states that variation naturally occurs in a population (no two things are alike). A large group of the population (processes, analyses, etc.) cluster around the middle and form what is referred to as a bell shaped curve (Figure 1). Descriptive statistics used to explain the population include the mean (average of the population) and the standard deviation. Three standard deviations to each side of the mean (average) explain 99.7 percent of the variation in a population.

The Pareto chart and the cause and effect diagram (fishbone chart) are problem solving techniques that augment the frequency histogram and control chart. The Pareto chart helps to prioritize customer complaints using a frequency histogram format. The fishbone chart assists in pinpointing the cause of the problem by focusing on the sources of potential variation (material, machine, methods, personnel, and environment).

Procedures for Developing a Frequency Histogram

Step 1. Collect samples or measurements during processing. Sample collection requires the application of sampling (MF-2036 Sampling: Procedures for Feed) and evaluation (MF-2037 Evaluating Feed Components and Finished Feeds) techniques that enable a representative characterization of the population.
Step 2. Find and mark the largest and smallest number in the data set.
Step 3. Calculate the range (difference between the largest and smallest values) of the measurements.
Step 4. Determine the intervals for the frequency histogram. The interval is calculated by dividing the range by the number of intervals (divide by 7 when there are fewer than 50 data points; divide by 10 when there are more than 50 data points). Either round up or down to arrive at a value that is easy to plot (e.g., 2.47 could be rounded to 2.5, or 1.03 can be rounded to 1, etc.).
Step 5. Assign boundaries and midpoints.
Step 6. Determine the frequency of occurrences within each interval.
Step 7. Prepare a frequency histogram.

Example 1:
A feed mill reported the following protein contents for the past 32 loads of soybean meal.
42.38 42.87 42.73 42.87 42.72 44.10 43.56 42.83
43.63 43.59 42.99 43.15 42.78 43.27 44.30 43.36
44.39 42.98 43.48 43.11 42.57 42.10 41.78 43.93
43.10 43.85 43.06 43.05 42.80 42.73 42.33 43.01

Step 1. Collect and evaluate the sample of soybean meal.
Step 2. Find and mark largest (44.39) and smallest (41.78) values.
Step 3. Calculate range: 44.39 - 41.78 = 2.61
Step 4. Determine interval width: 2.61 ÷ 7 = .37
Note: The data set consists of fewer than 50 measurements; therefore, seven intervals were selected. The interval width of .37 is then rounded off to 0.4 to facilitate plotting the frequency histogram.

Step 5. Assign boundaries and midpoints.
The beginning boundary is 41.7; this is based on the smallest value in the data set which was 41.78. The midpoint is equivalent to the lower boundary value (41.7) plus half the interval width which equals 0.2 percent protein. The columns for midpoint, interval width, and boundaries are completed in the Frequency Histogram Worksheet (Figure 2).

Step 6. Tally occurrences within each boundary and calculate frequency (Figure 2). Perform this activity by placing a 1 in the appropriate tally column for each of the values located in Step 1 (e.g., for the first measure 42.38, place a 1 in the second row in the tally column. The frequency column is calculated by adding all the 1’s in the tally column by row, dividing by the total measures (n = 32) and multiplying by 100 (e.g., row one frequency is calculated as follows: 1 ÷ 32 = .031, .031 x 100 = 3.1).

Step 7. Finally, plot the frequency histogram in the space below the worksheet (Figure 2).

Interpretation of Frequency Histogram
The results of the bar graph communicate several important pieces of information:
• The distribution appears normal.
• The protein content of the different lots is centered at 43.1 percent.
• More than 50 percent of the soybean meal had a protein content greater than 42.9 percent.

The guaranteed minimum protein content was 42 percent, and all feed rations were based on this protein level. Therefore, an opportunity exists to reformulate rations for different protein levels in soybean meal.
Refer to the cause and effect diagram for ways to improve the process and improve corporate profitability.

Using Frequency Histograms for Economic Analysis
In a second example, complete feed was analyzed for protein content to estimate the variation in the finished feed and to calculate costs associated with over-fortifying feed protein content. The following 28 data points were used to prepare a frequency histogram and estimate the cost of over-fortifying feed to ensure that the minimum label content was provided. The label protein content was 17.0, the feed mill had an 18 percent protein target, approximately 650 tons of this feed was manufactured per month, and the cost of over-fortifying finished feed by 1 percent protein was assumed to be $5.60 per ton. (Note: See bulletin MF-2506 Sampling: Statistical and Economic Analysis for procedures to calculate the value of 1 percent protein.)

