Statistical Process Improvement for Thin Walled Thermoformed Products

Gary R. Wilkes
Dart Container of MI, LLC

27SEP2016

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Once Upon A Time

A young Chemical Engineer with a love of Applied Mathematics was introduced to a Polymeric sheet-making process. In the laboratory testing of that material, that young Engineer met Thermoforming, which would soon become an important pursuit of that Engineer’s career. Soon, that Engineer found that Thermoforming had several branches and was drawn into study of Thin Wall Thermoforming.

Unlike many fairy tales that start with “Once Upon A Time”, this is a true story, “only the names have been omitted to protect the innocent”.

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Through Thick and Thin

- Thermoforming of plastics has been applied for producing articles of many different shapes and materials

<table>
<thead>
<tr>
<th>Typical Process Component</th>
<th>Thin</th>
<th>Thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Thickness</td>
<td>Between 0.2 and 2.5 mm (0.008 and 0.100 in)</td>
<td>Between 3 and 20 mm (0.120 and 0.5 in)</td>
</tr>
<tr>
<td>Material Feed Source</td>
<td>Roll-fed or Direct Extrusion Sheet Feed</td>
<td>Pre-cut Extruded sheet</td>
</tr>
<tr>
<td>Simultaneous Produced Parts</td>
<td>1 - 250</td>
<td>1 - 10</td>
</tr>
<tr>
<td>Thermoforming Cycle Time</td>
<td>1.7 - 6</td>
<td>&gt; 4</td>
</tr>
<tr>
<td>Product Characteristics</td>
<td>Low-cost/Short use life</td>
<td>Durable/Long Use Life</td>
</tr>
<tr>
<td>Common Product Examples</td>
<td>Drinking cup lids</td>
<td>Toys</td>
</tr>
<tr>
<td></td>
<td>Bowls</td>
<td>Flower Pots</td>
</tr>
<tr>
<td></td>
<td>Dinnerware plates</td>
<td>Transit Vehicle seats</td>
</tr>
<tr>
<td></td>
<td>Take-out containers</td>
<td>Aircraft components</td>
</tr>
<tr>
<td></td>
<td>Cups</td>
<td>Refrigerator Door Liners</td>
</tr>
</tbody>
</table>

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Some Thin-Walled Thermoformed Product Examples


Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Basic Thin Wall Thermoforming Equipment

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
A Trim Press Close-up

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
From A Different Aspect

• One Dictionary definition of the word Aspect is “a particular part or feature of something”
• A very important aspect of the thermoforming process is the Aspect Ratio for the product
• The Aspect Ratio ($R$) is simply the height of the product part ($h$) divided by the square root of its thermoformed area ($A$)

\[ R = \frac{h}{\sqrt{A}} \]

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Thin-Walled Thermoforming Aspect Ratios

Low: ~0.05 - ~0.2
- Cup Lid
- 9” Dinner plate

Medium: ~0.2 - ~0.5
- 2-piece Takeout Tray
- 12-ounce bowl

High: ~0.5 – 2.5
- 8-ounce Portion Container
- 44-ounce cup

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
What Does Aspect Ratio Have to Do With Process Improvement?

• Aspect Ratio is important to understanding Thin Wall Thermoforming processes, because some materials do not perform well with some aspect ratios.
• The maximum practical Aspect Ratio for a material is a function of how the selected material stretches and flows near its forming temperature
• Examples
  – BOPS (Biaxially Oriented Polystyrene), and even HIPS has been brittle in Low Aspect ratio applications
  – Clear Polypropylene can be hazy in Low Aspect ratio applications
  – PMMA/PEA Blends are very hard to form with Aspect ratios above ~1.4

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Apparent Difficulty of Thin Wall Thermforming Success as Function of Product Aspect Ratio

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Chemical Engineer Tools of the Trade

- A Bucket and Stopwatch
  - Anecdotally, perhaps, young Chemical Engineers are taught that their most important “Tools of the Trade” are the Bucket and the stopwatch
    - The Bucket to catch liquid product for measurement
    - The Stopwatch to record the time to fill the bucket
  - Like Medical Doctors and their stethoscopes, these two tools can be applied with knowledge to help the Chemical Engineer monitor the process of their interest to determine that it is working properly

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
The Thermoforming Process Engineer
Tools of the Trade

• A Weigh Scale and Stopwatch
  – Now for Thermoforming Process Engineers, the Weigh Scale replaces the “Bucket” in the “Tools of the Trade”, because the materials of interest are in the solid phase, not the liquid phase.
  – When comparing certain weight measurements of what the Thermoforming Process is doing and what it should be doing, the Thermoforming Process Engineer can ensure the health and performance of the Thermoforming process.

