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THE IMPROVEMENT OF MANUFACTURING PROCESS THROUGH THE USE OF STATISTICAL PROCESS CONTROL

Key words: improvement, process stability, process capability, Statistical Process Control (SPC).

Abstract: In the present paper, we describe a sample application of Statistical Process Control aimed at improving the manufacturing process and enhancing the quality of the manufactured product. The selected object of study included a high-density polyethylene (HDPE) film manufacturing system and mass-produced plastic bags. The examination carried out during technological tests confirmed process capability for manufacturing a oproduct of proper quality. The reexamination which followed the identification of non-conformance of the product indicated the loss of this capability. It resulted in detecting variations and their source and, consequently, any non-conformances arising in the manufacturing process were eliminated.

Doskonalenie procesu produkcyjnego folii polietylenowej wysokiej gęstości z zastosowaniem SPC

Słowa kluczowe: doskonalenie, stabilność procesu, zdolność procesu, statystyczne sterowanie procesem (SPC).

Streszczenie: Przedstawiono przykład zastosowania Statystycznego Sterowania Procesem (SPC) w celu doskonalenia procesu produkcyjnego oraz poprawy jakości produkowanego wyrobu. Jako obiekt badawczy przyjęto system produkujący folię polietylenową wysokiej gęstości HDPE oraz torebki foliowe w warunkach produkcji masowej. Badania przeprowadzone w trakcie prób technologicznych potwierdziły zdolność procesu do produkcji wyrobu o odpowiedniej jakości. Powtórne badania przeprowadzone po wykryciu niezgodności wyrobów gotowych wskazały na utratę zdolności do produkcji odpowiedniej jakości wyrobów. W wyniku przeprowadzonych badań zidentyfikowano nieprawidłowości występujące w procesie produkcyjnym, wskazano przyczyny ich występowania oraz zaproponowano rozwiązania pozwalające na wyeliminowanie wykrytych niezgodności.

Introduction

The occurrence of variability in a manufacturing process is one of the major threats that manufacturers face in their efforts to attain a high quality of the products. According to the definition of quality, outlined by Montgomery [1], "quality is inversely proportional to variability." One of the means of evaluating the degree of variability in the manufacturing process is the application of statistical methods. The use of statistical methods of quality assurance is presently gaining popularity and becoming common in bigger manufacturing companies [2–5] However, for economical reasons, it is not being adopted in small and medium-sized enterprises [6–7]. On the one hand, such a state of affairs may be accounted for by deficiencies in human resources and, on the other hand, by the lack of knowledge about the benefits provided by the usage of Statistical Process Control.

The issue regarding the effective usage of statistical methods for the evaluation and improvement of manufacturing processes has been looked at by many authors [8–10]. Paper [8] is concerned with the strategies for improving qualitative process capability by diagnosing parameters that mark its variability. The research discussed in [8] focused on determining the impact of variability symptoms on the process with regard to the adopted tolerance limits. Paper [9] presents selected practical applications of SPC tools, such as control charts used in decreasing the cost of the manufacturing process. In paper [10], the use of control charts $\bar{x}-s$ to detect shifts in the manufacturing process is described.

The present paper demonstrates how Statistical Process Control can be used in a plastics processing company. A polyethylene film and plastic bag manufacturing system was chosen as the object of the study. In the course of the manufacturing process, problems connected with breaking at the side seals were detected during tensile strength tests. The improvement of the manufacturing process was carried out with the use of control charts $\bar{x}-s$ and based on the analysis of the 12-month lifetime of the product. The paper includes examples of the use of Statistical Process Control methods in the phase of technological tests, in the phase of detecting non-conformances in the process of production, as well as the phase of implementing a corrective action plan.

1. Problem description

The process of manufacturing polyethylene plastic bags constituted the object of study. The process of creating a plastic bag comprises two main steps: extrusion of film in the extruding machine and sealing the bags in a welding machine (Fig. 1).

Fig. 1. The process of plastic bags production

The extruder is equipped with special sensors for thickness profile measurement. The results are transferred to the main computer where the data are verified and the appropriate response of the air ring is provoked (Fig. 2).

