Statistical Process Control Guideline

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CONSTRUCTION INNOVATION HUB

UK Research and Innovation

Contents

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Use of this Guide

The Statistical Process Control (SPC) 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.

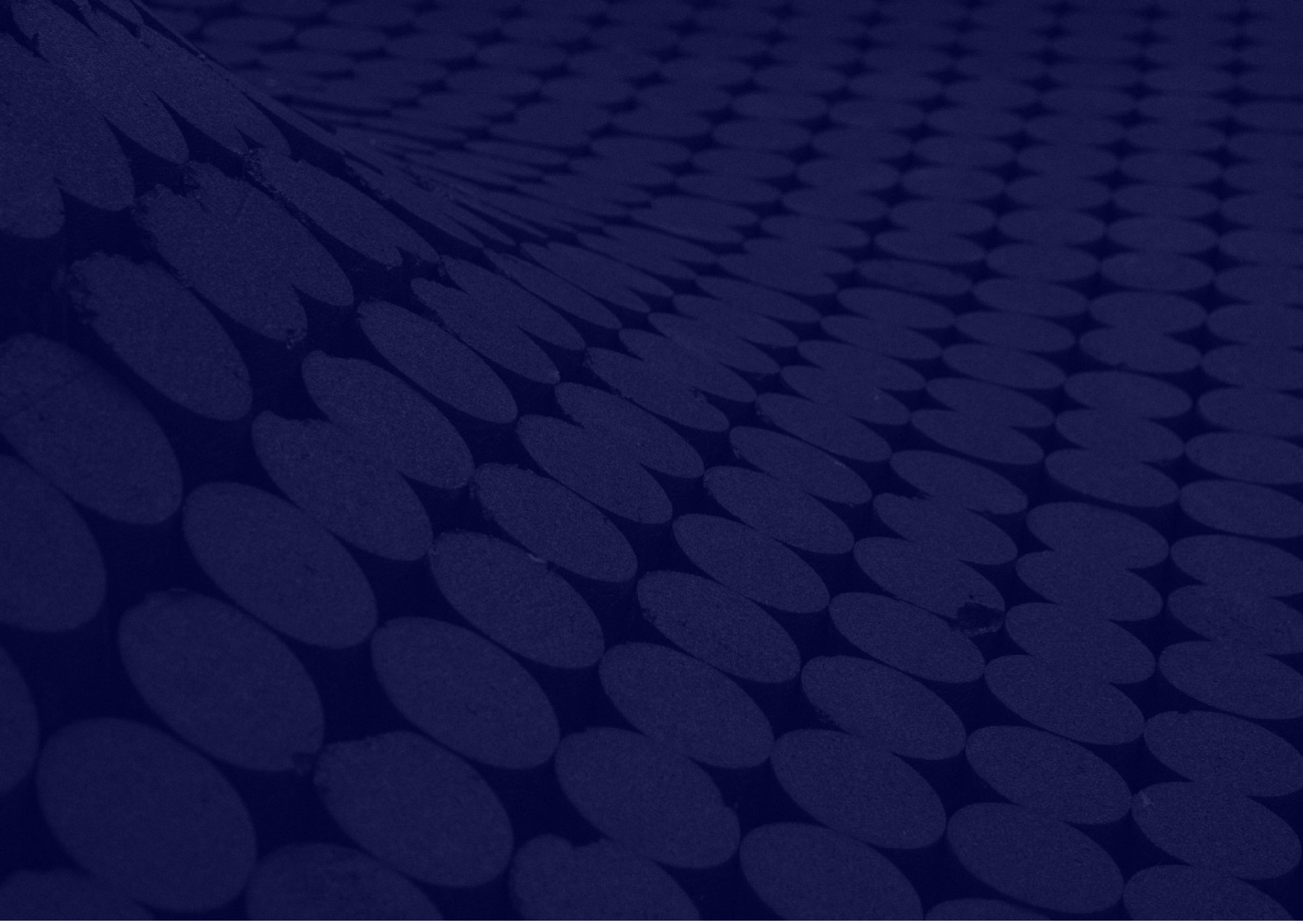
This guideline is for use within the Construction Product Quality Planning (CPQP) process and should be used in conjunction with the CPQP Guide and other tool guidelines published by the Construction Innovation Hub.

The target audience for the guidelines are companies manufacturing offsite construction products largely using the CPQP process with their customers and suppliers. It is intended to provide enough knowledge to enable the CPQP team to apply SPC methods, 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

Statistical Process Control (SPC) methodologies provide effective means of driving a zero defects culture within an organisation. SPC is one such methodology for monitoring and controlling the quality of a production process and products. It is an analytical tool that quantifies the amount of variation between products from the same production line and then subsequently identifies the sources of variation that exist within the given process or product. SPC is often used in conjunction with error-proofing methodologies to provide consistent and predictable quality within the manufacturing process.

Error-proofing is another process control methodology used to avoid nonconformance during manufacture (also known as fail-safe mechanism). It is commonly referred to with the Japanese term 'Poka-yoke', which is a method to mistake-proof a process by preventing inadvertent errors. For example, in the construction industry, the use of a fastener solution that can be fitted in only one possible way to connect parts would mistake-proof the assembly process and eliminate product defects as a consequence of human error. Therefore, SPC and error-proofing together provide a robust, process control method that can be used to build quality into any process and ensure constancy of performance by minimising sources of variation. The implementation of SPC ensures that a process is producing conforming parts with predictable quality; delivering cost benefits in the products being manufactured.

As there are multiple sources, of variation such as the production method, materials used, environmental conditions, etc., no two products derived from the same production process will ever be identical. In manufacturing, automated processes are preferred as the human element is eliminated and thus greater repeatability and reproducibility can be achieved.

The fundamental purpose of implementing statistical control methods is to ensure constancy of performance by reducing process variation. This is achieved by monitoring the performance of a process, identifying the sources of variation within the system, and consequently finding solutions for any identified production issues.

Background

SPC was initially developed by Walter A. Shewhart at Nokia (Bell Laboratories, USA) in the early 1920s. The concept of statistical control was successfully applied in military research and munitions manufacture in 1934. As a result, Army Ordnance decided to collaborate with George Edwards of AT&T on the use of the quality control and quality assurance approach among its contractors during WWII [1]. Since then, the approach has been used in other sectors, from automotive and aerospace to furniture and pharmaceutical industries. Companies have rapidly acknowledged the benefits of implementing SPC. For example, in the aerospace sector, Airbus has implemented the use of SPC to establish a tightly controlled process, ensuring minimal variation during the assembly of the fuselage with the aircraft cabin [2].

Purpose

The main purpose of using the Statistical Process Control (SPC) is to understand what is 'normal' and what is 'special' about a given process by identifying faults in the production line and ensuring that the final product falls within the acceptable quality limits. SPC relies heavily on statistical methodologies, and when applied correctly it can be a powerful tool for maximising production output whilst reducing waste.

SPC charts can be used to highlight areas that require concentrated focus, and then determine whether improvement measures are actually improving the process. SPC methodologies, and in particular the SPC charts, are used to:

- Investigate whether the process is meeting customer requirements;
- Identify whether a process is in control and is stable over time;
- Graphically differentiate between common cause variation and special cause variation present in a product or process;
- Enhance the decision-making process through better understanding the nature of variation observed in the manufacturing process;
- Drive for continuous improvement by testing the stability of a process prior to any redesign work; and
- Minimise other quality control and inspection activities as data becomes available to determine process capability over time.

Benefits

SPC in manufacturing helps to monitor and measure the process performance and to detect and remove any variations that may cause quality or nonconformance issues in the final product. SPC charts can graphically show whether a particular process can meet a specific target (Voice of Customer).

There are several benefits for manufacturers and businesses associated with achieving consistent quality, including:

- Reduced rework and manual inspection;
- Increased productivity, operational efficiency, and client satisfaction; and
- Reduced maintenance cost, recurring cost, and warranty claims.

