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Economical and Statistical Optimization of the Maintenance in the Production Process

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The article presents a comprehensive example that demonstrates the control of a plastic injection process in practice. The demonstrated example is from an unnamed company and the data had to be adjusted by a coefficient. It includes measurement and analysis of the production process, its control using a control diagram to bring the production process to a state under statistical control by applying tests of non-random clusters and subsequent evaluation of process capability. The paper shows a histogram and control charts from the measured values that were obtained from the production process at the time.
The last part of the article gives an example of the maintenance of economical statistical optimization for four scenarios. Here, the costs that the company incurs in maintaining the machinery are taken into account. The data in the example was again modified by the author so that the company was not easily traceable.

Keywords: Quality control, control chart, process capability, process control, injection moulding, plastic maintenance management, economic and statistical optimization, non-conforming process management

1 Non-conforming moulding process management

The non-conforming moulding process management is a set of activities aimed at:

- Detecting, identifying, and marking non-conforming mouldings.
- Finding moulding defects and identifying their causes.
- Ensuring the elimination of no repairable non-conformed mouldings.
- Establishing corrective action.
- Analysing the costs of non-conformed mouldings and ensuring their registration.

A non-conformed moulding is a moulding that does not meet the specified requirements (e.g., in size, shape, mechanical, or aesthetic properties). Non-conformed mouldings can be found during the incoming inspection, during individual production stages, during the final inspection, or at the customer's site.

As part of the process of monitoring and measuring the moulding, the inspection worker performs the following activities:

- Control of the first piece.
- Record the inspection of the first piece in the relevant document and in the information system.
- Inter-operational control during the production in cooperation with the machine operator.
- Process suitability check.
- Output control.
- Recording of non-conformed mouldings.

The production controller evaluates the suitability of the process or the ability of the production process to achieve permanently prescribed quality marks daily for selected mouldings using the SPC tools. The recording of the measured data of these quality marks is transferred by the process control into the information system of the SPC control module. These data are automatically passed to the Process Eligibility Protocol document, where they are evaluated. A similar topic was addressed in these articles [10], [11].

At the beginning of each new shift, the inspection worker has the duty to inspect the products by measuring the required values (SPC marks), which are defined in the information system. This involves, for example, measuring five pieces of each mould that is currently being produced. To do this, the drawing documentation of the moulding is typically used, where the relevant dimensions or other properties (listed in the system) can be found, showing which parts of the moulding should be measured. If the process is eligible (as determined by the initial evaluation), production can start within the given shift. In the case of a dimensional control for which the process control is set, the message "*Process is ineligible*" appears after evaluating the values of the information system; the measurement control officer must inform the shift manager and adjuster or technologist to ensure that necessary maintenance and process optimization will be performed.

During the final inspection, the prescribed number of parts is taken from each complete package, which is determined by the used acceptance plan (normal, stricter, mitigated). Visual inspection of these parts is performed according to the reference samples, the defect catalogue, or by verifying the findings of customer complaints. Then the inspection workers put these inspected parts back into the package and check the correctness of the production labels on the packaging (name, colour, number, page, date, and operator). If an inconsistent moulding is found, the packaging is marked with a red label. Products that are produced according to the technical documentation are marked with a green label.

In some cases, the human factor fails in this control process, which may, for example, be caused by temporal inattention or a lax approach of the control workers. Such errors at the control stage can have great consequences in terms of costs. There may be situations where the inspector forgets to measure the moulding or performs the measurement late during production, when a large amount of non-conformed mouldings was already produced. Sometimes, other situations may occur when workshop or reference samples are mixed in production, failing to detect a non-conformed moulding (defects in their appearance) during a random inspection of the production. Another type of error occurs when the finished product packages are not properly marked or read by the barcode reader.

An employee who identifies a non-conformed moulding in the production process is obliged to isolate it from other mouldings, so that confusion with mixing it with conformed mouldings is avoided. Furthermore, the adjuster or shift control manager is required to inform the present adjuster or shift control manager of the occurrence of the found defect. The adjuster eliminates the production process discrepancy, for example, by readjusting the machine or changing the mould. The inspection worker releases (due to the machine stopping) the first piece again so that production can continue. After a 100% inspection of the parts manufactured since the last identical inspection, the operator places the non-conforming pieces in the scrap box and records their quantity in the production evidence. The shift master will make an entry in the document "Book of non-conformed mouldings". Non-conforming parts are then transported to areas reserved for non-conforming products.

