JOURNAL OF ENGINEERING SCIENCES

Volume 10, Issue 2 (2023)

Haievskyi O., Kvasnytskyi V., Haievskyi V., Szymura M., Sviridova L. (2023). Refinement of the process capability index calculation. Journal of Engineering Sciences (Ukraine), Vol. 10(2), pp. B8–B15, doi: 10.21272/jes.2023.10(2).b2

Refinement of the Process Capability Index Calculation

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Article info:

Submitted:	May 31, 2023
Received in revised form:	September 23, 2023
Accepted for publication:	September 26, 2023
Available online:	September 27, 2023

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Abstract. The variability of product performance is the reason for the introduction of special methods to ensure product quality, particularly statistical methods. These include introducing statistical process control (SPC) in production and calculating the process capability index to determine the manufacturing ability to meet the product's quality requirements. To a large extent, the ability of a process to meet the requirements was determined by the location of the process or the mathematical expectation of the controlled quality characteristic value. Process setup center variability within the boundaries of the Shewhart control chart of the average values was supposed to be the natural state for a statistically controlled process. However, the calculation of the process capability index did not consider the possibility of a shift in the actual value of the process setup center for a controlled characteristic from its mathematical expectation. It was proposed to adjust the process capability index for the setup center's possible deviation. It demonstrated the possibility of critical errors in determining the ability of a production process to meet requirements without considering the process setup center. The effectiveness of the proposed solutions was also demonstrated by the example of determining the ability of the welding wire manufacturing process to meet the requirements for metal yield strength of the welded joint of metal bridge span constructions.

Keywords: statistical process control, Shewhart control chart, control limit, specification limit.

1 Introduction

Variability of the production processes implementation terms leads to variability of the product characteristics values at the output. This causes additional difficulties when performing tasks of applied mechanics, including ensuring compliance of product quality characteristics with the established requirements, evaluating performance parameters of materials, structures, and machines in operating conditions, and ensuring a given level of reliability of structures and processes. As a result, there is some uncertainty in production terms and a need to apply statistical methods to estimate the values of product and process indicators and determine their acceptability. Thus, there is a need to apply statistical methods and appropriate Capability indicators to both measurement and production processes [1, 2].

The modern world is characterized by more sophisticated products and, hence, more sophisticated production processes. This increases the probability of product failures during operation and complicates the possible consequences of such failures. Thus, the risk of failure in meeting product quality requirements also increases [3].

The possibilities to influence the consequences of failures during product service are limited. Therefore, the only available risk mitigation method is to reduce the probability of failure by applying quality control methods in production that allow the detection of nonconformities in time or even prevent their occurrence [4].

The process capability index helps avoid nonconformities by providing a "safety margin" to ensure that controlled quality indicators do not fall outside the range of acceptable values [5, 6].

Research aimed at refining the calculation of the process capability index is relevant and essential as it facilitates the reduction of product failure risks.

The subject of this study is the impact of variability on the ability of production processes to meet product quality requirements. The object of the research is the method of calculating the process capability index.

2 Literature Review

The traditional approach to ensuring product compliance is timely detection of non-conformances and management of non-conforming products when such non-conformities are detected.

With this approach, a 100 % or selective check of compliance of products with established requirements is carried out.

Applying 100 % verification is not always possible [7]. First, verification methods may involve destructive testing. In this case, we receive information about the quality (compliance with established requirements) of the research object but lose the object and the possibility of its further use.

Secondly, there are limitations of resources for inspection, including the number of employed personnel, measuring equipment and equipment, and measurement works' performance time. In addition, the possibility of slippage of defects should be considered even with 100 % control [8].

These factors led to the need to develop methods of random inspections [9, 10]. In the case of a random inspection of a sample of a relatively small volume, a conclusion is made about the acceptability of the general population. A batch of products that should be accepted or rejected is considered as a general population. A batch of products may be purchased, manufactured, or shipped for further use. Methods of statistical sampling control are widely used to determine control plans.

The most widespread is statistical selective control on alternative and continuous features [11].

The application of plans ($n – c$) of statistical selective control on an alternative basis involves selecting a statistically justified number of samples n from the controlled batch of products. If the number of non-conforming values x does not exceed the acceptance number c, then the entire batch of products is considered acceptable and accepted.