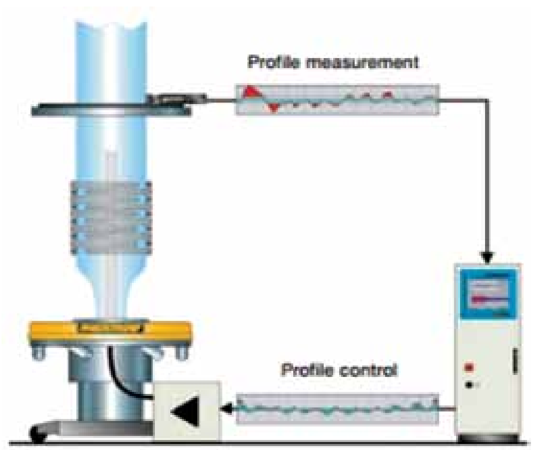

Fig. 2. Film profile measurement and automatic adjustment of film thickness by means of air ring

The main raw material used in the process is high-density polyethylene (HDPE). The finished product must meet the customer's requirements with regard to physical, mechanical, and chemical parameters. One of the significant technical parameters is the bag's thickness, which is directly related to the thickness of the plastic film used for its production. In the analyzed case, the customer's specification requested that the mean thickness of polyethylene film was 20 µm +/- 2 µm. Figure 3 presents a microscopically magnified cross section of the PE film (digital microscope VHX-6000 series) and the results of the measurement.

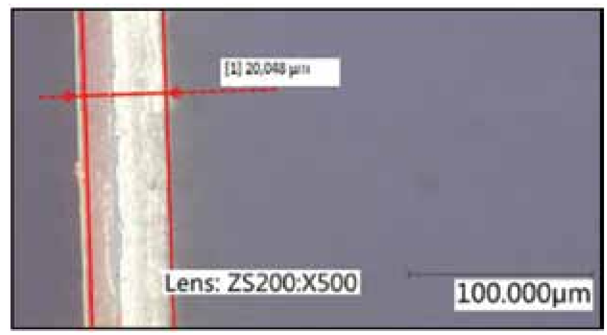

Fig. 3. A microscopically magnified cross section of the PE film and the results of the measurement

Due to stringent size tolerance limits, a statistical analysis of the manufacturing process was performed in order to confirm the possibility of manufacturing the product according to the assumed specification. On the technological side, it is essential to check the value of the standard deviation from the average thickness measured on the roll's circumference. A methodology for improving the process of production was then employed, consisting of three phases: the pre-production phase, the production phase, and the phase of detecting errors and implementing a corrective action plan.

The pre-production phase included the collection of data and checking the data for normality. Next, control charts $\bar{x}-s$ were constructed and analyzed. Then, process capability was tested with indices P_p and P_{pk}.

After observing a significant increase in the defectiveness of the final and semi-finished product in the production phase, control charts $\bar{x}-s$ were revised and analyzed, and indices of process capability C_p, C_{pk} and P_p, P_{pk} were determined. In the final phase, the causes of variation were identified, a recovery plan was implemented and the process capability was evaluated again.

The following part of the paper will present the particular phases of production process improvement.

2. Pre-production phase

The pre-production step required the collection of data relating to the thickness of the manufactured polyethylene film and the plastic bags made of it. The measurements were taken in 20 evenly distributed points on the circumference, which, given the total circumference length of 2.8 m, results in measurements repeated every 0.14 m. The measurements were made at 20 points along the coil length. In total, 400 measurements were taken whose average values and range were presented in Table 1. Next, 20 samples of the final product (plastic bags) were collected from the welding machine and each was measured at 20 evenly distributed points. Given the nominal length of the bag's circumference of 0.92 m, the measurements were taken every 0.046 m. Altogether, there were 400 measurements of thickness of the final product taken. The mean value and standard deviation of the measurement were presented in Table 2. During the collection of the samples, technological parameters remained unchanged and the process was not stopped.