Example 2:
17.47 17.95 18.91 18.87 18.35 18.44 18.71
18.60 18.80 18.84 19.41 18.82 18.19 18.75
19.01 18.27 18.60 19.46 18.08 18.24 17.73
18.40 19.26 18.64 19.46 19.23 18.53 18.12

The equation used to calculate the cost of over-fortifying feed is calculated for each bar above the target protein level of 18 percent. No deduction was taken for feed falling below 18 percent since the label protein content was 17 percent.
Values were calculated as follows:
(Frequency) x (% protein over target) x (protein cost) x (tons/month)
.179 frequency x .15 protein x $5.60 x 650 tons = $97.73
The total cost per month for over-fortifying this one feed was $2,369.

Figure 2. Frequency Histogram Worksheet
Attribute or Process: Soybean Meal Protein Content

<table>
<thead>
<tr>
<th>Midpoint</th>
<th>Interval</th>
<th>Boundaries</th>
<th>Tally</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>41.90</td>
<td>0.4</td>
<td>41.70-42.09</td>
<td>1</td>
<td>3.1</td>
</tr>
<tr>
<td>42.30</td>
<td>0.4</td>
<td>42.10-42.49</td>
<td>11</td>
<td>12.5</td>
</tr>
<tr>
<td>42.70</td>
<td>0.4</td>
<td>42.50-42.89</td>
<td>1111</td>
<td>28.1</td>
</tr>
<tr>
<td>43.10</td>
<td>0.4</td>
<td>42.90-43.29</td>
<td>1111111</td>
<td>31.2</td>
</tr>
<tr>
<td>43.50</td>
<td>0.4</td>
<td>43.30-43.69</td>
<td>1111</td>
<td>12.5</td>
</tr>
<tr>
<td>43.90</td>
<td>0.4</td>
<td>43.70-44.09</td>
<td>11</td>
<td>6.2</td>
</tr>
<tr>
<td>44.30</td>
<td>0.4</td>
<td>44.10-44.49</td>
<td>11</td>
<td>6.2</td>
</tr>
</tbody>
</table>
The total savings potential or opportunity cost associated with over-fortifying protein content in this feed ration is $1,557 per month or $18,684 per year.

Procedures for Developing a Control Chart

Step 1. Collect samples or measurements during processing. This is similar to Step 1 for the frequency histogram. In some cases, multiple measurements for a particular process are collected, such as when monitoring bag weight or tracking conditioned mash temperature.

Step 2. Perform preliminary calculations with the data set. If there are multiple measurements (subsamples), calculate the average and the range of these measurements. Next, calculate the overall sum and average for these values.

Step 3. Calculate the control limits (upper control limit \(UCL_m\) and lower control limit \(LCL_m\)) for the mean and the upper control limit for the range \(UCL_R\). These control limits are set at three standard deviations. A simplified method for calculating control limits involves the use of Table 1, which presents factors for calculating control limits. The \(A2\) column provides a list of factors used to calculate the \(UCL_m\) and \(LCL_m\) for data sets with subsamples (Example 3). The \(D4\) column is used to calculate the \(UCL_R\).

Example 3. Bag Weight

Step 1. Collect sample data; in this example 5 bags for 20 lots of feed.

<table>
<thead>
<tr>
<th>Midpoint</th>
<th>Interval</th>
<th>Boundaries</th>
<th>Tally</th>
<th>Frequency</th>
<th>Economic Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.55</td>
<td>.3</td>
<td>17.40-17.69</td>
<td>1</td>
<td>3.6</td>
<td>$0.00</td>
</tr>
<tr>
<td>17.85</td>
<td>.3</td>
<td>17.70-17.99</td>
<td>11</td>
<td>7.1</td>
<td>$0.00</td>
</tr>
<tr>
<td>18.15</td>
<td>.3</td>
<td>18.00-18.29</td>
<td>1111</td>
<td>17.9</td>
<td>$97.00</td>
</tr>
<tr>
<td>18.45</td>
<td>.3</td>
<td>18.30-18.59</td>
<td>1111</td>
<td>14.3</td>
<td>$243.00</td>
</tr>
<tr>
<td>18.75</td>
<td>.3</td>
<td>18.60-18.89</td>
<td>11111111</td>
<td>32.1</td>
<td>$876.00</td>
</tr>
<tr>
<td>19.05</td>
<td>.3</td>
<td>18.90-19.19</td>
<td>11</td>
<td>7.1</td>
<td>$271.00</td>
</tr>
<tr>
<td>19.35</td>
<td>.3</td>
<td>19.20-19.49</td>
<td>11111</td>
<td>17.9</td>
<td>$880.00</td>
</tr>
</tbody>
</table>

The total savings potential or opportunity cost associated with over-fortifying protein content in this feed ration is $1,557 per month or $18,684 per year.