International standards maintain the control plans ($n – c$) and depend on the product's batch volume N and the acceptable quality level (AQL). The disadvantage of this approach is the relatively large sample size n, which can be significantly reduced by using statistical sampling control on a quantitative basis.

Statistical sampling control for a continuous characteristic is carried out according to a plan ($n – ks$). This approach is statistically proven and requires relatively small sample volumes, but it is focused on controlling individual batches of products and does not contain signs of a modern process orientation [12]. That is, there is a reaction to the emergence of non-conforming products, and the task is to prevent the appearance of non-conformities.

The following studies [13, 14] have shown that the prevention of inconsistencies is facilitated by implementing the principles of system and process approach [15] to product quality assurance.

The implementation of the system approach involves ensuring product quality at all stages of its life cycle [16, 17], including the stages of marketing, product design, and development of processes necessary for manufacturing, procurement, preparation of production and production, quality checks, sales, installation, and product use support.

For all processes, it is essential to ensure the coordination of work [18], provide the necessary resources, perform activities to monitor processes and their inputs and outputs, set target values for controlled process indicators, and ensure the motivation of personnel involved in the processes. All processes of the life cycle of products are significant. However, operations that actively shape product quality indicators are part of production processes. Therefore, production processes are crucial from the point of view of ensuring compliance of products with established requirements.

All processes of the life cycle of products are significant. However, operations that actively shape product quality indicators are part of production processes. Therefore, production processes are crucial from the point of view of ensuring compliance of products with established requirements.

Modern methods of implementing the principle of a system approach to ensuring product quality are supplemented using statistical methods of managing product compliance by ensuring the ability of the production process to meet requirements. These methods include statistical process control (SPC), based on the application of Shewhart control charts [19], and the method of determining the process capability index [5, 6]. These two methods are used together. The use of Shewhart control charts makes it possible to determine the statistical controllability of the process and the output data for calculating the values of the process capability index. The index values determine the ability of the statistically controlled production process to meet the requirements. The Process Capability Index is used to find opportunities to reduce variability when applying the Six Sigma concept [20]. The decrease in variability results in increased customer satisfaction [21] and improved economic activity indicators [22].

The analysis of literature, as well as the practice of applying the process capability index, indicates a certain inconsistency in the approaches to the use of the values of the production process setup center (mathematical expectation of the quality indicator value) in the approaches adopted in statistical process control and in determining the process capability index. Statistical process control allows for natural variability of the values of the production process setting center within the Shewhart control chart's limits (LCL – UCL). However, the process capability index value is calculated based on the center line ordinate (CL), and the possibility of the variability of the location of the production process setup center is not considered. This can lead to incorrect conclusions when assessing the ability of a production process to meet quality requirements.

The research aims to investigate the impact of shifts in the production process setup center on the value of the process capability index.

The research objectives are as follows:

– to determine the possibilities of specifying the values of the process capability index to consider the variability of the location of the production process setup center;

– to study the effectiveness of applying the proposed refinement to determine the ability of the production process to meet product quality requirements.

3 Research Methodology

3.1 Methodology for determining the process capability index

The study is based on the well-known methodology for assessing the ability of a process to meet quality requirements by the process capability index [6].

A quality indicator is an indicator x for which requirements are specified for the range of acceptable values. This range can be bilateral or unilateral. The upper limit of the range of acceptable values is denoted as the upper specification limit USL, and the lower limit of the range of acceptable values is denoted as the lower specification limit LSL.

The process capability index is determined by the bilateral specified tolerance or separately by the USL – upper limit and LSL – lower limit of the specified tolerance.

The bilateral specified tolerance determines the process capability index:

$$C_p = \frac{USL-LSL}{6\sigma}, \qquad (1)$$

where σ is the root mean square deviation of the monitored indicator x.

A larger index corresponds to a more significant difference between the width of the range of permissible values and 6σ – the width of the range of natural dispersion of the monitored indicator. In the meantime, the process potentially has a more significant margin in terms of fulfilling the requirements in the given USL – LSL – a range of permissible values. According to the index, the following target minimum acceptable value is set:

$$C_p^0 \geq 1.66. \qquad (2)$$

That is, the higher the index value, the higher the ability of the process to meet the requirements, but for each case, a target level C_p^0 is set separately, which should not be less than 1.66.

