Abstract

Purpose

A process improvement sampling methodology, known as Process Variation Diagnostic Tool (PROVADT), was proposed by Cox et al (2013). The method was designed to support the objectivity of Six Sigma projects performing the Measure-Analyse phases of the Define-Measure-Analyse-Improve-Control (DMAIC) cycle. An issue in PROVADT is that it is unable to distinguish between measurement and product variation in the presence of a poor Gage R&R result. In this paper PROVADT's sampling structure is improved and addresses this issue by enabling a true Gage R&R as part of its design.

Design/methodology/approach

This paper derives an enhanced PROVADT method by examining the theoretical sampling constraints required to perform a Gage R&R study. The original PROVADT method is then extended to fulfil these requirements. To test this enhanced approach, it was applied first to a simulated manufacturing process and then in two industry case studies.

Findings

The results in this paper demonstrate that enhanced PROVADT was able to achieve a full Gage R&R result. This required twenty additional measurements when compared to the original method, but saved up to ten additional products and twenty additional measurements being taken in future experiments if the original method failed to obtain a valid Gage R&R. These benefits were highlighted in simulation and industry case studies.

Originality/value

The work into the PROVADT method aims to improve the objectivity of early Six Sigma analyses of quality issues, which has documented issues.

Keywords

Six Sigma, Shainin, Design of Experiments, Quality Measurement, Process Capability, Sampling Plan

Classification

Case study

1 Introduction

As discrete manufacturing operations move from high-volume to low-volume production runs, there is a tendency to use subjective analysis to resolve quality problems (Julien and Holmshaw, 2012). A new concise process improvement sampling methodology, known as Process Variation Diagnostic Tool (PROVADT), was proposed by Cox et al (2013). The PROVADT method was designed to support the objectivity of Six Sigma projects, which follow the Define-Measure-Analyse-Improve-Control (DMAIC) cycle in low- and medium-volume manufacture. This was achieved by sampling from a process, in a structure that enables the application of the required statistical metrics from Six Sigma's measure and analyse phases. The sampling structure, also, allowed the use of graphical analysis tools from the Shainin System (Cox et al., 2012, 2013).

PROVADT typically requires the sampling of 20 products, each measured three times in a specific sequence. From those 60 results four improvement tools can be applied: a Multi-Vari chart and an Isoplot from the Shainin system (Bhote and Bhote, 2000; Shainin, 2012; Steiner et al., 2007); a Gage R&R (Repeatability and Reproducibility) analysis and a provisional process capability study from Six Sigma (George et al., 2005; Harry and Schroeder, 2000; Pande et al., 2000). Compiling the statistical sampling requirements for these techniques in one sample, shortens the analyse phase.

An issue in PROVADT is that it is unable to distinguish between measurement and product variation in the presence of a poor Gage R&R result. In this paper PROVADT's sampling structure is improved to address this issue. This is achieved by enabling a true Gage R&R to be calculated as part of the enhanced PROVADT design.

This paper is structured to provide: a review of current literature of quality improvement in low-volume process in section 2; an outline of where PROVADT fits in a quality improvement initiative and the tools it implements to achieve this in section 3; the sampling constraints required by PROVADT to perform statistically valid analysis are defined in section 4; an enhanced approach is suggested in section 5 addressing the poor Gage R&R issue of the original PROVADT proposed in (Cox et al., 2012, 2013); in section 6 a worked example is provided which directly compares the original and enhanced approaches; two industrial case studies of PROVADT's implementation are detailed in section 7; and the paper is concluded in section 8.

2 Literature Review

In a manufacturing process that experiences chronic quality problems, process improvement initiatives are implemented to assist an engineer determine the root cause of the issue (Juran and Gryna, 1988). This is achieved by applying a process improvement methodology, whereby each step taken has an associated suite of statistical and non-statistical tools to aid the analysis of the quality issue (De Mast, 2004). Examples of process improvement initiatives include Taguchi methods (Fowlkes and Creveling, 1995; Gu et al., 2014), Total Quality Management (Porter and Parker, 1993), Shainin System (Shainin, 2012; Steiner et al., 2007) and Six Sigma (Pande et al., 2000; Schroeder et al., 2008), to name a few.

Out of these approaches Six Sigma and the Shainin System are the most closely linked. They provide a step-wise approach to identify root causes affecting a products Critical-to-Quality (CtQ) characteristics (Bhote, 2003; De Mast, 2004; Shanmugam and Kalaichelvan, 2014; Sharma and Chetiya, 2009). Taguchi somewhat diverges from this, providing an approach more suited to improving system robustness through optimization experiments (Thomas and Antony, 2005), whereas Total Quality Management offers a quality philosophy rather than a step-wise approach (De Mast, 2004).

The Six Sigma approach has been widely researched in academia (Aboelmaged, 2010; De Mast and Lokkerbol, 2012; Schroeder et al., 2008; Senapati, 2004) and applied in industry (Antony et al., 2005; Gijo et al., 2014; Pulakanam, 2012; Suresh et al., 2015) since its inception at Motorola in the 1980s. It employs a data driven approach to process improvement, the backbone of which is the DMAIC cycle. The first three steps aim to concisely define the issue, validate the ability to measure it and then analyse data to identify its root causes.

An issue with the DMAIC approach is in the *'exploration'* of quality problem (De Mast, 2004). At the analyse stage, Six Sigma applies screening techniques such as fractional factorials (Goh, 2001) or non-statistical approaches such as brainstorming (Julien and Holmshaw, 2012) to identify root causes of variation. In the first instance, reduced numbers of experiments are use to make an investigation manageable but at the expense of understanding higher order interaction effects (Juran and Gryna, 1988). In the second situation, subjective reasoning is used instead of objective analysis, and this is particularly prevalent in low-volume manufacturing where large numbers of products to fulfil statistical tests are impossible to obtain (Julien and Holmshaw, 2012).

A different process improvement algorithm, which has parallels with Six Sigma, is the Shainin System (De Mast et al., 2000). There is less academic literature on the Shainin System, but there are industrial cases (Goodman and Wyld, 2001; Jegadheeson et al., 2012; Shanmugam and Kalaichelvan, 2014; Thomas and Antony, 2004). Six Sigma and the Shainin System have strong methodological similarities in their approaches, including the systematic approach to establishing a problem, validating a measurement system, identifying suspect variables, optimising these variables and implementing process control.

The key difference between these problem solving approaches is in the *'exploration'* of a quality problem (De Mast, 2004). Six Sigma aims to find root causes or suspect variables in a manner which has been identified as problematic. Whereas, the Shainin System narrows-down or focuses-in on suspect variables by objectively ruling out variables which have an insignificant effect on a final CtQ (De Mast, 2004; Shainin, 2012; Steiner et al., 2007).

There are instances were both methods have been used in conjunction to take advantage of their respective strengths (Cox et al., 2012, 2013; Sharma and Chetiya, 2009). (Steiner et al., 2007) goes further, stating elements and tools from the Shainin System *'should be incorporated into other process improvement methodologies'*. It is the integration of Six Sigma and Shainin System that this paper builds on to provide an effective sampling strategy for process improvement.

3 PROVADT Tools

The PROVADT methodology enables a user to move a Six Sigma improvement project from its measure through its analyse phase with a single sampling strategy (Cox et al., 2012, 2013). This is achieved by utilising principles from the Shainin System. PROVADT's integration of elements and tools from both is shown in Figure 1.

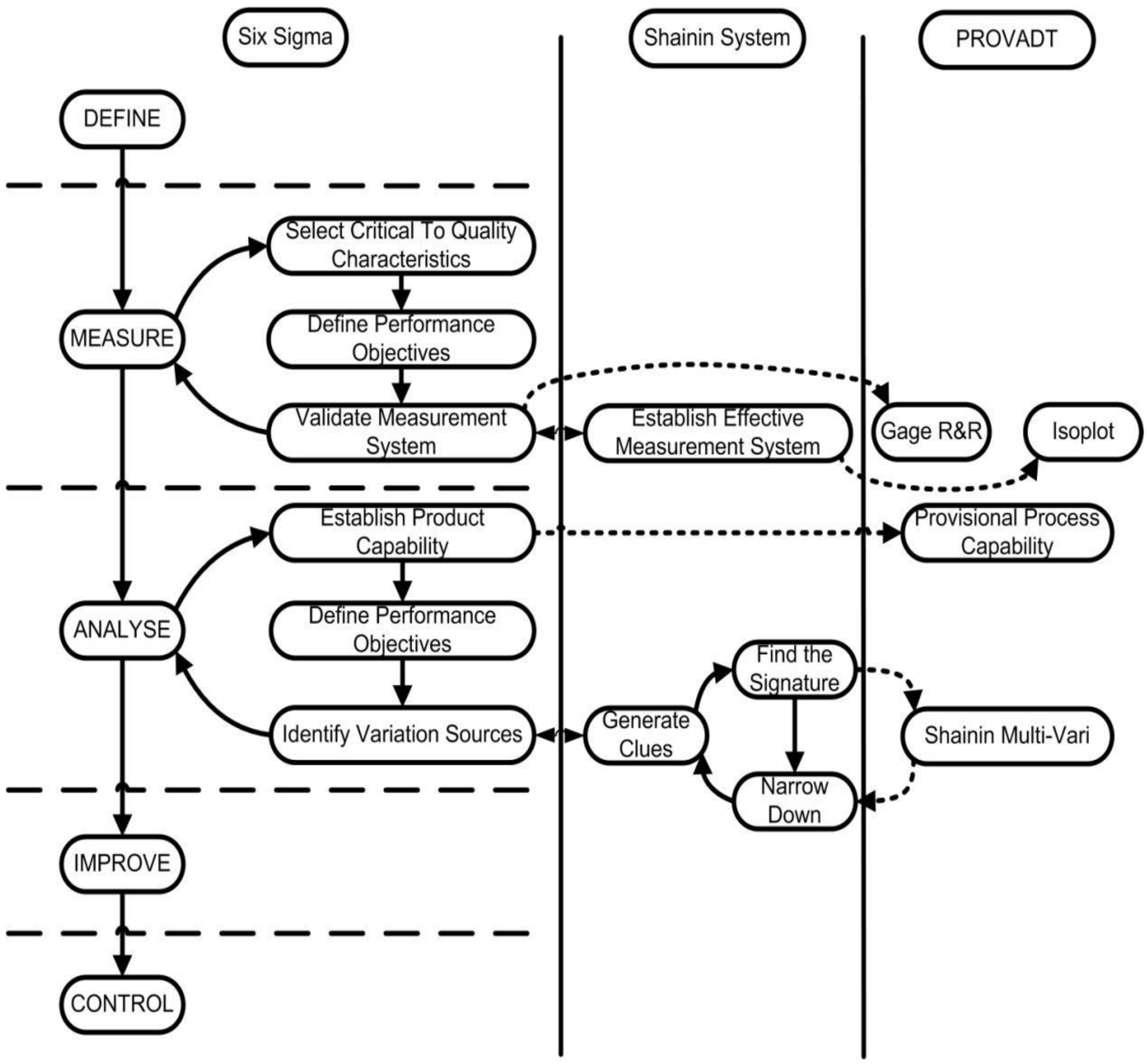


Figure 1: Outline of tools used in PROVADT (Cox et al., 2013).

PROVADT achieves its analysis by using four process improvement tools: Multi-Vari Chart, Isoplot, Gage R&R and Process Capability Study.

The Multi-Vari chart is the principal technique for 'clue generation' in the Shainin System (Bhote and Bhote, 2000; Shainin, 1993; Steiner et al., 2007). Recent examples of its practical implementation, are given in (Doganaksoy and Hahn, 2014; Shanmugam and Kalaichelvan, 2014; Zaciewski and Németh, 1995). The use of Multi-Vari charts within a Six Sigma framework to assist the analyse phase is illustrated in (Goh, 2002; Snee, 2005); for recent case studies see (Cox et al., 2012, 2013). In either context, it allows a practitioner to narrow down to a few potential root causes of variation objectively by means of a stratified experiment which identifies the 'signature of variation' (De Mast et al., 2001; Seder, 1990). This is achieved by separating the variation that occurs from repeatedly measuring a product (within-piece variation), from measuring consecutive products (piece-to-piece variation) and from measuring between sample time periods (time-to-time variation).

Isoplots are graphs that are used to identify the scale of variation in a measurement system relative to the variation in the process (Steiner et al., 2007). This is achieved by two appraisers measuring the same CtQ on typically thirty products. From the results, the measurement system variation is displayed graphically against process variation to see which has the greatest effect.

Gage R&R is a measurement system analysis tool. It is classically used at the measure phase within DMAIC to statistically validate the consistency and stability of the measurement system. Repeatability (σ_E^2) is the variation caused by the measuring equipment. The ability of a measuring device to provide consistent measurement data is important in the improvement of any process. Reproducibility (σ_A^2) is variation caused by the appraisers, which requires measurement readings to be acquired by different appraisers under the same conditions (AIAG, 2002). The total Gage R&R variation, which is the sum of σ_E^2 and σ_A^2, is then expressed as a percentage of design tolerance. This should be less than 10% to be deemed an adequate measurement system. If it is between 10% and 30% then it is considered marginal and anything above 30% is inadequate (AIAG, 2002).

