Measurement System Analysis Guideline

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CONSTRUCTION INNOVATION HUB

UK Research and Innovation

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Use of this Guide

The Measurement System Analysis (MSA) guideline is part of the Construction Product Quality Planning (CPQP) process and should be used in conjunction with the CPQP Guide and its toolset, published by the Construction Innovation Hub.

Intended as a guideline to aid the process of conducting an MSA study, this document provides the basic principles and a suggested methodology. The templates provided can be changed and modified to suit individual companies.

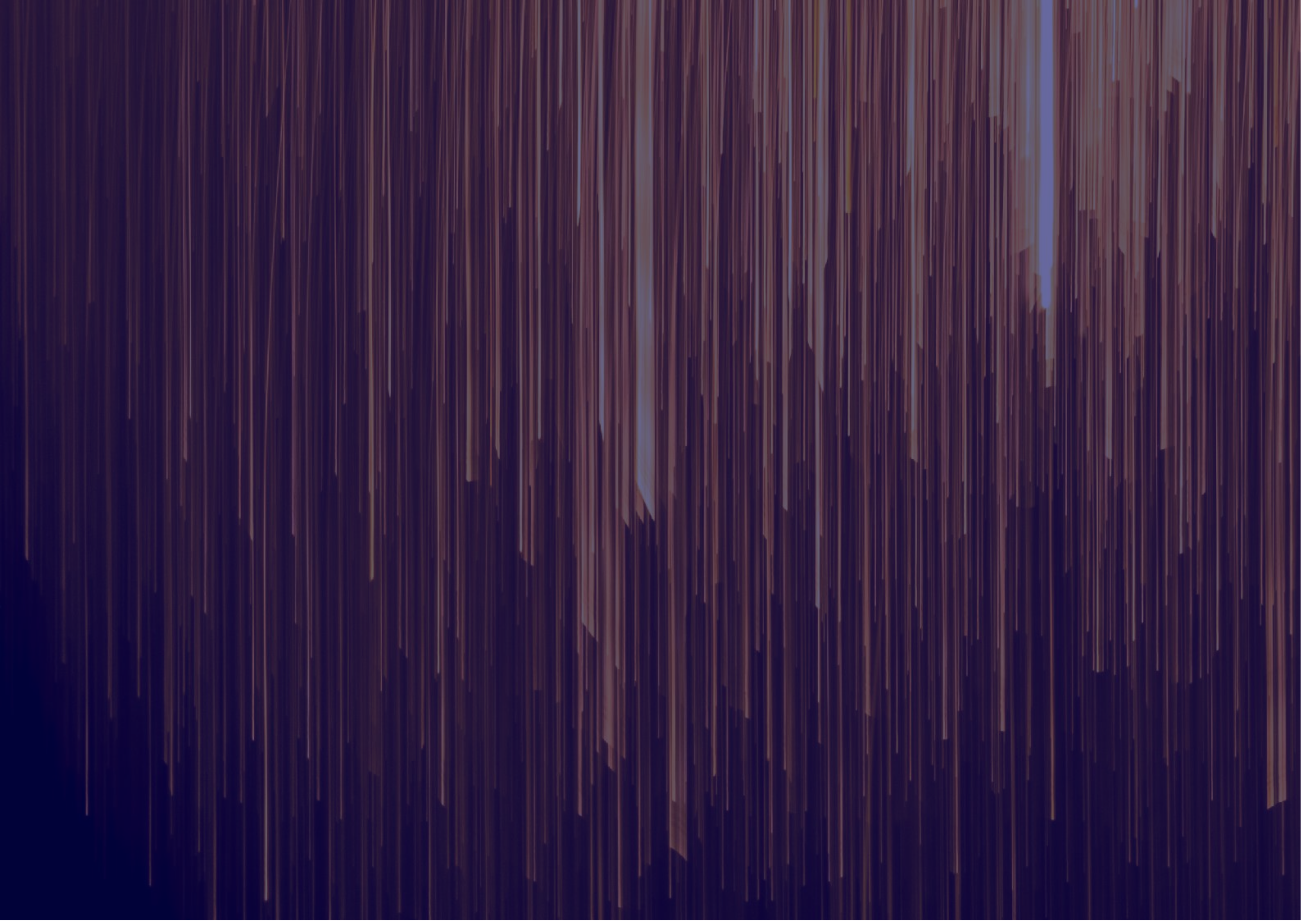
This guideline is intended for use by companies manufacturing offsite construction products largely using the CPQP process with their customers and suppliers. It aims to provide enough knowledge to enable the CPQP team to complete an MSA study, particularly where this subject is new to them,

as well as to provide ongoing aid. Over time, companies will develop their own expertise, methods and standards through training and practice.

For a list of the acronyms and abbreviations used in this document, refer to Appendix B – List of Abbreviations.

For the various terms used in this document, refer to Appendix C – Glossary of Terms.

For further information about the CPQP Guide and its toolset please contact:
cpqp@constructioninnovationhub.org.uk



Introduction

Introduction

Measurement System Analysis (MSA) is a tool used to identify and quantify the different components of variation within any given measurement system. Data collected through different sources can help guide decisions.

The greater the errors present within the measurement system, the less robust is the quality of the decision-making process. Factors such as the operator, part, location, environment, and the procedure itself can all directly introduce variation in the measurement process. The influence of all these factors is considered in an MSA study and is discussed in greater depth in the next sections.

Background

The definition of measurement systems finds its roots in ancient Egyptian times, using the ‘Royal Cubit’ to measure the length of the marble blocks to build the pyramids [1]. As building methodologies and technologies evolved, increasingly accurate measurements were required. It also became crucial to control the uncertainties and variations within the defined measurement systems.

Due to the well-known problems caused in the calculation of measurement uncertainty, the international Bureau of Weights and Measures decided in 1977 to develop an international agreement on the expression of measurement uncertainty and in 1995 the ISO Advisory Group on Metrology published the ‘Guide to expression of uncertainty in measurement’ (GUM) [2]. However, prior to this, different automotive and manufacturing companies (such as Ford and Bosch) had published their own corporate guidelines for the evaluation of measurement systems. In the same year as GUM, the Automotive Industry Action Group (AIAG) launched the MSA guide as a reference manual to QS9000 (set of Automotive Quality Standards) [2]. Since then, many updated versions of the MSA guide from AIAG have been released with the aim of standardisation, but they did not succeed in replacing corporate guidelines [2].

This highlights the need for manufacturing driven industries to adopt and implement the MSA methodology. The ability to address measurement uncertainty and variations will significantly contribute to the successful development and introduction of a new product.

Purpose

The purpose of an MSA study is to comprehensively validate the data quality of a measurement system (consisting of the gauge, procedure, environment and operator) and assess the capability, performance and likely areas of uncertainty for a given measurement system. MSA uses experimental and mathematical methodologies to determine the amount of variation that exists within a measurement system.

Benefits

The MSA is at the core of any decision-making process based on quantitative data. It ensures that the data captured to describe features or performance of a process or product is accurate, precise, and conforms to a set of criteria predefined to reflect customer’s requirements.

Achieving robust data quality through the MSA implementation will lead to the following benefits:

- **Time, labour and cost savings:**
  Dealing with product recalls from customers' reporting non-conforming or defective products has a direct impact on time and labour, which automatically leads into increased production costs. Implementing the MSA methodology directly contributes to the reduction of product recalls;

- **Increased customer satisfaction:**
  An effective MSA study allows for bad parts to be rejected before they are handed over to the customer, resulting in increased customer satisfaction; and

- **Reduced waste:**
  Through accurate, reliable, and appropriate measurement of data, it is possible to identify non-conformance issues and adopt corrective actions, reducing, in this way, the production waste related to non-conforming parts.

How Does MSA Fit in with Construction Product Quality Planning?

The Construction Product Quality Planning (CPQP) process supports the development of new products for manufacturing led-construction approaches. The process covers the entire product development cycle, from concept design through to product launch. The Construction Product Quality Planning (CPQP) process has been broken down into five phases as shown in Figure 1. The MSA Plan is initiated in the third phase (Process Design and Development) and it shows how the CPQP team aims to have capable gauges for measurement prior to final checks being carried out on the shop floor for production parts. The validation of the plan is then performed in the fourth phase (Product and Process Validation) by assessing the data recorded in the gauge report. The MSA validation constitutes the fifth main pillar that enables a successful implementation of the CPQP process.

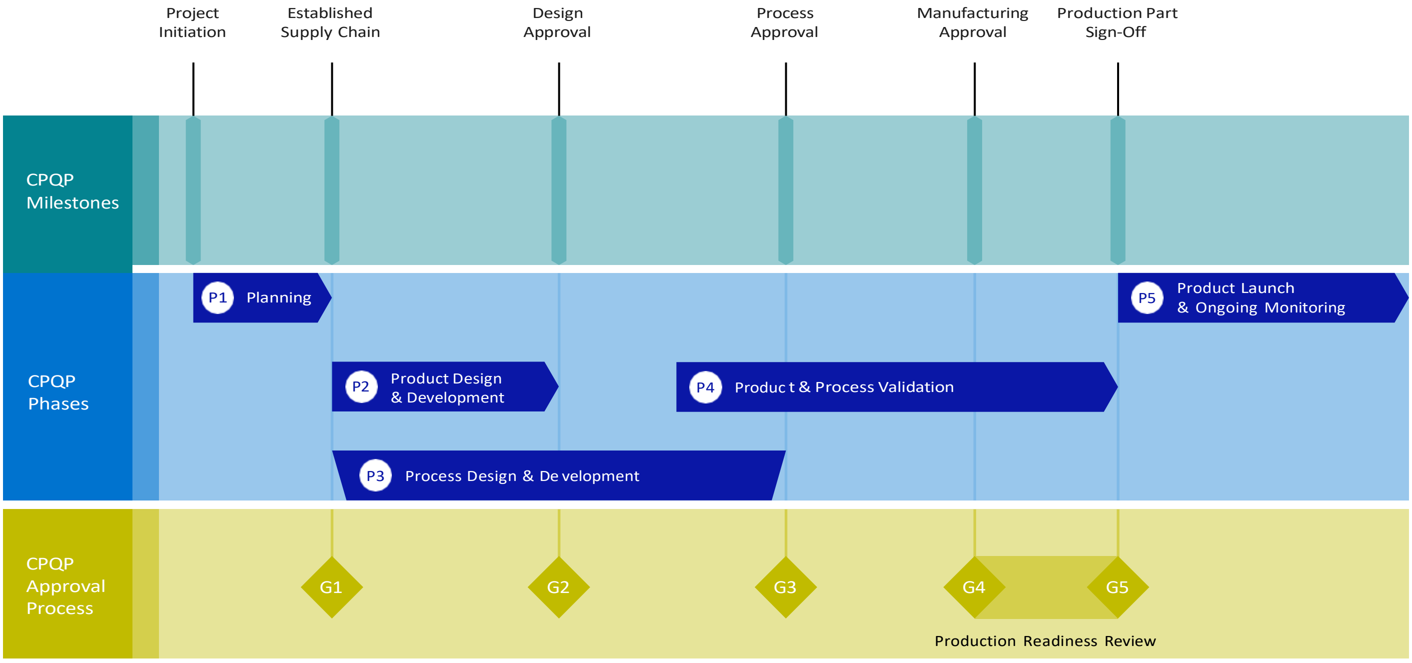


Figure 1. Construction Product Quality Planning (CPQP) Process

Team Approach

The advanced planning method in the CPQP process is built upon a team-based approach. Similarly, the effective use of the MSA methodology requires the engagement and participation of the cross-functional team. The team composition will vary by organisation and the needs of the product. However, the team should include members from a variety of disciplines with relevant knowledge and experience (i.e. design engineering, process engineering, manufacturing engineering, and quality). It should also include either an external customer representative or an internal party who represents the customer.