The value of the squared deviations from the mean (SDM) of the monitored indicator x is estimated by the sample range R or s – the sample standard deviation value. The estimation of the mean square value through the sample standard deviation is a more accurate estimate. In this case, the standard deviation is determined as follows:

$$\sigma = s = \sqrt{\frac{\sum_{i=1}^{n}(\bar{x}-x_i)^2}{(n-1)}}, \qquad (3)$$

where n is the sample size of the values of the monitored quality indicator x; x_i is individual value of indicator x in the sample (i = 1, 2, .,., n); $\bar{x}$ is the arithmetic mean value of indicator x in the sample.

The arithmetic mean value of the indicator x in the sample is defined as

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}. \qquad (4)$$

The arithmetic mean value is used to determine the location of the production process setup center for the monitored parameter x or its mathematical expectation μ.

The process setup center significantly influences the process's ability to meet the quality requirements for the monitored parameter. However, the process capability index on the bilateral specified tolerance does not consider the process setup center. Therefore, it only allows for the potential ability of the production process to meet the requirements.

The process capability indexes C_{pl}, C_{pu}, and C_{pk} are used to consider the impact of the process setup center on its ability to meet the requirements.

The lower limit of the range of acceptable values determines the process capability index:

$$C_{pl} = \frac{\mu-LSL}{3\sigma}. \qquad (5)$$

The process capability index is determined at the upper limit of the range of permissible values:

$$C_{pu} = \frac{USL-\mu}{3\sigma}. \qquad (6)$$

For the bilateral tolerance range, the process capability index with the process setup center μ is defined as the minimum value of the two C_{pl} and C_{pu}:

$$C_{pk} = \min\,(C_{pl}, C_{pu}). \qquad (7)$$

For a unilateral range of permissible values, the corresponding index for the lower or upper limit is used:

$$C_{pk} = C_{pl} \cup C_{pu}. \qquad (8)$$

Considering the process setup center, a higher value of the process capability index corresponds to a more remarkable ability of the production process to meet the requirements set by the x indicator. The target value of the index C_{pk}^0 is set for each case separately. This is based on the following conditions:

$$C_{pk}^0 \geq 1.33. \qquad (9)$$

It is impossible to increase a process's ability to meet requirements compared to its potential ability by setting it up, even if it is the most optimal. Therefore, it is always a fair ratio:

$$C_p^0 \geq C_{pk}^0. \qquad (10)$$

The question of the ability of a process to meet the quality requirements for x makes sense only if the process is stable in terms of this indicator. That is, the process is statistically controlled, and uncontrolled spontaneous “leaps” in the quality indicator are excluded. Such “leaps” can put the indicator’s value outside the range of acceptable values. A quality indicator value outside the range of acceptable values is a non-conformance. Non-conformance can lead to product failure or restriction of its functionality. Thus, there are risks associated with failing to meet the established requirements.

3.2 Methodology of statistical control of the production process

The second basic research methodology is the method of statistical process control (SPC) [19].

Statistical process control is based on the use of the Shewhart control chart.

The field of the control chart consists of three parallel lines. In the middle is the central line - CL. From above, the control chart field is bounded by the upper control limit – UCL. From the bottom, the control chart field is bounded by the lower control limit – LCL (Figure 1).

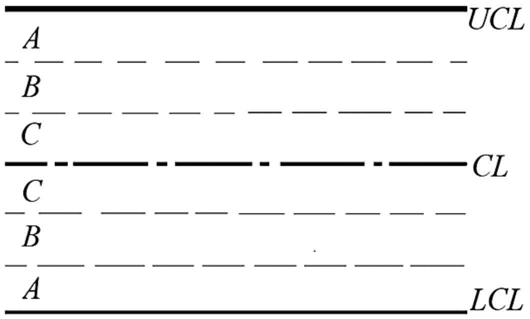

Figure 1 – Shewhart control chart field

Above and below the center line, the control chart field is divided into three zones (A, B, and C) of equal width.