If the adjuster does not eliminate the discrepancy by adjusting the machine, the shift manager decides, in agreement with the inspection worker, to stop production. The production manager is familiar with the situation and decides on the next step.

2 SPC diagram in plastic injection

In this section, we will deal with a comprehensive example demonstrating the control of the plastic injection moulding process in practice. Values do not correspond to reality, because highly valued company data would leak, so the numerical values are multiplied by a coefficient. Table 1 records the measurement that was performed when the moulds were produced in a single-shift operation regime. In the next, we will focus on the evaluation of these data, using statistical tools.

The values from the table are shown in the histogram in Figure 1.

Tab. 1 *Measured values for shift (8 hours) (for a single-shift operation)*

Length [mm]	Date	6. 11.								
	Time	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00
Samples	1	121.334	121.335	121.337	121.334	121.335	121.334	121.334	121.335	121.334
	2	121.335	121.333	121.335	121.335	121.334	121.333	121.335	121.336	121.335
	3	121.335	121.334	121.336	121.337	121.336	121.336	121.337	121.337	121.333
	4	121.338	121.335	121.333	121.332	121.338	121.335	121.338	121.336	121.336
	5	121.332	121.336	121.334	121.331	121.332	121.333	121.333	121.335	121.333

2.1 Histogram

The basic tool for determining the stability of the process is the frequency histogram, which can be used to determine the type of distribution of the monitored quality characteristics and the behaviour of the process itself. On the basis of the histogram shape, it is also possible to estimate the suitability of the process.

From the shape of the histogram, we estimate the values of the monitored quality characteristic, which is (in this case) the length of the moulding. In the presented case, the histogram indicates an approximately normal distribution since the shape of the histogram is almost identical to the shape of the standard Gaussian curve.

The resulting process should be put into a statistically controlled state where only random components of variability should affect it, as can be seen in Figure 1.

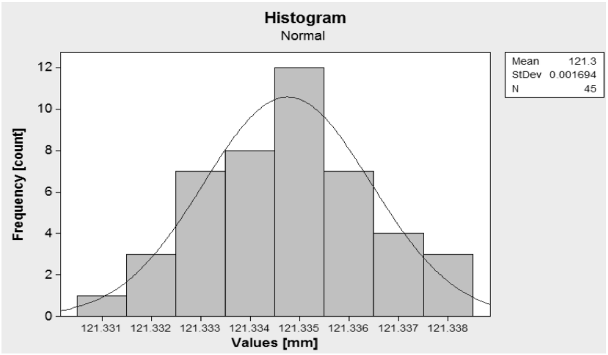

Fig. 1 *Histogram for a single-shift operation (one day interval)*

2.2 Control chart

With the help of control diagrams, it is possible to monitor the stability of the production process in the long term. A control diagram for the mean and range was chosen (for the given process):

- The quality mark, which is the length of the mould, is measured.
- The size of individual subgroups is set to five.

The data obtained were processed in the statistical software Minitab 14, which determined the position of the central line (CL) from the given values and subsequently also the value of the upper and lower control limits (UCL and LCL). These two boundary lines determine the area in which the value of the selected quality feature is located with a probability of 99.73%.

