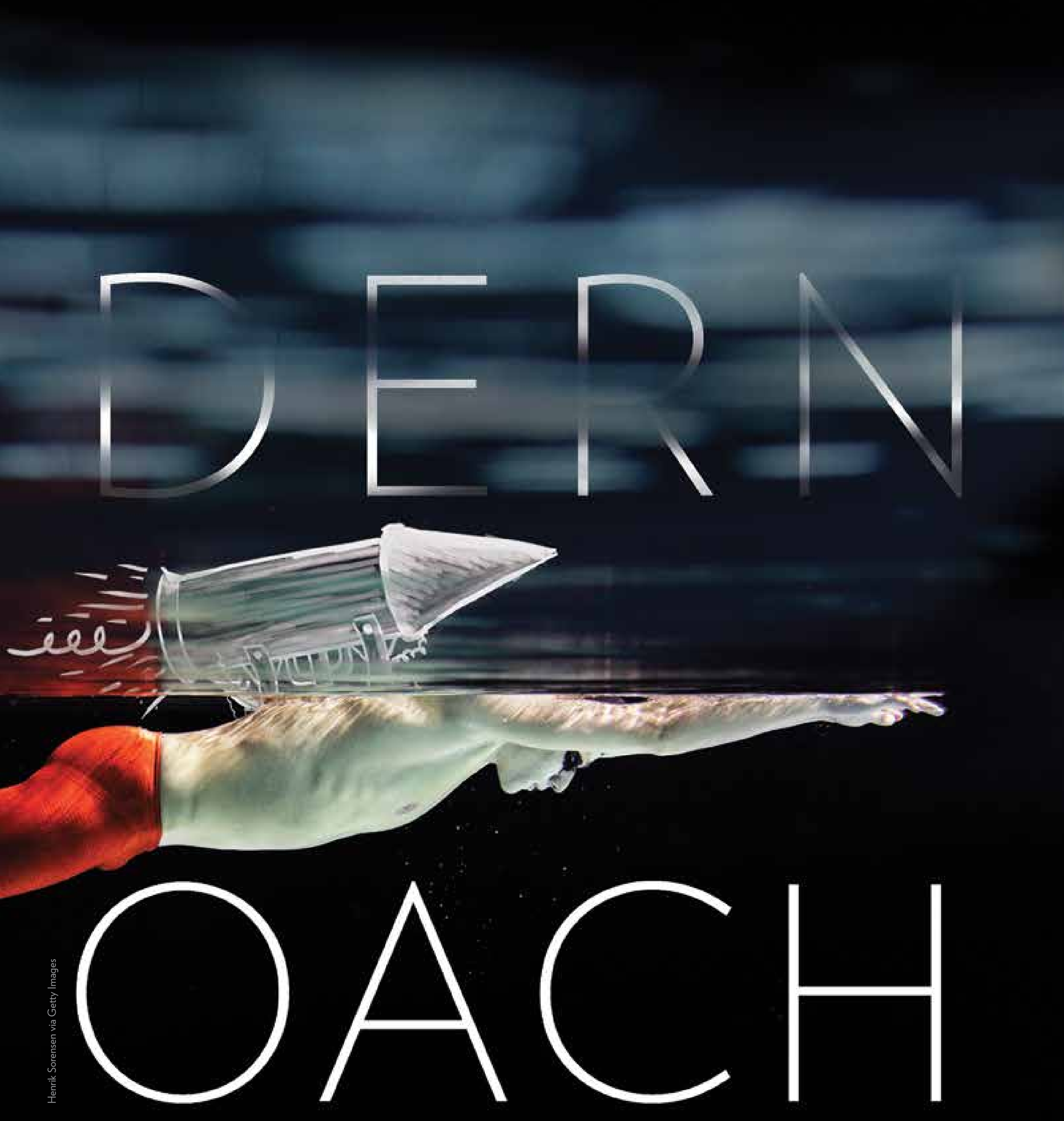
JUST THE FACTS

Traditional process capability analysis no longer is the best way to model performance in today's digital age, where dynamic environments and remote process monitoring require more rapid data analysis cycles to support automation.