Process capability indices are used to express numerically a process's ability to produce CtQs within their specified tolerances. Two common indices are C_p, which represents the process precision, and C_{pk}, which reflects the process accuracy and precision. A value of C_{pk} greater than 1.33 identifies most processes as capable of working within the required tolerance.

4 Sampling Constraints

In order to maintain the statistical significance of the four tools used, PROVADT's sampling strategy must uphold the following strict sampling constraints:

- The number of time periods (α) to sample from should be five or greater and there should be at least three consecutive products (β) in each sample period, to formulate a Multi-Vari study (Bhote and Bhote, 2000). Hence, $\alpha \geq 5$ and $\beta \geq 3$.
- The sample size (n) is defined as:

$$n = \alpha\beta, \tag{1}$$

and n must be greater than 10 products to produce a provisional process capability (AIAG, 2005; Juran and Gryna, 1988), but ideally at least 20 products to produce an initial set of Isoplots. Therefore, $n \geq 20$.

- The total number of measurements (r_{total}) taken is dependent on three factors: the number of locations to be measured in; the number of appraisers to take measurements in each location; and the number of repeat measurements each operator makes in each location. Where a different location, is a different measurement position in the same product to check uniformity. See Figure 2 for an example of three locations, which are external diameter measurements, used to check the ovality of a shaft. Therefore, $r_i^{(1)}$ expresses the number of repeat measurements taken by appraiser i in location 1. If ε_1 is defined as the total number of appraisers taking measurements in location 1, the total number of measurements taken at location 1 is $\sum_{i=1}^{\varepsilon_1} r_i^{(1)}$. This is then extended to a second measurement location to calculate r_{total}, as follows:

$$r_{total} = \sum_{i=1}^{\varepsilon_1} r_i^{(1)} + \sum_{j=1}^{\varepsilon_2} r_j^{(2)} . \qquad (2)$$

As a minimum, $\varepsilon_1 \geq 2$ appraisers and $\varepsilon_2 \geq 1$ appraiser, hence, $r_{total} \geq \varepsilon_1 + \varepsilon_2$.

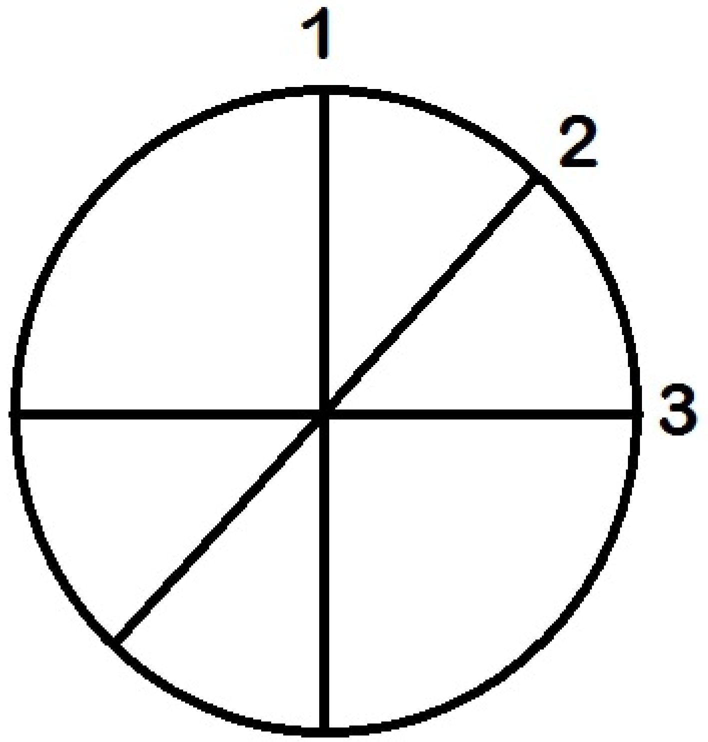


Figure 2: Locations measured to assess shaft ovality.

- The number of total measurements (φ) is defined as:

$$\varphi = nr_{total}, \tag{3}$$

To complete a Gage R&R study (AIAG, 2002), $\varphi \geq 60$.

From these constraints the minimum sampling requirements for PROVADT are:

- $\alpha = 5$ sample time periods.
- $\beta = 4$ consecutive products.
- $n = 20$ total products.
- $\varepsilon_1 = 2$ and $\varepsilon_2 = 1$, i.e. two appraisers, with $r_1^{(1)} = 1$, $r_2^{(1)} = 1$ and $r_1^{(2)} = 1$ measurements.
- $r_{total} = 3$ repeats.
- $\varphi = 60$ measurements.

The order the appraisers measure in, is swapped after the first 10 products. From this arrangement all four tests (Multi-Vari, Isoplot, Gage R&R and Process Capability) can be performed.

An important issue in PROVADT following the sampling strategy outlined is the possibility of lacking a sufficient Gage R&R, since it only quantifies variation in the measurement system distorted by variation between locations measured within a product's CtQ. A Gage R&R which follows industry guidelines, (AIAG, 2002), only measures a product in one location. This is due to its focus on determining only measurement variation. Hence, the σ_E^2 in a true Gage R&R is given by:

$$\sigma_E = \frac{6\overline{R_E}}{d_2^*}, \tag{4}$$

where, $\overline{R_E}$ is where the average range between repeat measurements and d_2^* is Hartley's statistical constant, values can be found in (Duncan, 1974). However, PROVADT is a diagnostic tool and therefore aims at capturing variation sources. This results in a Gage R&R where repeated measurements are taken at different locations on a CtQ. It also confounds measurement and product variation, in which case Equation (4) becomes:

$$\sqrt{\sigma_E^2 + \sigma_P^2} = \frac{6\overline{R_P}}{d_2^*}, \tag{5}$$

where σ_P^2 is the product-within-piece variation and $\overline{R_P}$ is the average range between repeat measurements at different locations. A low Gage R&R score shows there is little measurement or product variation. However, a high Gage R&R does not clear identify if this is truly a result of a poor measurement system. This conflicts with traditional Gage R&R assessment approaches and provides the motivation for an enhanced PROVADT method eliminating this problem.

5 Enhanced PROVADT

A new method has been developed based on the original PROVADT constraints. Extra constraints must be added to ensure a true Gage R&R is obtained, as well as quantifying product-within-piece (σ_P^2) variation.

In the original PROVADT repeated measurements at the same location would result in a true Gage R&R, but would not capture the effect of σ_P^2. If repeated readings are taken, in the same experiment, at different locations and by the same appraiser that took repeat readings for the Gage R&R, it is possible to show how σ_P^2 can be assessed analytically by subtracting the square of Equation (4) from the square of Equation (5), i.e.:

$$\begin{aligned} \sigma_P^2 &= (\sigma_E^2 + \sigma_P^2) - \sigma_E^2 \\ \sigma_P^2 &= \left(\frac{6\overline{R_P}}{d_2^*}\right)^2 - \left(\frac{6\overline{R_E}}{d_2^*}\right)^2. \end{aligned} \tag{6}$$

Following this approach separates measurement, σ_E^2, and product-within-piece, σ_P^2, variation. However, to perform this calculation separate estimates of $\overline{R_E}$ and $\overline{R_P}$ need to be made. Hence, two additional sampling constraints need to be introduced to capture these estimates:

A. The minimum repeated measurements in one location are $\sum_{i=1}^{\varepsilon_1} r_i^{(1)} \geq 3$ with $\varepsilon_1 \geq 2$ and $r_1^{(1)} \geq 2$. Repeating measurements by multiple operators in one location is critical to estimate $\overline{R_E}$, enabling the calculation of a true Gage R&R.
B. Additional measurements on at least $m \geq 10$ products to be made by a minimum of one appraiser in two new locations, such that $\varepsilon_2 \geq 1$ and $\varepsilon_3 \geq 1$. A minimum of three measurement locations is critical to obtaining an estimate of $\overline{R_P}$. This results in the total measurements made by enhanced PROVADT (φ_{En}) is:

$$\varphi_{En} = n\sum_{i=1}^{\varepsilon_1} r_i^{(1)} + m\left(\sum_{j=1}^{\varepsilon_2} r_j^{(2)} + \sum_{k=1}^{\varepsilon_3} r_k^{(3)} + \cdots\right). \tag{7}$$

These additional constraints allow the definition of a minimum sampling strategy for enhanced PROVADT. For example, if a sample of products is collected from a process, $n \geq 20$ products must be maintained to perform a basic Isoplot. If this sample is minimised to $n = 20$ products, then this impacts the number of sample time periods, α, and the number of consecutive products collected in each sample time period, β, such that $\alpha\beta = 20$. To perform a Multi-Vari chart the sample time periods are minimised to $\alpha = 5$, resulting in $\beta = 4$.

To fulfil the new constraint A for enhanced PROVADT, these 20 products must be measured in one location by a minimum of two appraisers, $\varepsilon_1 = 2$. One of these appraisers needs to repeat this measurements so that $r_1^{(1)} = 2$ and $r_2^{(1)} = 1$, hence, $\sum_{i=1}^{2} r_i^{(1)} = 3$. This set of measurements results in a true Gage R&R, by first calculating the mean range ($\overline{R_E}$) of appraiser 1 in location 1. To find this, the absolute difference between appraiser 1 measurements in location 1 is averaged:

$$\overline{R_E} = \frac{\sum_{a=1}^{20} \left| x_1^{(1,1,a)} - x_2^{(1,1,a)} \right|}{n}, \tag{8}$$

where, $x_i^{(1,1,a)}$ is the measurement taken by appraiser 1 in location 1 for product a of the n products collected. $\overline{R_E}$ is used to estimate repeatability or equipment variation (σ_E^2) using Equation (4) for 20 products and 2 repeats and $d_2^* = 1.128$ (Duncan, 1974):

$$\sigma_E = \frac{6 \times \overline{R_E}}{1.128}. \tag{9}$$

In order to calculate an estimate of reproducibility or appraiser variation (σ_A^2), the mean measurement of repeat 1 for appraiser 1 ($\overline{X_1^{(1,1)}}$) and appraiser 2 ($\overline{X_1^{(2,1)}}$) at location 1 is used as follows:

$$\sigma_A = \sqrt{\left(\frac{6 \times \left|\overline{X_1^{(1,1)}} - \overline{X_1^{(2,1)}}\right|}{d_2^*}\right)^2 - \frac{\sigma_E^2}{nr}}, \tag{10}$$

where, n is the number of products and r is the number of repeats. Hence, for minimum enhanced PROVADT, where, $d_2^* = 1.41$:

$$\sigma_A = \sqrt{\left(\frac{6 \times \left|\overline{X_1^{(1,1)}} - \overline{X_1^{(2,1)}}\right|}{1.41}\right)^2 - \frac{\sigma_E^2}{40}}. \tag{11}$$

Summing the squares of σ_E and σ_A enables the calculation of the total Gage R&R ($\sigma_{RR}^{(enhanced)}$) by:

$$\sigma_{RR}^{(enhanced)} = \sqrt{\sigma_E^2 + \sigma_A^2} \tag{12}$$

Also, this set of measurements taken across the 20 products by appraiser one can be used to calculate the capability in this location.

The second new constraint B is completed by re-measuring some of the 20 products by at least appraiser one in at least two new locations. If this constraint is minimised, $m = 10$ products are re-measured in two new locations by one appraiser, hence, $\varepsilon_2 = 1$ and $\varepsilon_3 = 1$. This results in $\sum_{j=1}^{\varepsilon_2} r_j^{(2)} = 1$, $\sum_{k=1}^{\varepsilon_3} r_k^{(3)} = 1$ and, therefore, $\varphi_{En} = 80$ total number of measurements in a minimised enhanced PROVADT. It is recommended that these additional measurements are taken at new locations are spread across the 5 sample time periods. One way to achieve this is to number products in a sample sequentially as they are collected, by making additional measurements on the odd number products. From this, within-product variation can be estimated by first calculating the mean range ($\overline{R_P}$) of appraiser 1 in all locations:

$$\overline{R_P} = \frac{\sum_{b=1}^{10} \max\left\{\left|x_1^{(1,1,b)} - x_1^{(1,2,b)}\right|, \left|x_1^{(1,1,b)} - x_1^{(1,3,b)}\right|, \left|x_1^{(1,2,b)} - x_1^{(1,3,b)}\right|\right\}}{10}. \tag{13}$$

where, $x_1^{(1,y,b)}$ is the measurement taken by appraiser 1 in location y for product b of the m products measured in multiple locations. $\overline{R_p}$ is used to estimate the within-product variation (σ_P^2) using Equation (6) for 10 products and 3 repeats and $d_2^* = 1.72$ (Duncan, 1974):

$$\sigma_P = \sqrt{\left(\frac{6R_P}{1.72}\right)^2 - \left(\frac{6R_E}{1.128}\right)^2}. \tag{14}$$

A comparison of original and the minimum enhanced PROVADT can be seen in Table 1.

Table 1: PROVADT variants including test appraisers and locations for measurements.

		Appraiser 1				Appraiser 2
Location		**1**	**1**	**2**	**3**	**1**
Original PROVADT		●		●		●
Enhanced PROVADT	Odd Products	●	●	●	●	●
	Even Products	●	●			●

The use of the enhanced PROVADT procedure to generate Multi-Vari, Isoplot, Gage R&R and Process Capability studies is highlighted in the next section. This provides a test study generated with a manufacturing simulation and is used to provide a worked example.