There are more than ten varieties of Shewhart control charts. Based on the study’s objectives, we will focus on using the average value control chart.

The construction of a control chart consists of the following stages. The first one is data collection. With the settings of the process under study unchanged, data are collected on the value of the controlled characteristic *x* in *m* = 25 samples of a given volume *n*.

The second stage is to determine the statistical characteristics of each sample. For each sample, the process setup center μ_j is calculated as the mean arithmetic value (4) and σ_j – is the mean square deviation of the characteristic *x* as the standard deviation in the sample (3).

The last stage is to determine the values generalized from 25 samples. The value of the process tuning center for *m* = 25 samples is calculated as the average of the mean values:

$$\mu = \frac{\sum_{j=1}^{m} \mu_j}{k}. \tag{11}$$

Calculate the mean square deviation for *m* = 25 samples:

$$\sigma = \sqrt{\frac{\sum_{j=1}^{m} \sigma_j^2}{k}}. \tag{12}$$

This stage is based on the preparation of the Shewhart control chart. The lines on the Shewhart control chart are calculated.

The center line:

$$CL = \mu. \tag{13}$$

The upper control limit:

$$UCL = CL + k\sigma. \tag{14}$$

The lower control limit:

$$LCL = CL - k\sigma, \tag{15}$$

where *k* is a coefficient, the value of which depends on the volume of the sample *n* (Table 1).

Table 1 – Values of the coefficient *k* for the Xbar control chart using standard deviations

n	2	3	4	5	6	7	8	9	10
k	2.65	1.95	1.62	1.42	1.28	1.18	1.09	1.03	0.97

The calculated values of the lines to scale are entered in the Shewhart control chart field.

The distance between the center line and the control limits is divided into three equal parts. This is how the field is prepared, and the control chart’s A, B, and C zoning is done.

In the last fourth step, the 25 values of the process setup center μ_j, obtained for each sample are transferred to the control chart field as points. Segments and the following seven criteria sequentially connect the points are used to identify samples that were formed under the influence of a particular cause:

1) one or more points are outside the control limit;

2) three consecutive points are on the same side of the center line. Two of these three points are in zone A or further from the center line;

3) five consecutive points are on the same side of the center line. Four of these five points are in zone B or further from the center line;

4) nine consecutive points are on the same side of the center line, regardless of the location zone;

5) six consecutive points arranged in ascending or descending order;

6) 14 consecutive points are alternately located from top to bottom;

7) 15 consecutive points are in zone C on both sides of the center line.

The absence of points (groups of points) on the control chart that meet at least one criterion for the influence of special causes is evidence of the stability and statistical controllability of the process according to the controlled characteristic.

The process capability index can be determined considering the process setup center for a statistically controlled production process.

Typically, C_{pk} is calculated using the value of μ as the arithmetic mean of 25 samples. The exact value is the ordinate of the CL line on the control chart. This approach does not consider the possibility of a natural shift of the process setup center within the limits of the Xbar control chart.

4 Results

The Xbar control chart, with its control limits, defines the range of natural dispersion of the values of the process setup center for the controlled parameter x.

In the traditional approach to calculating the process capability index regarding the process setup center (7) and (8), the value of μ is used as the center line on the control chart. Meanwhile, the possible actual values of the process tuning center are not limited to the center line (Figure 2).

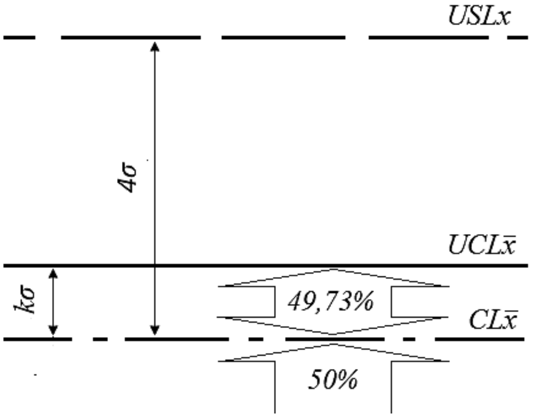

Figure 2 – Range of possible values for the set point of a statistically controlled process

As shown in the example of the upper part of the control chart, inverse to the upper permissible value of USL, there is a 50 % probability that the process setup center is located below the CL line, in which case the actual value of C_{pk} will be greater than the one calculated by (7) and (8). In this situation, we get an additional “strength margin” for meeting the requirements set for the controlled parameter x.