Statistical Terminologies Definition

Data variation can be divided into further sub-components by grouping them into the source or nature of the observed variation. These sub-groups are known as variance components and they assess the amount of variation observed as a result of various random factors. Some key statistical terminologies are fundamental to the Analysis of Variance (ANOVA) and are defined below.

Repeatability

The variation observed when the same operator measures the same part repeatedly using the same gauge, under the same conditions. This is also referred to as the Equipment Variation (EV).

Reproducibility

The variation observed when different operators measure the same part with the same gauge, in a stable environment. This is also referred to as the Appraiser Variation (AV).

Part-to-Part Variation

Part-to-Part Variation (PV) is the difference between individual parts produced by the same process. For example, if a sensor is used to measure the temperature of different rooms, the Part-to-Part Variation is the inherent variation between the different rooms, e.g., room size, location, number of radiators, etc.

A good MSA study has large Part-to-Part Variation (PV) as a percentage of the Total Variation (TV) or the total tolerance. This assures that the study was carried out well by considering a large portfolio of varying parts.

Number of Distinct Categories

The Number of Distinct Categories (NDC) represents the number of different groups of parts within the experimental data that the measurement system can distinguish between.

Measurement System Analysis is well established in the automotive and aerospace sectors. According to the Automotive Industry Action Group (AIAG) [3], if:

NDC > 5 a. Measurement system can distinguish between parts well. Thus, continue with study.

NDC < 5 b. Measurement system cannot sufficiently distinguish between parts. Thus, study needs to start over and should include more parts that span across the full specification limits.

Gauge Repeatability & Reproducibility

Gauge Repeatability and Reproducibility (R&R) measures the amount of variation in the measurement system arising from the measurement device itself (EV) and the operators taking the measurement (AV). It should be noted that gauge R&R does not measure the quality of the parts, but the quality of the measurement system. Figure 2 visually depicts the relation between gauge R&R, the Equipment (EV) and Appraiser Variations (AV).

Total Variation

Total Variation (TV) is simply the entire variation that is inherent within a measurement system by taking the gauge R&R and Part-to-Part Variation (PV) into consideration. During the analysis of variation, TV is used to evaluate the capability of a measurement system when compared to customer tolerance limits or the gauge R&R. Figure 2 below shows a diagram, which visually depicts gauge R&R, Part Variation (PV) and Total Variation (TV).

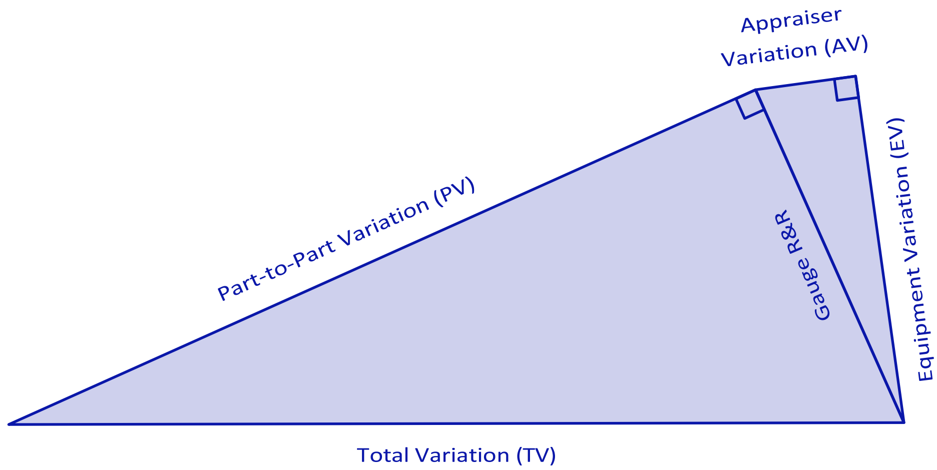
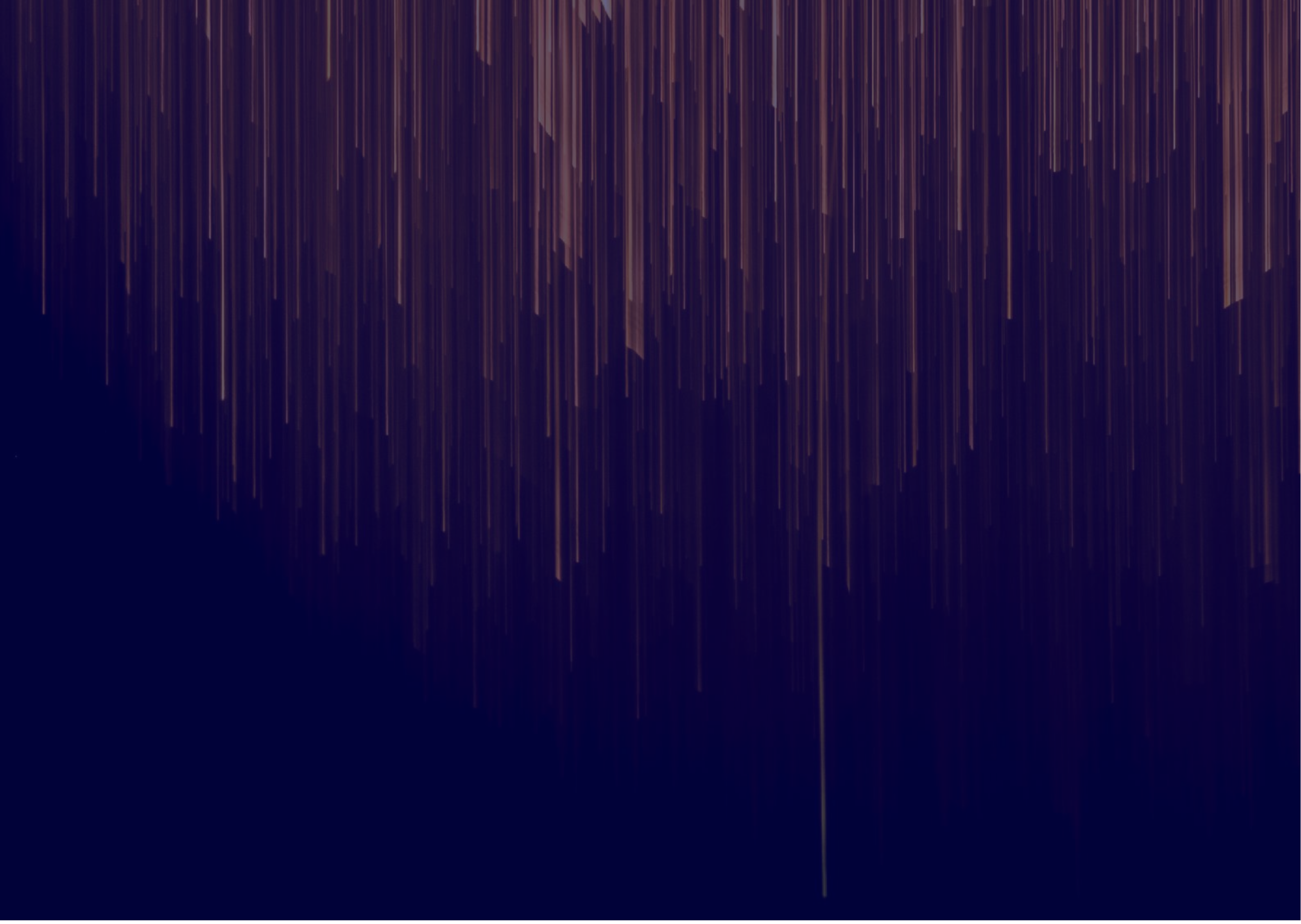


Figure 2. Visual representation of relationship between Gauge R&R, PV and TV



Methodology

Methodology

A properly conducted MSA study can contribute to identifying areas for improvement within a measurement system. These include key variance components such as repeatability, reproducibility, resolution, bias and precision.

Measurement system analysis studies fall into two categories: variable and attribute studies. Each category requires the measurement of a specific set of data prior to the MSA analysis. The type of analysis depends on both the type of data and the objective of the analysis. Figure 3 shows a process flow chart specifying the most relevant MSA studies for the offsite manufacturing industry in relation to the data types (variable and attribute).