6 Simulation Work Example

6.1 Simulation Set-Up

The results in this section are taken from a teaching simulation known as PIMS (Process Improvement Methods Simulation) (Cox, 2011). This simulation reflects a batch manufacturing process and allows users to explore different quality improvement methods to determine which stage of the simulated process is the root cause of variation in the product's CtQ. Figure 3 provides an overview of the PIMS process, which has three manufacturing stages followed by an opportunity to measure the final product.

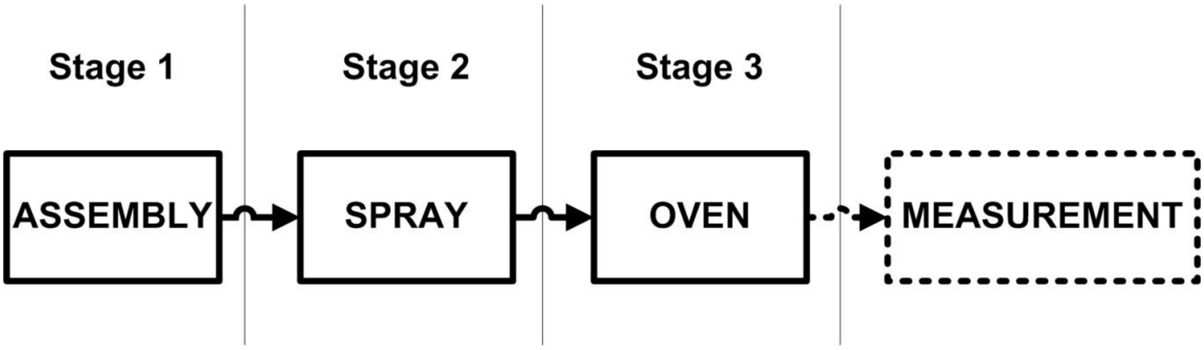


Figure 3: Outline of PIMS process.

In the assembly stage five components, A, B, C, D and E, are added onto a substrate. In these components there are different patterns of variation representing different potential issues. Components A, B and D have a normally distributed variable feature representing slight differences in components of the same type from a supplier. In C there is a variable feature which has a step-change every 18 components to reflect the effect of different batches from a supplier. Component E has a variable ovality in what should be a perfect circle, see Figure 2.

This assembly then goes through a spray process which has variation in two parameters pressure and viscosity, uniformly distributed. The assemblies then go through an oven curing process in batches of nine products, where there is potential variation caused by the oven position occupied during the curing.

The simulation set-up can be modified so that each input variable has some or no effect on the measured CtQ of the final product. The goal of the simulation is to identify which inputs affect the final product allowing the process to be improved. The product has a dimensional CtQ with a unilateral tolerance of target, $T = 100$ mm, and lower tolerance limit, $l = 55$ mm. To achieve this both a minimised original and enhanced PROVADT where implemented to compare results.

The sampling and measurements for original PROVADT were structured using the minimal setup. To fulfil these requirements, individual batches were selected to represent a single sample time period. From five separate batches four products were collected. This gave a total of twenty products to test, which was done between two appraisers. The results are presented in Appendix A.

The sampling and measurements for enhanced PROVADT were, also, structured using the minimal setup. The sampling was conducted in the same manner as the original approach. The results are presented in Appendix B.

These results are then analysed with a Multi-Vari Chart, Isoplot, Gage R&R and Process Capability Study, as follows.

6.2 Multi-Vari Chart

The Multi-Vari chart uses all gathered measurements which are plotted in Figure 4(a) for original PROVADT and Figure 4(b) for enhanced. These measurements are divided into three strata on the chart for within-piece, piece-to-piece and time-to-time variation.

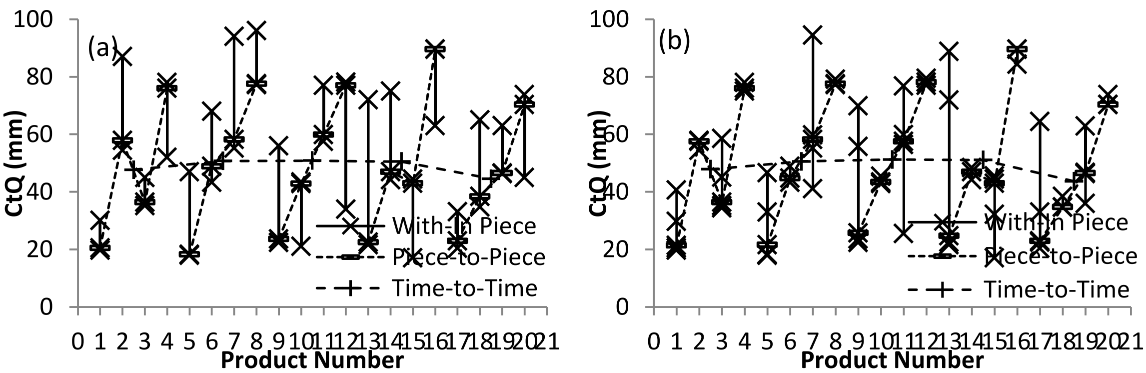


Figure 4: Multi-Vari study of simulation results using (a) original and (b) enhanced PROVADT.

In Figure 4(a) the largest or Red X variation is within-piece. This is indicated by the vertical groups of three measurements per product. The second largest or Pink X variation is piece-to-piece and there is little time-to-time effect.

In Figure 4(b) the largest or Red X variation is within-piece. This is indicated by the vertical groups of three and five alternating measurements per product. The second largest or Pink X variation is piece-to-piece and there is little time-to-time effect.

From Figure 4(a) and (b), it is important to note that the σ_P^2 variation is represented in the within-piece variation on all products using original PROVADT, but only represented in odd numbered products using enhanced. However, both approaches identify within-piece variation as the Red X. Following the Shainin System philosophy the root cause of the Red X variation is the first to be investigated. This is done initially by examining the results again using an Isoplot study in the next section.

6.3 Isoplots

From the data in Appendices A and B, two Isoplots can be created. The first plot compares the measurement repeatability of appraiser 1. To do this, the two repeated measures taken in the same location are plotted against each other in Figure 5(a) and (c) for original and enhanced, respectively. The second Isoplot compares the measurement reproducibility between appraisers 1 and 2. This variation is shown in Figure 5(b) and (d) for original and enhanced, respectively, by plotting the results of appraiser 1 against appraiser 2 from the same location.

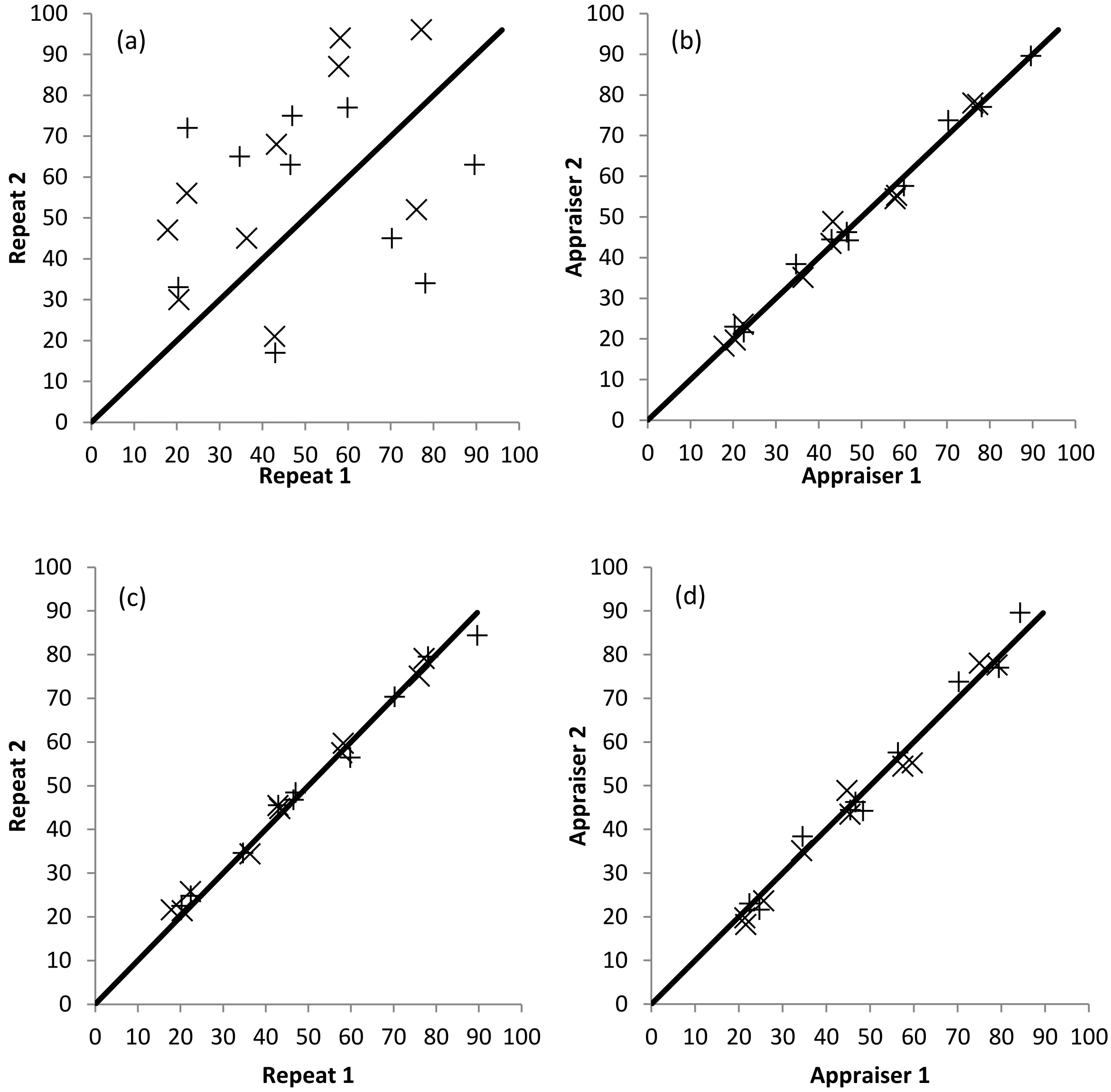


Figure 5: Isoplots of simulation original results (a) Repeatability of appraiser 1; (b) Reproducibility of appraiser 1 against appraiser 2 and enhanced results (c) Repeatability of appraiser 1; (d) Reproducibility of appraiser 1 against appraiser 2.

The plots in Figure 5 show the results as one homogeneous group, indicating that the test does not affect the process. Highlighted in Figure 5(a), is that there is variation both along the 45° line and perpendicular to it, which suggests that there is excessive repeatability variation, indicating that the measurement system is contributing to the within-piece Red X. However, this result should be taken with caution since as mentioned before original PROVADT confounds repeatability and product-within-piece variation. From Figure 5(b), it is shown that there is more variation along the 45° line than perpendicular to it. This indicates little reproducibility variation in the measurement system. Both Figure 5(c) and (d), also highlight, that there is more variation along the 45° line than perpendicular to it. This means that there is greater piece-to-piece process variation than measurement variation, indicating that the measurement system is not contributing to the within-piece Red X; this is quantified by a Gage R&R study as shown in the next section.

6.4 Gage R&R Study

A derivation of a Gage R&R study for original PROVADT is in (Cox et al., 2013). This is applied to the sampling results at Appendix A to give a total Gage R&R, as a percentage of tolerance, $\sigma_{RR}^{(original)} = 308.9\%$. This suggests the measurement system is inadequate, due to $\sigma_{RR}^{(original)} > 30\%$ (AIAG, 2002). In Figure 6 it is shown that the repeatability variation is the biggest contribution to the overall Gage R&R effect. This is consistent with the Isoplot observations in Figure 5(a) and (b).

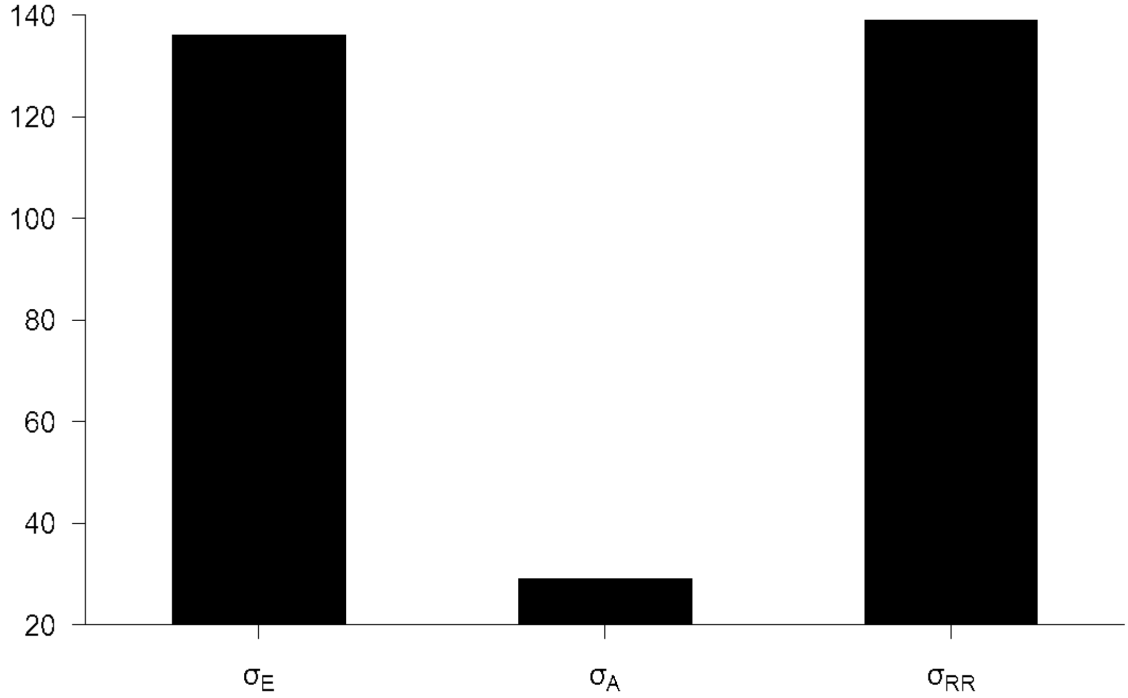


Figure 6: Effective contribution of repeatability and reproducibility to original Gage R&R.