The authors propose a new method that applies process capability and stability concurrently, which allows samples to be refreshed more frequently, thereby capturing the dynamic shifts in processes.

The authors answer the question: How can process capability methods be adapted to analyze non-normal time series data, such as that which occur in lean processes seeking to minimize cycle time or maximize productivity?



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Analyzing the capability of lean processes

by Roope M. Turunen and Gregory H. Watson

Process capability was developed at Bell Labs to supplement statistical process control (SPC) and indicate process design capability. It originated in the *Western Electric Statistical Quality Control Handbook*,[1] and Japanese quality managers adapted it to interpret their industrial processes.[2] This article describes how traditional process capability analysis can be adapted to analyze time-based processes that do not follow the normal distribution, as well as adapted to other performance metrics that exhibit "long tails" in their outcomes. This could be from bias caused by driving performance in a desired direction for the measure: productivity (bigger is better), cycle time (smaller is better), or cost (smaller is better).

This approach to analyzing process performance is relevant in the digital age in which dynamic environments and remote process monitoring require more rapid data analysis cycles to support automation. We recommend a new approach to advance process capability methods for exploratory data analysis applications of process control in which operating conditions have a single-bounded distribution that occurs when forcing a metric's performance behavior toward a minimum or maximum limit (for example, forcing the cycle time function toward its minimum level or driving performance toward a maximum).

In either case, the normal distribution no longer is the best way to model performance, and a different approach must be taken.

Typically, a process is considered capable if its mean is three to six standard deviations from the upper and lower boundaries of its specification limits.

Evolution of process capability as a method

The concept of process capability originated in the same Bell Labs group where Walter A. Shewhart developed SPC. Bonnie B. Small led the editing team for the *Western Electric Statistical Quality Control Handbook*, but the contributor of the process capability concept is not identified. The handbook proposes two methods by which to calculate process capability: first, "as a distribution having a certain center, shape and spread," and second, "as a percentage outside some specified limit."[3]

These methods were combined to create a ratio of observed variation relative to standard deviation, which is expressed as a percentage. The handbook does not call the ratio an index; this terminology was introduced

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by two Japanese quality specialists in their 1956 conference paper delivered to the Japanese Society for Quality Control (JSQC). M. Kato and T. Otsu modified Bell Labs' use of percentage and converted it to an index, and proposed using that as a C_p index to measure machine process capability. Subsequently, in a 1967 JSQC conference paper, T. Ishiyama proposed C_{pb} as a measurement index of bias in nonsymmetric distributions. This later was changed to C_{pk}, where "k" refers to the Japanese term *katayori*, which means "offset" or "bias."[4]

Since then, process capability has matured and developed. Many contributions occurred between 1986 and 1992 when 16 academic articles were published. They range from a 1986 overview by Victor E. Kane[5] to a 1988 proposal by Lai K. Chan, Smiley W. Chen, and Frederick A. Spiring to use non-normal data in capability.[6] The articles also include a series of pragmatic ideas on the use and abuse of capability studies by Berton H. Gunter.[7-10] A variety of capability analysis applications were cited in a book by Davis R. Bothe[11] and the doctoral dissertation of Mats Deleryd.[12]

Throughout this period, many "technical aid" columns by Lloyd S. Nelson were dedicated to pragmatic hints about how to manage these studies.[13] Most recently, a master's thesis by Roope Turunen coped with the idea of developing real-time applications of process capability analysis using digital monitoring of time series performance data in a more modern approach.[14]

Bell Labs proposed two ways to analyze productive processes. The first—the control chart method—uses time series analysis in what W. Edwards Deming called an analytic approach to data inquiry. The second method uses enumerative data in an exhaustive analysis of all observations to summarize overall results, similar to big data analysis.

According to Deming, the analytic approach is appropriate for determining causality among data in a distribution, and the enumerative approach is appropriate for determining risk relative to conformance to specified tolerance limits.[15] Thus, the best approach to maximizing process information is to use both methods together, rather than separately.

Process capability measurement methods follow Shewhart's 1930s teachings.[16] While the core principles remain relevant, the method is somewhat outdated in the environment of real-time digital data analytics. The method needs revision to accommodate the current state of data analytics. The normality assumption does not apply to single-bounded indicators such as time series data, which are captured by data historians as unitary observations. Shewhart's assumptions originated from his attempt to focus on the measurement process and eliminate measurement errors.