Table 1. The mean values and standard deviations of the thickness measurement of polyethylene film produced in the Alpine 4 extruder

Sample	1	2	3	4	5	6	7	8	9	10
$\bar{x}$	20	20.2	20.1	20	20	20.1	19.9	20.1	20	19.9
s	0.46	0.37	0.31	0.46	0.32	0.45	0.31	0.45	0.39	0.31

Sample	11	12	13	14	15	16	17	18	19	20
$\bar{x}$	20.1	20.1	20	20	19.9	20	20	20.1	20.1	20.1
s	0.31	0.39	0.46	0.51	0.31	0.46	0.46	0.31	0.51	0.51

Table 2. The mean values and standard deviations of the thickness measurement of the final product – plastic bags made by a welding machine

Sample	1	2	3	4	5	6	7	8	9	10
$\bar{x}$	20	20	20.1	20.1	20	20.1	19.9	20.1	20	20
s	0.39	0.46	0.31	0.39	0.32	0.39	0.31	0.39	0.39	0.39

Sample	11	12	13	14	15	16	17	18	19	20
$\bar{x}$	20.1	20.1	19.9	20	20	20.1	20	20	20	20.2
s	0.31	0.39	0.31	0.51	0.39	0.51	0.46	0.56	0.46	0.37

Following the collection of measurement data, their normality was checked. On the basis of subsequent calculations, it was assumed that the distribution of the obtained measurements was normal.

Prior to calculating an index of process capability, its stability must be determined [11]. For this project, the stability of production process was established with the use of Shewhart control charts. To calculate upper and lower limits as well as the center line, we applied formulas recommended by PN-ISO 8258+AC1 Norm [12]. Due to a relatively large number of samples, the $\bar{x}-s$ control chart was used. To construct this chart, one must identify the values of standard deviations in the sample as well as the average values from the measurements in the sample, obtained as a result of subsequent examinations of the viewed variable.

Four primary lines were drawn on the control chart: the center line representing the mean process value ($\bar{\bar{x}}$ – the average of the mean values and $\bar{x}$ – average standard deviation), a line representing the behavior of the process over time (average values and standard deviation), and the Upper Control Limit (UCL) line and Lower Control Limit (LCL) line.

The first step was to estimate the average of the mean values $\bar{\bar{x}}$ and average standard deviation $\bar{s}$. For polyethylene film produced in the Alpine 4 extruder, we obtained the average of the mean value of 20.010 µm and the average standard deviation of 0.404 µm. For the finished plastic bags made by the welding machine, the average of the mean values was 20.008 µm, and average standard deviation was 0.39 µm.

The next step was to calculate the control chart parameters for x track (Formula 1) and s track (Formula 2) as follows:

$$UCL = \bar{x} + A_3\bar{s} LCL = \bar{x} - A_3\bar{s} \quad (1)$$

$$UCL = B_4\bar{s} LCL = B_3\bar{s} \quad (2)$$

where

x – the center line,
$\bar{s}$ – center line,
UCL – upper control limit,
LCL – lower control limit,
A_3 – array constant,
B_3 and B_4 – array constant [15].

Array constants A_3, B_3 and B_4 necessary for plotting control lines were adopted on the basis of the sample count n = 20 [12] A_3= 0.680, B_3= 0.510, and B_4= 1.490. The following values of control chart parameters were obtained: for polyethylene film produced in the Alpine 4 machine: track $\bar{x}$ – LCL=19.735, $\bar{\bar{x}}$ = 20.010, UCL = 20.285; track s – LCL=0.20468, $\bar{s}$ = 0.40468, and UCL = 0.60288. For plastic bags made by a welding machine: track $\bar{x}$ – LCL = 19.734, $\bar{\bar{x}}$ = 20.008, UCL = 20.281; track s – LCL = 0.20495, $\bar{s}$ = 0.40168, and UCL = 0.59840.

After developing control charts, the measurements of the film's average thickness and standard deviation were plotted on them. Figures 4 (a) and (b) and 5 (a) and (b) present $\bar{x}-s$ control charts for the collected results along with calculated limits.

The analysis of these control charts demonstrated that the production process was stabilized. In accordance with the guidelines included in [12], it was assumed that an even distribution of control points on both sides of the center line with none exceeding the upper or lower control limits was an indicator of process stability. Consequently, the developed control charts were adopted for the monitoring of the manufacturing process.