However, there is a 49.73 % probability that the actual value of the process setup center will be greater than the calculated (11) value of μ, i.e., it will be above the CL line. In this case, the actual value of C_{pk} will be less than the calculated value in (7) and (8).

The possible actual values of the production process setup center for the controlled parameter x can significantly differ from the calculated (11) value of μ. The degree of deviation is determined by the value of the coefficient k (Table 1). Simultaneously, the more significant the sample size n, the smaller the value of the coefficient k and the smaller the possible deviation of the actual values of the production process setup center for the controlled indicator x from the calculated (11) value μ.

Figure 3 shows a situation with the lowest possible value of the coefficient $k = 0.97$ at the maximum possible sample size $n = 10$ (Table 1).

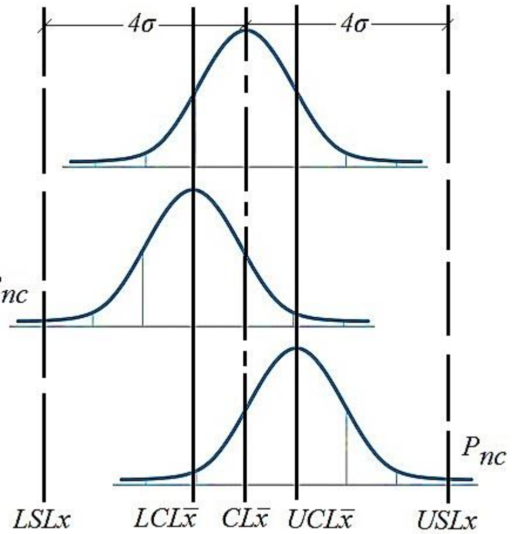

Figure 3 – Application of the traditional approach to defining the process capability index considering the process setup center

This situation corresponds to the minimum possible deviation of the actual values of the production process setup center for the controlled indicator x from the calculated (11) value of μ.

Figure 3 shows that even under the most favorable conditions ($n = 10$, $k = 0.97$), there is a significant possibility of non-compliance even with acceptable calculated values of the process capability index. The calculation according to the upper limit of acceptable values (6) provides the following result:

$$C_{pu} = \frac{USL-\mu}{3\sigma} = \frac{4\sigma}{3\sigma} = 1.33, \qquad (16)$$

which can be considered a perfectly acceptable value of the process capability index, considering the process setup center.

Meanwhile, there is a possibility of 0.27 % non-conformity with the lower limit of acceptable values and the same possibility of non-conformity with the upper limit of acceptable values. The total probability of non-conformity of 0.57 % is quite significant. That is, 57 out of 10,000 cases will result in a discrepancy. If such non-conformity is associated with a potential threat to human life and health, the situation contains an unacceptable risk level.

Thus, applying the traditional approach to calculating the process capability index, considering the process setup center, leads to significant non-conformity risks for potentially hazardous products.

To overcome this situation and reduce the probability of non-conformity, we propose to adjust the value of the process capability index for possible deviation of the process setup center by calculating the process capability index at the lower limit of the range of permissible values using the revised formula:

$$C^*_{pl} = \frac{(\mu-k\sigma)-LSL}{3\sigma}, \qquad (17)$$

the process capability index at the upper limit of the range of acceptable values should be determined more precisely:

$$C^*_{pu} = \frac{USL-(\mu+k\sigma)}{3\sigma}. \qquad (18)$$

Figure 4 shows the effect of updating the process capability index calculation on the range of acceptable values width.