The advantage of the enhanced PROVADT method is that a true Gage R&R value is calculated. This is achieved in for the simulation case using the sampling results in Appendix B and Equations (4) - (12), which gives $\%\sigma_{RR}^{(enhanced)} = 22\%$. Using the guidelines from the TS/ISO 16949 standard reference manual, the score of 22% would rate this as marginal.

The individual components of variation are summarised in Figure 7, which shows that the effect of variation within the product itself is considerably larger than the measurement system variation. This is consistent with the findings from the Isoplots in Figure 5(c) and (d).

It also further narrows down the potential root causes of the within-piece Red X variation as a result of the product and not the measurement system.

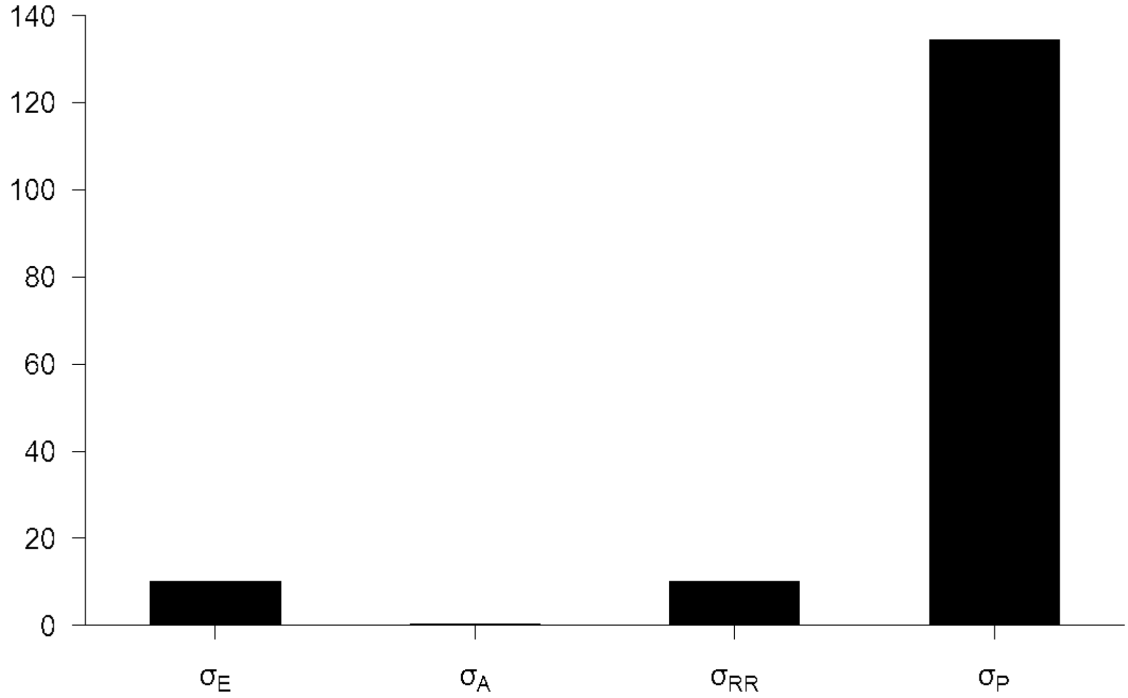


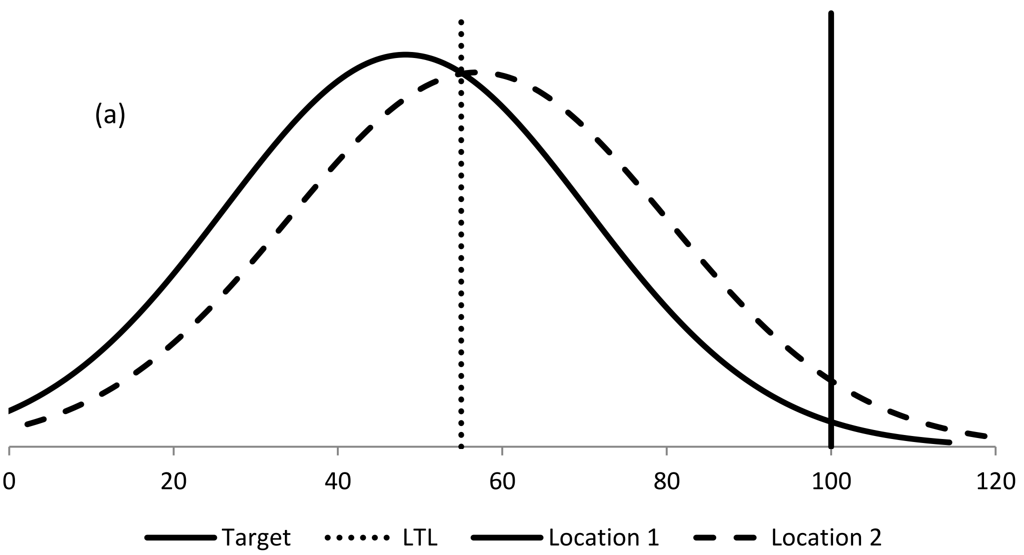
Figure 7: Gage R&R of simulation results within-piece variation sources.

This set of results shows a significant difference in the original and enhanced PROVADT methods in determining a true Gage R&R. At this stage the original approach would have determined that the within-piece Red X variation, identified in the Multi-Vari study, was a result of an inadequate measurement system. However, due to the known confounding of repeatability and product-within-piece variation, a follow-up gage analysis would need to be performed to separate these issues. This would take more time and testing resource, as a fresh gage analysis uses a minimum of 60 new measurements. In the case of the enhanced approach, no further gage studies are required, with the addition of only 20 measurements to the original PROVADT. Not only, are the repeatability and product-within-piece variations not confounded, but all variation sources are quantified. Thus, the within-piece Red X is further narrowed down to an issue of non-uniformity in the product. This shows the improvement of the enhanced PROVADT over the original.

6.5 Provisional Process Capability Study

Just as the Gage R&R quantifies the within-piece variation seen in the Multi-Vari chart, the provisional process capability study quantifies the piece-to-piece variation. The enhanced PROVADT allows the calculation of process capability at the three measured locations.

In this worked example the product has a unilateral tolerance; therefore, only C_{pk} is calculated. For original PROVADT this is performed for the two measurement locations by using average results for appraiser 1 across the 20 products i.e. $\overline{X_1^{(1,1)}}$ and $\overline{X_1^{(1,2)}}$ and Equation (2). This leads to $C_{pk}^{(1)} = -0.1023$ and $C_{pk}^{(2)} = 0.0289$, which implies the process has a poor overall capability. These results are plotted in Figure 8(a). Given the inadequate Gage R&R evaluation these results would be considered not reflective of the process but of the excessive measurement variation. Again, this highlights the importance of obtaining a true Gage R&R.



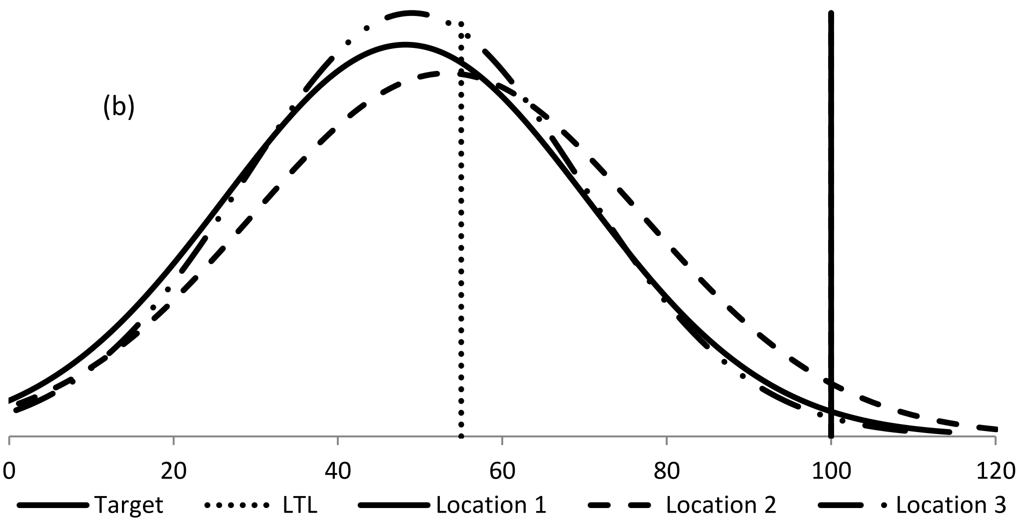


Figure 8: Process capability results of (a) original and (b) enhanced PROVADT.

For enhanced PROVADT, the capability calculations are performed using the location means for appraiser 1 repeat 1 ($\overline{X_1^{(1,1)}}$, $\overline{X_1^{(1,2)}}$, $\overline{X_1^{(1,3)}}$) and Equation (2). This leads to $C_{pk}^{(1)} = -0.1023$, $C_{pk}^{(2)} = -0.0236$ and $C_{pk}^{(3)} = -0.0981$, which implies the process has poor capability in all three locations. The negative results indicate that the process mean is outside of the tolerance limit. This capability study is consistent with the Multi-Vari chart in that, despite the Red X within-piece issue, there is a strong piece-to-piece Pink X underneath, that is quantified by a poor C_{pk}. These results are summarised in Figure 8(b).

It is clear to see that both original and enhanced PROVADT offer similar capability results. The two advantages the enhanced method has shown is that it provided the capability in a third location and the complement of a valid Gage R&R result allows these results to be used without further testing.

6.6 Summary

Both original and enhanced PROVADT assisted the user to narrow down towards the root cause of variation. In this example it was an ovality issue in the circle component E that caused product-within-piece variation in the final CtQ. This is determined by analysing product using a technique such as paired comparisons, with a reduced number of potential variation sources. However, the difference between the original and enhanced approaches was that the original approach needed further experimentation to validate the measurement system. Whereas, enhanced could go straight into the paired comparison analysis. The following section details two industrial case studies are presented were enhanced PROVADT has been applied.

7 Industrial Case Studies

7.1 Overview

In this section two industrial case studies are detailed, where enhanced PROVADT has been applied. The first is at Rettig, Team Valley, UK, who manufacture steel radiators for the Myson and Purmo brands. The second is at Coveris, Stanley, UK, who manufacture rigid packaging for the food industry. In both cases a sample of products is collected as per the minimum enhanced PROVADT structure. Then these results are analysed, in the same manner as previously outlined, by Multi-Vari chart, Isoplot, Gage R&R study and Provisional Process Capability, in that order. The subsequent actions in these cases are then summarised.

7.2 Rettig

7.2.1 Background

Rettig brings together Europe's leading brands for radiators, underfloor heating, valves and controls. Its site at Team Valley was built in 1958, and was acquired by Rettig (Myson) in 2000, to manufacture radiators for the Myson and Purmo brands. In 2003 Rettig invested 30 million euros in a new production hall equipped with two new fully-integrated high-speed welding lines. Down these two lines, called Round Top 1 (RT1) and Round Top 2 (RT2), the side panels for all the non-electric radiators are manufactured. The only difference between the two lines is RT1 is measured in metric units; whereas RT2 is measured using imperial units. The two lines work as a mirror image along the factory.

Both assembly lines produce single and double panelled radiators. A welding wheel running down the edge of each panel creates the top seam. The double panelled radiators are two single panels manufactured one after each other in which the first panel is rotated and then lifted to enable the second panel to move underneath for welding. Once the radiators have been through testing and painting an optional grilling attachment is placed on top.

7.2.2 Problem Definition

The problem Rettig experienced was the positioning of grilling on double panelled radiators. The top seams on each panel were not parallel along their own length and, hence, the grille on occasion did not fit flush on top of the radiator. Rettig wanted to understand the root cause of this variance and to compare the scale of variation in RT1 and RT2 production lines. It was decided that both the seam depth and height of each panel must be measured to capture all potential sources of variation. This means that four concurrent enhanced PROVADT studies took place.