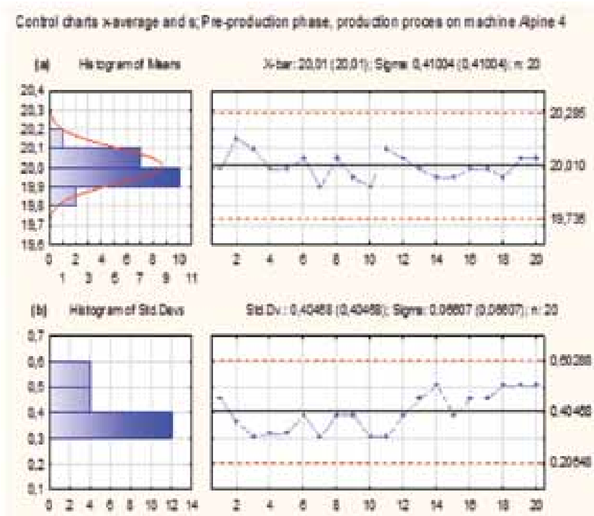

Fig. 4. (a) the average of the mean values of thickness measurements from the Alpine 4 machine; (b) average standard deviations of thickness measurements from Alpine 4 machine

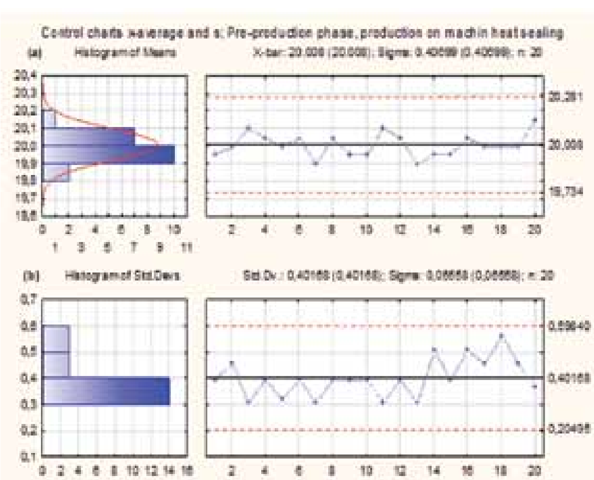

Fig. 5. (a) the average of the mean values of plastic bag thickness measurements from a welding machine; (b) average standard deviations of plastic bag thickness measurements from a welding machine

The analysis of process capability with the use of P_p and P_{pk}.indices.

A number of issues relating to indices C_p, C_{pk} and P_p, P_{pk} used in analyses of process capability and their interpretation and application have been addressed in numerous studies [14–16]. In paper [14], the author defines *capability* as the ability of the process to fulfill the requirements set out in a specification. According to guidelines included in [15, 16], the application of process capability indices C_p and C_{pk} should be limited only to situations when the process is stable. In situations where the process is not stable or the monitoring only begins, P_p and P_{pk} indices should be used.

Guidelines defining the required values of P_p and P_{pk} indices were adopted analogically to C_p and C_{pk} [8].

To calculate P_p and P_{pk} indices, Formulas (3) and (4) [1] were applied:

$$P_p = \frac{(USL - LSL)}{6s} \tag{3}$$

$$P_{pk} = MIN \frac{(USL - \bar{x})}{3s}; \frac{(\bar{x} - LSL)}{3s} \tag{4}$$

where

USL – upper specification limit,

LSL – lower specification limit,

$s = \sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 / (n-1)}$ – standard deviation,

$\bar{x}$ – mean value.

With regard to the customer-specified limits of the parameter measured, the values of process capability indices P_p and P_{pk} were obtained as follows: for polyethylene film produced in the Alpine 4 machine: P_p = 1.64, P_{pk} = 1.631 and s = 0,4047; and for plastic bags: P_p = 1.652, P_{pk} = 1.646 and s = 0.4017.

Capability ratios P_p, calculated for the thickness of the film as well as the plastic bags, were higher than 1.6, which proves the production process capability. P_{pk} ratios for the film as well as the plastic bags were also higher than 1.6 and were similar to P_p, which means that the process is centered. The process is thus capable of meeting the requirements laid down by the customer's specification. No problems were found relating to the tensile strength of the film or its side seals which were controlled in the process of heat sealing. It was, therefore, assumed that the standard deviation of film thickness s = 0.404 did not have a negative effect on the quality of strength parameters.