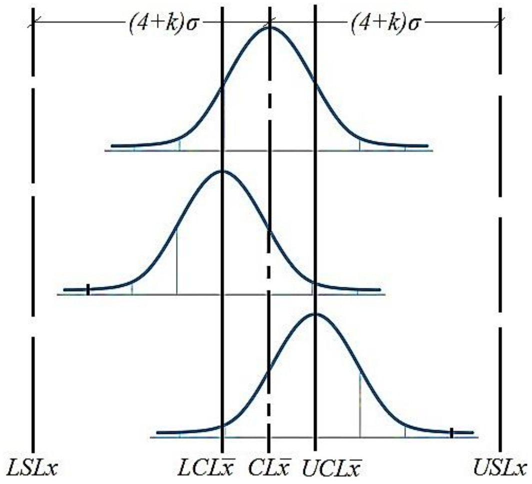

Figure 4 – Application of the updated calculation to determine the process capability index with consideration of the process setup center

From the abovementioned, it can be concluded that the distance of 4σ from the calculated process setup center μ to the USL and LSL specification limits of the values is insufficient to consider the process acceptable at the level of $C^0_{pk} = 1.33$. To ensure process compliance at $C^0_{pk} = 1.33$, increasing this distance to $(4 + k)\cdot\sigma$ is necessary. This increase allows the process to be suitable even if the process setup center is on the limit of the mean value control chart.

As an example of updating the value of the process capability index for a possible deviation of the process setup center, the results of determining the ability of the X-3Si1 welding wire manufacturing process to meet the requirements of state building codes DBN B.2.3.-26:2010 for welded structures of metal bridge spans are presented.

S355J0WP (10KHSND-2, C390) 14 mm rolled steel is used to construct metal bridge spans. Therefore, pilot samples were made from this rolled steel in the production experiment. The welded edges were developed using the V-shaped method.

During the experiment, welding wire from one production batch was manufactured under the same production process settings. During production, 10 m of wire was taken every two hours to weld a series of three samples.

Each series (sample) of three samples was welded at the same settings of the arc welding process in the M21 active gas mixture. Thus, twenty-five samples were formed, with three samples in each sample. Simultaneously, each sample differed in the time of welding wire production.

The minimum allowable yield strength of the weld metal of metal bridges made of S355J0WP steel (10KHSND-2, C390) is required to be 390 MPa.

Table 2 shows the yield strength values obtained in twenty-five samples.

Table 2 – Yield strength of metal butt joints of 14 mm 10KhSND-2 (C390) rolled products welded with X-3Si1 wire in M21 mixture

Sample no.	σ_T, MPa			μ_j, MPa	σ_j, MPa	C_{pkj}
	1	2	3			
1	495	493	524	504.0	17,36	2,19
2	498	519	488	501.7	15,82	2,35
3	528	493	497	586.0	19,16	2,02
4	499	471	507	492.3	18,90	1,80
5	531	497	505	511.0	17,78	2,27
6	522	539	501	520.7	19,04	2,29
7	488	497	509	498.0	10.54	3.42
8	479	483	489	483.7	5.03	6.20
9	491	472	470	477.7	11.59	2.52
10	505	479	493	492.3	13.01	2.62
11	538	497	499	511.3	23.12	1.75
12	509	482	479	490.0	16.52	2.02
13	485	496	472	464.3	12.01	2.62
14	499	483	520	500.7	18.56	1.99
15	531	496	521	516.0	18.03	2.33
16	540	487	533	520.0	28.79	1.51
17	527	483	472	494.0	29.10	1.19
18	488	544	507	513.0	28.48	1.44
19	508	539	523	523.3	15.50	2.87
20	537	521	502	520.0	17.52	2.47
21	485	487	534	502.0	27.73	1.35
22	498	493	555	515.3	34.44	1.21
23	479	482	509	490.0	16.52	2.02
24	507	477	469	484.3	20.03	1.57
25	490	533	507	510.0	21.66	1.85
Generalized values for 25 samples				502.47	19.05	1.97

To determine the statistical controllability of the electrode wire manufacturing process in terms of the weld metal yield strength, the Xbar control chart for 25 samples was constructed according to Table 2 (Figure 5).