On both production lines every radiator is manufactured to a technical specification. The panel height and seam depth is specified with a 6mm tolerance (-2mm+4mm either side of the target). Each panel was manufactured to the same specification. This meant that all the radiators coming off both production lines had the potential to be used for a double panelled radiator with grilling. They should have had a parallel top seam so that all radiators could be tested.

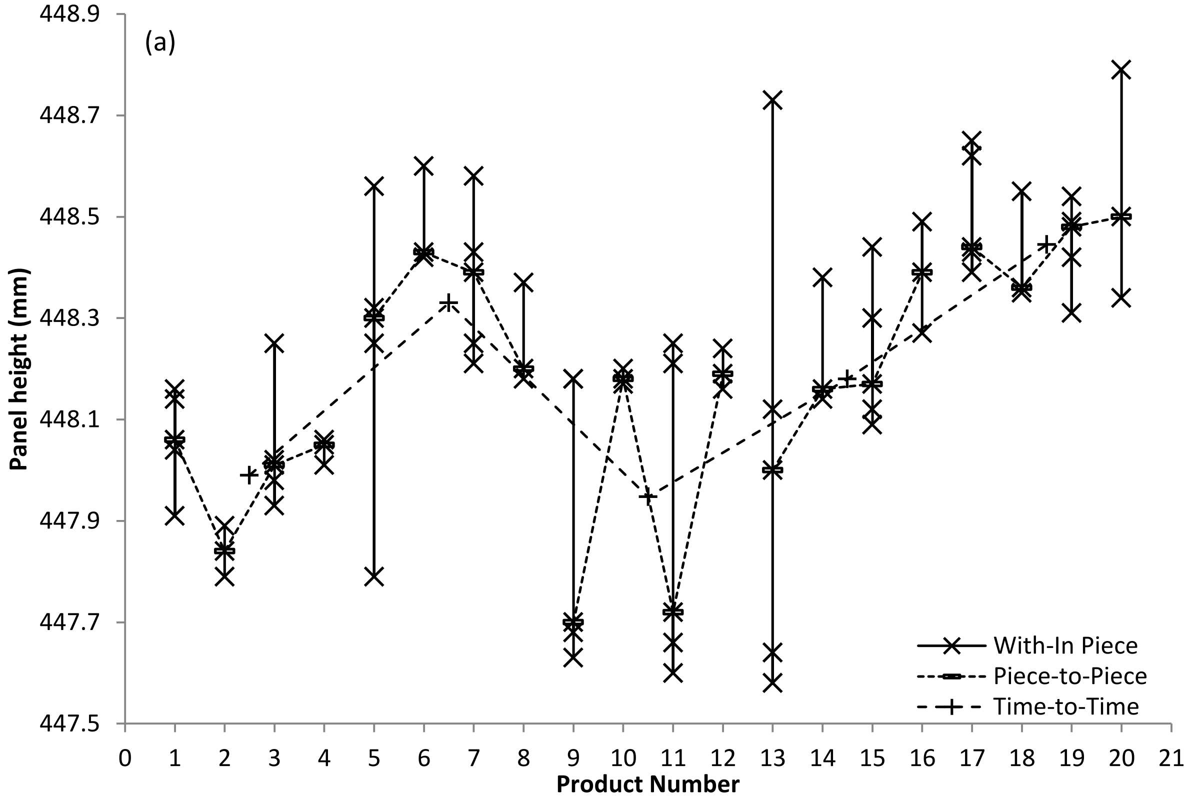
7.2.3 Measurement Method

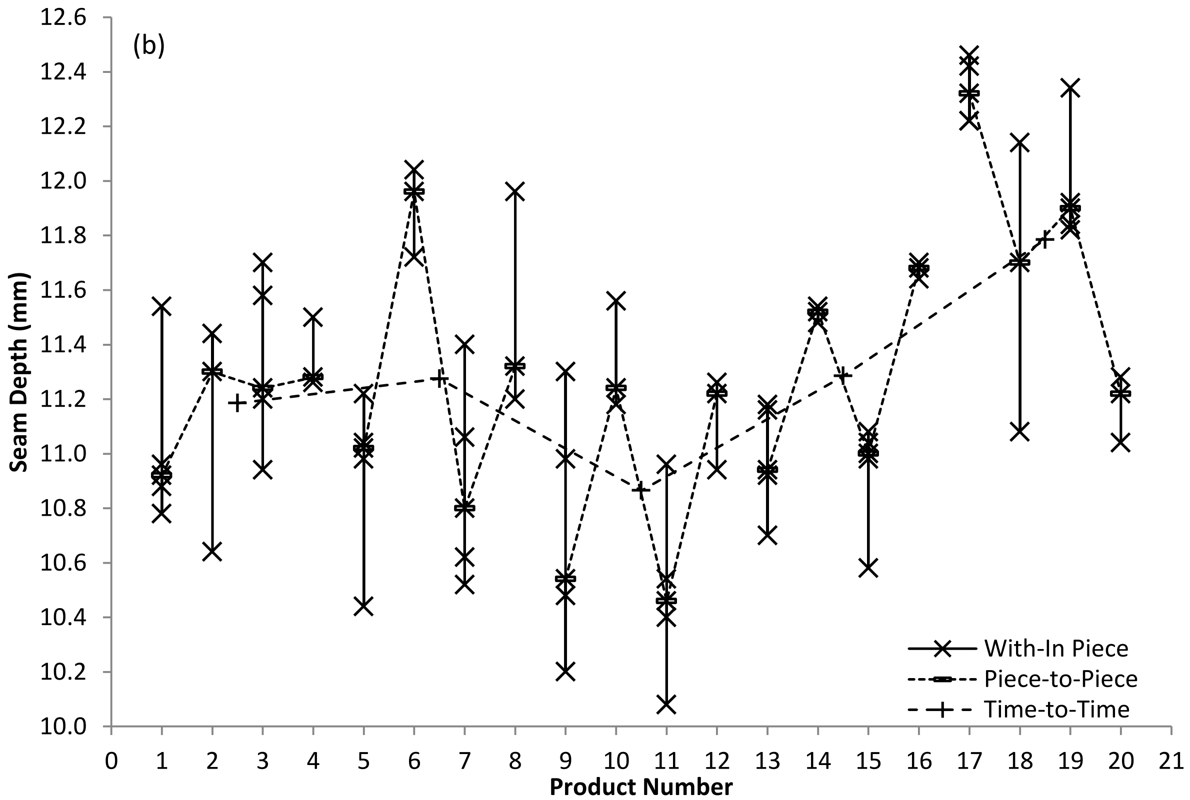
The testing at Rettig is non-destructive and data were gathered as per the minimum enhanced PROVADT requirements. This meant that four consecutive products were collected at five sample time periods resulting in a total of twenty products in the sample. Once the products were collected, five measurements were taken from every other of the twenty products (odd numbered products) and three measurements taken from the remainder (even numbered products). Appraiser 1 measured twice in a primary location for all products and Appraiser 2 measured once in the same primary location. Appraiser 1 then measured twice more in a secondary and tertiary location for each odd numbered product. The order in which the appraisers measured was swapped after 10 products had been measured.

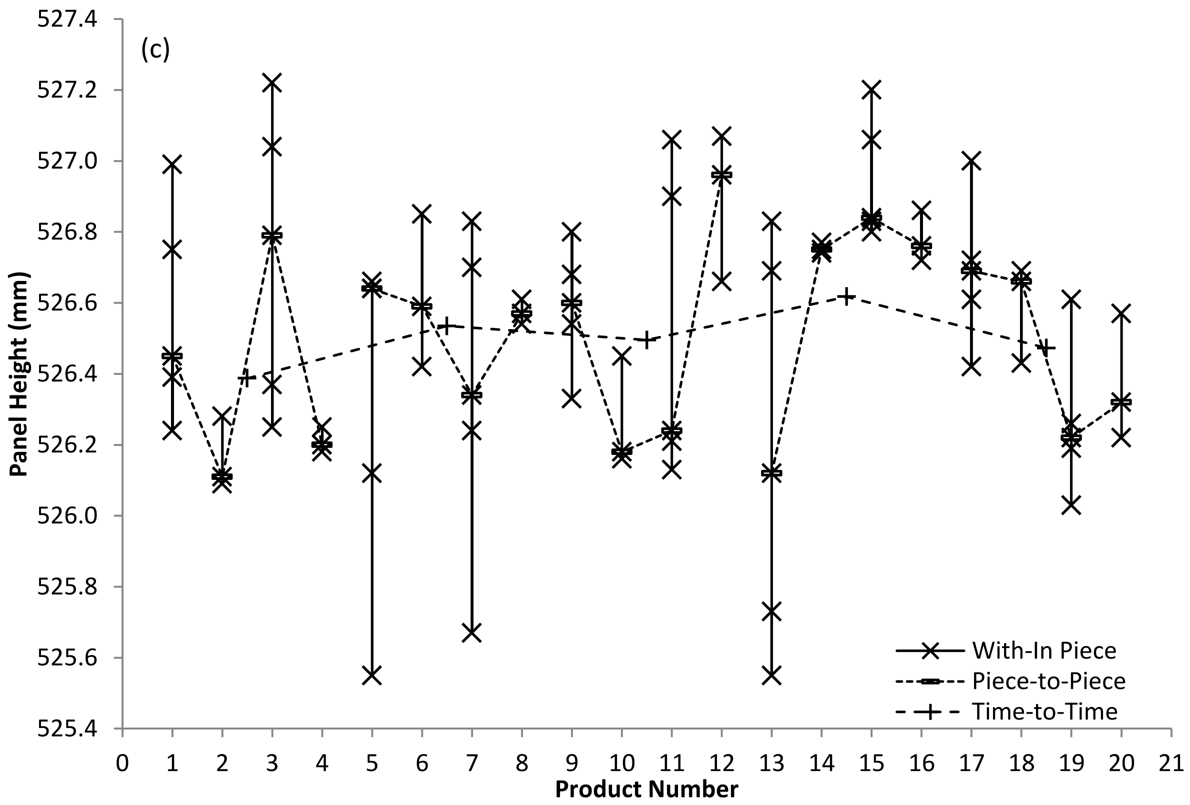
The seam depth was measured with the depth gauge on Vernier callipers and a larger version was used to measure the radiator height. Both callipers had a precision of 0.01mm. There was no other measuring instrument available; hence, the two appraisers for this testing were two different operators. The results for RT1 and RT2 panel heights and seam depths are presented in Appendix C - F.

7.2.4 Multi-Vari Chart

Multi-Vari charts were derived for the four data sets of RT1 and RT2, seam depth and panel height. These show, that in all cases, the Red X is Within-Piece but with a Pink X of Piece-to-Piece. These Multi-Vari charts are shown in Figure 9(a) – (d).


(a)
Panel height (mm)
448.9
448.7
448.5
448.3
448.1
447.9
447.7
447.5
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Product Number
With-In Piece
Piece-to-Piece
Time-to-Time


(b)
Seam Depth (mm)
12.6
12.4
12.2
12.0
11.8
11.6
11.4
11.2
11.0
10.8
10.6
10.4
10.2
10.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Product Number
With-In Piece
Piece-to-Piece
Time-to-Time