SPC is unique to alternative methods of quality control as it focuses on the detection and prevention of issues, rather than implementing temporary corrective actions after an issue has occurred. Therefore, it is important to introduce SPC methods as they help to monitor and control the variability of processes and thus deliver consistently conforming products. Through the various SPC charts, it is possible to understand and differentiate between different causes of variation within a particular process, and, once the relative causes have been identified, SPC charts assist in developing continuous improvement actions.

How does SPC 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. The third phase focuses on the design and development of the processes for manufacturing a product as shown in Figure 1. The SPC methodology helps monitor and control the quality of the production process and product. Hence, SPC fits suitably with the CPQP process, ensuring that the production process remains in statistical control during the ongoing monitoring phase. The SPC methodology is a key tool during phase 5 (Production Launch & Ongoing Monitoring) when the project is handed over to the production team to focus on ramping up production to full volumes.

Team Approach

The advanced planning approach in the CPQP is built upon a team-based approach. Similarly, the effective use of SPC methodology requires the engagement and participation of the cross-functional team. The team composition will vary by organisation and according to 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).

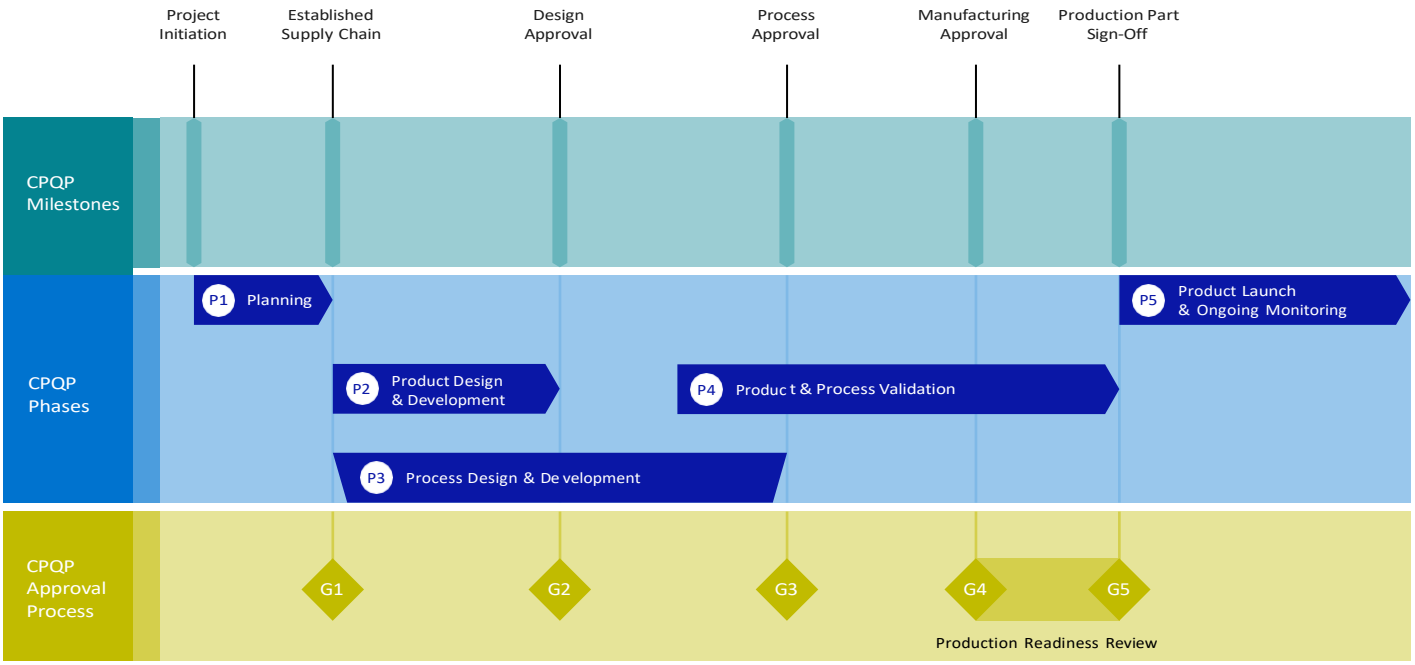


Figure 1. Construction Product Quality Planning (CPQP) Process

Key concepts

Process variability

One of the biggest challenges in controlling a process is dealing with the variability. The desired state of a process is more consistency and less variability so that the process operates within established limits; the process is then deemed in control.

Typically, process variation is attributed to two main causes, namely common cause and special cause of variation, which can be described as follows:

Common Cause Variation:

A stable, predictable and random source of variation caused by unknown factors, which is an inherent part of the system.

Special Cause Variation:

An unstable and often unpredictable cause of variation due to assignable causes that result in a shift in output. It is usually caused by a specific factor outside of the process, such as environmental conditions.

Figure 2 shows a simple exercise used to illustrate the different types of variation that arises in writing signatures. When comparing a series of signatures written by an individual using their dominant hand and then using their non-dominant hand, the common cause and special cause variation can be clearly distinguished. The variation observed within the signatures made using the dominant hand is a common cause variation, i.e. only small differences are observable to the naked eye which arise randomly. Similarly, the variation observed within the signatures made by the non-dominant hand is also a common cause variation. However, variations between the first group of signatures done by the dominant hand and the second group of signatures done by the non-dominant hand represent special cause variation, i.e. there is a non-random and assignable cause given the lack of ability to sign with the non-dominant hand.

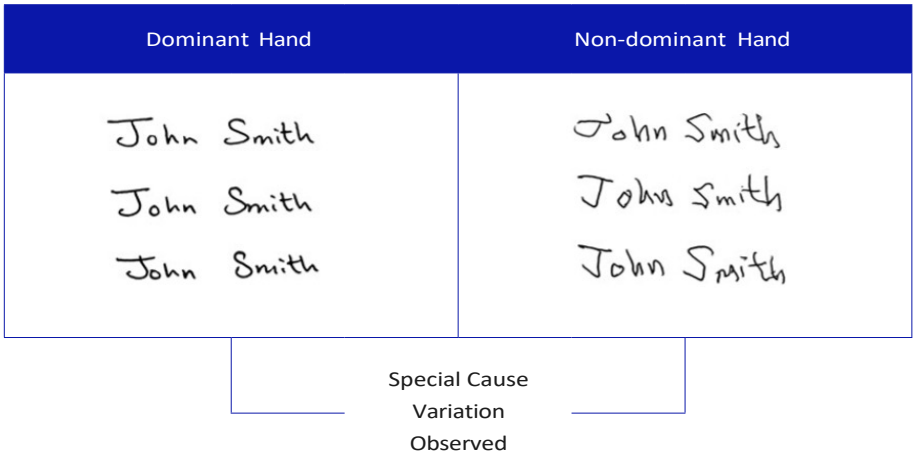


Figure 2. Visual representation of common and special causes of variation

Figure 3 shows a visual representation of the dispersion (spread) of the outcomes of a process. The bell-shaped curve in Figure 3 is known as normal distribution and it tends to spread symmetrically around an average value. The normal distribution is used as an example in this guide, but other process distributions can be also considered. An important parameter to describe a distribution is the measure of the data dispersion or spread.

This is usually captured by the standard deviation (sigma, σ). The standard deviation calculates the average distance of a data point from the mean value of the data set. A relatively large standard deviation value means that the data spreads out away from the mean. The standard deviation of a set of numbers or data can be easily determined using various calculators, readily available spreadsheets or statistical programs.