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Why Weight?

• Top 3 reasons: Cost, Cost, Cost
  – In our world, the costs of raw materials have been based upon their mass and composition.
  – Mass and weight are directly related by gravity
• But there is more than just direct material cost.
  An object generally has to be functional and that requires it to have enough strength to support not only its own weight, but also to resist the forces involved in its function.
  The amount of heat energy that a thermoformer must supply to soften the sheet is related to its mass and of course, since the Area geometry and the material density is fixed, that means the object converting energy cost is also related to its thickness.
• And the List goes on

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
What About Tools of the Trade?

• So what do the
  – Doctor’s Stethoscope
  – Chemical Engineer’s Bucket & Stopwatch
  – Thermoforming Process Engineer’s Weigh Scale & Stopwatch

Provide in Common. One Word: DATA

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Now That We Found **DATA**
What Are We Going to Do With It?

- This question is a paraphrase of a song released in 1978 about another Four-Letter Word, but a Good One, **LOVE**
- Quite thought provoking for both words!
- The song proposed several options for the future and that also would be the case for **DATA**
- But let us leave the **LOVE** question alone
- **DATA** requires interpretation
  - Doctors use their knowledge of anatomy and body mechanisms
  - Engineers use *Statistics*

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
So What is *Statistics*?

- One Dictionary definition of the word Statistics is “a branch of applied mathematics concerned with the collection and interpretation of quantitative data and the use of probability theory to estimate population parameters”

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
“Statistics Don’t Lie, But Liars Use Statistics”

• This title is a paraphrase of an old uncredited quote about Figures and their possible misuse

• Statistics were designed to allow a user to extrapolate the findings of a small sample to a larger and sometimes entire population
  – This is based upon the central limit theorem, which states that the arithmetic mean of a sufficiently large number of iterates of independent random variables, each with a well-defined expected value and finite variance, will be approximately normally distributed

• Users of Statistics become Liars when:
  – They try to apply the statistical descriptions to a specific single specimen of a population
  – The findings for one cause of an effect are applied to other potential causes without proof of a relationship
  – The sample size is too small to represent the entire population of interest
  – The distribution is not close to a normal (bell shaped) distribution

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
SQC Vs. SPC

• The American Society for Quality (ASQ) website page [http://asq.org/learn-about-quality/statistical-process-control/overview/tutorial.html](http://asq.org/learn-about-quality/statistical-process-control/overview/tutorial.html) provides a detailed overview of this specific subject and lists the 14 generally accepted statistical tools utilized by both concepts.

• Statistical quality control (SQC) is the application of the 14 statistical and analytical tools to monitor process outputs (dependent variables).

• Statistical process control (SPC) is the application of the same 14 tools to control process inputs (independent variables).

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Don’t Become A Liar Using SQC/SPC for Thin Walled Thermoforming

• While the 14 statistical and analytical SQC/SPC tools should provide everything necessary for the Thermoforming Process Engineer to be successful for improving Thin Wall Thermoforming process performance, perhaps due to the perceived complexity of those SQC/SPC tools, there have been some practitioners that have tried to take shortcuts and thus failed to identify those key sources that have been limiting process performance

• So,

Rule #1: Treat the product from each individual mold location as if it were made by its own process until proven otherwise

− Rule #2: Make sure that a representative number of sample specimens from one mold location to provide sufficient confidence in the statistics of that location

− There are a couple more “Rules” but let us hold for now

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Whoa!!! Buddy

• Couldn’t that be an enormous number of tests?

<table>
<thead>
<tr>
<th>Typical Process Component</th>
<th>Thin</th>
<th>Thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Thickness</td>
<td>Between 0.2 and 2.5 mm (0.008 and 0.100 in)</td>
<td>Between 3 and 20 mm (0.120 and 0.5 in)</td>
</tr>
<tr>
<td>Material Feed Source</td>
<td>Roll-fed or Direct Extrusion Sheet Feed</td>
<td>Pre-cut Extruded sheet</td>
</tr>
<tr>
<td>Simultaneous Produced Parts</td>
<td>1 - 250</td>
<td>1 - 10</td>
</tr>
<tr>
<td>Thermoforming Cycle Time</td>
<td>1.7 - 6</td>
<td>&gt; 4</td>
</tr>
<tr>
<td>Product Characteristics</td>
<td>Low-cost/Short use life</td>
<td>Durable/Long Use Life</td>
</tr>
<tr>
<td>Common Product Examples</td>
<td>Drinking cup lids</td>
<td>Toys</td>
</tr>
<tr>
<td></td>
<td>Bowls</td>
<td>Flower Pots</td>
</tr>
<tr>
<td></td>
<td>Dinnerware plates</td>
<td>Transit Vehicle seats</td>
</tr>
<tr>
<td></td>
<td>Take-out containers</td>
<td>Aircraft components</td>
</tr>
<tr>
<td></td>
<td>Cups</td>
<td>Refrigerator Door Liners</td>
</tr>
</tbody>
</table>