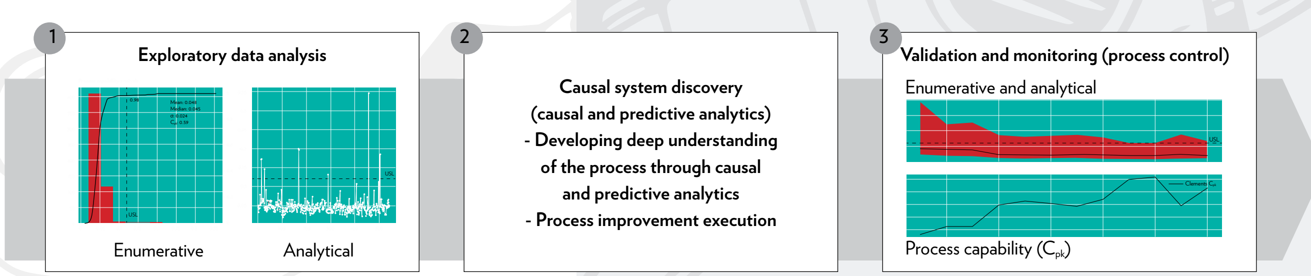
This assumption no longer is necessary because accurate sensor devices and sufficient computational power are available to process precise observations of real-time data with the support of advanced data analytics methods and visualization tools to provide clear interpretations for decisions. Specifically, the question this article addresses is: How can these process capability methods be adapted to analyze non-normal time series data, such as that which occur in lean processes seeking to minimize cycle time or maximize productivity?

Principles of process capability analysis

Measuring and monitoring process capability is necessary for two main reasons: to ensure sufficient quality of deliverables as judged by a specified critical-to-quality indicator, and gain insight into

FIGURE 1

Process capability as an improvement method—analytics workflow



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a process design to determine where to improve the process performance and reduce risk.

Process capability as a quality indicator. Classical process measurement originates from Shewhart's concepts of process capability and stability.[17] A process should be designed so its output is within a range where customers tolerate its performance. That means the process operates consistently within its specification limits.

Typically, a process is considered capable if its mean is three to six standard deviations from the upper and lower specification limits. If a process remains stable, it will predictably yield conforming output. To ensure process stability, control charts are used to monitor process mean and variation shifts, and thereby detect special-cause variations, which are changes that occur in the process's operating conditions due to a change in some process factor. The detection of special-cause variation initiates process improvement activity to shift the process output back to the desired zone of conformance.

Process capability as an improvement method. Data-driven process improvement can be managed in three phases, as illustrated in Figure 1 (p. 18):

1. Exploratory data analysis of the current state, which identifies issues indicative of process problems.
2. Causal system discovery and predictive analytics of their implications. This is a process of understanding the systems that create the problems. It discovers the relevant independent factors or the root causes of issues.
3. Verification and validation followed by monitoring for process control. In this phase, technical analysis of the proposed solution and in-situ assessment of its feasibility in its operating environment is conducted, and improvements are implemented. This step concludes whether the issue is solved or further analysis is required.

Process capability measurement is important for determining baseline performance, detecting issues, and validating outcomes of improvement actions. Process monitoring depends on the measurements to control post-improvement performance by comparing the new results to the baseline condition.

Weaknesses in classical process capability analysis. Shewhart recommended that process capability be applied only to stable processes.[18] Following his guidance, applying process capability typically is restricted to cases with stable processes after special causes of variation have been eliminated. This restriction does not support service or business processes, which tend to be dynamic and unstable by nature.

The trend toward developing more agile enterprises increases process activity, and this dynamic nature of processes must be analyzed. In such cases, process capability and stability need constant reassessment to ensure that inherent shifts and drifts are captured in a robust analysis method.

The objective of process improvement is to obtain tangible results of improved quality and productivity, increased customer satisfaction, and reduced operating costs. Therefore, the methods used should clarify process insights to enable appropriate operational response and manage results within desired performance limits. This dictates a need to improve methods for calculating and controlling process capability for real-time, non-normal data.