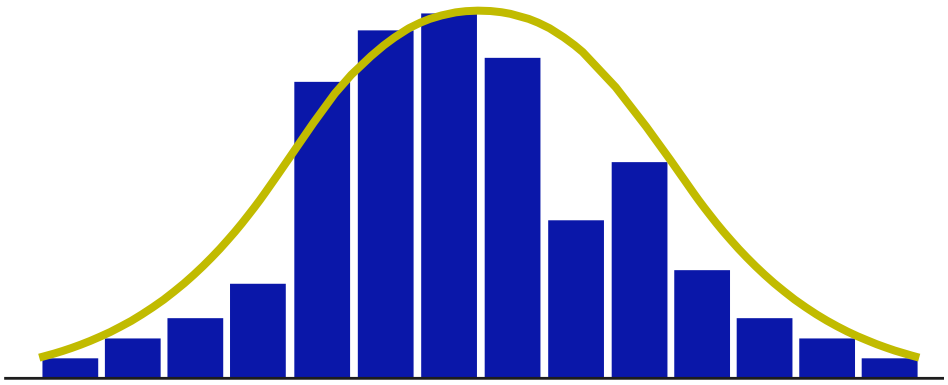


Figure 3. Representation of the normal distribution of a process

Control limits

In order to control the variability of a process, it is then relevant to establish the limits within which a process is considered in control, that is, the control limits. Figure 4 illustrates the distribution of a process, which typically shows some dispersion around the average or mean value. The control limits are defined in such a way that the probability of having data points outside the limits is reduced. Rather than having the control limits set by any one individual, they are determined based on the data. For a process like the one shown in Figure 4, the upper control limit (UCL) and the lower control limit (LCL) are set at three standard deviations away from the mean, ensuring that there is a 99.7% probability that the data points are within the control limits set.

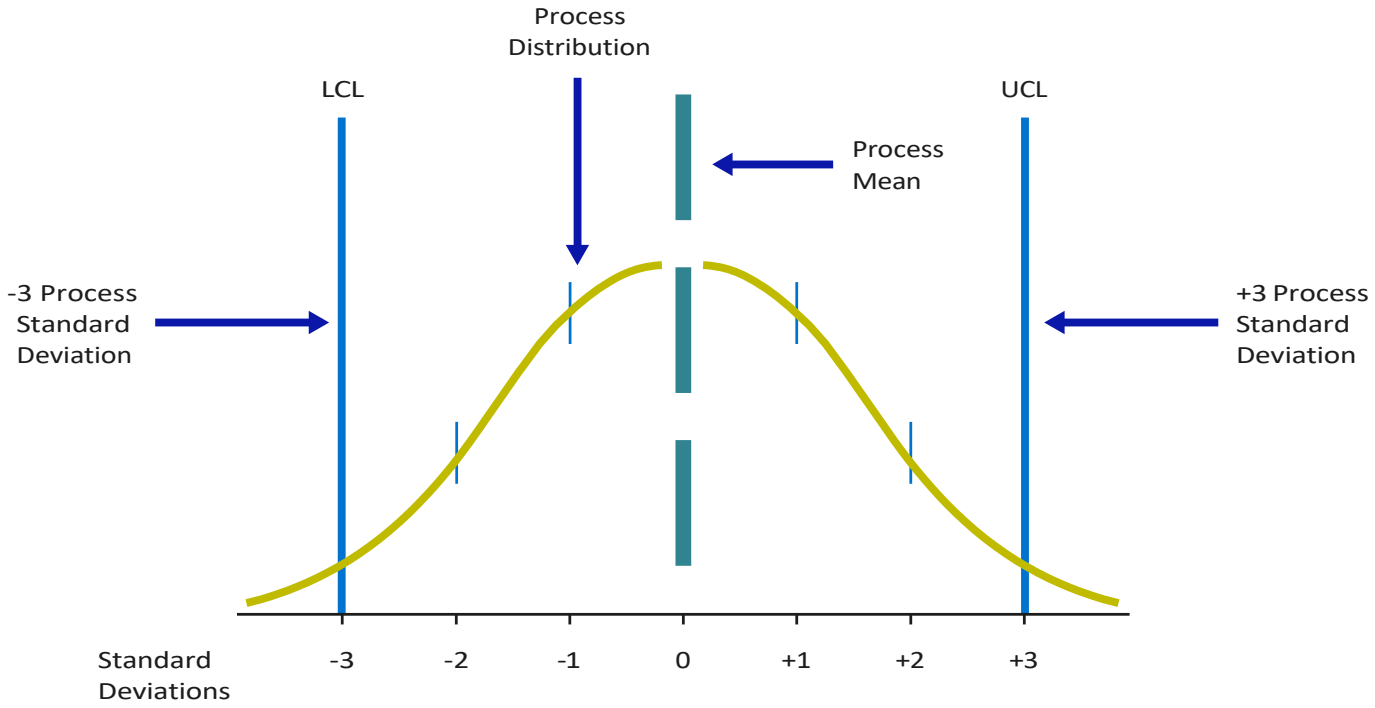


Figure 4. Process distribution with control limit defined

It should also be noted that the control limits (LCL and UCL) are not the same as the tolerance or specification limits set by the customer or the designers. Control limits are dependent on the process spread and thus defined by the measured data. Therefore, as the process becomes more capable, the process distribution becomes smaller and as a result the control limits become tighter. This, however, does not change the tolerance or specification limits which remain the same.

Methodology

Methodology

Statistical Process Control (SPC) is a well-established methodology for measuring, monitoring, and controlling quality during the manufacturing process.

Three key phases are defined for successful implementation of SPC in this guideline, namely Pre-SPC, SPC and Post-SPC. Figure [5] shows an SPC flow diagram covering the three key phases and the main activities.