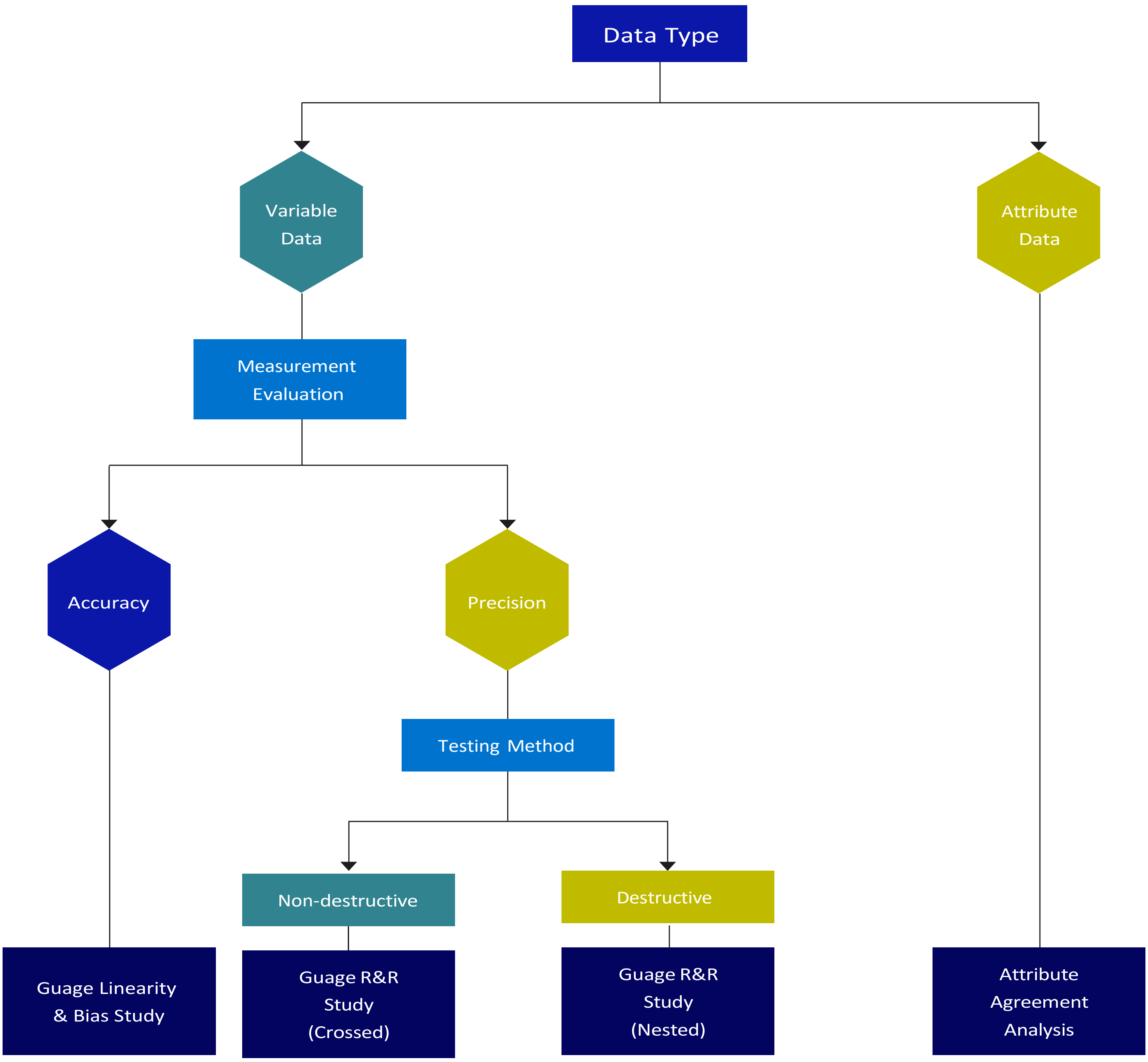


Figure 3. Process flow chart with key inputs and outputs when carrying out the MSA study

The sections below outline the type of data and the most relevant studies for each of the categories, as per process flow in Figure 3.

Variable Data and Study

Variable data are quantitative data that can be measured or counted and are acquired through taking measurements. Construction-related examples may include the thickness of a structural insulated panel, the time taken during the installation of a module, or the temperature of a volumetric pod. Variable data are essentially data that can be measured to get a value that could differ from one sample to another.

The two main studies, relevant for the offsite construction industry relate to the assessment of accuracy and precision. However, it is important to note that the studies should not be limited to these if additional assessments are required, such as stability, resolution, or tolerance.

Accuracy/Bias Study

Accuracy represents the difference between the target value and the average value obtained from the measurement system, or in other words, the closeness to a defined target [4]. The accuracy/bias assessment is a relatively quick and simple check that consists of calculating the difference between the observed average value from measurements and the predefined reference value, as shown in Figure 4.

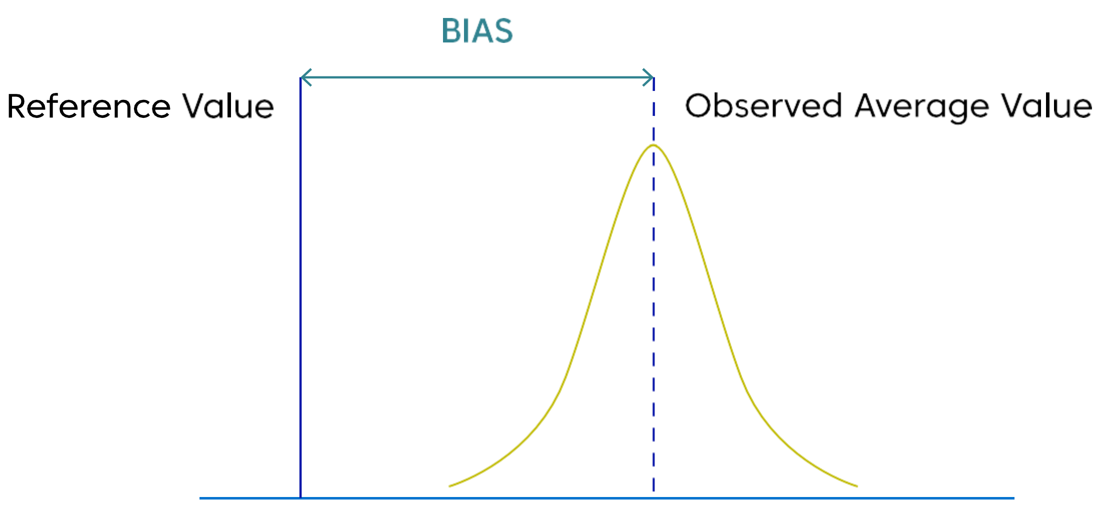


Figure 4. Accuracy/Bias definition

Gauge Linearity Study

This assessment falls within the overall accuracy assessment as it evaluates the bias values throughout the expected operating range of a measurement device. In a construction-related example, this assessment would evaluate the bias of the device used to measure the thickness of a structural insulated panel throughout its operating range, e.g. 0-300mm. The gauge bias could potentially be smaller when measuring 50mm thick panels than when measuring 200mm thick panels (Figure 5). The assessment is carried out by evaluating the bias at the different operating conditions.

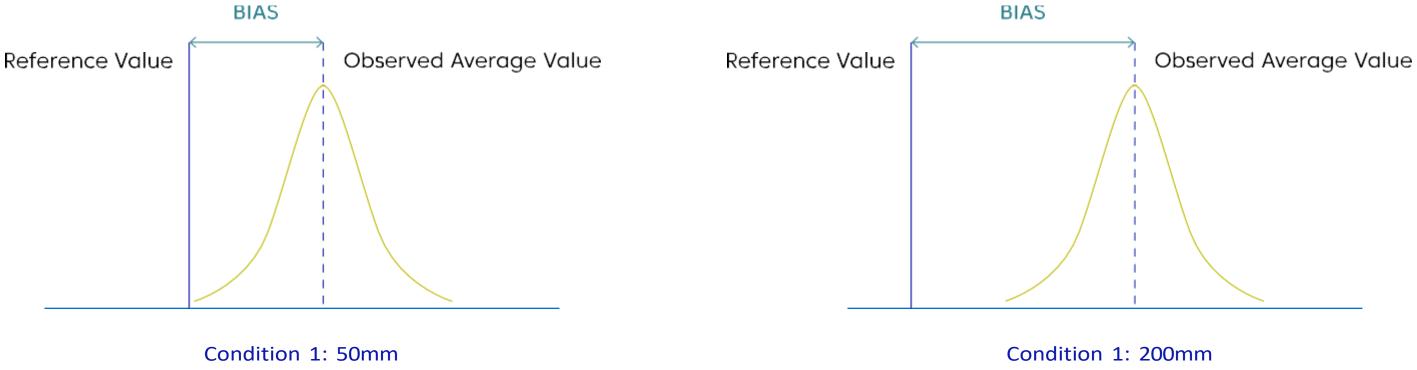


Figure 5. Gauge Linearity Assessment for 2 operating conditions

Gauge R&R Study

This assessment is normally carried out at the next stage after completing the bias and gauge linearity studies [6]. It allows for a deeper understanding of the variation in the measurement system due to the device itself (EV) and the operators taking the measurement (AV). As highlighted in the Statistical Terminologies Definition section, gauge R&R does not measure the quality of parts, but the quality of the measurement system.

The type of gauge R&R study depends on the testing method being performed. In the case of destructive tests, in which each physical part can be measured once, as they are destroyed or altered by the measurement or test, a gauge R&R (nested) study can be performed where the parts are nested within the operator. In the case of non-destructive tests, a gauge R&R (crossed) study can be performed as the parts are not destroyed or altered during the measurement process. It is important to highlight that crossed studies can be performed also for destructive tests, but only when it is possible to obtain similar parts is it possible to consider them to be the same part; care should be taken to ensure that this homogeneity assumption is valid [6]. Figure 6 shows the difference between nested and crossed studies.

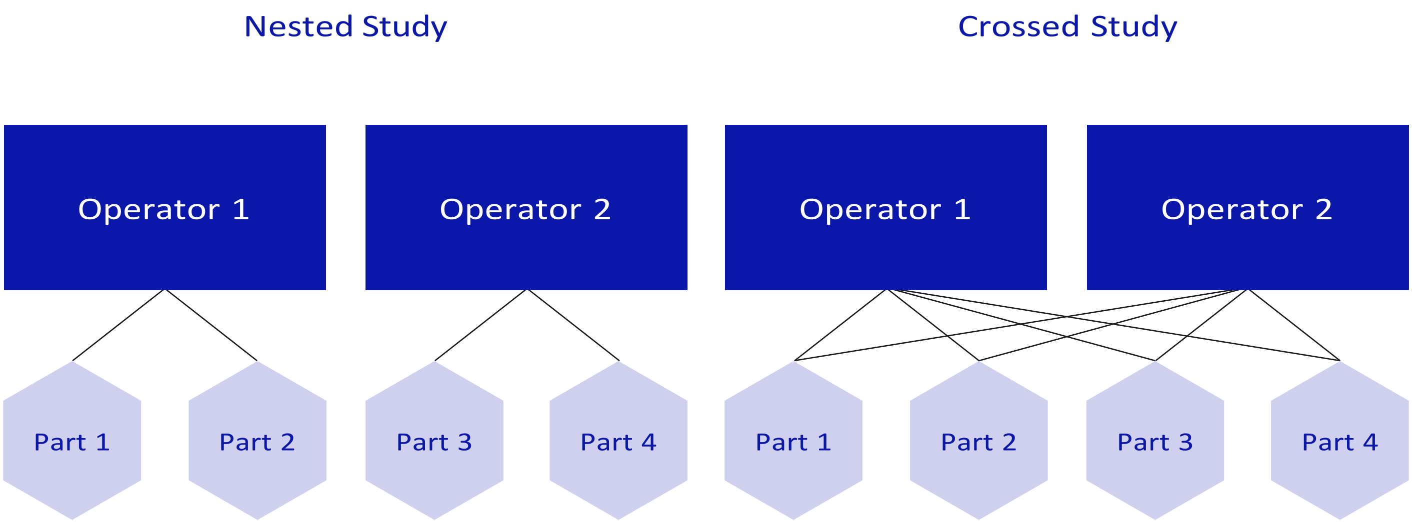


Figure 6. Nested vs Crossed Study

The goal of the gauge R&R study is to determine whether the measurement system is poor or acceptable. Figure 7 and Figure 8 below visualise how the measurement system can be deemed as poor/acceptable depending upon the gauge R&R as a percentage of the total variation.