3. Mass production phase

When the technological tests were over, the product entered the mass production phase without introducing any changes to the process. As there were no significant problems in plastic bag production and no complaints were made by customers, statistical process control was not implemented over a period of a few months. Ten months after the start of plastic bags production, a sudden increase in production waste and defective film rolls was observed. Strength tests revealed rupture at the side seals. The tests was carried out according to the frequency determined by the control plan and on the number of samples specified therein. The tests consisted in stretching the film on the bag's side seal so as to assess its strength. The problem was investigated using a Ishikawa diagram, and it was concluded that the rupture was caused by the uneven thickness of the film measured on the circumference of the strip. Standard deviation of film thickness measured on faulty rolls allocated for bag production was calculated, and its value turned out to be 1.8 (with the pre-production phase value estimated at 0.404). It was also noticed that the problem of breaking at the side seals appeared when production was restarted in a new extruder – Kiefel 5. This change was due to the malfunction of the Alpine 4 and the need to complete the customer's order.

In order to examine the problem in depth, a decision was made to increase the frequency of measurements to include 6 shifts and take film samples for measurement from the two extruders. Polyethylene film samples were obtained from the extruder operating since the pre-production phase (Alpine 4). From each of the 14 rolls manufactured, 5 samples were taken and each sample was subject to 20 measurements. This resulted in a total of 1,400 measurements. The mean value and standard deviation of these measurements are presented in Table 3. Then, samples of polyethylene film were obtained from Kiefel 5 extruder, launched about 10 months after the mass production had started. The number of samples collected and the number of measurements performed were identical as in the case of Alpine 4. The mean values and standard deviations are shown in Table 4.

Owing to a large count of the sample, a decision was made to continue the control process with the use of a $\bar{x}-s$ control chart [1]. On the basis of the measurement data included in Tables 3 and 4, new control limits were calculated.

The next step in the construction of $\bar{x}-s$ control chart was to calculate the control chart parameters with the use of the same procedure as in the case of the pre-production phase, applying Formulas (3) and (4).

Figures 6 (a) and (b) and Figures 7 (a) and (b) present $\bar{x}-s$ control charts for the collected results along with calculated limits. In the case of film thickness measurements, where all the samples were made in the same extruder as in the pre-production phase (Alpine 4), the process is statistically stabilized as none exceeds beyond the calculated control limits and there are no apparent patterns either.

Table 3. Average values and standard deviations of PE film thickness measurements produced in Alpine 4 extruder

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
$\bar{x}$	20	20.2	20.1	20	20	20.1	19.9	20.1	20	19.9	20.1	20.1	20	20	20	20	20	20
s	0.46	0.37	0.31	0.32	0.32	0.39	0.31	0.39	0.39	0.31	0.31	0.39	0.46	0.51	0.39	0.46	0.46	0.51

Sample	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
$\bar{x}$	20.1	20.1	20.1	20.1	20	20	20	20	20	20	20.1	20.1	20	20.2	20.1	20	20	20.1
s	0.51	0.51	0.31	0.39	0.46	0.51	0.39	0.46	0.46	0.51	0.51	0.51	0.46	0.37	0.31	0.32	0.32	0.39

Sample	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
$\bar{x}$	19.9	20.1	20	19.9	20	20.2	20.1	20	20	20.1	19.9	20.1	20	19.9	20	20.2	20.1	20
s	0.31	0.39	0.39	0.31	0.46	0.37	0.31	0.32	0.32	0.39	0.31	0.39	0.39	0.31	0.46	0.37	0.31	0.32

Sample	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
$\bar{x}$	20	20.1	19.9	20.1	20	19.9	20	20.2	20.1	20	20	20.1	19.9	20.1	20	19.9
s	0.32	0.39	0.31	0.39	0.39	0.31	0.46	0.37	0.31	0.32	0.32	0.39	0.31	0.39	0.39	0.31