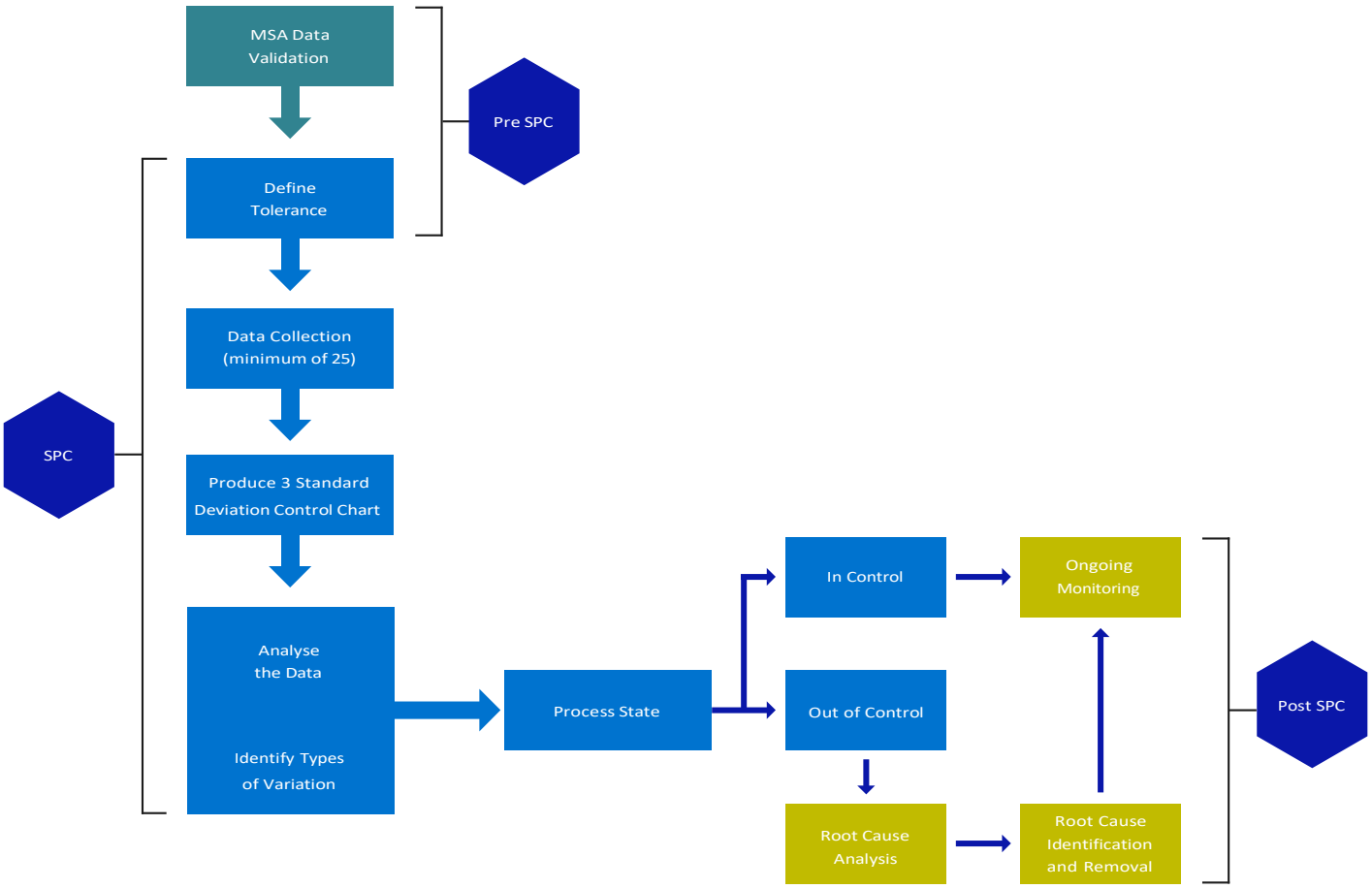


Figure 5. SPC flow diagram

Phase 1: Pre-SPC

SPC is based on the analysis of data and thus relies on the quality of the data. Therefore, this initial stage focuses on identifying the right data to measure/analyse; ensuring that the quality of the data collected through the measurement system is at an acceptable level. Once the data to be analysed is defined, there are two relevant actions to be completed in this initial phase:

1. Measurement System Analysis (MSA)
   This process aims to validate the measurement system and the quality of the data being measured. All measurement systems include a level of measurement error due to different causes (e.g. equipment, appraiser, environmental). If the error exceeds an acceptable level, the data cannot be processed reliably. The principles and methodology behind this are discussed in the Measurement System Analysis Guideline.

2. Definition of Process Tolerance
   This should be clearly defined and is usually specified by the designers based on the Voice of the Customer (VoC). Defining the tolerance would highlight any deviations from the target requirements of the product or process and this can be observed in the SPC chart.

Phase 2: SPC

During the SPC phase, the initial data is gathered and analysed to determine whether the process variability is within the acceptable limits specified and whether the product or process meets the target requirements set by the customer. The first activity in this phase is the collection of data using the already validated measurement system. A well-defined data sampling strategy would consider data subgroups that span the full range of the process distribution so factors such as seasonal effects or operator changes, are captured and thus considered in the analysis. The data set is then plotted on an SPC chart, like the one shown in Figure 6 below. The control limits (blue horizontal lines in Figure 6) are also drawn in the chart and they define the limits within which a data point is considered acceptable. The control limits (UCL and LCL) are usually drawn three standard deviations above and below the mean or average value of the sample, respectively.

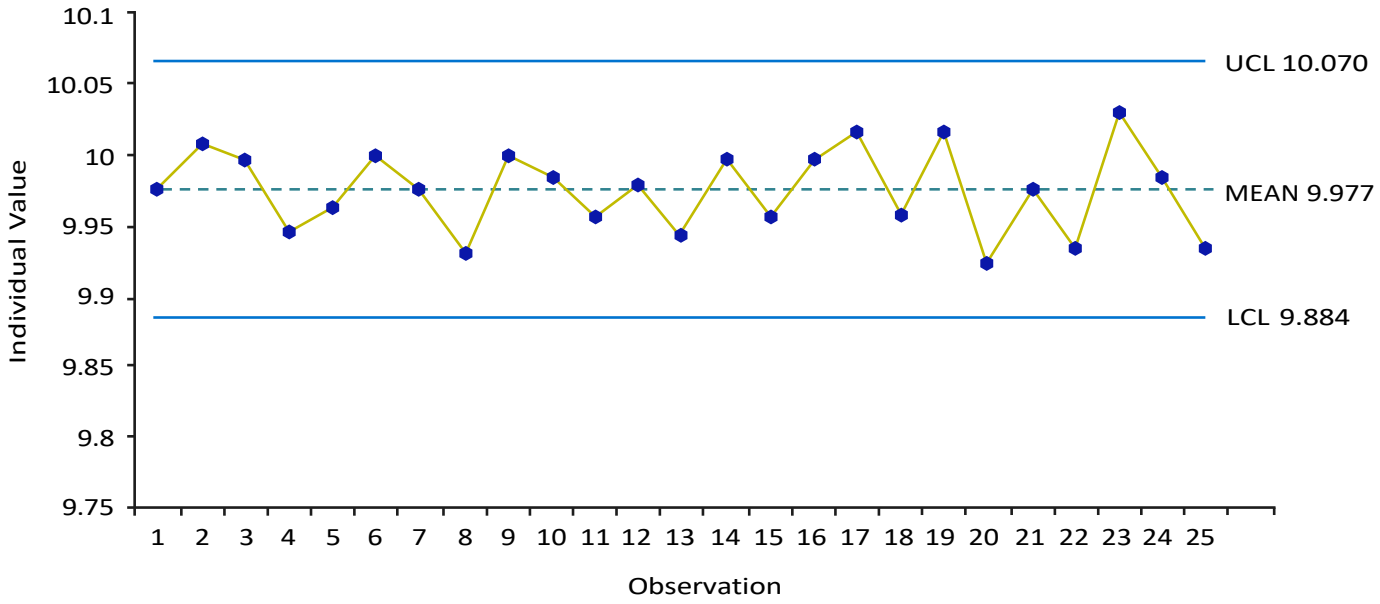


Figure 6. SPC chart example with the Mean, UCL and LCL defined

An analysis of the chart helps differentiate between common and special causes of variation by identifying unusual characteristics within the data set and the chart. As stated earlier, common cause variation is inherent in the process, whereas special cause variation is unstable and often unpredictable with a specific root cause. The analysis considers a set of pre-programmed rules to identify data points which lie outside of the control limits or trends, indicating the potential presence of some kind of special cause variation within the process.

Figures 7-14 below depict some of the rules usually considered to analyse the charts. These rules are pre-programmed in any SPC software, which will flag any instance where they are broken and thus enable an investigation into identifying the root cause of this variation. These rules can also be easily implemented using a spreadsheet when conducting a similar analysis. The SPC charts shown in the figures below are for reference purposes only as most SPC software would automatically highlight these instances of special cause variation. Using SPC enables the team to identify special causes of variation in the process and timely define and implement corrective actions to reduce the risk of producing defective or non-conformance products.