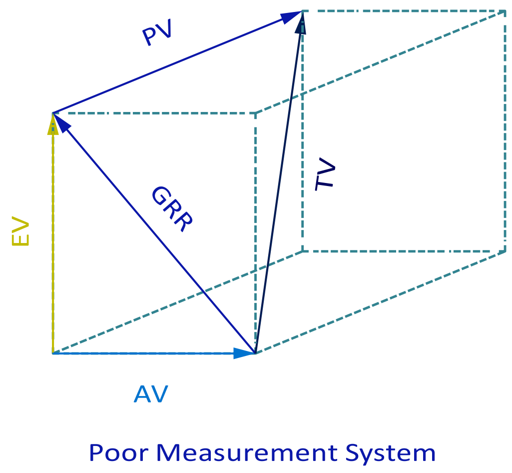


Figure 7. Visual representation of a poor measurement system

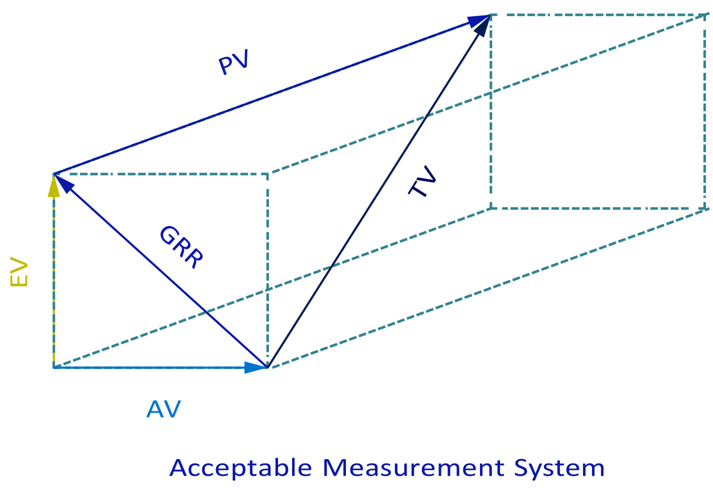


Figure 8. Visual representation of an acceptable measurement system

Figure 7 represents a poor measurement system with a large cross-sectional face (gauge R&R) and a short length (PV). This means that the measurement system contributes a large amount of variation to the total variation present in the system and only a small amount of variation is introduced by the different parts used in the study.

On the other hand, Figure 8 represents an acceptable measurement system relative to Figure 7 as it has a smaller cross-sectional face (therefore smaller gauge R&R) and a longer length for the cuboid (hence greater part variation). This implies that the measurement system only contributes a small fraction of the total variation observed in the MSA study and most of the variation is introduced by the differences in parts being measured. This is required for an acceptable measurement system as it shows that the measurement system (including the operator and equipment) is suitable to check a large portfolio of components without introducing either repeatability or reproducibility errors in the study.

According to the AIAG [7], the validity of a measurement system is generally defined as follows:

- *gauge R&R < 10%:* The measurement system is acceptable.
- *10% < gauge R&R < 30%:* The measurement system is acceptable depending on the application, the cost of the gauge, the cost of repairs or other factors. This percentage may vary for construction products depending on classification, i.e., critical or significant product (refer to CPQP Guide) [8].
- *gauge R&R > 30%:* The measurement system is unacceptable and requires improvement.

Attribute Data and Study

Attribute data are data with an associated quality characteristic, associated with it and which can often be evaluated as pass/fail or can be compared with visual references. For example, in construction it could be the assessment made by an inspector whether the colour of a wall matches with the customer's template. Attribute data simply classifies whether the attribute meets or fails to meet product specifications.

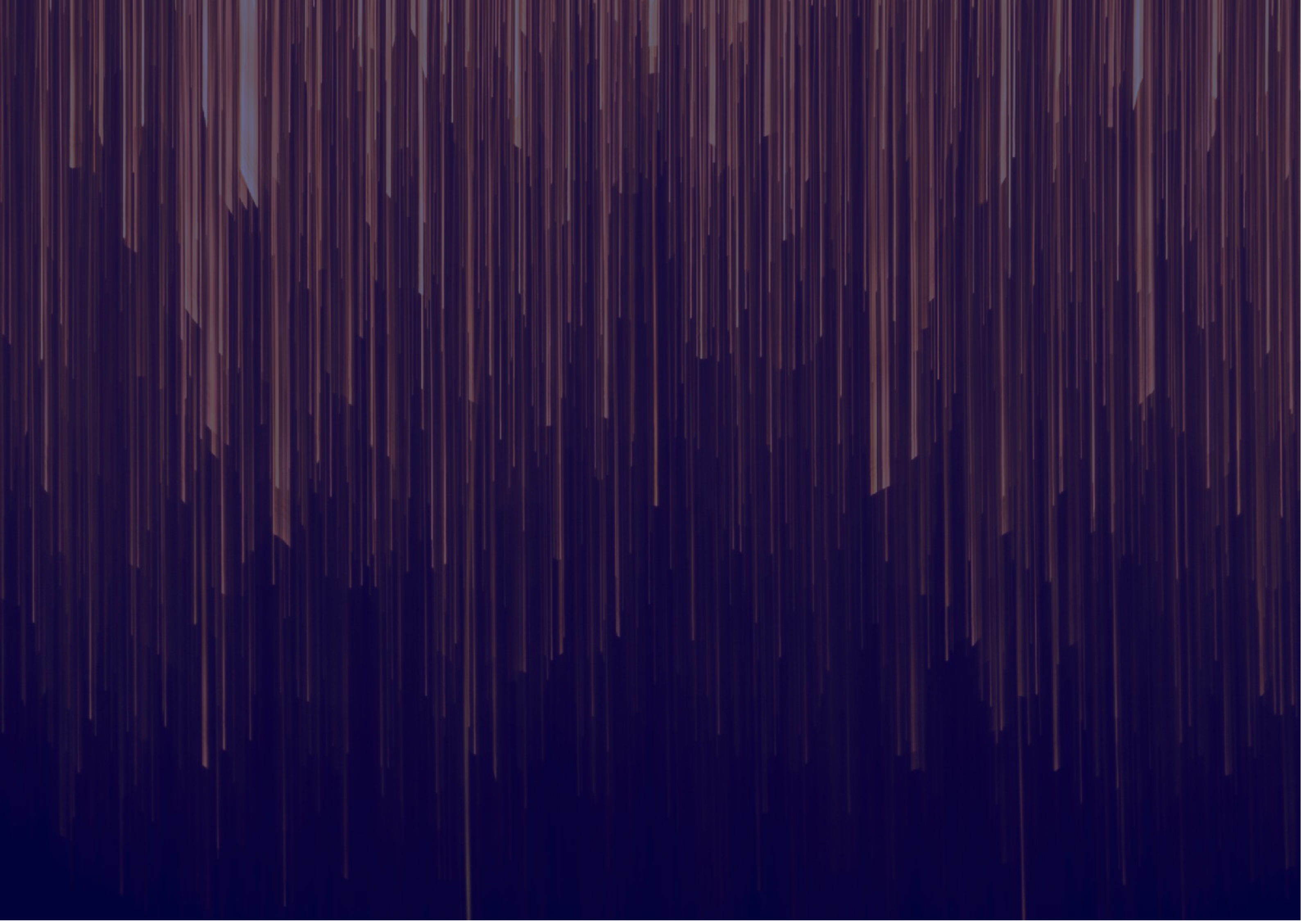
In order to assess how well inspectors are in agreement within their own inspections (repeatability) and with each other (reproducibility), the Kappa Statistic value is introduced [9]. The kappa value summarises the level of agreement between inspectors after agreement by chance has been removed, and it is calculated as follows:

$$K = \frac{P_{observed} - P_{chance}}{1 - P_{chance}}$$

where:

$P_{observed}$ is the portion of units classified in for which the inspectors are in agreement.

P_{chance} is the portion of units for which one would expect agreement by chance.



Guideline

Guideline

The purpose of Measurement System Analysis (MSA) is to objectively assess the validity of a measurement system and minimise the factors contributing to process variation that are caused by the measurement system itself. Table 1 below lists the key considerations to take into account before starting an MSA study.

Do	Avoid
Conduct the study in the current state that the measurements are recorded under, in order to acquire feedback for present processes.	Avoid artificially creating 'golden samples' under optimum laboratory conditions.
Conduct the study under current standard operating procedures; operators should not be briefed to measure parts any differently.	Operators should not measure parts with all repeats in quick succession. Instead it must be in a randomised sequence.
Collect samples from the process that spans the entire specification range. Consider parts outside of the specification limits.	Do not conduct the study with only highly skilled operators. Ensure regular operators are included who differ in terms of experience and skill levels.
Ensure samples have been measured by an independent body outside of the laboratory as these measurements will serve as a reference.	Avoid giving operators any biased assumptions. This can be ensured through a blind sample technique.

Table 1. Key applicable and non-applicable factors to consider during an MSA study

Data Collection Process

The first and fundamental step for the assessment of a measurement study is Data Collection. For any MSA study to be valid and reliable, it requires a statistically acceptable number of repeats per operator. Table 2 below shows the minimum number of repeats required when the number of parts and operators differ. As an example, a minimum acceptable number of parts/scenarios is 10 when working with three different operators taking three measurements each at random [10]. Changing the number of repeated measurements or number of people used in the study will either increase or decrease the minimum number of parts/scenarios required, as shown in Table 2.