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table is published by the American Society for Quality
Control.) In this example, select the value from the row
n=5, since there are five measurements for each sample
collection period (the select value is 2.114). The upper
control limit is derived by multiplying D4 by the
average range R:
\[ UCL_r = 2.114 \times 0.1645 \]
\[ UCL_r = 0.348 \]

Calculate the upper (UCL) and lower control
(LCL) limits for the averages. Using Table 1, identify
the value A2 based on the number (n=5) of measure-
ments per sampling period.

Multiply A2 by the average range, then add and
subtract this value from the average mean to arrive at
the upper and lower control limits.

A2 times R = 0.577 x 0.1645 = 0.0949
\[ UCL_x = 40.121 + 0.0949 = 40.21 \]
\[ LCL_x = 40.121 - 0.0949 = 40.03 \]

Step 4. Plot the data on the control chart (Figure 4).

**Interpretation of the Control Chart**

In Example 3, the following interpretations are
included:

- The bag weight data resulted in fairly narrow upper
  and lower control limits; this indicates that little
  product is given away.
- The lower control limit of 40.03 kg indicates that
  there is little likelihood of under filling bags and
  shorting customers of product when the bagging
  process is under control.
- Bag weight measurements occur in nearly equal
  proportions above and below the mean.
- The process, while appearing to perform well, is out
  of control.

The control chart differentiates between normal
population variation and variation due to an assignable
cause. Normal variation typically occurs within upper
and lower control limits. The UCL and LCL were
plus and minus three standard deviations from the
mean. (Note: Three standard deviations from the mean
accounts for 99.7 percent of the variation in a popula-
tion.)

Thus, there is a low probability (3 in 1,000) that a
measurement will fall outside the control limits due to
random chance.

For the bag weight control chart (Figure 4), the third
event in the average control chart occurred below
the lower control limit. Thus, the process was out of
control. The cause could be due to failure to cali-
brate the bagging scale or, perhaps, an error by the
operator. The cause and effect diagram can be used
to help identify the problem, the control chart only
lets us know when the event occurred. Looking at
the range control chart in Example 3 (Figure 4) the
16th event resulted in an average range value that
was above the upper control limit, again, indicating
the process was out of control.

**Additional Rules for Interpretation**

In addition to assessing if points occur outside the
control limits, it is important to detect whether non-
random patterns of data occur within the control limits.
Specifically, if seven consecutive data points occur all
above or below the mean (even if they are within the
control limits), it is correct to conclude that the process
is out of control. To help understand why, consider the
probability that you will get heads if you flip a coin; it
is 50 percent. Now, what is the probability of flipping
two heads in a row? The answer is 50 percent times 50
percent (0.5 x 0.5) or 25 percent. Carrying this calcula-
tion through seven times results in a probability of less
than 1 percent of getting heads seven times in a row. At
this point, we reject the possibility that this event
occurred through random change.
Similar to the coin illustration, the possibility of having seven consecutive measurements in ascending or descending order also is unlikely unless there is a change in the process. Thus, if either of these events occur, the process is considered out of control.

**Example 4. Individual and Range Control Charts for Finished Feed Protein Content**

Step 1. Collect sample data. In this example, the value represents finished feed protein content. There are 28 total measurements.

<table>
<thead>
<tr>
<th>Batch Number</th>
<th>Protein Content</th>
<th>Moving Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.47</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>17.95</td>
<td>.48</td>
</tr>
<tr>
<td>3</td>
<td>18.91</td>
<td>.96</td>
</tr>
<tr>
<td>4</td>
<td>18.87</td>
<td>.04</td>
</tr>
<tr>
<td>5</td>
<td>18.35</td>
<td>.52</td>
</tr>
<tr>
<td>6</td>
<td>18.44</td>
<td>.09</td>
</tr>
<tr>
<td>7</td>
<td>18.71</td>
<td>.27</td>
</tr>
<tr>
<td>8</td>
<td>18.60</td>
<td>.11</td>
</tr>
<tr>
<td>9</td>
<td>18.80</td>
<td>.20</td>
</tr>
<tr>
<td>10</td>
<td>18.84</td>
<td>.04</td>
</tr>
<tr>
<td>11</td>
<td>19.41</td>
<td>.57</td>
</tr>
<tr>
<td>12</td>
<td>18.82</td>
<td>.59</td>
</tr>
<tr>
<td>13</td>
<td>18.19</td>
<td>.63</td>
</tr>
<tr>
<td>14</td>
<td>18.75</td>
<td>.56</td>
</tr>
<tr>
<td>15</td>
<td>19.01</td>
<td>.26</td>
</tr>
<tr>
<td>16</td>
<td>18.27</td>
<td>.74</td>
</tr>
<tr>
<td>17</td>
<td>18.60</td>
<td>.33</td>
</tr>
<tr>
<td>18</td>
<td>19.46</td>
<td>.86</td>
</tr>
<tr>
<td>19</td>
<td>18.48</td>
<td>.98</td>
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<tr>
<td>20</td>
<td>18.24</td>
<td>.16</td>
</tr>
<tr>
<td>21</td>
<td>17.73</td>
<td>.51</td>
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<td>22</td>
<td>18.40</td>
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<td>23</td>
<td>19.26</td>
<td>.86</td>
</tr>
<tr>
<td>24</td>
<td>18.64</td>
<td>.62</td>
</tr>
<tr>
<td>25</td>
<td>19.46</td>
<td>.82</td>
</tr>
<tr>
<td>26</td>
<td>19.23</td>
<td>.23</td>
</tr>
<tr>
<td>27</td>
<td>18.53</td>
<td>.70</td>
</tr>
<tr>
<td>28</td>
<td>18.12</td>
<td>.41</td>
</tr>
<tr>
<td>Total</td>
<td>521.54</td>
<td>13.21</td>
</tr>
</tbody>
</table>