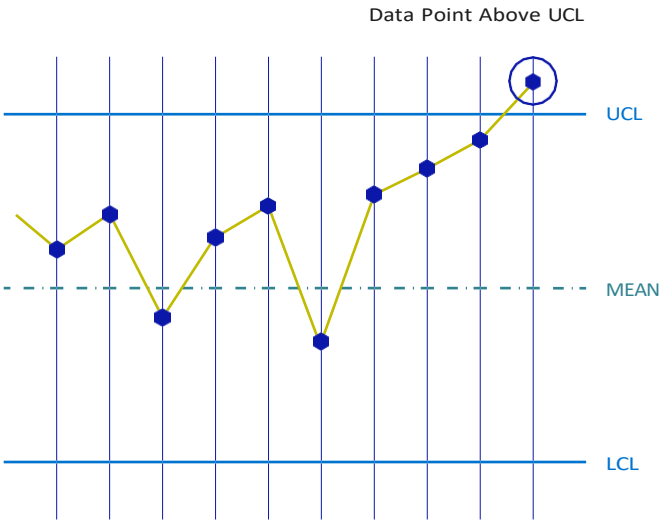


Figure 7. Rule1 – Data point above UCL

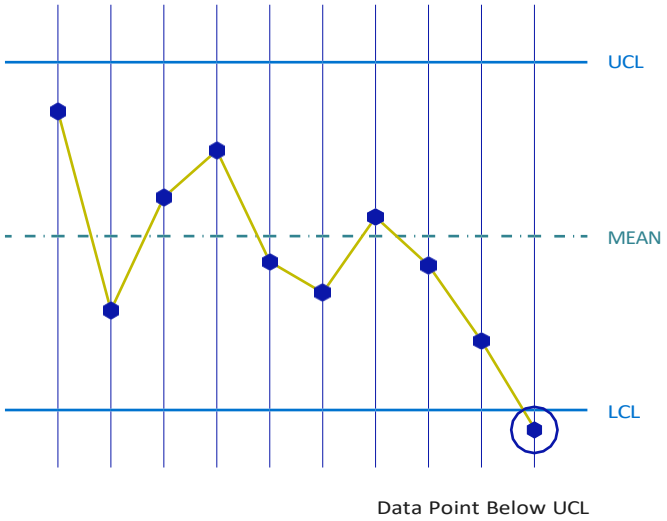


Figure 8. Rule 2 – Data point below LCL

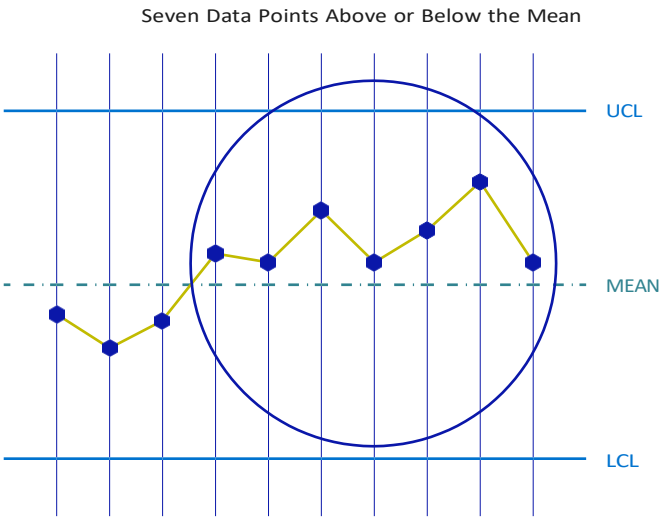


Figure 9. Rule 3 – Seven data points above the mean

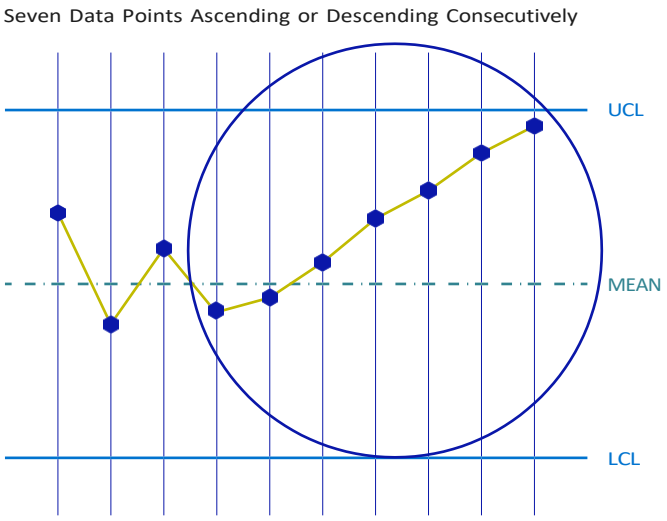


Figure 10. Rule 4 – Seven data points consecutively ascending

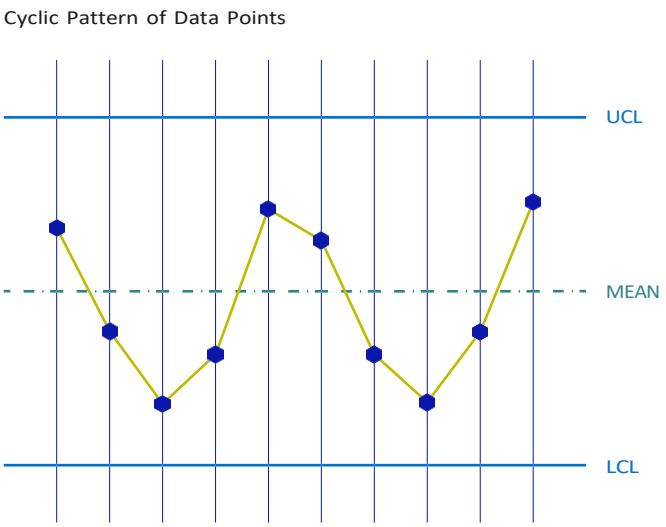


Figure 11. Rule 5 – Unusual cyclic pattern within control limits

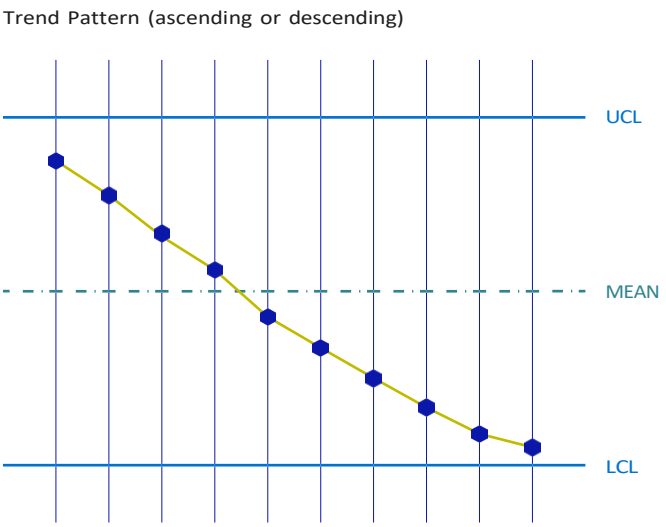


Figure 12. Rule 6 – Descending trend pattern within control limits

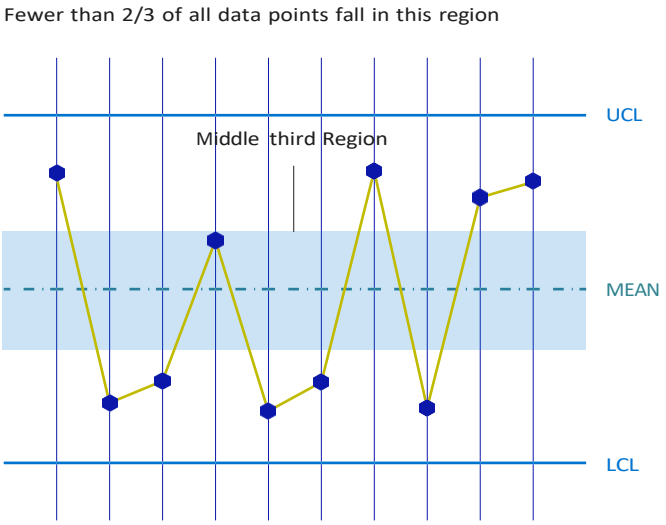


Figure 13. Rule 7 – Less than 2/3 of all data points fall within the middle third zone