Table 4. Average values and standard deviations of PE film thickness measurements produced in Kiefel 5 extruder

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
$\bar{x}$	20.1	20.2	20.2	20.1	19.9	20.1	19.8	20.1	20	21	20.1	19.1	20.2	20.1	20.2	21.1	20.1	20.5
s	2.11	2.09	2.08	2.38	2.27	2.38	2.26	2.65	2.09	1.97	2.65	2.02	2.48	2.1	2.46	1.92	1.71	1.54

Sample	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
$\bar{x}$	19.6	20.8	19.6	20.6	19.8	20.5	19.5	20.6	19.4	20.5	20.1	20.7	19.6	20.2	20.8	20.7	20.1	20.3
s	1.39	1.48	1.35	1.47	2.24	1.54	1.32	1.5	1.27	1.54	2.13	2.18	2.16	2.08	1.92	1.76	2.07	1.86

Sample	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
$\bar{x}$	20.1	20.2	20	20.1	20.1	20.3	19.7	20.1	19.6	20.2	19.4	20.2	19.5	20.2	20.2	20.2	19.6	19.7
s	1.36	2.08	1.38	1.48	2.11	1.07	1.3	2.09	1.32	2.08	1.27	2.08	1.24	2.17	2.14	2.16	1.36	2.16

Sample	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
$\bar{x}$	20.6	20.6	20	21.2	20.7	20.8	20.4	20.3	20.3	21.3	20.1	20.7	20.6	20.2	21.3	20.6
s	1.54	1.57	0.46	2.03	1.53	1.48	2.01	1.26	1.25	2.08	1.07	1.49	2.09	1.58	2.12	1.64

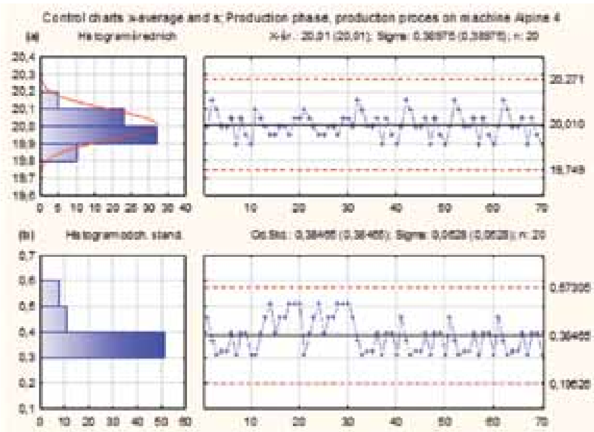

Fig. 6. (a) The average of the mean values of thickness measurements from the Alpine 4 machine; (b) average standard deviations of thickness measurements from the Alpine 4 machine

In the other case, where film samples were obtained from the machine started in the production phase (Kiefel 5), the s chart shows measurements going beyond control limits as well as six subsequent progressively decreasing points. This indicates that a cause exists for a cumulative deterioration of process parameters. The $\bar{x}$ chart revealed fourteen measured values alternately increasing and decreasing, which suggests the emergence of a factor causing periodicity of process parameters [12]. This would mean that the process is not statistically stable. Calculating process capability indices C_p, C_{pk} and P_p, P_{pk}.

Due to process instability in the case of polyethylene film obtained from the Kiefel 5 machine, it was decided that P_p, P_{pk} indices should be used in evaluating process capability with the use of Formulas (3) and (4).

On the other hand, indices C_p, C_{pk} [15] with the use of Formulas (5) and (6) were used to evaluate the process capability of the film obtained from the Alpine 4 machine:

$$C_p = \frac{(USL - LSL)}{6s} \tag{5}$$

$$C_{pk} = MIN \frac{(USL - \bar{\bar{x}})}{3s}; \frac{(\bar{\bar{x}} - LSL)}{3s} \tag{6}$$

where
USL – upper specification limit,
LSL – lower specification limit,
$\bar{\bar{x}}$ – the average of mean values,
$s = \frac{\bar{s}}{C_4}$ – standard deviation,
C_4– array constant,
$\bar{s} = \frac{s_1 + s_2 + \ldots + s_m}{m}$ – average standard deviation,
m – number of samples,
$s = \sqrt{s^2}$ – standard deviation,
$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2$ – variance,
n – sample count.