\[ x = 18.62 \quad \text{MR} = 0.489 \]

Step 2. Calculate the moving range for each pair of data; note the range between two measures is calculated as a positive value. Then summarize the values and calculate the mean and moving range average. Notice that the average (x) is calculated by dividing the total (521.54) by 28 and the moving range (MR) total (13.21) is divided by 27 since there are only 27 moving range values.

Step 3. Calculate the upper control limit for the range chart. Select the factor from Table 1 under the column titled D4. In this example, select the value from the row n=2 which is the smallest value in the table, since there is one measurement per event. The upper control limit is derived by multiplying D4 by the average range R:

\[ UCL_R = 3.268 \times 0.489 = 1.6 \]

Calculate the upper and lower control limits for the average control chart. Divide the moving range average by 1.128 (d2), multiply by three (the desired number of standard deviations) and then add and subtract this value from the average mean.

\[ UCL = x + 3(MR/d2) \]
\[ LCL = x - 3(MR/d2) \]

Where \( x \) = mean of all lots

**Figure 5. Finished Feed Protein Content**

For this example, the calculations for UCL and LCL are as follows:

\[ UCL = 18.62 + 3(0.489/1.128) = 19.92 \]
\[ LCL = 18.62 - 3(0.489/1.128) = 17.31 \]

Step 4. Plot the data on the control chart (Figure 5).
Procedures for Developing a Pareto Chart

A Pareto chart is a special type of frequency histogram that records the most frequent problem as the first bar, the next most frequent problem as the next bar, and so on. This procedure helps prioritize problem solving activities.

Steps for developing a Pareto chart are as follows:
Step 1. Categorize the type of complaint: e.g., moldy feed pellets, too many fines, etc.
Step 2. List the most serious defect first under the defect column, followed by the second, etc.
Step 3. Report the number of occurrences for each incident in the frequency column.
Step 4. Complete the cumulative complaints column by adding, in succession, the number of complaints.
Step 5. Calculate the cumulative frequency by dividing the cumulative complaints by the total number (n = 24) of complaints.
Step 6. Plot the results.

Process Improvement Using a Cause and Effect Diagram

The cause and effect diagram shows in picture or graph form how causes relate to the stated effect or to one another. Also referred to as a fishbone diagram, the main causes or “bones” of the fishbone are:
- Material
- Machine
- Environment
- Method
- Operator

For example, suppose finished product protein content is found to fluctuate by 2 percent. While in most cases the product meets label requirements for nutrient content, management is concerned about giving away protein, which is the same as giving away money. To address this problem, a team of employees, including the production supervisor, quality assurance manager, receiving technician, and lab technician, meet to solve the problem. They use the cause and effect diagram as a guide to discuss the source and solution to the problem. It is discovered that a wide range in soybean meal protein content occurs between lots. The soybean meal protein content is not identified in the warehouse, therefore, it is treated as having the same protein content by production personnel. The team decides to reformulate rations based on 1 percent soybean meal protein increments and identify the protein content of different lots of soybean meal in the warehouse. Therefore, the plant production personnel can match feed rations with the appropriate soybean meal content. The variation in finished product protein content ceases and the company reports a substantial profit increase during the next business quarter.

Summary

Statistical process control (SPC) finds many applications in the feed manufacturing industry. Examples illustrating the application of four SPC tools (frequency histogram, control chart, Pareto chart, and cause and effect diagram) are presented in this bulletin. Additionally, a list of other ways in which SPC may be applied to control the process and improve product uniformity are presented in the bulletin. SPC relies on the application of statistical principles and procedures to improve product quality and profitability. The benefits derived from SPC in the areas of reduced internal and external failures should offset any additional costs incurred from sample collection, testing, and data analysis.
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