Xbar chart

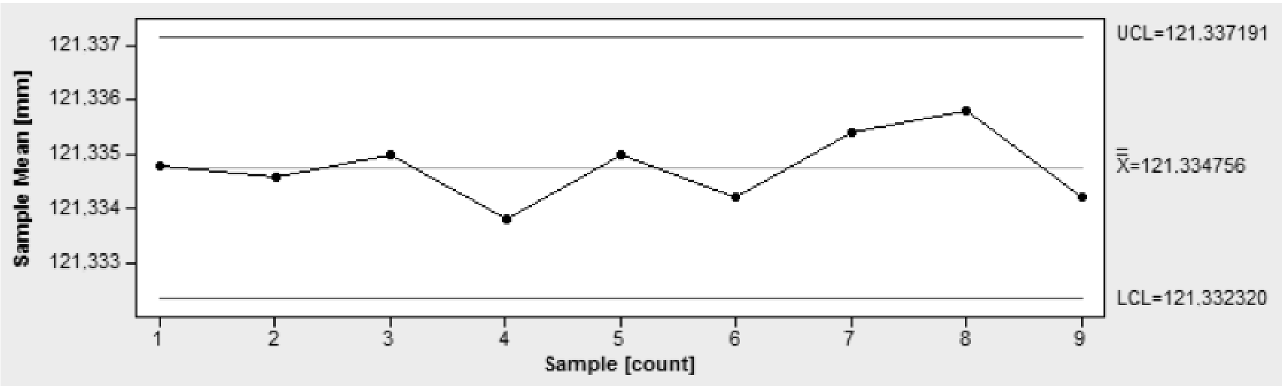

Fig. 2 *Control chart (Xbar) single-shift operation during one day*

R chart

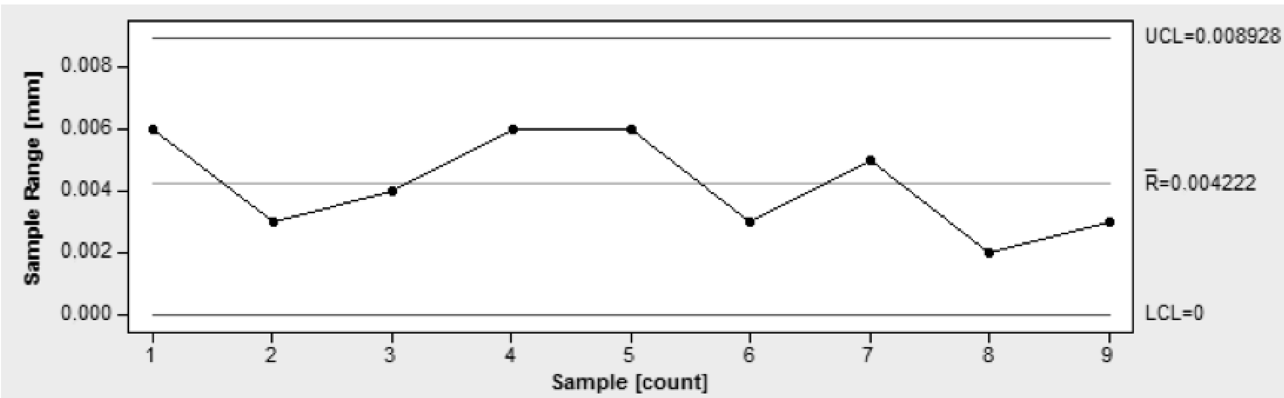

Fig. 3 *Control chart (R) single-shift operation during one day*

After compiling the control diagram, it is necessary to verify whether the process is actually affected only by random influences. This is done using the test of definable causes, which is described in the standard ČSN ISO 8258: 1991.

After checking the individual points by a test of definable causes, we can state that none of them was found in the above UCL and therefore the process can be considered stable. Therefore, it is considered statistically mastered and affected only by random causes of variability. In summary, it can be seen from Figure 2 and Figure 3 that the process is under statistical control.

2.3 Process Capability

The aim of statistical process control is to keep the monitored attributes within the regulatory limits and, if necessary, to indicate specific causes of defects if they occur in the process. These failure causes must be identified and eliminated and measures must be taken to prevent their recurrence. If there are no specific (definable) causes in the process, then the process should be under a statistically controlled state. This means that neither the position of the centre of gravity of the process nor its variability changes over time, and that the process is predictable. The behaviour of a statistically controlled process must be compared with the requirements that are imposed on it.

Process capability indicates the relationship between the natural variation of the process, which comes from a statistically mastered process due to random causes of variability, and technical input (range of tolerances). Process eligibility can be quantified using eligibility indicators.

All calculated values of eligibility indicators are statistics (random variables), and therefore it is possible to determine their probability distribution, and to construct the confidence intervals for them.

When determining eligibility indicators, it is assumed that not only the process is "statistically acquired" but also that the monitored quality mark (random variable) has a normal distribution. Both assumptions must be verified before calculating the eligibility indicators. If the quality mark does not have a normal distribution, the procedure for calculating eligibility indicators is different, so it is always necessary to verify both assumptions.