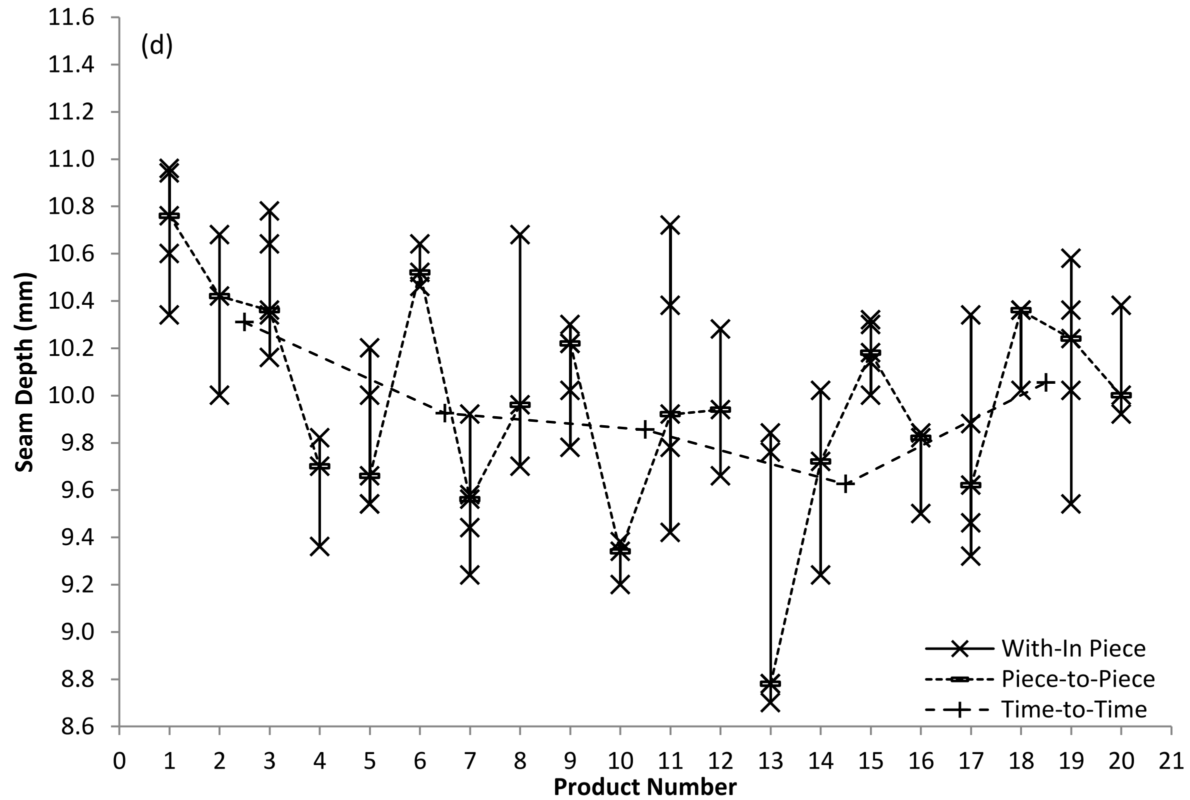
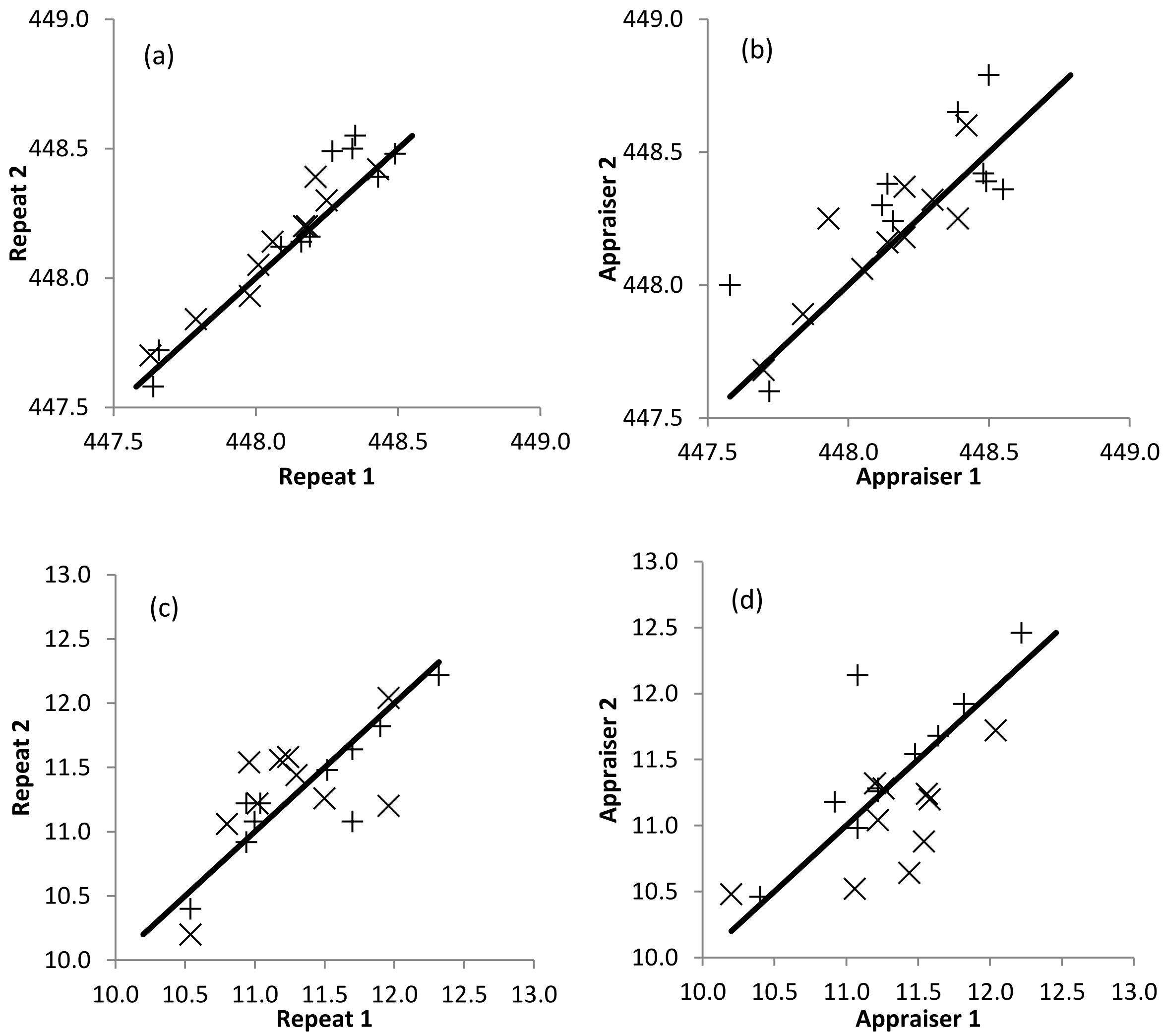


Figure 9: Multi-Vari charts for (a) RT1 panel height; (b) RT1 seam depth; (c) RT2 panel height; (d) RT2 seam depth.

The difference between the within-piece points show the variation caused by the product and measurement system. The larger within-piece spread on odd products indicates that the product variation has a large contribution to the overall variation.

7.2.5 Isoplots

In this analysis, the within-piece measurement variation is compared with the piece-to-piece variation. Therefore, indicating whether the measurement system is capable relative to the overall piece-to-piece variation. The results for RT 1 and RT2 radiator heights and seam depths are shown in Figure 10(a) – (h).



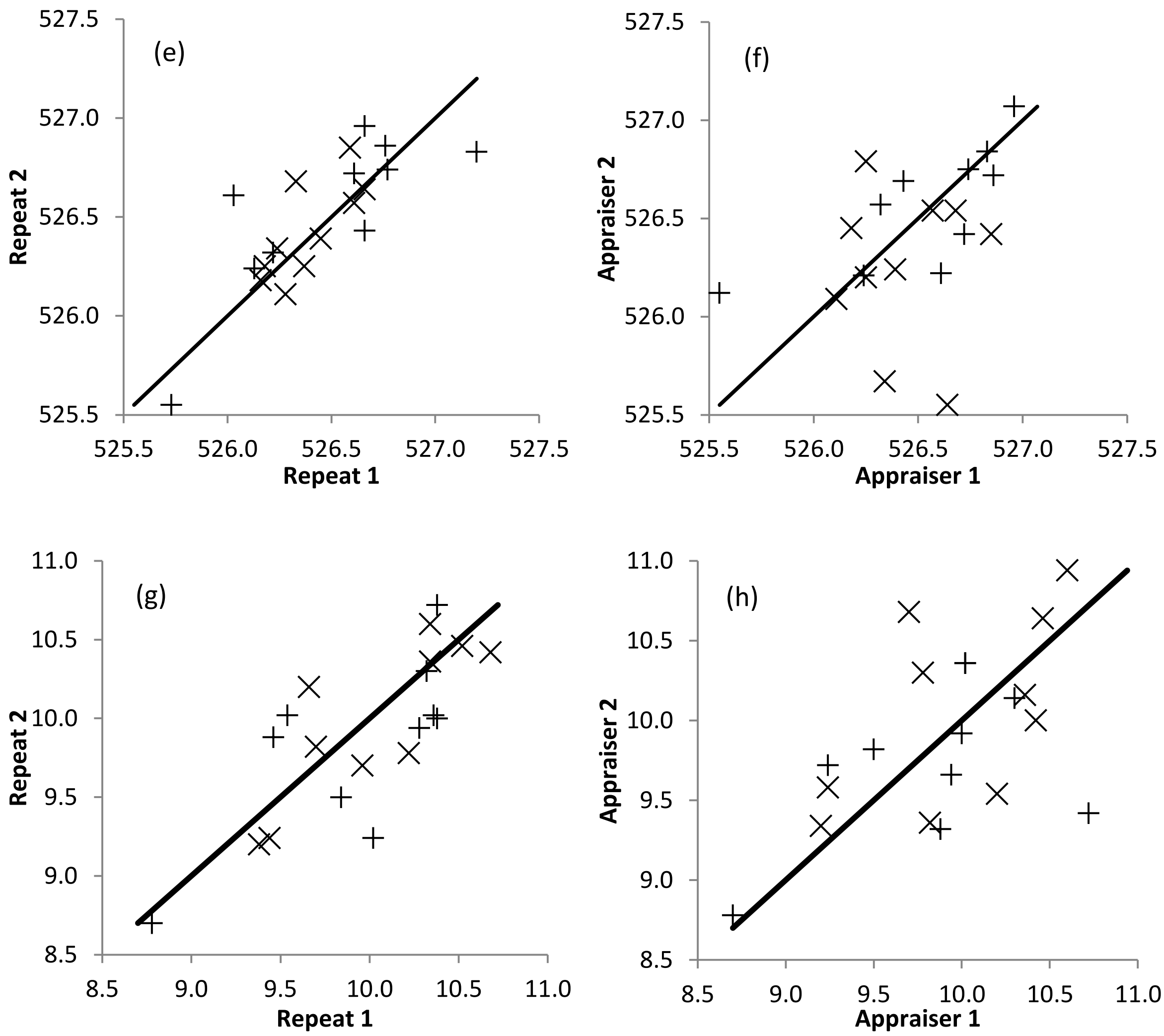


Figure 10: Isoplots for RT1 panel height between (a) appraiser 1 repeat measures and (b) appraisers; RT1 seam depth between (c) appraiser 1 repeat measures and (d) appraisers; RT2 panel height between (e) appraiser 1 repeat measures and (f) appraisers; RT2 seam depth between (g) appraiser 1 repeat measures and (h) appraisers.

In all charts there are no obvious separate groupings, indicating that the measurement system is not having an effect on the product. Figure 10(a), (c), (e) and (g) show the Isoplot for repeatability or consistency of the measurement system between repeated measurements by the same appraiser in the same location. Results are spread along the 45° line than away from it, highlighting that there is more piece-to-piece than repeatability variation in the measurement system. Figure 10(b), (d), (f) and (h) show the reproducibility or variation between different appraisers' measurements in the same location. These demonstrate more piece-to-piece variation than measurement system variation due to different appraisers. However, there is clearly a large deviation in some results away from the 45° line; therefore, reproducibility is the most significant component of measurement variation.

7.2.6 Gage R&R

From the Multi-Vari it was shown that there is within-piece variation caused in part by the product. The Isoplot verified that the measurement system is a non-destructive test. Therefore, calculation of a Gage R&R value is imperative to quantify statistically how much of the within-piece variation is due to measurement. This was unachievable with the previous version of PROVADT; however, it is possible with enhanced PROVADT and the results are displayed in Table 2. In this table, σ_P, σ_E, σ_A and σ_{RR} have been calculated using Equations (8) – (14).

Table 2: Gage R&R analysis for seam depth and radiator height on RT2 and RT1.

	RT2		RT1	
	Seam Depth (mm)	Rad. Height (mm)	Seam Depth (mm)	Rad. Height (mm)
σ_P	0.799	1.959	1.525	1.409
σ_E	1.559	0.883	1.309	0.375
σ_A	0	0.268	0	0.333
σ_{RR}	1.559	0.923	1.309	0.502
$\%\sigma_{RR}$	25.9%	15.3%	21.8%	8.3%

Table 2 highlights that the measurements systems should be categorized as marginal, according to (AIAG, 2002), meaning they are sufficient for non-critical CTQs. The results in Table 2 also show the relative differences between σ_P, σ_E and σ_A. This highlighted that the product-within-piece (σ_P^2) component of variation is at least twice as large as the total measurement-within-piece variation (σ_{RR}^2) for RT1 and RT2 radiator heights. Therefore, to reduce the size of the Red X within-piece variation, the investigation focused on causes of σ_P^2 causing a non-uniform radiator height in the product.

7.2.7 Process Capability

A final analysis from the enhanced PROVADT sampling allows the calculation of provisional process capability study in each measurement location in order to quantify statistically the Pink X piece-to-piece variation. These results are presented in Table 3, where it is shown that there is consistency in capability across all measurement locations. Since the variation in each location is of a similar magnitude. This is a result of consistent variation across the product and not a result of one location being constantly different from the others.

Given that this is a provisional study with a small sample of products, larger discrepancies would be needed to alert an operator.

Table 3: Provisional process capability for RT2 and RT1.

	RT2						RT1					
	Seam Depth			Rad. Height			Seam Depth			Rad. Height		
Location	1	2	3	1	2	3	1	2	3	1	2	3
C_p	2.04	2.39	2.28	3.03	3.36	3.36	2.00	1.25	2.07	3.80	4.74	3.93

The provisional process capability results for RT1 andRT2 panel height and seam depth, in Table 3, show that these processes are very capable. The minimum C_p of 1.25 demonstrates that the piece-to-piece variation is small relative to the design tolerances.

However, the C_{pk} values for panel height on both RT1 and RT2 were lower than the C_p. This indicated that the process was not operating exactly on the design target. This was quickly rectified and the seam welding machines were readjusted to move the process closer to the technical target. Given the high C_p values once the process had been moved back on target there was no economic reason to minimise the Pink X variation further.

7.2.8 Overall Analysis Provided to Rettig

Enhanced PROVADT enabled the analysis of production lines RT2 and RT1 from one set of 20 products. It was shown that the main source of variation was within-piece. The majority of this variation was due to non-uniformity in the product, which is now under further investigation.