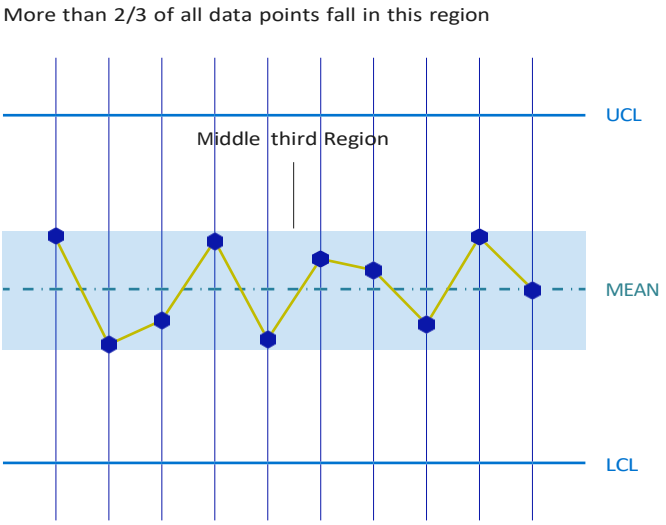


Figure 14. Rule 8 – More than 2/3 of all data points fall within the middle third zone

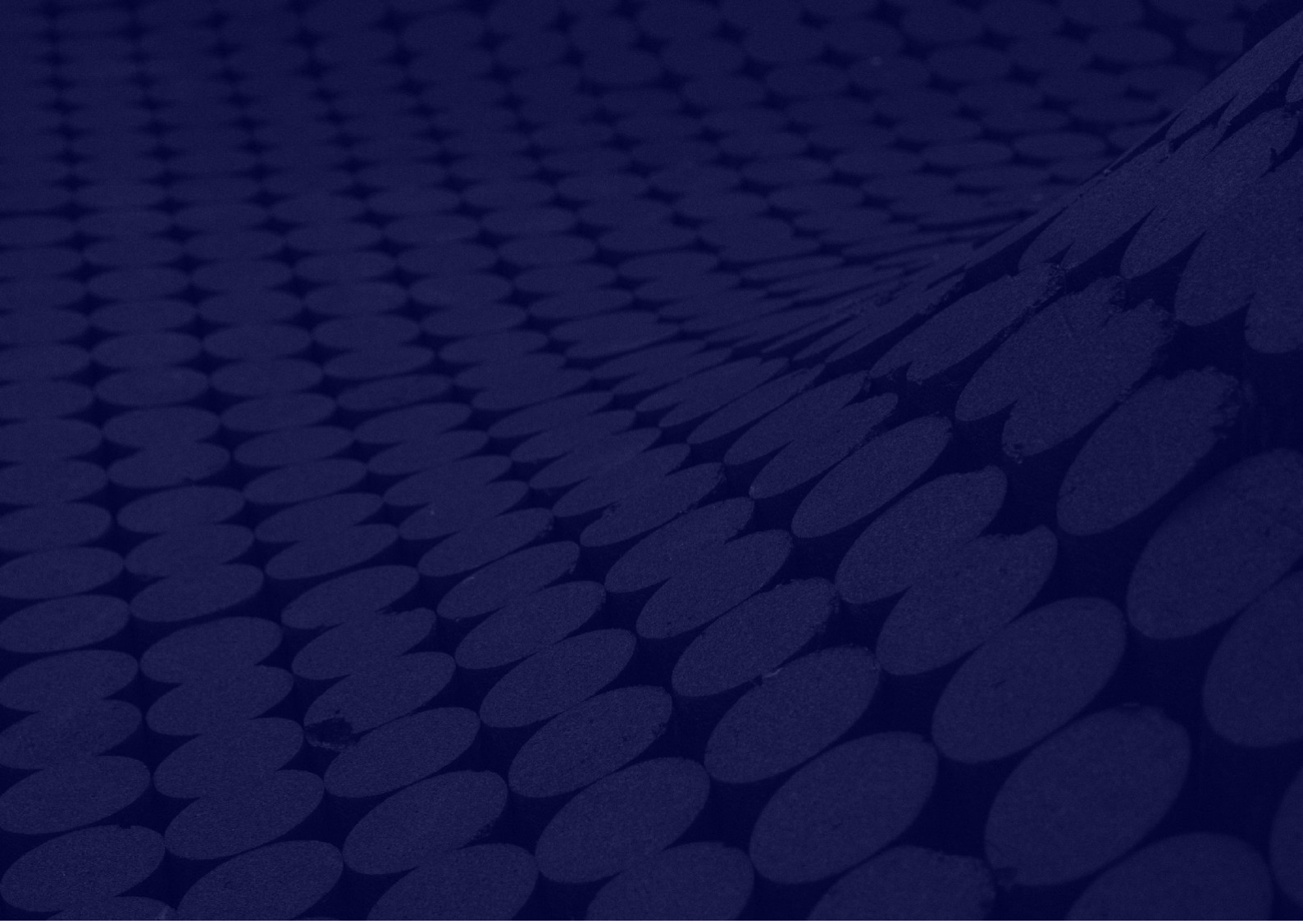
It should also be noted that in cases where no special cause variation is observed, the process can be deemed to be producing output with a statistically predictable quality or with only common causes of variation within the process. Therefore, by focusing on reducing this predictable form of variation, the process can be further improved.

Phase 3: Post SPC

The purpose of this phase is to identify the root cause of the observed variation and then implement corrective and preventative measures to return the process to a state of statistical control.

The root cause of any special cause variation needs to be identified for which several problem-solving methodologies can be used by the CPQP team (e.g. Eight Disciplines of Problem Solving (8D) approach, Five (5) Why's, Cause and Effect Fishbone diagram). Identifying the root cause allows the team to define corrective and preventive measures to remove the root cause of the special cause variation. Actions should include error-proofing methodologies (e.g. Poka-Yoke) to mistake-proof the process and prevent future occurrences from arising.

Once all such sources of special cause variation have been removed, the process is deemed to be in a state of statistical control. Finally, as the process becomes more mature and capable, ongoing monitoring would ensure that the data points are closer to the nominal target value and as a result, less variation would be observed in the product or the process. This also ensures that further analysis can be conducted to understand the operational capability of the process.



Guideline

Guideline

Based on the methodology discussed in the previous section, the implementation of the SPC comprises three key phases; Pre-SPC, SPC, and Post-SPC. The steps taken in these phases are outlined in this section.

Phase 1: Pre-SPC

Step 1:

Verify that the data quality is acceptable based on the Measuring System Analysis (MSA) report. The Measurement System Analysis guideline provides the necessary information to complete the validation of the measurement system and is also accessible as part of the CPQP supporting documentation.

Step 2:

The tolerance for the product or process is usually defined by the designers based on the Voice of the Customer (VoC).

Phase 2: SPC

Step 1:

Review the client's requirements (i.e. target values and tolerance) to have a clear understanding of the product or process to be analysed.

Step 2:

Measure and collect the data for the product or process using the already validated measurement system. A minimum of 25 data points is considered a statistically acceptable sample size.

Step 3:

Plot the data set in time order to create the SPC chart. The chart can be created using readily available SPC software, but it can also be easily created in a spreadsheet.

Step 4:

Draw the upper control limit (UCL) and lower control limit (LCL) to complete the SPC chart. The limits are positioned three standard deviations on either side of the process mean.

Step 5:

Identify special and common causes of variation within the process using the SPC chart. By considering the predefined rules, special causes of variation can be identified. The SPC software will highlight special cause variation by recognising where the pre-programmed rules and patterns were broken. Similarly, the rules can be easily pre-programmed and implemented in a spreadsheet.

Phase 3: Post-SPC

Step 1:

Identify production issues after the SPC phase and categorise whether they are linked to common cause variation or special cause variation.

Step 2:

If a special cause of variation is identified, the CPQP team needs to find the root cause of this special cause of variation. Following this, a problem-solving methodology is advised (e.g. 8D problem resolution approach, 5 Why's, Cause and Effect Fishbone diagram, etc.). The 8D problem resolution guideline is also accessible as part of the CPQP supporting documentation.