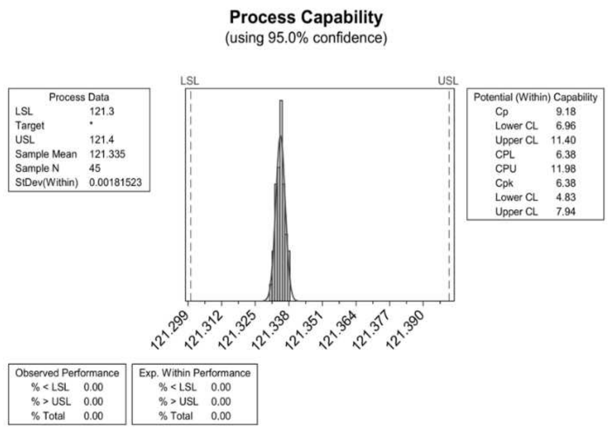

Fig. 4 *Process capability for a single-shift operation (one-day interval)*

The eligibility calculation was performed using Minitab 14, as shown in Figure 4, and the process is eligible according to the c_p value because its value is higher than 1.33.

Table 2 records the measurement performed when the mouldings were produced in a three-shift operation regime.

Tab. 2 *Measured values for shift (24 hours) (three-shift operation during one day)*

Length [mm]	Date	6. 6.						7. 6.		
	Time	6:00	9:00	12:00	15:00	18:00	21:00	0:00	3:00	6:00
Samples	1	121.334	121.333	121.335	121.335	121.337	121.335	121.334	121.335	121.335
	2	121.335	121.336	121.334	121.334	121.334	121.336	121.333	121.336	121.336
	3	121.336	121.334	121.336	121.336	121.333	121.338	121.338	121.336	121.336
	4	121.334	121.333	121.333	121.333	121.338	121.337	121.337	121.337	121.335
	5	121.335	121.334	121.332	121.335	121.335	121.336	121.339	121.335	121.334

Here again, the histogram is formed; see Figure 4. The measured lengths of the mouldings show a normal distribution, since the shape of the histogram is almost identical to the shape of the Gaussian curve. Therefore, only random effects seem to have affected the process itself.

After compiling the control diagram, it is necessary to verify again whether only random effects really influence the given process. This is done using the test of definable causes, which is given in the standard ČSN ISO 8258: 1991, see [1] and [2] for details.

After checking individual points by the definable cause test, we can state that no random groupings were found in the above control diagram and therefore the process in Figure 6 and Figure 7 can be considered stable and statistically mastered, influenced only by random causes of variability, [4], [5], [6], [7], [8].