Process capability indexes must be redefined because the normality assumption, which originally was cited to simplify the method, actually distorts interpretations of time-based data that generate a "long tail" when non-optimal performance occurs. Depending on the actual distribution of output measures, the normality assumption either causes a more optimistic or more pessimistic approximation of process capability. This can be problematic when comparing alternative supplier performance when their processes' outputs have different distributions.

The proposed method applies process capability and stability concurrently, rather than assessing them consecutively.

Another issue with normal distribution tails is they extend to infinity, which is an unrealistic assumption when a process is bounded by a limiting natural condition. It calculates probabilities that are impossible in the real-world process. Process performance targets calculated using normality assumptions may result in larger-than-necessary investments in reducing process variation, while overly optimistic performance evaluation may result in increased cost of poor quality.

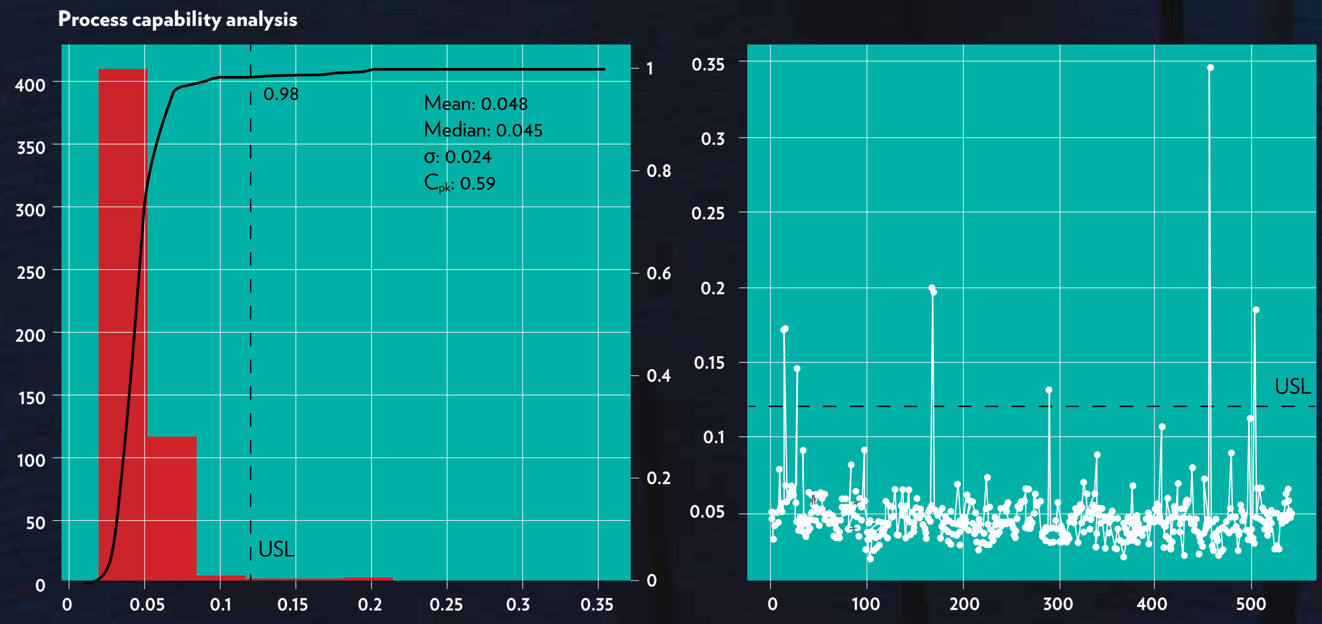
Considering these limitations of traditional process capability methods, an improved approach must be developed.

Modern approach to measuring process capability

The proposed method applies process capability and stability concurrently, rather than assessing them consecutively. Using simultaneous analysis allows samples to be refreshed more frequently and thereby captures the dynamic shifts in processes. These analyses should be done in parallel to gain a comprehensive view of the current process state. An enumerative analysis displays the sample distribution to provide insight into central tendency and variation. The analytic view illustrates the time dependency of individual data observations to indicate whether performance changes over time. A combined enumerative and analytic approach corresponds to the functions of a control chart and presents a side-by-side, comprehensive view of process performance. The enumerative view is displayed first to summarize the process state, while

FIGURE 2

Example of combined enumerative and time series capability analysis



USL = upper specification limit **Note:** These graphs are for illustrative purposes only.