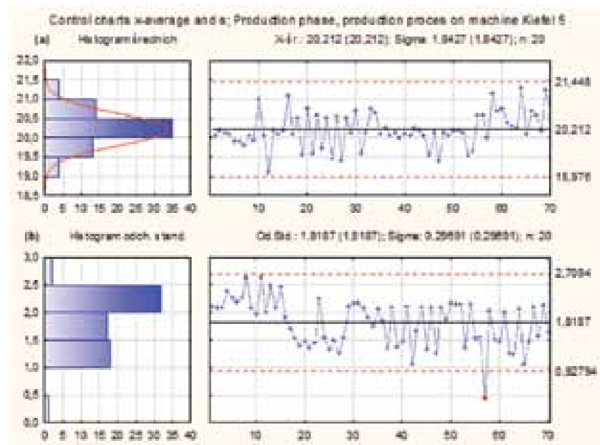

Fig. 7. (a) The average of the mean values of thickness measurements from the Kiefel 5 machine; (b) average standard deviations of thickness measurements from the Kiefel 5 machine

For the limits set in the customer's specification regarding the parameter measured, we obtained values of process capability indices C_p, C_{pk}. For the polyethylene film produced in the Alpine 4 machine, these were $C_p = 1.711$ and $C_{pk} = 1.702$. For the polyethylene film produced in the Kiefel 5 machine, these were $P_p = 0.333$ and $P_{pk} = 0.333$.

For the film produced in the Alpine 4 machine, the C_p index is >1.6, which means that the process is capable. The C_{pk} index is >1.6; therefore, process control and centering the average value against tolerance limits are not required. The indices C_p, C_{pk} are similar, which means that the process is centered. Standard deviation s = 0.3897 indicates that there are no significant differences in film thickness measured on the roll's circumference. It is further confirmed by the fact that there were no problems whatsoever connected with bursting of the bags at the side seals during strength tests carried out in the welding machine during the process of production.

In the case of film produced in the Kiefel 5 extruder, the index $P_p = 0.333$ indicates that the process is out of control. Low index $P_{pk} = 0.333$ suggests that process control and centering the average value against tolerance limits are required. The calculated s = 1.874 is far higher than the assumed (s = 0.404).

It indicates that the obtained thickness of the film measured on the roll's circumference was uneven. As a result, problems were encountered, such as bursting of the film at the bag's side seals during strength tests. The results achieved were unsatisfactory. Therefore, steps were taken in order to stabilize the process and eliminate the causes of variation.

Following the identification of the cause and the implementation of corrective action, new measurements of the thickness of the film produced in the Kiefel 5 machine, which was started in the mass production phase, were taken on the roll's circumference. The measurements were taken over the period of one month. The results were laid out in a tabular form. Then, the algorithm of the procedure was repeated as above. As the analysis of control charts indicated process stability, indices C_p, C_{pk} [14–15] were used in evaluating its capability using Formulas (5) and (6) [1]. The calculations yielded the following values: $C_p = 1.58$ and $C_{pk} = 1.56$.

On the basis of these calculations, it is clear that process indices changed to C_p and $C_{pk} > 1.5$. It may be concluded that the process is stable and centered. Problems such as bursting of the film at the side seals did not occur during strength tests carried out in the bag production process, which confirmed that standard deviation s = 0.4226 enabled the obtainment of the even thickness of the film measured on the roll's circumference. The process could now be assumed to be in control.

Conclusion

The above analysis demonstrated how the main cause of variation in the production of film and plastic bags can be identified through the use of Statistical Process Control methods. The loss of capability between pre-production and mass production phase shows that a non-critical variable may become critical if we introduce a change to the process (in this case, a new extruder) without assessing its stability and capability anew. The application of Statistical Process Control helps improve the process by avoiding additional costs generated by manufacturing faulty semi-product or finished product as well as preventing possible complaints from customers. It should thus be determined with the use of control charts and process capability indices whether the process is stable and capable of meeting the customer specifications, in situations, when there is a need to commence production on a new machine.

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