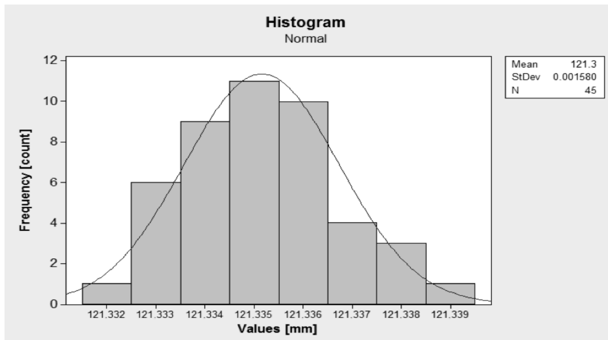

Fig. 5 *Histogram for a three-shift operation during one day*

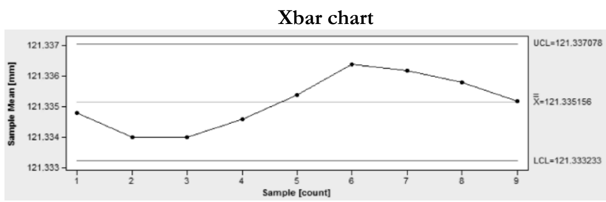

Fig. 6 *Control chart (Xbar) for a three-shift operation during one day*

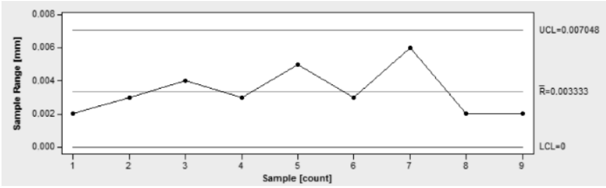

Fig. 7 *Control chart (R) for a three-shift operation during one day*

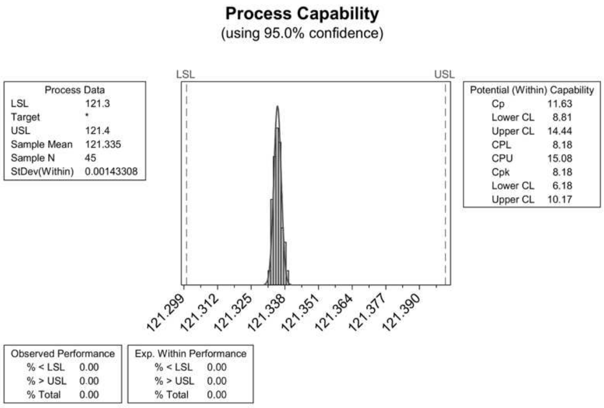

Fig. 8 *Process capability in a three-shift operation during one day*

The eligibility calculation was performed Minitab 14, as shown in Figure 8, and the process is eligible according to the c_p value.

3 Economical optimization assessment

An important factor to be properly adjusted in the plastic injection moulding process is the cooling time of the moulding, as it strongly affects the number of pieces produced during one shift. As an example, let us have a total cycle length of 30 seconds, then 960 cycles will be performed during one shift (8 hours). If we add an input system that will consist of six moulds, 7 680 pieces can be made in one shift. By shortening the length of one cycle to 20 seconds, 1 440 cycles will be performed in one shift (8 hours). If we think that 8 mouldings will be produced in one cycle, the machine will produce 11 520 pieces, provided that the machine will run without a malfunction or intervention of the machine maintenance. Of course, if the machine has to stop for adjustment or setup, the machine downtime will arise, which is undesirable for the company (such a situation is not considered in the example in Table 3).

Tab. 3 *Example of the cycle duration (time) of the production [author]*

Total cycle length [sec]	Number of cycles per shift (8 hours)	Considering 8 mouldings in cycle [pcs]	Number of mouldings per year (252 work days) [pcs]
20	1 440	11 520	2 903 040
21	1 371	10 971	2 764 800
22	1 309	10 473	2 639 127
23	1 252	10 017	2 524 383
24	1 200	9 600	2 419 200
25	1 152	9 216	2 322 432
26	1 108	8 862	2 233 108
27	1 067	8 533	2 150 400
28	1 029	8 229	2 073 600
29	993	7 945	2 002 097
30	960	7 680	1 935 360

It means that by shortening the cycle length from 30 seconds to 20 seconds, the annual production will increase from 1 935 360 pieces to 2 903 040 pieces.

4 Economical-statistical optimization of maintenance

In statistical process control, costs occur during the monitoring of the regulated quantity, which we will explain in more detail here.

It is well known that separate measurement and execution of individual inspections result in fixed costs. Fixed costs, which we denote by C_F, are costs that do not change during sampling and we assume that they are constant. The variable costs that we call C_V are costs that depend on the number of samples taken. If we take more samples, the variable costs will increase. The relation $C_s = C_F + m\, C_V$ describes the cost of one inspection, where m is the sample size. These costs are associated with collecting data during a control.

False signals often occur during the control variable monitoring. We will denote the cost of finding a false signal as C_f. In the case when there is no false signal and a detectable cause has occurred, we will incur the cost of finding a detectable cause (process failure), which we will label C_z. Then we will find the detectable cause and the cost of repairing it, which we will label C_r. Quality cost, when the process is under statistical control, we call C_I, and quality costs outside statistical control, which we will denote C_O.

In the presented example, which we present below, we assume the costs for the input parameters, which we obtained from previous measurements of the monitored production process. Due to the fact that the production process is significantly affected by random influences, it is not possible to determine all the costs of its management in advance. However, if we have at least a rough idea of the probability distribution of these random effects, we can use the results of mathematical statistics to calculate the corresponding expected costs, the expected number of false signals, the expected hourly loss, etc.

First, we calculate the expected quality costs per process cycle, which we refer to as C_Q. Second, the type is the expected sampling cost per process cycle, which we denote C_S, must be established. Third, the expected costs of detecting and correcting the detectable cause must be specified. We denote them C_D. Together, these three types of expected costs define the total expected costs per cycle in the process.