As a result of the experimental work a small adjustment was made to the measurement system. This improved on the height measurement between RT2 and RT1, resulting in a decrease in the Gage R&R value so the measurement system became adequate.

Process Capability was above 1.33 on both production lines with regards to the seam depth, so it is within its specified tolerance and once the welding machines were realigned the panel height also operated with a high capability. The data collected confirmed Rettig's suspicions that although the process has the capability to produce within the specification limit it can have within-piece variation, within the top seam.

7.3 Coveris

7.3.1 Background

Coveris is a company formed from the merger of five top-ranking plastics packaging companies. Currently, Coveris is the 6th largest plastics packaging company in the world. Its site in Stanley, UK, specialises in the co-extrusion and thermoforming of rigid packaging for the food industry.

7.3.2 Problem Definition

Coveris recently installed a new co-extrusion facility at its Stanley site, known as EREMA. This facility processes raw plastic into rolled sheets which are then used for the thermoforming of food packaging. The EREMA process produces batches of sheet plastic, which are wound up into reels. A typical production run produces 5-10 reels. The machine set-up is then changed to produce a product with a different chemical composition and/or gauge of thickness.

As this process was newly established, the company wanted to investigate the capability and variation patterns of plastic gauge thickness in the reels. As the process contains over 15 controllable parameters, Coveris wanted to narrow its focus down on which parameters needed adjustment. To achieve this, enhanced PROVADT was implemented.

7.3.3 Measurement Method

In order to gather a sample as required by enhanced PROVADT, five consecutive batches (reels) from the same production run where selected to represent sample time periods. From these reels a section was cut away from the end, which was then sub-divided into four consecutive products, as shown in Figure 11.

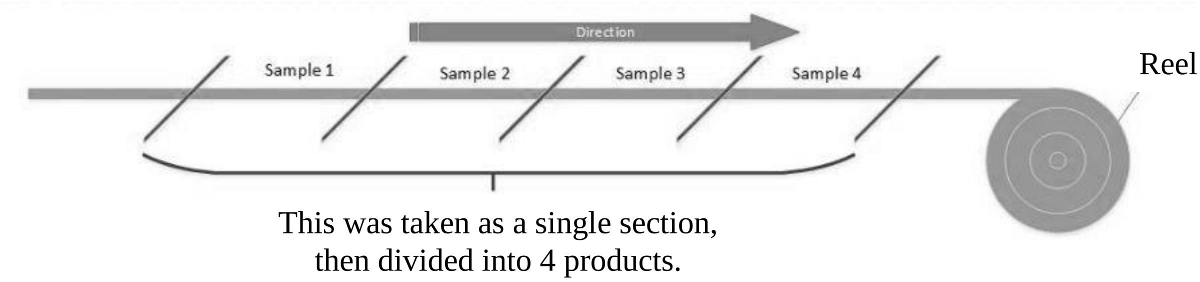


Figure 11: Collection of products from a single reel.

To measure the plastic gauge thickness, a custom depth gauge jig was used and two operators were used as appraisers. Each product was then measured in a primary location twice by appraiser 1 and once by appraiser 2. This primary location is labelled as (a) in Figure 12.

Appraiser 1 measured in this location first for the first half of the products in the sample. Appraiser 2 then measured first for the second half of the products in the sample.

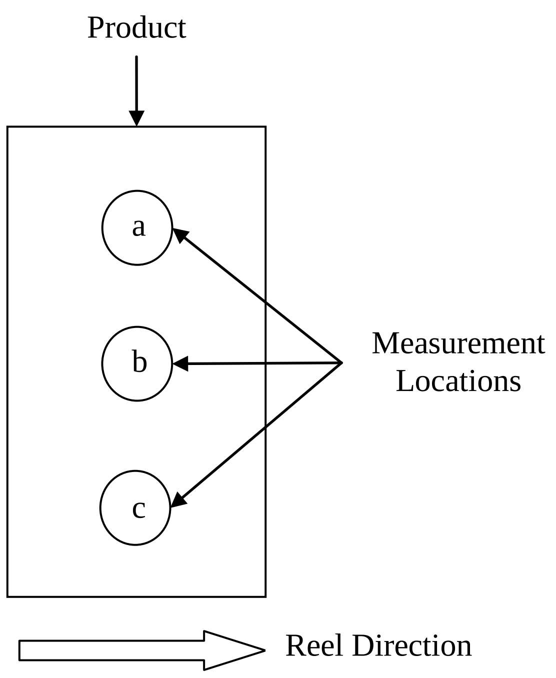


Figure 12: Measurement locations.

Appraiser 1 then measured every alternate or odd numbered product in the sample in a secondary and tertiary location, which are marked as (b) and (c), respectively, in Figure 12. These extra location measurements provide information assessing product-within-piece variation. The target gauge for these products was 1.150±0.058mm and the recorded measurements are presented in Appendix G.

7.3.4 Multi-Vari Chart

Figure 13 shows the Multi-Vari chart plotted for the plastic gauge thickness results. It is clearly shown that the Red X is within-piece variation, and a piece-to-piece Pink X.

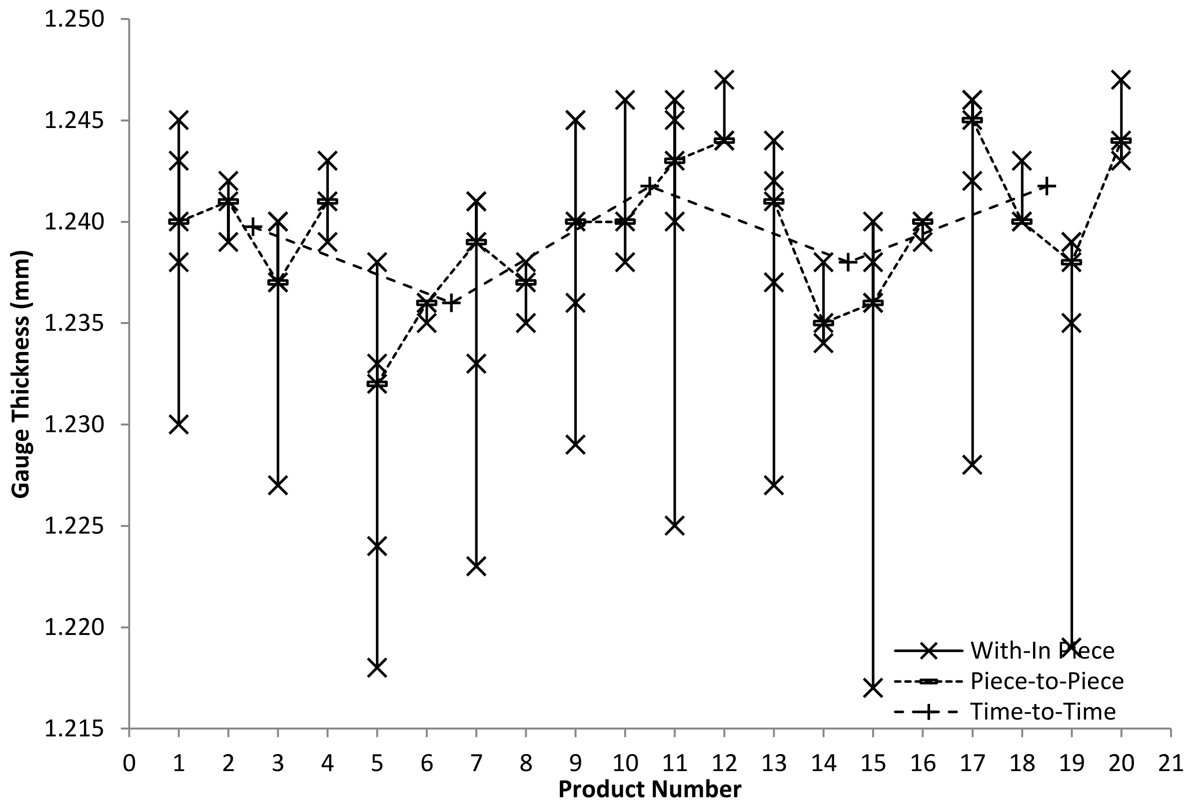


Figure 13: Multi-Vari chart for product thickness.

Therefore, this project focused on understanding the cause of this variation, which could be measurement or product-within-piece variation. Isoplots were used for narrowing down the root cause.

7.3.5 Isoplots

The repeatability and reproducibility Isoplots generated from the enhanced PROVADT sampling are displayed in Figure 14.

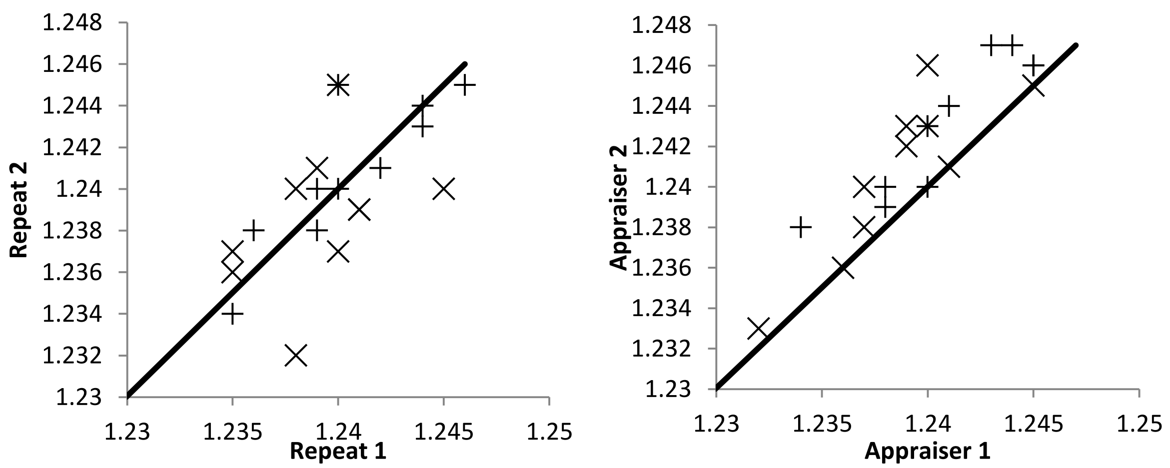


Figure 14: Isoplots for product thickness between (a) appraiser 1 repeat measures and (b) appraisers.

In both Figure 14(a) and (b) there are no obvious separate groupings, hence, the measurement system is not affecting the product. It is also shown that the spread of results is greater along the 45° line than across it. This indicates that the piece-to-piece variation is greater than the measurement-within-piece variation, implying that the Red X is a result of product-within-piece variation. These implications are further quantified by the Gage R&R study in the following section.

7.3.6 Gage R&R

The Gage R&R results are given in Table 4, which were calculated based on the measurements recorded in Appendix G. The two key results from this analysis are the percentage Gage R&R score and the relative size of the σ_P against this measurement deviation.

Table 4: Gage R&R for product thickness.

	Thickness (mm)
σ_P	0.0596
σ_E	0.0114
σ_A	0.00897
σ_{RR}	0.0145
$\%\sigma_{RR}$	12.64%

The Gage R&R of 12.64% categorises the measurement system as marginal but is close to the adequate boundary. This gave the investigation confidence that the measurement system was able to detect changes in the process that were significant relative to the tolerance. It also reinforced the finding, from the Isoplot, that the Red X is unlikely to be a result of measurement variation. The second analysis of comparing σ_P and σ_{RR}, can be done by reviewing the variance values presented in Table 4, more clearly displayed in Figure 15.

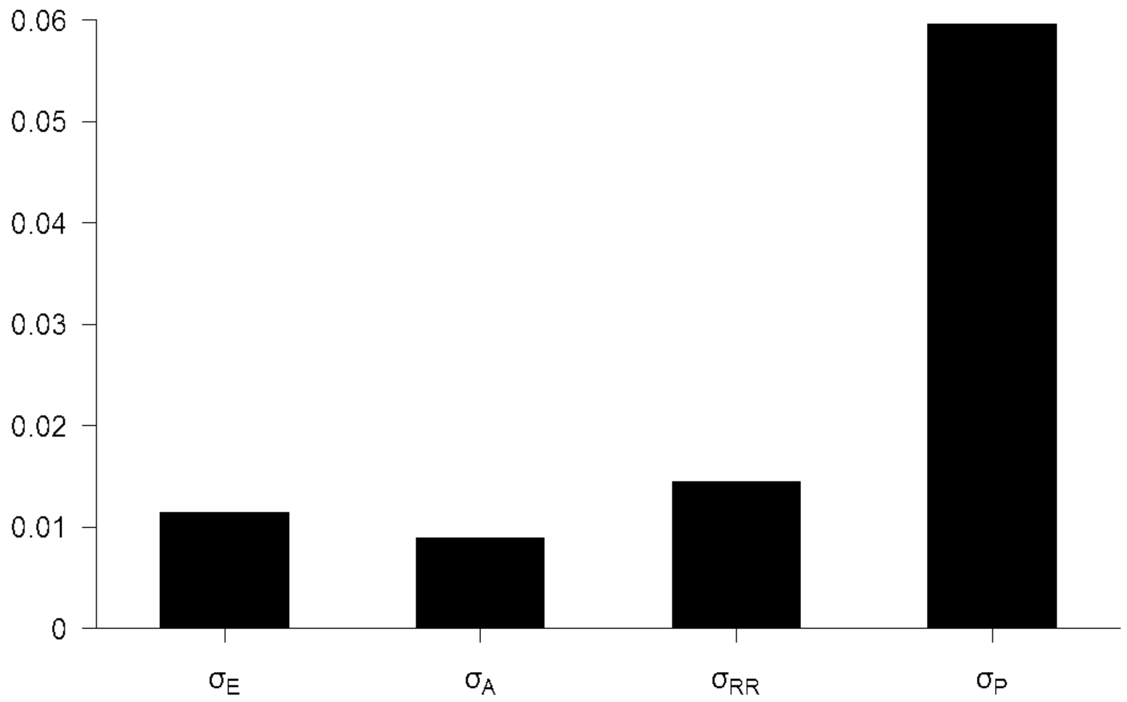


Figure 15: Gage R&R of Coveris sample.