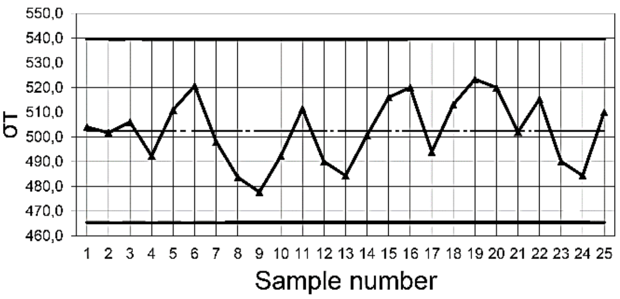

Figure 5 – Xbar control chart values of yield strength σ_T. MPa. for metal welded with X-3Si1 electrode wire

The points of the control chart were inspected according to the criteria for the influence of special causes. None of the criteria was detected.

The presented control chart does not contain signs of the influence of special causes. Thus, the yield point of the weld metal statistically controls the process of manufacturing the X-3Si1 electrode wire. The arithmetic mean value of the yield strength (center of the process setup) generalized for 25 samples is μ = 502.5 MPa, and the root mean square deviation σ = 19.1 MPa. Simultaneously, the process has a sufficiently high value of the process capability index:

$$C_{pl} = \frac{\mu - USL}{3\sigma} = \frac{502.47 - 390}{3 \times 19.05} = 1.97. \quad (19)$$

However, after considering the possibility of shifting the setup center of the wire production process to the LCL of the Xbar control chart (Figure 4), the calculation for the value of the coefficient k = 1.954 with a sample size of n = 3 should be specified:

$$C^{*}_{pl} = \frac{(\mu - k\sigma) - USL}{3\sigma} = \frac{(502.47 - 1.954 \times 19.05) - 390}{3 \times 19.05} = 1.31. \quad (20)$$

The obtained updated value of the process capability index is 34 % less than the evaluated C_{pl} = 1.97 and less than the minimum acceptable value of the target level (9) C^{0}_{pk} = 1.33. Therefore, due to the shift of the center of the process setup, the process capability index can take values lower than the target level of 1.33. This is also evidenced by the recorded low process capability index values in the seventeenth sample (C_{pk} = 1.17) and the twenty-second sample (C_{pk} = 1.21).

5 Discussion

Inconsistencies in the yield strength of weld metal due to too low values of the process capability index are a source of risks and may become a potential issue when using X-3Si1 wire for welding potentially hazardous objects, which include metal bridge spans.

As a result, it was decided not to use the studied production batch of X-3Si1 wire for arc welding in a mixture of M21 shielding gases on metal bridge span structures made of 14 mm S355J0WP (10HSND-2, C390) rolled products. The reason for the failure was the determined inability of the production process to meet the requirements for the yield strength of the weld metal.

The assumption about the possibility of shifts in the center of adjustment of the process is the statistical basis of the concept of Six Sigma. The application of this concept is aimed at ensuring customer satisfaction [16], improving economic activity indicators [22], providing conditions for Lean Production [23], and organizing continuous improvements based on a comprehensive reduction of variability [20].

However, fully implementing the concept of Six Sigma in production processes is a rather challenging problem. As shown in the example, the proposed Refinement of the Process Capability Index Calculation allows with minimal costs to consider the possibility of shifts in the center of the process setting when assessing the process acceptability.

6 Conclusions

Based on the possibility of changing the location of the setup center of a statistically managed production process within the control limits of the Shewhart control chart, it is proposed to adjust the value of the process capability index for the possible deviation of the process setup center $k\sigma$.

It is shown that even under the most favorable conditions of applying the well-known calculation of the process capability index, the incorrect acceptance of the production process may be acceptable in terms of the ability to meet the requirements at the level of C^{0}_{pk} = 1.33.

Simultaneously, up to 0.57 % of non-conforming products may appear because of the deviation of the process setup center. The proposed update to the calculation of the process capability index prevents such an error from occurring.

In the example of assessing the acceptability of the welding wire manufacturing process, it is shown that with the calculated value of the process capability index C_{pl} = 1.97, the actual possible value with the proposed refinement was C^{*}_{pl} = 1.31.

The timely information obtained about the unsuitability of the production process to meet the requirements for the yield strength of the weld metal made it possible to prevent unacceptable risks of inconsistencies when using the studied production batch of X-3Si1 wire for arc welding in a mixture of shielding gases M21 of the structures of metal bridge spans made of 14 mm S355J0WP (10HSND-2, C390) rolled products.

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