Overall, the time in which these costs can appear can be divided into several parts, which we will discuss in more detail later. Before starting the statistical procedure, we assume that the process is in a state under statistical control. This state lasts for time T_{In}. At an unknown time moment μ, a detectable cause (failure) occurs in the process, causing the monitored characteristics to deviate from the required level, bringing the process out of statistical control. We denote the duration of this state by T_{Out}. If we add these two times, we get the total length of the cycle $T = T_{In} + T_{Out}$.

For optimization purposes, we will consider a finer distribution of the cycle T. Assume that the detectable cause and the associated shift in process behaviour occurred between s-th and $(s + 1)$-st inspection. The time from the beginning of the process run to the s-th inspection is denoted by T_s.

During this period, we take samples and the production process is in a state under statistical control. The time from the s-th inspection to the m-th inspection, which signals a detectable cause, is denoted T_d.

The time to draw and calculate the standard tests of one result during the inspection, if the process is out of statistical control, is denoted T_{gn}. The symbol T_f indicates the time required to find the identifiable cause that caused the change in the production process.

Next, the time period T_r representing the time required to repair the production process and return it to a state under statistical control must be established. This time is included in the total cycle length only if the manufacturing process is manufactured during the repair. If the process produces costs during the repair period, the time $T_r = 0$ is not included in the total cycle duration. Figure 9 shows the total duration of the production process cycle. In the following text, we assume that the time between h inspections does not change due to the process regulation. Let us further assume that we know the distribution of time to the occurrence of a detectable cause (time to failure).

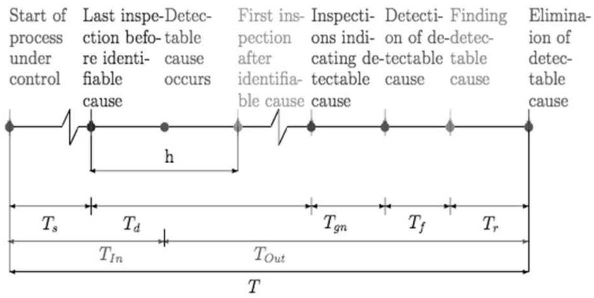

Fig. 9 *Total process cycle length [2]*

Economical-statistical optimization consists in minimizing the expected loss per unit time, shown in Figure 10. Under certain conditions and from a certain point of view, the production process can be considered as a recovery process, i.e., a process operating in certain cycles called recovery cycles. For these cycles, we assume that their lengths are independent random variables with the same probability distribution. Let us denote the assumed loss for the whole cycle in the process as $E(C)$ and the assumed cycle length in the process as $E(T)$, then we can express the assumed loss $E(L)$ equation (1) per unit time as the ratio of $E(C)$ (equation (2)) to $E(T)$ (equation (3)) , which is expressed by:

$$E(L) = E(C)/E(T) \quad (1)$$

In this analysis, we again start from the above relationship. We define the expected cycle length as the sum of all cycle times multiplied by the probabilities of the individual scenarios. This can be expressed as:

$$E(T) = E[T|S_4]\,P(S_4) + E[T|S_5]\,P(S_5) + E[T|S_6]\,P(S_6) + E[T|S_7]\,P(S_7) \quad (2)$$

Similarly, the expected costs per cycle are the sum of the expected costs of the individual scenarios, which we multiply by the probabilities of the individual scenarios. We can express them as follows:

$$E(C) = E[C|S_4]\,P(S_4) + E[C|S_5]\,P(S_5) + E[C|S_6]\,P(S_6) + E[C|S_7]\,P(S_7) \quad (3)$$

The description of individual scenarios can be found in [3].

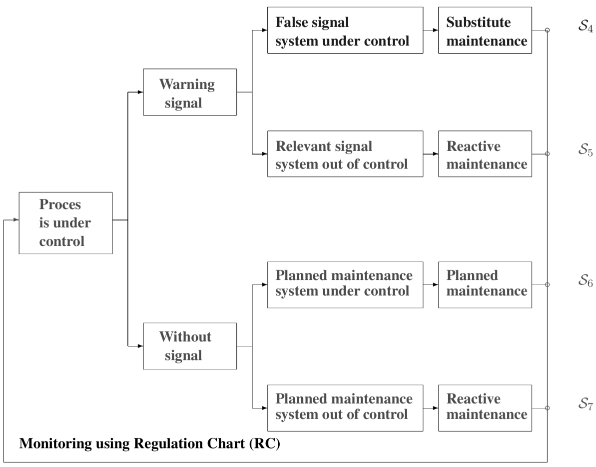

Fig. 10 *Integrated model of control chart and maintenance management [2]*

Consider the process controlled by the Shewhart control diagram $\overline{X}$, where we assume the input parameters of the process, from which we calculate the optimal loss function of the production process. [1], [2], [9].