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the analytic perspective presents the time dimension to interpret stability and special causes of variation. The proposed process capability combination chart is shown in Figure 2.

A proposed combined chart displays a frequency histogram with an overlaid cumulative distribution function (CDF) estimated from the sample population. This enumerative presentation of the data is intuitively pleasing because the histogram shows the experienced data on the left-hand Y-axis, while the CDF indicates an expectation of the proportion of nonconforming outputs on the right-hand Y-axis. An additional insight is generated by referencing the natural limits of the process as percentile ranges (for example, the fifth and 95th percentiles). The CDF should be calculated by a non-parametric method, such as the kernel density estimation (KDE) method, to overcome the inaccuracies from the normality assumption.[19, 20]

The right-hand chart in Figure 2 represents an intuitive time-series view using an individuals chart to display individual observations in time order of occurrence (similar to a run chart, but with the upper specification limit added). This reduces issues from poor sampling, which are common for X-bar R/S charts, and increases the traceability of dynamic process data.

The traditional unity chart uses control limits set at ± 3 standard deviations from the process mean to indicate special-cause variation from excessive variation based on its normality assumption. Control limits should be replaced with their corresponding upper and lower percentile values (ξ) calculated with a non-parametric distribution estimation to consider the shape of the output distribution.[21]

Control limits should be used with caution as incorrect use may lead to false alarms that distort process insights. Samples over long periods may include data from multiple causal systems, which causes the control limits to be too wide due to the increased variation, resulting in reduced outlier detection sensitivity. The cure for this problem is to segment samples into stages of rational subgroups that have individual limits. However, this requires detailed process knowledge to identify the rational subgroups for segmentation. A minimalist and straightforward approach is to exclude the control limits, as depicted in Figure 2. The process specification limits are used on this chart to establish a reference point for the enumerative and time-series graphs.

Applying process capability indexes using a modern approach

A graphical approach to process capability is the most intuitive way to compare two or more process outputs, but it might not be the most accurate. An explicit number, such as a process capability index, provides an accurate comparison (for example, comparing either before and after analysis, or assessing alternative supplier quality for making the same parts).

Process capability indexes expand the range of capability measurement beyond 100% conformance by using distance to specification limits as the unit of measurement. In other words, a process can be completely within the specification limits, yet there can be a better process with less variance and a median further from the specification.

Classic C_p and C_{pk} indexes lack robustness and accuracy due to their simplicity and normality assumption. A different approach to calculating process capability is to use a percentile-based estimate. The formula for C_{pk} using the percentiles method is illustrated in Figure 3. The percentile method for C_{pk} calculation is also called the Clements' method.[22] The percentile values should be estimated using a distribution estimation method, such as the KDE. Fitting the data to a normal distribution would be the same as using the classic C_{pk}.

Managing the time dimension in productive processes

Process improvement of lean processes controls time using process capability analysis, but these processes are not normally distributed. Lean processes are characterized by non-production environments with low stability. Examples include customer service and financial processes. Thus, the traditional use of process capability for processes in statistical control, based on Shewhart's recommendation, is not viable for such processes.[23]

Even though these processes cannot be controlled like production activities, there must be some method for estimating and monitoring their performance. Because lean processes are less stable due to multiple uncontrollable external factors, this increases the need for real-time capability monitoring. Therefore, a new view of process capability applicable to this circumstance is required.

One proposed solution combines plots of the time-series distribution with process capability. This combined approach retains intuitiveness by showing real data, while the capability index history gives a direct estimate of capability at a given time. This can be represented as a line plot, with process output on the y-axis and time on the x-axis. Three lines are plotted: one for the upper natural percentile (for example, the 99.865^{th} percentile), one for median and one for the lower natural percentile (for example, the 0.135^{th} percentile). The median expresses the central tendency while all three lines combine to show distribution shape and variation. Specification limits may be added to establish context. The second combination plot expresses the process capability index for each period. Figure 4 gives an example of this graph.