		Number of Parts/Scenarios								
		2	3	4	5	6	7	8	9	10
Number of Operators	2	21	11	8	6	5	5	4	4	3
	3	11	6	5	4	3	3	3	3	3
	4	8	5	4	3	3	3	3	3	3
	5	6	4	3	3	3	3	3	3	3
	6	5	3	3	3	3	3	3	3	3

Table 2. Minimum number of repeats for a statistically acceptable MSA study (attribute or variable)

For the purpose of this guideline, the combination of 10 parts and three operators is considered. The data collection process for a crossed study is carried out as follows:

1. Create a list of all the different parts to be considered in the study. The parts need to range the full span of the operating conditions, taking environmental conditions into account (10 different parts/scenarios are considered).

2. Select three random operators, who regularly perform inspection of those parts. The operators need to range from high, medium to low with regards to experience and skill levels.

3. Select a random part to be measured. This step is performed by the moderator.

4. Define a template form or an appropriate means to collect the data. The moderator must ensure that all operators are under the same working conditions.

5. Select, in a randomised manner, the first operator. This step is performed by the moderator.

6. Start measurement by the operator, following their normal procedure.

7. Record measurement values on template form or the recording system previously defined. This step is performed by the moderator.

8. Randomly select the next operators, for example, operator 1, 2 and 3, and repeat step 6. The respective measurement reading is recorded by the moderator, as per step 7.

9. Repeat steps 5 to 8 for all three operators, with 3 repeats each, in a randomised order.

10. Repeat steps 3-9 for all the remaining nine parts (total 10 parts).

Variable Study

Variable data are those that have a value which differs from one sample to another. An example of this would be the weight of a baby, length of a table or the time taken to run a marathon. Measurement devices or gauges that are used to collect variable continuous data use gauge repeatability and reproducibility (gauge R&R) to evaluate the amount of inherent variation within a measurement system. To conduct a gauge R&R variable study, perform the following steps:

1. Select the gauge to be evaluated;
2. Obtain a minimum of 10 random parts that have been manufactured during a regular production run. Ensure they span the customer specification limits, including some undersize and oversize non-conforming products;
3. Obtain reference values by measuring parts through an independent body;
4. Select three random operators who regularly perform the inspection to measure the parts;
5. Perform a minimum of 3 measurements on each part per operator, using the same gauge. Use the steps defined in Data Collection Process as reference; and
6. Input data into statistical software to determine the amount of variation within the measurement system (gauge R&R), the part variation and the total variation. Results are visualised in a graphical format and the system is sentenced as poor or acceptable.

It should be noted that:

- Before interpreting the gauge R&R results, the repeatability and reproducibility components should be assessed. Hence:
  - A large repeatability error indicates an issue with the gauge used in the study and as a result the gauge may need to be replaced or recalibrated;
  - A large reproducibility error indicates that the variation is introduced through the operator and consequently, the operator may require further training or may require the implementation of a poka-yoke methodology to assist them in the use of the gauge;
- The study is only conducted when a new or different measurement system is introduced into any measurement process; and
- The study is conducted following any improvements or changes that have been made to a current measurement system. Individuals and operators carrying out measurements are considered part of the measurement systems, so it is sensible to update the MSA studies at 6-12 month intervals to account for staff rotation.

Attribute Study

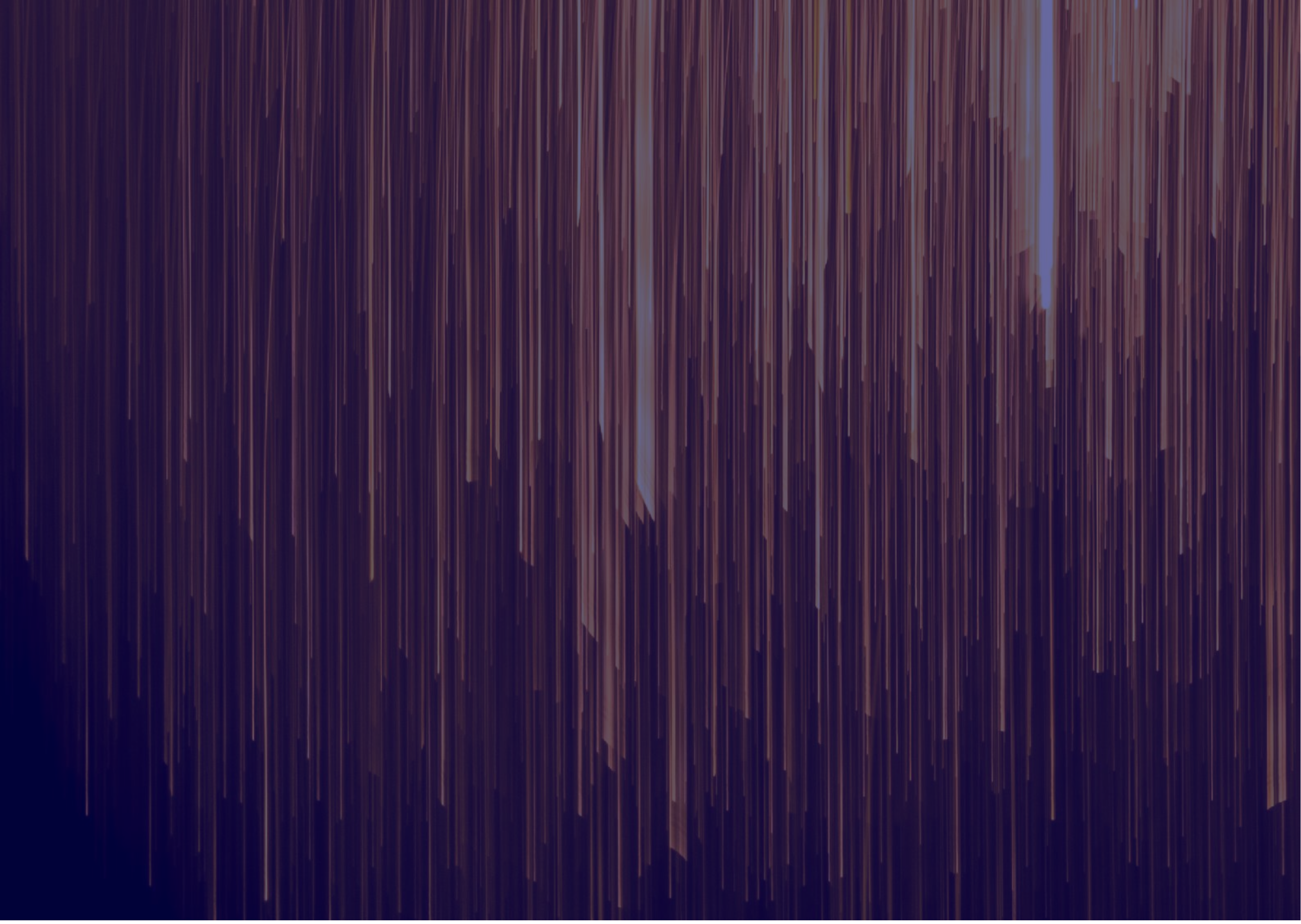
Attribute data are qualitative data that have quality characteristics (or attributes) that distinctly meet or fail to meet product specification. An example of attribute data could be the number of non-conforming parts produced per million or the final inspection comparing the colour of a façade with a template provided by the customer. These characteristics can be counted and put into categories, and are often evaluated as either pass/fail or go/no go. There are only two possible outcomes per measurement.

Measurement system variation of an attribute gauge can be conducted as follows:

1. Select the attribute gauge to be evaluated;
2. Obtain a minimum of 10 random parts that have been manufactured during a regular production run;
3. Select three random operators who regularly perform the inspection;
4. Perform the measurement process a minimum of three times with each operator, using the same gauge on the same part. Use the steps defined in Data Collection Process as reference; and
5. Input data into statistical software or the available MSA spreadsheet which calculates the kappa value.

It should be noted that:

- A kappa study evaluates consistency of agreement of the operators themselves (within appraiser agreement), degree of agreement between different operators (inter-appraiser agreement) or agreement with a reference (standard) provided by an expert.
- The higher the kappa value, the stronger the degree of agreement:
  - Kappa = 1 — Perfect agreement exists
  - Kappa = 0.60 – 0.80 — Good agreement
  - Kappa = 0.20 – 0.40 — Fair agreement
  - Kappa < 0.20 — Poor agreement
  - Kappa < 0 — Weaker agreement than expected by chance, but this is rare
- An attribute gauge will simply indicate whether a part is within a specification limit or not. It does not specify the location of the part with respect to the nominal value.



Worked Example

Worked example

The following worked example shows the application of Measurement System Analysis (MSA) for assessing the quality of temperature readings of 10 different rooms of a residential building.

The variation in temperature measurements is investigated using a single temperature sensor. An MSA variable study is conducted to evaluate how accurately the temperature of 10 different rooms is measured by three operators taking three repeat measurements each. A process tolerance of 2˚C (±1˚C) is considered as a customer’s requirement.

By the end of the study, the main sources of variation are identified (Equipment, Appraiser and Part-to-Part). The accuracy, precision, and stability are quantified.

The example should not be regarded as a complete and comprehensive case study, but it aims to illustrate the process for conducting an MSA study in a simple manner.

Variable Study

Using the steps defined in the Guideline - Variable Study section, the following is performed:

1. For the purpose of this application, a wireless sensor that detects motion and monitors temperature is selected. The operating ranges and associated accuracy provided by the manufacturer are as follows:

Operating Range	Accuracy
+5˚C to +15˚C	±2˚C
+15˚C to +30˚C	±1˚C
+30˚C to +50˚C	±1˚C

2. A list of 10 vacant locations (Table 3) is made, considering a wide variety of environmental factors such as location, building type, room size, room occupancy, and ease of hub connectivity.

Part Number	1	2	3	4	5	6	7	8	9	10
Location Name	Bedroom 1	Living Room	Master Bedroom 1	Study Room	Kitchen	Small bedroom	Bathroom	Gym	Master bedroom 2	Dining Room

Table 3. Location list of each part referenced in the study

3. For each of the 10 locations, the moderator places both the reference sensor and the temperature sensor for 5 minutes to acclimatise. The reference temperature is recorded for each location.