We assume a shift in the mean value of $\delta = 2$. Moreover, let the probability of time to failure has a Weibull distribution with the scale parameter $\lambda = 0.05$ and the shape parameter $\rho = 1$. Among the known parameters that relate to the costs belong, among others:

- Costs per hour of the process in the state under statistical control $C_O = 200$ EUR.
- Costs per hour of the process under statistical control $C_I = 10$ EUR.
- Costs of false signal $C_f = 100$ EUR.
- Costs of finding and removing the detectable cause $C_{zr} = 25$ EUR.
- Reactive maintenance costs $C_R = 50$ EUR.
- Costs of scheduled maintenance $C_P = 75$ EUR.
- Replacement maintenance costs $C_C = 100$ EUR.
- Costs depending on the number of samples taken and drawing a selection point in control diagram $C_V = 1.0$ EUR.
- Costs that do not depend on the number of samples $C_F = 5$ EUR.

We assume that we know the time to draw and calculate standard tests of one result during inspection, if the process is outside statistical control $T_g = 0.05$ h, the time to find a detectable cause $T_r = 2$ h, the time to find a false signal $T_f = 1$ h, the time to search for a detectable cause $T_z = 1$ h, the time to perform reactive maintenance $T_R = 3$ h, and the time to perform scheduled maintenance $T_P = 8$ h. We also assume that we know the number of samples before the planned maintenance $m_p = 100$.

Using the Nelder-Mead method, optimal values were obtained for the selection range $m = 5$, the interval between inspections $h = 1.5$ and the width of the control limits $k = 2$.

The value of the loss function $L = 217.4586$ was obtained from Figure 11.

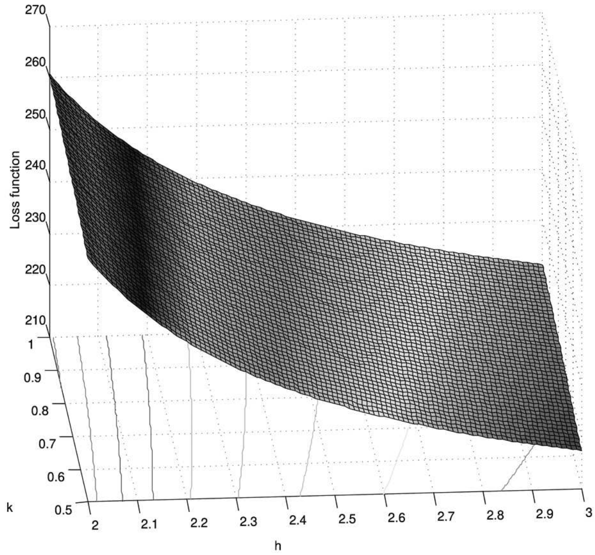

Fig. 11 *The shape of the loss function for four scenarios for the value m = 5*

5 Conclusions and remarks

This paper demonstrates an economical and statistical approach to process management using appropriate statistical tools. Specifically, the histogram was used for the basic analysis of the measured data (distribution type, process centering, and degree of variability). After verifying the assumption of normality, the Xbar - R control diagram was used, with the help of which it was verified that the monitored process is under statistical control, i.e., that only random causes of variability affect it. Subsequently, it is possible to proceed with the evaluation of the process capability, which provides us with information about the ability of a particular production process to stay within predetermined tolerance limits. This parameter is often part of the contract with the end-customer of the product. In the case of production with an injection moulding machine, the resulting productivity can also be optimized by a suitable setting of the cycle length or by using an inlet system that allows the production of several mouldings in one cycle. This aspect is described in Section 3. Finally, an example of the use of economic - statistical optimization of maintenance minimizing the variable costs of the process management is given.

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