Regardless of process characteristics, capability measurement over longer periods is needed to provide a strategic

FIGURE 3

C_{pk} for USL and LSL according to the percentile method

$$C_p,\ upper = \frac{USL - \xi_{0.5}}{\xi_{0.99865} - \xi_{0.5}} \qquad C_p,\ lower = \frac{\xi_{0.5} - LSL}{\xi_{0.5} - \xi_{0.00135}}$$

C_{pk} = process capability index

LSL = lower specification limit

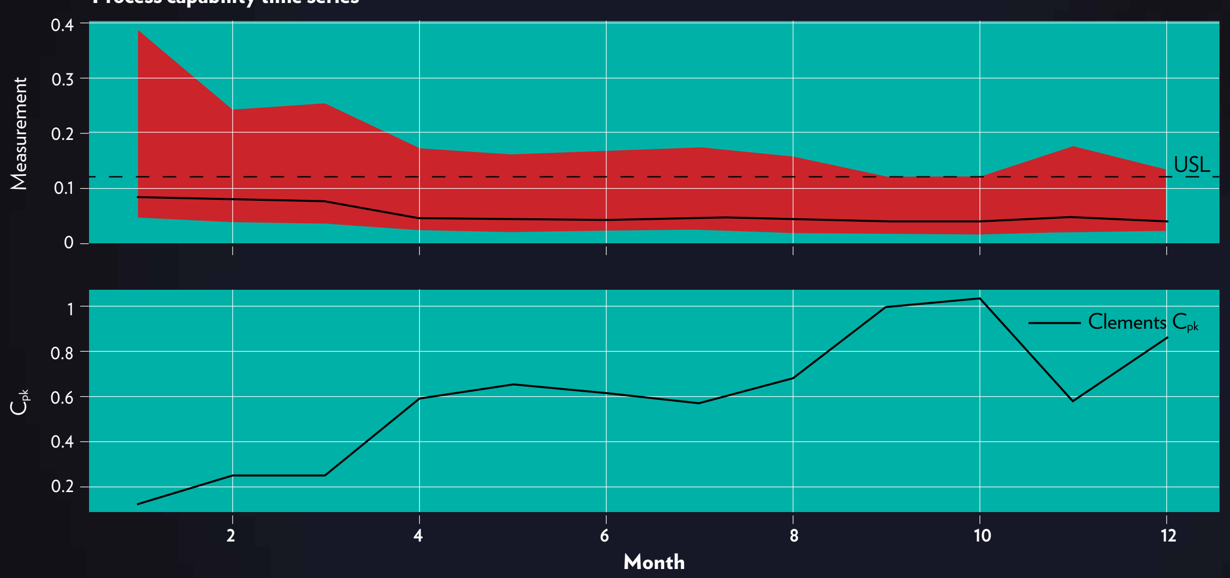
USL = upper specification limit

LEARN MORE

To learn more about process capability (C_p), visit ASQ's Learn About Quality page, "What Is Process Capability?" It covers everything from assessing C_p to practical concerns when conducting C_p studies, and includes a list of additional resources. Check it out at asq.org/quality-resources/process-capability.

FIGURE 4

Process capability analysis over longer time periods



USL = upper specification limit

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view for process capability to detect longer-term trends. The proposed chart may be used for different time frames depending on the stability of the process. Data over longer periods may be expressed as a series of box plots. This method is viable and presents change in central tendency and variation over time.

A new method

This article proposes a novel, robust method for process capability measurement as an innovative, action-oriented approach. The proposed method is based on the original concepts of process capability and process stability, which have been reconstructed using Clements' approach to capability analysis of non-normal time-series data and applied to manage rapid cycle-time adjustment of dynamic processes.

The analysis output merges enumerative and analytic views into a single chart. The enumerative process perspective combines a frequency histogram with a cumulative distribution function to indicate distribution shape and percentage of outputs within specification. The time-series perspective complements the enumerative one by displaying the time dependency of the process outputs to illustrate process stability. To control capability over time, a chart integrates the output percentile values with the process capability measures as a time-series plot. This method is applicable for real-time data analytics and may be implemented using engineering process control systems. **QP**

EDITOR'S NOTE
References listed in this article can be found on the article's webpage at qualityprogress.com.

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