The bar chart in Figure 15 graphically shows that the σ_P is four times larger than σ_{RR}. This confirms that the Red X within-piece variance is a result of product-within-piece variation which is caused by a non-uniformity across each product and is not caused by excessive measurement variation.

7.3.7 Process Capability

The final PROVADT analysis of the provisional process capability aided the investigation to put the overall variation in the EREMA process into perspective. The capability indices for all locations are $C_p^{(1)} = 5.89$, $C_p^{(2)} = 3.67$ and $C_p^{(3)} = 4.01$, and $C_{pk}^{(1)} = -3.32$, $C_{pk}^{(2)} = -1.82$ and $C_{pk}^{(3)} = -1.17$.

The C_p results of greater than 3.5 indicate that the overall variation in the process is very low with respect to the tolerances. However, the negative C_{pk} results of indicative of a process operating outside of its tolerances. These variation spreads are plotted in Figure 16, and from this it can be see that the overall process is outside its tolerance. If original PROVADT had been used, the C_p and C_{pk} values would have only been calculated in two rather than three locations.

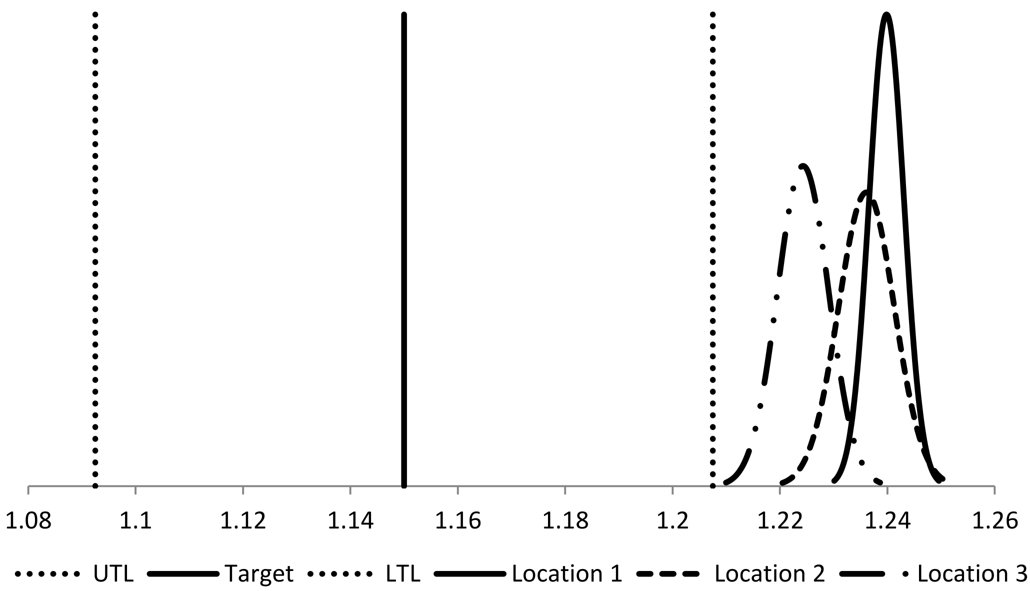


Figure 16: Process Capability for Coveris sample.

7.3.8 Overall Analysis Provided to Coveris

As a result of this overall analysis a single control parameter that affected the flow of plastic extruded was identified, enabling the re-centring of the process. Further action was taken to establish set-up protocols to ensure process operators adjusted this parameter so the process remained on target.

Further investigations were undertaken to identify and optimise parameters which effect the product-within-piece variation. These gains ultimately lead to Coveris minimising the quantity of plastic used to produce plastic reels, thus leading to financial savings, whilst also providing its customers with a more consistent product.

8 Conclusion

This paper has illustrated the application of an updated PROVADT sampling plan (Cox et al., 2013). The enhanced PROVADT approach addresses a compromise in the original method of not always providing a true Gage R&R. The benefits of incorporating a true Gage R&R enables the assessment of whether within-piece variation is caused by measurement variation or product variation. This new sampling procedure now allows a practitioner to apply a Multi-Vari chart, Isoplots, Gage R&R and provisional process capability study to one sample of outputs. From this, the signature of the dominant cause of variation is diagnosed and the scale of process variation is contextualised.

The enhanced PROVADT procedure narrows down the focus of a quality improvement project. It moves the project from the measure to analyse phase, in the DMAIC cycle, using passive experimentation, that does not disturb an on-going process, and narrows the focus using objective, data driven analysis.

The application of the approach has also been outlined, using both a worked example from a simulation and two real industrial case studies. The flexibility of the approach was demonstrated in the case studies, with one company producing radiators in a discrete process and the other producing extruded plastic in continuous batches. In both cases it was possible to measure within-piece in multiple locations, by identifying sufficient sample time periods to assess the process variation and capturing consecutive products. The follow-up analysis, in both cases, drove the projects forward significantly in the search for the dominant cause of variation in their processes.

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10 Appendices

A. CtQ outputs from manufacturing simulation, presented in original PROVADT format.

	Location 1	Location 2	Location 1	
Piece No.	Appraiser 1	Appraiser 1	Appraiser 2	Piece No.
1	20	30	20	1
2	58	87	54	2
3	36	45	35	3
4	76	52	78	4
5	17	47	18	5
6	43	68	49	6
7	58	94	55	7
8	77	96	78	8
9	22	56	24	9
10	43	21	43	10
11	60	77	58	11
12	78	34	77	12
13	22	72	22	13
14	47	75	44	14
15	43	17	44	15
16	90	63	90	16
17	20	33	23	17
18	35	65	38	18
19	47	63	46	19
20	70	45	74	20

B. CtQ outputs from manufacturing simulation, presented in enhanced PROVADT format.

Piece No.	Location 1				Location 2	Location 3	Piece No.
	Appraiser 1	Appraiser 1	Appraiser 2		Appraiser 1	Appraiser 1	
1	20	21	20		30	41	1
2	58	57	54				2
3	36	34	35		45	59	3
4	76	75	78				4
5	17	22	18		47	33	5
6	43	45	49				6
7	58	60	55		94	41	7
8	77	79	78				8
9	22	26	24		56	70	9
10	43	45	43				10
11	60	56	58		77	26	11
12	78	79	77				12
13	22	25	22		72	89	13
14	47	48	44				14
15	43	45	44		17	32	15
16	90	84	90				16
17	20	22	23		33	64	17
18	35	35	38				18
19	47	47	46		63	36	19
20	70	70	74				20

C. RT1 radiator height.

Piece No.	Location 1				Location 2	Location 3	Piece No.
	Appraiser 1	Appraiser 1	Appraiser 2		Appraiser 1	Appraiser 1	
1	448.06	448.14	448.16		447.91	448.04	1
2	447.79	447.84	447.89				2
3	447.98	447.93	448.25		448.01	448.02	3
4	448.01	448.05	448.06				4
5	448.25	448.3	448.32		447.79	448.56	5
6	448.43	448.42	448.6				6
7	448.21	448.39	448.25		448.43	448.58	7
8	448.18	448.2	448.37				8
9	447.63	447.7	447.68		448.18	448.18	9
10	448.17	448.2	448.18				10
11	447.66	447.72	447.6		448.21	448.25	11
12	448.19	448.16	448.24				12
13	447.64	447.58	448		448.12	448.73	13
14	448.16	448.14	448.38				14
15	448.09	448.12	448.3		448.17	448.44	15
16	448.27	448.49	448.39				16
17	448.43	448.39	448.65		448.44	448.62	17
18	448.35	448.55	448.36				18
19	448.49	448.48	448.42		448.31	448.54	19
20	448.34	448.5	448.79				20

D. RT1 seam depth

Piece No.	Location 1				Location 2	Location 3	Piece No.
	Appraiser 1	Appraiser 1	Appraiser 2		Appraiser 1	Appraiser 1	
1	10.96	11.54	10.88		10.78	10.92	1
2	11.3	11.44	10.64				2
3	11.24	11.58	11.2		11.7	10.94	3
4	11.5	11.26	11.28				4
5	11.02	11.22	11.04		10.44	10.98	5
6	11.96	12.04	11.72				6
7	10.8	11.06	10.52		11.4	10.62	7
8	11.96	11.2	11.32				8
9	10.54	10.2	10.48		11.3	10.98	9
10	11.18	11.56	11.24				10
11	10.54	10.4	10.46		10.08	10.96	11
12	10.94	11.22	11.26				12
13	10.94	10.92	11.18		10.7	11.16	13
14	11.52	11.48	11.54				14
15	11	11.08	10.98		10.58	11.04	15
16	11.7	11.64	11.68				16
17	12.32	12.22	12.46		12.42	12.22	17
18	11.7	11.08	12.14				18
19	11.9	11.82	11.92		12.34	11.84	19
20	11.04	11.22	11.28				20

E. RT2 radiator height.

Piece No.	Location 1				Location 2	Location 3	Piece No.
	Appraiser 1	Appraiser 1	Appraiser 2		Appraiser 1	Appraiser 1	
1	526.45	526.39	526.24		526.75	526.99	1
2	526.28	526.11	526.09				2
3	526.37	526.25	526.79		527.04	527.22	3
4	526.18	526.25	526.2				4
5	526.66	526.64	525.55		526.12	526.64	5
6	526.59	526.85	526.42				6
7	526.24	526.34	525.67		526.7	526.83	7
8	526.61	526.57	526.54				8
9	526.33	526.68	526.54		526.8	526.6	9
10	526.16	526.18	526.45				10
11	526.13	526.24	526.21		526.9	527.06	11
12	526.66	526.96	527.07				12
13	525.73	525.55	526.12		526.69	526.83	13
14	526.77	526.74	526.75				14
15	527.2	526.83	526.84		526.8	527.06	15
16	526.76	526.86	526.72				16
17	526.61	526.72	526.42		527	526.69	17
18	526.66	526.43	526.69				18
19	526.03	526.61	526.22		526.26	526.19	19
20	526.22	526.32	526.57				20

F. RT2 seam depth.

Piece No.	Location 1				Location 2	Location 3	Piece No.
	Appraiser 1	Appraiser 1	Appraiser 2		Appraiser 1	Appraiser 1	
1	10.34	10.6	10.94		10.96	10.76	1
2	10.68	10.42	10				2
3	10.34	10.36	10.16		10.78	10.64	3
4	9.7	9.82	9.36				4
5	9.66	10.2	9.54		10	9.54	5
6	10.52	10.46	10.64				6
7	9.44	9.24	9.58		9.92	9.56	7
8	9.96	9.7	10.68				8
9	10.22	9.78	10.3		10.02	10.22	9
10	9.38	9.2	9.34				10
11	10.38	10.72	9.42		9.78	9.92	11
12	10.28	9.94	9.66				12
13	8.78	8.7	8.78		9.84	9.76	13
14	10.02	9.24	9.72				14
15	10.32	10.3	10.14		10	10.18	15
16	9.84	9.5	9.82				16
17	9.46	9.88	9.32		10.34	9.62	17
18	10.36	10.02	10.36				18
19	9.54	10.02	10.36		10.58	10.24	19
20	10.38	10	9.92				20

G. Enhanced PROVADT results plastic gauge thickness.

Piece No.	Location 1				Location 2	Location 3	Piece No.
	Appraiser 1	Appraiser 1	Appraiser 2		Appraiser 1	Appraiser 1	
1	1.245	1.24	1.243		1.238	1.23	1
2	1.241	1.239	1.242				2
3	1.24	1.237	1.24		1.237	1.227	3
4	1.241	1.239	1.243				4
5	1.238	1.232	1.233		1.224	1.218	5
6	1.235	1.236	1.236				6
7	1.239	1.241	1.241		1.233	1.223	7
8	1.235	1.237	1.238				8
9	1.24	1.245	1.245		1.236	1.229	9
10	1.238	1.24	1.246				10
11	1.24	1.245	1.246		1.243	1.225	11
12	1.244	1.244	1.247				12
13	1.242	1.241	1.244		1.237	1.227	13
14	1.235	1.234	1.238				14
15	1.236	1.238	1.24		1.236	1.217	15
16	1.239	1.24	1.24				16
17	1.246	1.245	1.246		1.242	1.228	17
18	1.24	1.24	1.243				18
19	1.239	1.238	1.239		1.235	1.219	19
20	1.244	1.243	1.247				20