4. Three random operators, who regularly perform the temperature measurements, are selected by the moderator.

5. The data collection process is performed as follows:

    a. A data template (Table 4) is created and used to input the measurement readings and a software is selected to analyse the variance of components;

    b. Moderator randomly selects the first operator to take the measurement;

    c. Operator goes to location 1 and switches on the temperature sensor for 90 seconds (timing him/herself), then switches it off;

    d. Moderator discretely records the temperature reading of the sensor from the live cloud and reset it. This ensures that the operator's future measurements are not influenced by previous measurements made;

    e. Next operator is called upon randomly and step f is repeated. Moderator records their temperature reading as per step d;

    f. Steps c-e are performed for all three operators, with three repeats each, in a randomised order; and

    g. Steps b-f are carried out for all the nine remaining locations (total 10 locations).

6. Experimental data are inputted onto the statistical software. The results are shown and discussed in the Results Analysis section.

Experimental Data

Table 4 below shows all 90 experimental measurements collected by the moderator with $\overline{x}$ denoting the average reading of each part by each operator.

Operator \ Part	1	2	3	4	5	6	7	8	9	10
1	17.4	16.6	20.9	24.7	22.5	23.7	21.7	24.8	25.1	24.8
	16.9	17.1	21.5	25.1	22.9	24.0	21.8	25.2	25.3	25.2
	16.2	17.4	21.7	25.1	23.1	23.7	21.5	26.4	25.8	25.8
$\overline{x}$ / °C	16.8	16.9	21.3	24.9	22.8	23.8	21.6	25.4	25.4	25.2
2	17.4	16.6	20.2	24.7	22.8	23.4	21.6	25.3	24.9	24.8
	16.7	17.3	21.1	25.1	23.0	23.7	21.7	26.1	25.1	25.2
	16.3	17.6	21.6	25.2	23.1	23.9	21.7	26.9	25.6	26.1
$\overline{x}$ / °C	16.8	17.1	20.9	25.0	22.9	23.6	21.6	26.1	25.2	25.3
3	17.4	17.0	20.7	24.5	22.9	23.5	21.9	25.0	25.1	24.6
	16.9	17.6	21.3	24.8	23.1	24.0	21.4	25.7	25.4	25.1
	16.4	17.7	21.7	25.0	23.3	23.8	22.0	26.7	26.1	25.2
$\overline{x}$ / °C	16.9	16.4	21.2	24.7	23.1	23.7	21.7	25.8	25.5	24.9

Table 4. Experimental data collected from 10 different locations

Results Analysis

From the experimental results obtained in Table 4, a crossed gauge R&R study is performed. The different variance components and standard deviations are computed through the use of the selected statistical software as shown in Table 5. The results obtained are assessed in terms of:

- % Contribution (VarComp) and % Study Variance (%SV): These statistics help to identify the amount of variation attributed from each source relative to the total variation. The data acknowledges the measurement systems level of acceptability and identifies whether the variance is largely due to operator, gauge or part [11]. The acceptance criteria differs between the two and for the purpose of this worked example, these are defined as follows:

$$Total\ GaugeR\&R\ \%Contribution < 10\%$$

or

$$Total\ GaugeR\&R\ \%StudyVar < 30\%$$

The results shown in Table 5 are computed following the equations below:

$$\%Contribution = \frac{VarComp}{TotalVariation}$$

$$Source\ StdDev\ (SD) = \sqrt{VarComp}$$

$$Source\ Study\ Var\ (SV) = SourceSD * 6$$

$$\%Study\ Var(\%SV) = \frac{Source\ SV}{Total\ Variation\ SV}$$

- % Tolerance: This value represents the percentage variation attributable to each source as compared to the specified process tolerance. This analysis is fundamental to understand whether the measurement system is capable of detecting non-conforming parts [11] and is computed as follows:

$$\%Tolerance = \frac{Source\ SV}{Process\ tolerance}$$

An acceptable gauge R&R %Tolerance would be 30% or below according to AIAG [3].

Source	VarComp	%Contribution (of VarComp)	StdDev (SD)	Study Var (SV)	%Study Var (%SV)	%Tolerance (SV/Tolerance)
Total Gauge R&R	0.1874	1.72%	0.4329	2.5974	13.13%	129.87%
Repeatability	0.1874	1.72%	0.4329	2.5974	13.13%	129.87%
Reproductibility	0	0%	0%	0%	0%	0.00%
Part-to-Part	10.6775	98.28%	3.2676	19.6059	99.13%	980.29%
Total Variation	10.8648	100.00%	3.2962	19.7771	100.00%	988.85%

Process tolerance = 2　　Number of distinct categories (NDC) = 10

Table 5. Gauge R&R Variance Results

%Contribution and %Study Variance Assessment

- Gauge R&R %Contribution is 1.72%
  and comes entirely from repeatability error (EV). No reproducibility error (AV) is observed and this means that no variation is introduced through the 3 operators. This value is also within the acceptable limit of 10%.

- Part-to-Part %Contribution is 98.28%
  This positively reflects on the study as it shows that the measurement system is highly capable of distinguishing between parts, or in this case, discern the temperatures of different locations.

%Tolerance Assessment

- Gauge R&R %Tolerance is 129.87%
  This means that the sensor will have a variation of ±2.6°C (129.87% of 2°C is ±2.6°C) when measuring the temperature of any location. As an example, if the temperature of part 1 (Bedroom 1) was measured to be 24°C, due to this variation, the actual room temperature could be anywhere between 21.4°C and 26.6°C. This would not meet the customers requirement of ±1°C and therefore the sensor cannot be validated for this particular use as the variation from the gauge is too large.

- An acceptable Gauge R&R %Tolerance would be 30% or below according to AIAG [3]
  Thus, for a process tolerance of (2°C), the maximum variation of temperature measurements would be ±0.67°C (30% of 2°C), which is an acceptable amount of error for the intended use of the gauge.

Number of Distinct Categories (NDC) Assessment

- The number of distinct categories (NDC) is 10
  so we can conclude that the measurement system can distinguish between different groups of parts very well. The AIAG recommends an acceptable system to have an NDC of 5 or more.

Graphical Analysis

As part of the Gauge R&R study, graphical analysis charts are produced aiming at validating the findings and obtain additional insights regarding the data. It is important to emphasise that the graphs plotted illustrate the effectiveness of the measurement system, and not the manufacturing process.

Components of Variation

Figure 9 shows that the majority of the variation comes from the Part-to-Part component in comparison to the gauge R&R. As a result, the gauge is able to distinguish that most of the variation comes from the varying temperatures observed between the 10 different locations. It is also clear that there is a small contribution to the Total Variation due to repeatability error (EV) and no variation as a result of reproducibility error (AV).

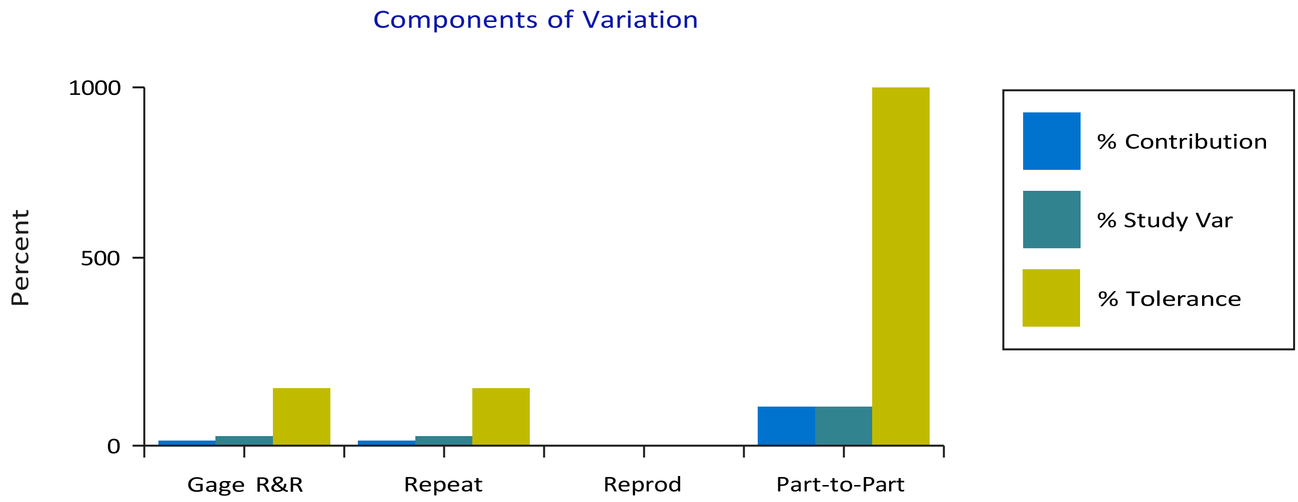


Figure 9. Variation arising from each variance component

Temperature by Room

Figure 10 shows the 'Temperature by Room' plot for all 90 measurements across the 10 locations. Most data points (in Hub lime) are close to the average (blue circle) which indicates small temperature variation within each room and therefore small variation between the different appraisers. This also validates the finding that there was no reproducibility error (AV).

Part 8 (Gym) shows the largest variation in temperature readings with a range of 2.1°C. In contrast, parts 4, 6 and 7 displayed the smallest temperature variation of 0.6°C.

It is also clear that a good selection of parts with a varying range of average temperatures was chosen, hence further supporting the high Part-to-Part Variation (98.28%) as a percentage of the Total Variation.

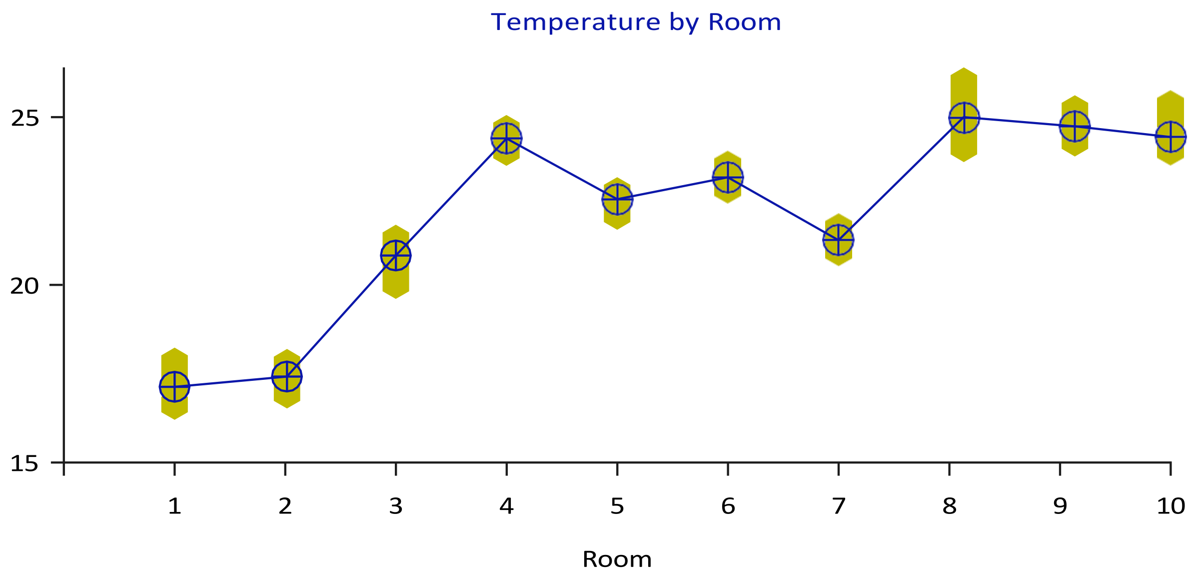


Figure 10. Temperature readings for all 10 locations

R Chart by Operator

The R Chart validates the level of operator consistency. If operators measure the parts in a consistent manner, the Range Chart (R Chart) ranges will be small relative to the data, and the data points should fall within the control limits [11].