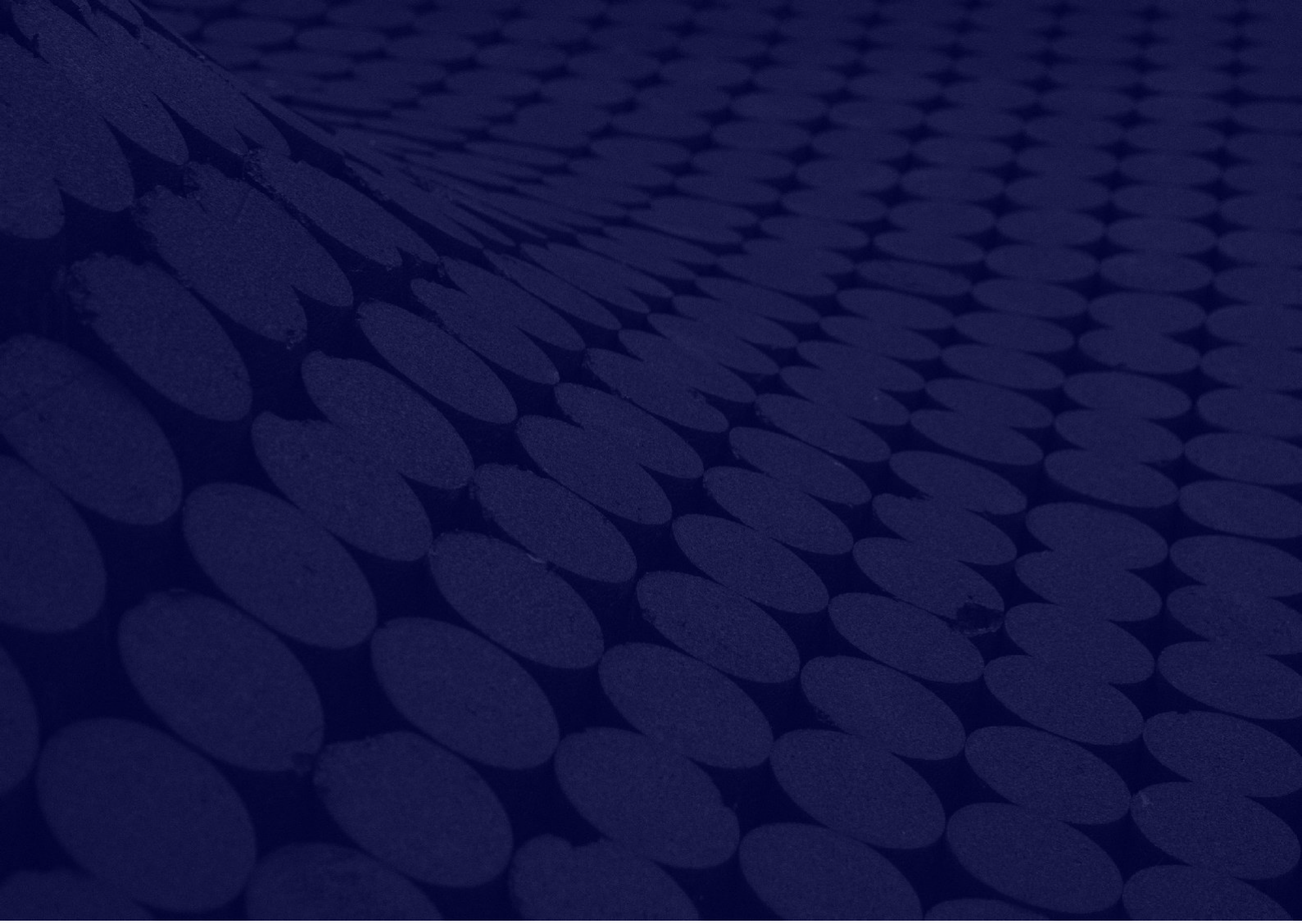
Step 3:

Define and implement measures for removing the special cause variation (e.g. Poka-Yoke or error-proofing mechanism, equipment calibration, automation). Both corrective and more importantly preventive actions should be implemented to ensure that the issue is unlikely to occur again in the future.

Step 4:

Validate the effectiveness of the implemented measures by running the SPC process again using a new data set (minimum of 25 measurements). Following this, ensure that any special cause of variation is analysed, and the necessary corrective and preventive actions are implemented.

Once the process is in a state of statistical control, further analysis can be conducted to understand key information such as the operational capability of the process, the number of defective parts per million and the associated costs.



Worked Example: Manufacturing of sawn boards

Worked example

In modern methods of construction, a large portion of the components is manufactured off-site. Every process will experience variability and hence every part produced will also be subject to variation [3].

Lumber manufacturing is an example in which SPC has been broadly adopted [4]. Lumber production in a modern sawmill occurs at high speeds and it is important to control part variation.

The example herein describes a hypothetical scenario and should not be considered as a complete case study, however, it aims to illustrate the process in the creation and analysis of the SPC charts in addition to assessing the process capability.

In practice, sawing variation refers to the variability both in the width and thickness of sawn boards. The variation in the boards is usually due to unintentional movement in the saws or part hold-down mechanisms. Part-to-part variation (e.g. width variation between different boards) is usually caused by saw or part positioning errors. In turn, within-part variation (e.g. thickness variation within a board) is usually due to excessive saw vibration or board movement during the cut. In a manufacturing setting, sawing is highly accurate, and variation although not visible to the human eye could cause fitting issues for customers using boards in secondary products or assemblies (e.g. furniture). If there are no suitable methods in place to control the variation, the issues could go undetected for a significant period of time and could lead to significant losses.

Phase 1: Pre-SPC

In this particular example, the specified width for a sawn board is 500mm with a tolerance of ±1mm. The manufacturer measures the width of each board using a non-contact laser scanning system with 0.025mm measurement resolution. The suitability and reliability of the measuring system were previously validated through a Measuring System Analysis (MSA). For the sake of simplicity in this example, it is assumed that the manufacturer measures the width of 25 boards.

Phase 2: SPC

The collected data is analysed using the control chart shown in Figure 15. The upper and lower control limits (UCL and LCL, respectively) are drawn at three standards deviations away from the average board width.

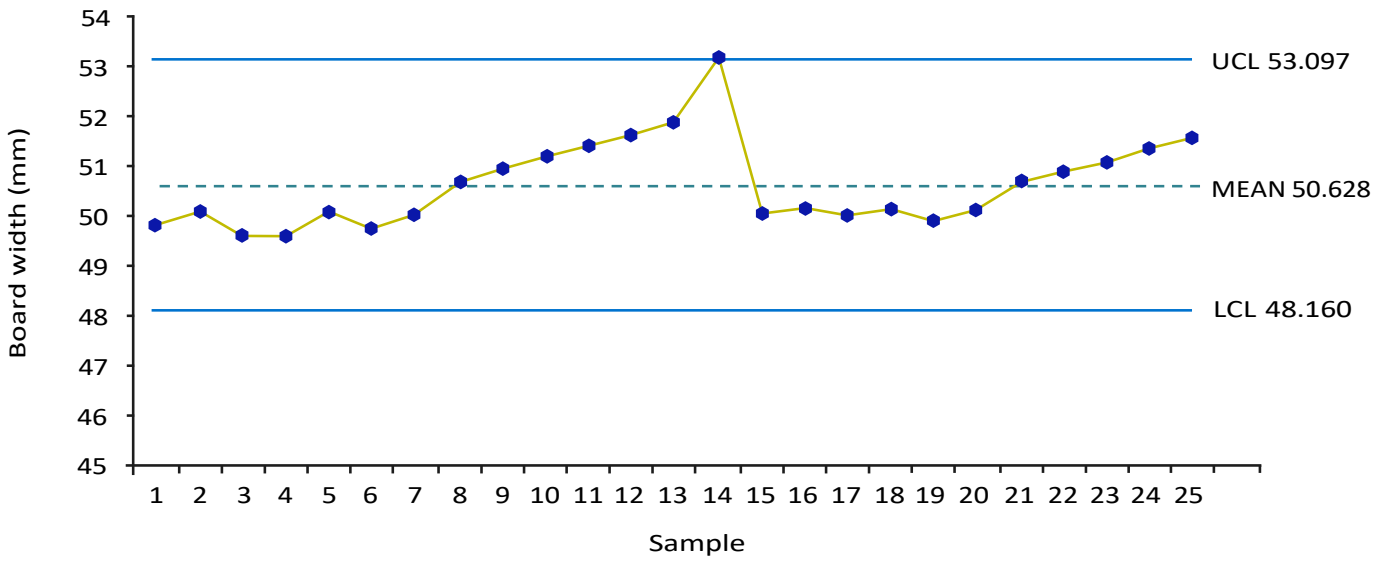


Figure 15. SPC chart for sawn board example (special cause of variation)