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
A Less Than Enormous Compromise

- While it is true that a full analysis of a 250-up thermoforming system would require measurement of at least 7,500 sample specimens if the baseline rule is applied for testing a minimum of 30 samples from all mold locations, a full analysis is not always required.
- Suggested Reduced Sampling for large (>64) number up systems
  - All Four Corners of the Mold Tooling
  - The 1 or 4 molds closest to the Tooling center
  - 4, 8, or 12 molds along the diagonals of the Tooling

Possible Compromise Sampling Strategy for a 10 by 10 mold

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
A Theoretical Example

- Examination of a simplified model for a 64-up thermoforming system may be beneficial
  - Line operating 25 cycles per min on a single product
  - Line staffed to run 5 days per week all year except ten Holidays
  - The line has 90% uptime annually, so it makes good product 5400 hours/year
  - Minimum acceptable product weight is 8.1 g
  - Quality Control data indicates product weight variation is ±8.0%
  - To be on the safe side for this product, manufacturing management has operated the line to produce with a minimum product weight of 8.2 g.

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Lane Chart of Trailing & Leading Row Part Weight with Maximum, Mean, and Minimum

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Potential Material Cost Savings for Reduction in Part Weight Variation

• This theoretical line can produce 518,400,000 good parts per year
• The target part weight with ±8.0% is 8.92 g in order to meet the 8.2 g minimum
• If the variation were to be reduced to ±5% then a target part weight could be reduced to 8.61 g
• Reducing the part weight by 0.31 g would then reduce the raw material requirement for this line by **150,400 lbs/year**

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
So What’s Behind This Magic Curtain

• While some may say Yeah, Right! and question how this would be possible, others might ask “what’s the catch? Or “How can you do that?”

• What is behind this curtain has been revealed by applying statistics and it was revealed simply by examining the product from just a few molds at a time.

• But as many disclaimers in Television commercials may say, “your results may vary”
It’s Not Magic, It’s Physics

• Veteran Operators will say that Thermoforming relies upon having the material throughout its area within the heating mechanism obtain the “right temperature” at the forming station

• Physics says solid materials soften before they melt

• The right temperature
  – Too cold → No formed part or unacceptably poor definition
  – Too hot → Melted holes in the sheet with a possibility of fire in the oven

• But for plastics, the “right temperature” is not really one temperature value, but it is a temperature range

• That right temperature range depends upon the material composition

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
So What is The “Right Temperature”?

• Reducing thermoformed product weight variation thus relies upon getting the entire area close to the same temperature at each of the thermoforming molds

• However, setting all the heating element temperatures within the oven to the same value, which appears to be a widespread practice, will not produce the same temperature within the heated area of the sheet

• Why? You ask

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Examination of the Design of Actual Thermoformer Ovens

• Thermoforming machines are designed for versatility, generally not for only one mold layout
  – While an ideal thermoforming oven would have a set of the same number of heating elements dedicated to each mold location, typically about three or four for both top an bottom of sheet, that would be prohibitively expensive for use with even a 16-up mold (3x2x16=) 96 controllers

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Examination of the Design of Actual Thermoformer Ovens - 2

• Because of the possibility of fire if temperatures are too hot, ovens are designed for quick access to one side
  – There is a Quick Opening side and a Fixed Geometry Side
  – Thus, the heat transfer to the sheet is different for the two oven sides.

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Examination of the Design of Actual Thermoformer Ovens - 3

• Additionally, because the leading edge of the sheet comes out of the oven before the trailing edge, the sheet near leading edge is several degrees cooler than the trial edge when the platen closes.

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Summary

• Do NOT pool data from different mold locations unless F-Test indicates the difference in variance AND t-Test indicate the difference between the means are NOT statistically significant

• Examine the statistics from each mold location separately with a Lane Chart or Equivalent

• Adjust the temperature zones of the thermoformer oven, if possible, to reduce the amount of heat away from the oven opening side

Data, Machinery, and Products exhibited are representative of a typical thin gage thermoforming process and do not specifically represent equipment or processes of Dart Container Corporation.
Thank you

• Any Questions?