Figure 11 below shows the R Chart by operators. It is evident that the operators have all measured the rooms consistently as the general trend for each operator is similar. Only operator 2 measured all 3 repeats exactly the same for part 7 and this is evident in Figure 11 as the range of temperature readings is zero. There is also a mean moving range ($\overline{R}$) of 0.807 for all operators and all the points are within the control limits specified which suggests that there were no special causes of variation (for more information regarding such special causes of variation, refer to the Introduction to Process Control guideline, which is also part of the CPQP toolset). The Upper Control Limit (UCL) of 2.077 is determined as being three standard deviations away from the mean.

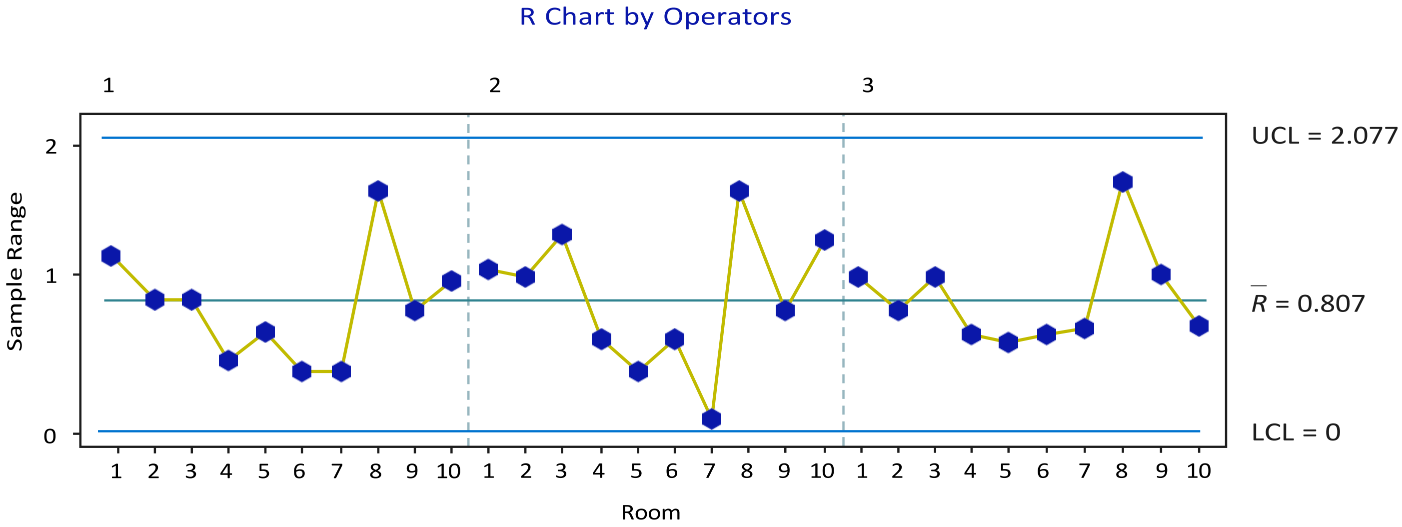


Figure 11. R chart for measurements made by each operator for all locations

Xbar Chart by Operator

The Xbar Chart evaluates part-to-part variation (PV) to the repeatability factor (EV). Measurements made by all 3 operators for all locations are plotted in Figure 12 as average values. The average temperature (X) for all locations, by all operators is found to be 22.49°C with an Upper Control Limit (UCL) of 23.32°C and Lower Control Limit (LCL) of 21.67°C. It should be noted that the UCL and LCL in the Xbar chart are a function of the average range ($\overline{R}$). Therefore, the R chart needs to be in control before carrying out further analysis. If the range is unstable, the control limits will not be relevant and could lead to misleading assessments of the process.

The Xbar plot depicts a large part-to-part variation due to the varying fluctuations of temperature readings considered in the study. On the other hand, it also highlights that the measurement system variation or repeatability (EV) is small in comparison to the large part-to-part variation (PV).

Xbar Chart by Operators

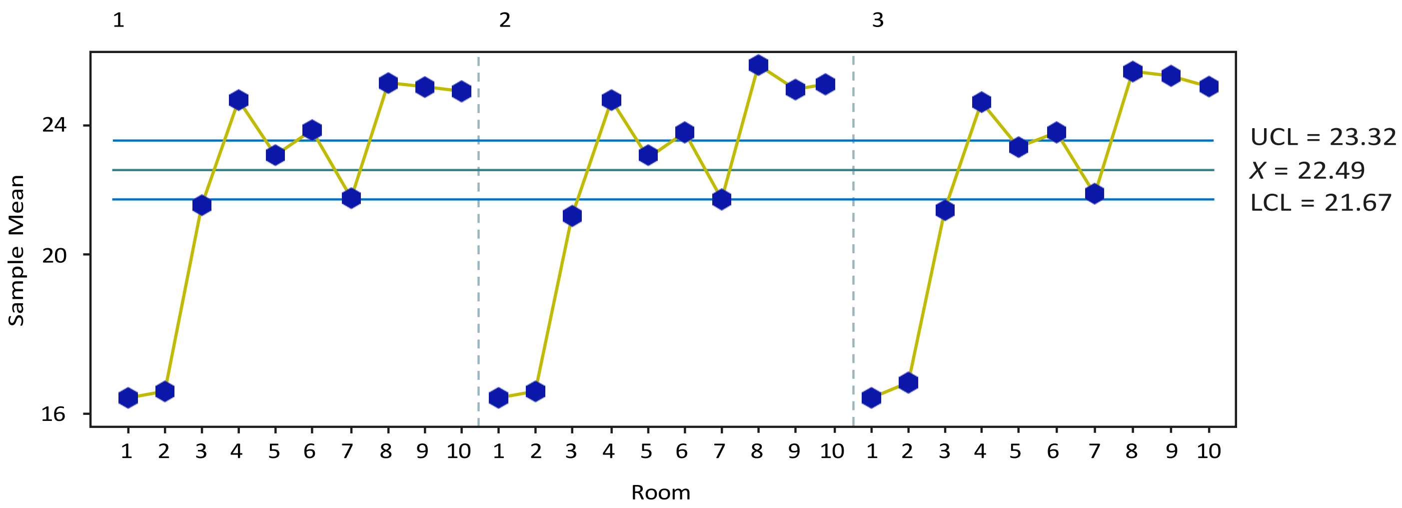


Figure 12. Xbar chart for temperature measurements made by each operator for each part

Box Plot – Temperature by Operator

The Box Plot study helps to identify if measurements and variability are consistent amongst the appraisers. From Figure 13, it is clear that there is little variability between operator measurements across all parts as the line connecting averages together is parallel to the x-axis, suggesting that the mean measurements of all operators are very similar. This supports the fact that there is no reproducibility error as shown in Table 5. It can be concluded that the operators are measuring the parts consistently using the same gauge, with small variation.

Temperature by Operators

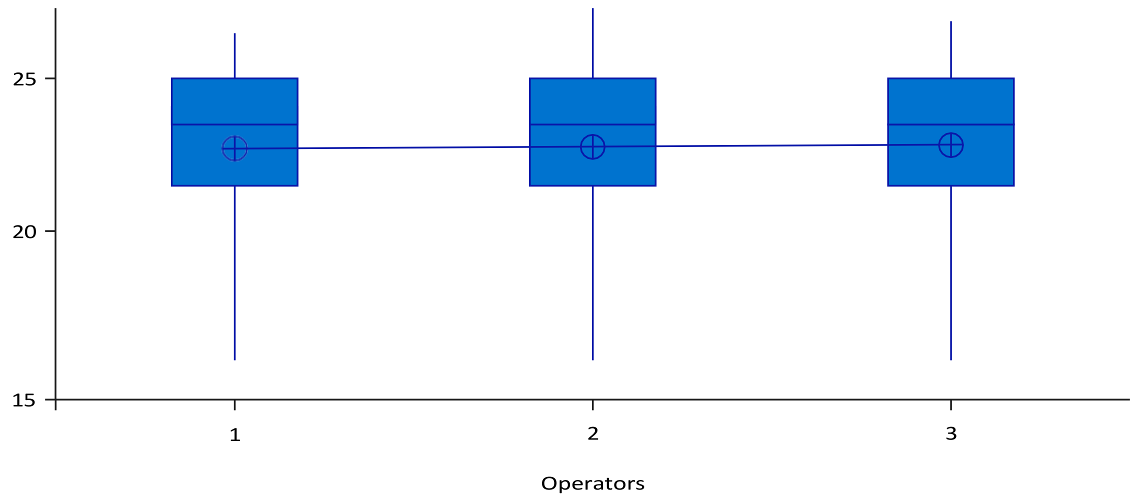


Figure 13. Average temperature measurements by operator

Operator Interaction

Figure 14 shows the average room temperature compared between all operators. For this study, the Room*Operators Interaction graph shows consistency between all operators for the average temperature measurements for all parts. This also supports the fact that there was no reproducibility error (AV) in Table 5.