Phase 3: Post-SPC

The production team carries out an investigation to identify the root cause of the issue. By using a problem resolution method (e.g. 8D problem resolution approach, 5 Why's, Cause and Effect Fishbone diagram), the team identifies that the movement of the log during the cut is the main cause of the variation. The log is kept in place by a pneumatic hold-down mechanism, which also moves along with the log as it is fed into the sawing system. After applying a problem resolution tool, the team identifies the root cause of the problem to be a worn-out hose which causes a variation in the pressure applied by the hold-on mechanism. A loss of pressure is detected as the log moves through the cutting line.

Once the defective hose is replaced, the team measures the width of another set of 25 boards. The SPC chart in Figure 16 shows the data collected along with the upper and lower control limits drawn at three standards deviations from the average board width.

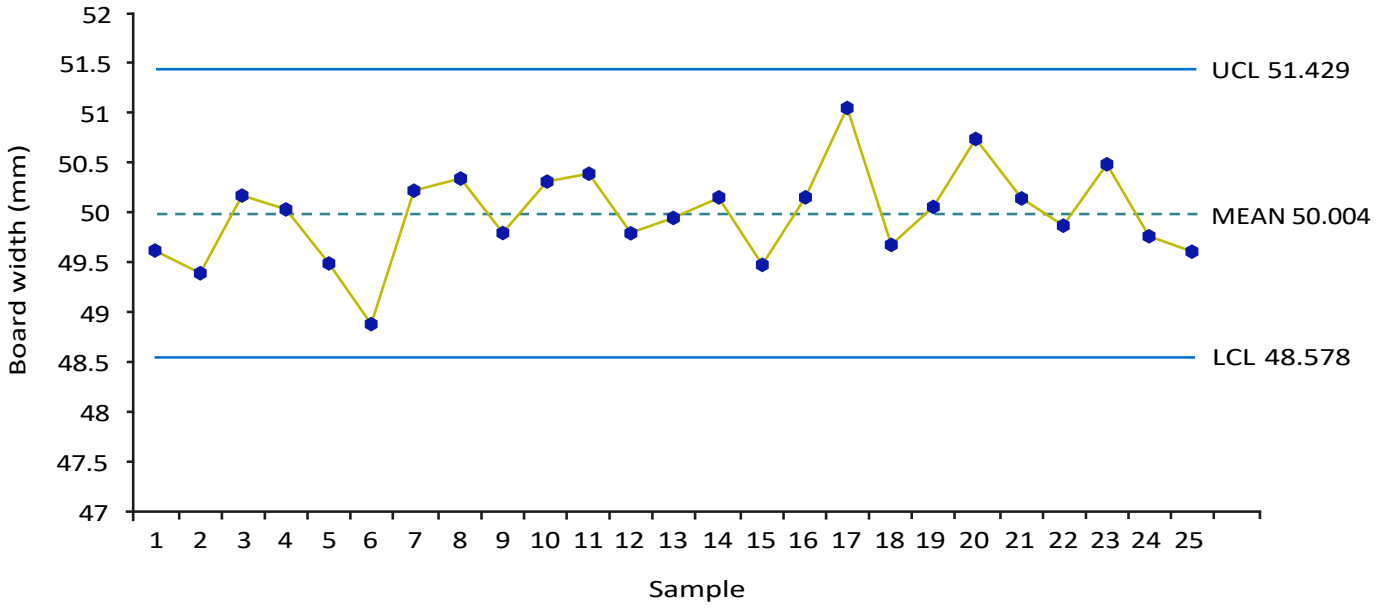


Figure 16. SPC chart for sawn board example – State of statistical control

Analysis of the SPC chart in Figure 16 shows that the special cause of variation has been effectively removed and, as a result, the SPC chart does not show any additional signs of special cause variation. Therefore, the process can now be deemed as in a state of statistical control with the observed variation attributed to common causes of variation. However, it should also be noted that this does not necessarily mean that all boards meet the customer specifications (i.e. width of 500mm ± 1mm). For instance, if the process spread is large, the control limit range could be wider than the tolerance defined by the customer and as a result non-conforming part would be produced. Further evaluation can then be completed once the process is in a state of statistical control to ensure that the process is capable of delivering parts within the customer specifications. This type of process capability evaluation is beyond the scope of this introductory guide.

References and Appendices

References

[1] Best, M. and Neuhauser D. (2006). Walter A. Shewhart, 1924, and the Hawthorne factory. In Quality and Safety in Health Care, Vol. 15, pp. 142–143.

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Appendices

Appendix A – Tool Template

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.

0-9	8D	Eight (8) Disciplines of Problem Solving
C	CPQP	Construction Product Quality Planning
L	LCL	Lower Control Limit
M	MSA	Measurement System Analysis
P	PC	Process Control
S	SPC	Statistical Process Capability
U	UCL	Upper Control Limit
V	VOC	Voice of Customer

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.

C Construction Product Quality Planning (CPQP)

An adaptation of Advanced Product Quality Planning (APQP) [4] that is aimed at those enterprises that will feed construction with new componentry for offsite builds.

Common Cause Variation

Common cause variation is a stable, predictable and random source of variation caused by unknown factors, which is an inherent part of the system. This results in a consistent distribution of output around the mean (average) of data [6].

Cause and Effect diagram

A cause and effect diagram (also known as a 'fishbone' diagram) is a problem-solving tool that helps to identify possible causes of a specific problem in a visual manner. It is a structured approach where the effect is highlighted at the head or mouth of the fish and where possible causes are listed on the smaller 'bones' under the different categories; Manpower, Method, Material, Machine, Measurement, and Mother Nature.

E Eight Disciplines of Problem Solving (8D)

A problem-solving approach originally developed by the Ford Motor Company, now used throughout the automotive industry; it has also been successfully applied in other industries, e.g. manufacturing, healthcare, and finance. A useful tool in both product and process improvement, 8D is a methodology for identifying, correcting and eliminating recurring problems.

F Five (5) Why's method

An iterative technique for problem-solving and root cause analysis developed by Sakichi Toyoda for use at Toyota Motor Corporation in the 1930s. It is part of the 'analyse' phase of six sigma and is often used in conjunction with a fishbone diagram.

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 Measurement System Analysis (MSA)

A comprehensive assessment methodology to assess and validate a measurement system to identify the type of variation.

P Process Control (PC)

Process control enables monitoring of the process in such a way that any variation that makes the process unstable can be quickly identified and acted upon.

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.

S Structural Insulated Panels (SIP)

A structural construction component with a sandwich layout including two external layers of board and an insulating layer in between.

Statistical Process Capability (SPC)

An analytical methodology to identify and quantify the type of variation within the process to be a quality assurance for parts to be produced within a specification limit.

Special Cause Variation

Special cause variation is an unstable and often unpredictable cause of variation due to assignable causes that result in a shift in output. It is usually caused by a specific factor like environmental conditions introduced from outside of the process.

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 Voice of the Customer (VOC)

A business term to describe the process of capturing the customer's requirements, aversions and preferences in an easy-to-interpret manner.

Variation

Variation is the difference between an actual measure and the target value of a product characteristic.

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