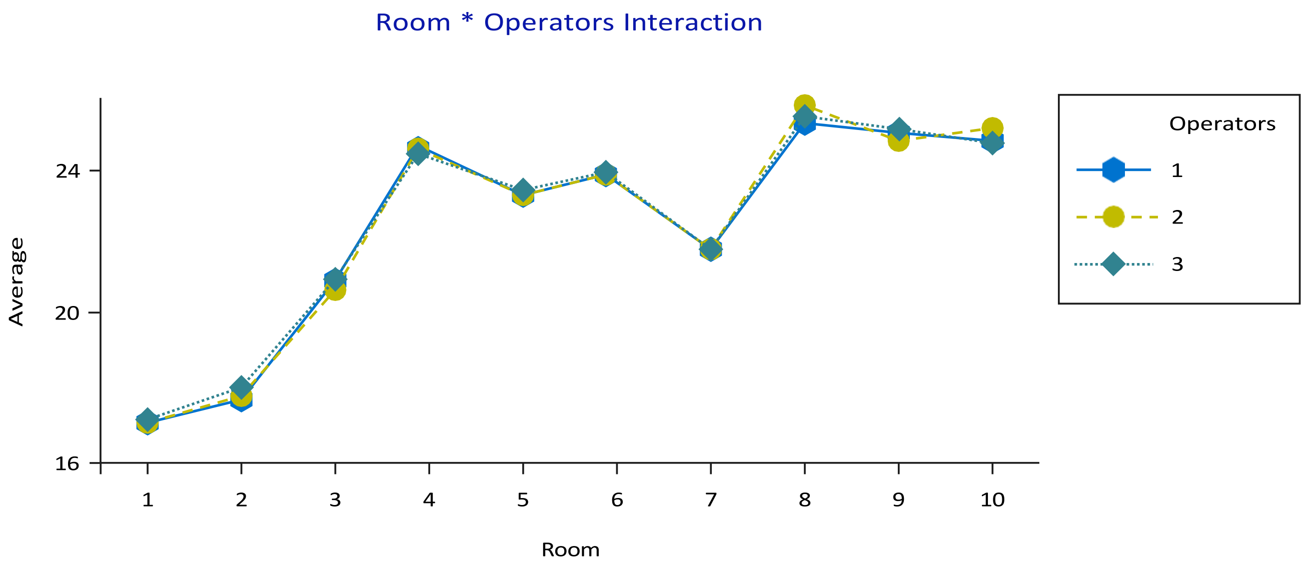
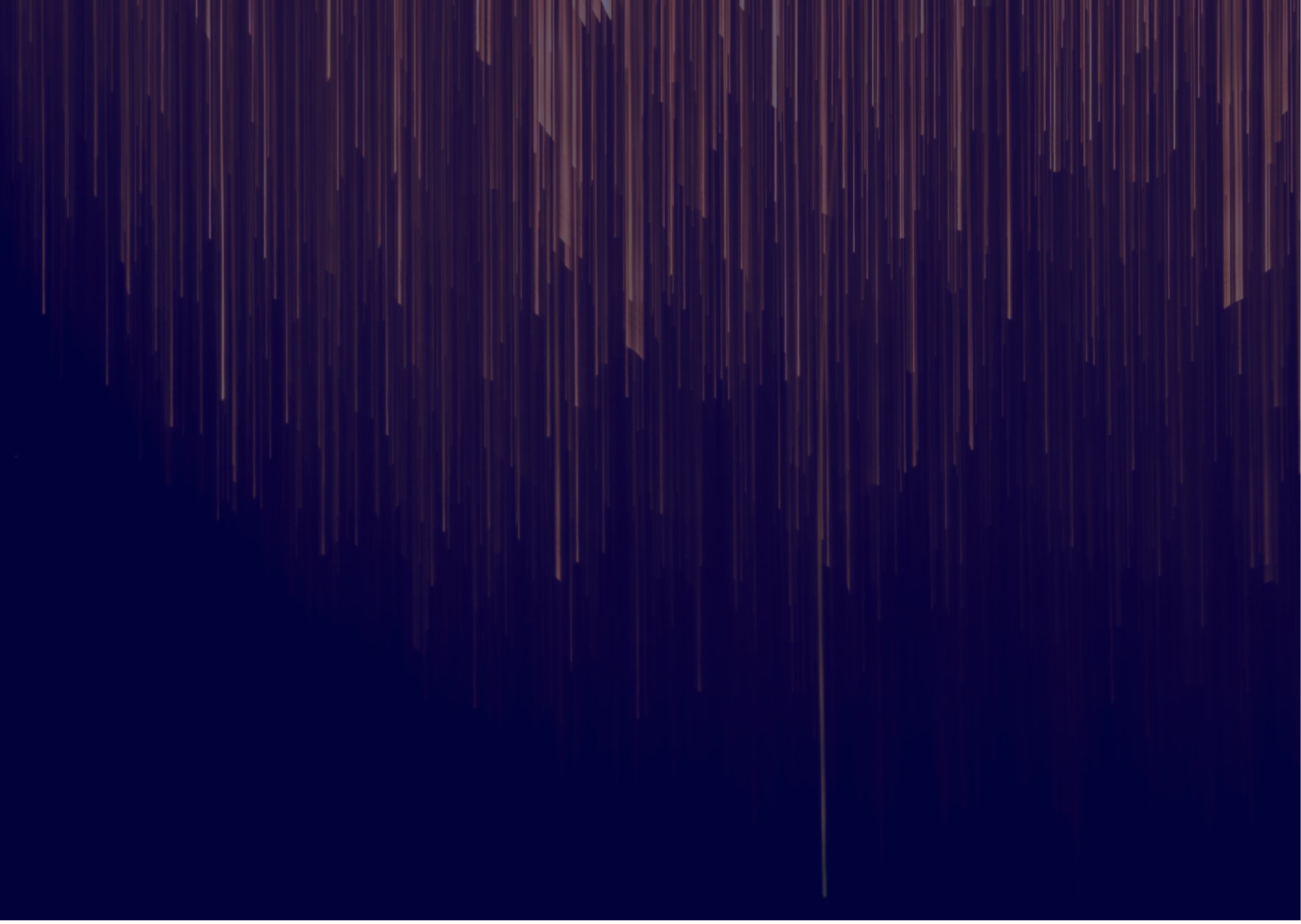


Figure 14. Comparison of room temperature by operator interaction

Conclusions

Following the MSA case study for the quality of temperature measurements of 10 different rooms for a newly constructed modular building, it can be concluded that:

- The measurement system variation (gauge R&R, which includes inherent variation due to the operator, gauge, procedure, environment etc.) contributes by 1.72% to the Total Variation (TV) and is within the acceptance limit of 10%.
- Most of the variation is a result of the Part-to-Part Variation (PV) which accounts for 98.28% of the Total Variation. This is a positive reflection of the study as it shows that the measurement system is capable of distinguishing between different locations.
- All the variation due to the measurement system comes from the repeatability error (EV) and none due to reproducibility error (AV). This means that there is no variation when the three operators take the same measurement of the same location at the same time, but a 1.72% variation is observed when a single operator repeatedly measures the temperature of the same location using the same sensor, three times. This is referred to as Equipment Variation (EV), as the operator is simply switching the measurement device on and off and no other source of variation is introduced.
- The main finding is that the temperature sensor has a maximum variation of ±2.6°C which makes it not suitable for the intended use as it is greater than the customer tolerance limit (±1°C). As a result, a room temperature reading of 24°C can in fact be anywhere between 21.4°C to 26.6°C. As a consequence, incorrect and poor-quality data for any application may be acquired, regardless of how small the measurement system variation tends to be.
- Crossed Gauge R&R studies like other MSA studies are designed experiments and therefore, for valid results, randomisation and representative sampling is vital. Hence, an appropriate sampling method should be considered for all investigations.



References and Appendices

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Appendices

Appendix A – Tool Templates

Templates to be used within the context of this guideline are available, please contact: cpqp@constructioninnovationhub.org.uk

Appendix B – List of Abbreviations

The following is a list of initialisations and acronyms used in this guideline.

A	AIAG	Automotive Industry Action Group
	ANOVA	Analysis of Variance
	APQP	Advanced Product Quality Planning
	AV	Appraiser Variation
C	CPQP	Construction Product Quality Planning
E	EV	Equipment Variation
L	LCL	Lower Control Limit
M	MSA	Measurement System Analysis
N	NDC	Number of Distinct Categories
P	PV	Part-to-Part Variation
R	R Chart	Range Chart
	R&R	Repeatability & Reproductibility
T	TV	Total Variation
U	UCL	Upper Control Limit

Appendix C – Glossary of Terms

The following is a list of commonly utilised quality, manufacturing and construction specific terms and their definitions within this context used within this guideline.

A

Accuracy

The closeness of a measured data with the true value or even a reference value.

Advanced Product Quality Planning (APQP)

A quality framework used for developing new products. It was developed by the automotive industry but can be applied to any industry and is similar in many respects to the concept of design for six sigma; see AIAG Reference [11].

Analysis of Variance (ANOVA)

Analysis of Variance is a collection of statistical models used to analyse the differences among group means in a sample.

Attribute Data

Qualitative data that have quality characteristics which distinctly meets or fails to meet product specification.

B

Bias

Difference between measured value and mean or average observed value.

C

Control limits

The control limits define the limits within which a process is considered in control. The upper and lower control limits are based on the random variation of the process.

Construction Product Quality Planning (CPQP)

An adaptation of Advanced Product Quality Planning (APQP) that is aimed at those enterprises that will feed construction with new componentry for offsite builds.

L

Lower Control Limit

Horizontal line found on a statistical process control chart and is usually three standard deviations below the centre line (actual process average).

M

Mean

The central value of a discrete set of numbers.

Measurement System

A system of related measures that enables the quantification of particular characteristics. It includes a collection of gauges, fixtures, software and operators required to validate a particular unit of measure.

Moving Range ($\overline{R}$)

Shows the variability between one data point and the next.

P

Poka-yoke

Based on the Japanese term for ’mistake proofing’ it more broadly refers to any mechanism within a product or process designed to prevent errors.

Precision

The closeness of a set of measured values in relation to one another.

S

Six Sigma

A disciplined, statistical-based, data-driven approach and continuous improvement methodology for eliminating defects in a product, process or service.

Stability

Evaluates the change in the measurement bias over a time period. A stable process is required for a process to be in ‘statistical control’.

Standard Deviation

Is a measure of the dispersion of values from the mean.

Study Variation

The amount of variation caused by the measurement system and differences between parts. It is calculated as 6 × the standard deviations of each source of variation.

U

Upper Control Limit

Horizontal line found on a statistical process control chart and is usually three standard deviations above the centre line (actual process average).

V

Variable Data

Data that can be measured and has a value that can vary from one part to another. Continuous variable data has an infinite number of values.

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bre