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DEVELOPMENT OF A SYSTEM FOR STATISTICAL QUALITY CONTROL OF THE PRODUCTION PROCESS

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Abstract. *By coupling computer with measurement devices, information measurement systems are being made, whose basic tasks are automation measuring and quality control of manufacturing processes, mathematical processing of measured results in real time, storing of measured results, documenting of measured results, process management, etc. Statistical methods for quality evaluation provide analyses of production processes which can serve as the basis for undertaking adequate preventive and correction measures in order to increase the total production quality. In this paper importance is emphasized for applying statistical quality control methods to evaluation of process stability and capability. There is a preview of structure and functioning of the developed applicative software for statistical process control. At the end, corresponding conclusions are given.*

Key words: *Statistical Process Control, Process Stability, Process Capability*

1. INTRODUCTION

Continual quality improvement as an imperative for the survival of a company requires the establishment of a process measuring system. In order to determine the possibilities for improving process effectiveness and efficiency, measurement data have to be arranged, processed and analyzed using adequate methods and techniques. A large number of factors influences each process and leads to output characteristics (process results) variation. As much as one tries to control the influencing factors, variations are unavoidable and therefore should be maintained on an acceptable level, while we strive towards their continual reduction.

First theoretical bases and first mathematic statistic formulations applied in a research paper can be found in the papers written by R. Fisher after the First World War. First

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practical attempts to apply mathematical statistics to quality control date from 1923, when the notions of producers risk and consumers risk in sampling were introduced. Great significance is attributed to the work of Walter Shewhart who entirely developed the theory of control charts. First control chart was developed in the 1920s in traffic industry; later, in 1930s, it was accepted in other industry branches as well. After the Second World War, in 1950s, statistic quality control methods began to be widely applied in Japanese industry, while America rejected the principles of statistic quality control. Only in 1980s, under the pressure of Japanese importers into the United States, did the company "Ford" adopt the principles of statistic quality control.

Statistic control is based on the application of statistic methods. Since the application of this control method determines changes and change trends of process characteristics, the term statistical process control (SPC) is often used. Statistical process control is the control of production process using statistic methods in order to prevent, detect and correct poor product quality. The purpose of the statistic quality control is the following:
- Determine product manufacturing process ability that satisfies set requirements;
- Monitor the process to reveal changes responsible for the process getting out of control;
- Take adequate measures for process correction and its preservation under control.

Statistical process control can only warn of the developed changes, while possible causes should be determined later. Statistic quality control neither measures deviation causes nor does it point to the measures that have to be taken in order to remove deviation causes.

During the statistical process control, the following phases can be singled out:
- data acquisition (defining data type and structure, defining acquisition period, defining acquisition location, defining acquisition participants, defining data acquisition manners),
- data preparation (counting data, arranging data, grouping data, forming statistical tables),
- results processing and analysis (processing statistic data, evaluating observed characteristics, determining improvement effects).

There are two groups of quality characteristics:
- Variables:
  - Characteristics that you measure, e.g., weight, length, size, height, time, ...;
  - Product characteristics that are continuous and can be measured;
  - May be in whole or in fractional numbers;
  - Continuous random variables.
- Attributes:
  - Characteristics for which you focus on defects, e.g., good – bad; yes - no, ...;
  - Categorical or discrete random variables;
  - Characteristics that can be evaluated with a discrete response.

Their mutual property is that the quality mark for a set of products is made on the basis of sample characteristics.

2. PROCESS STABILITY AND PROCESS CAPABILITY

Process stability is evaluated on the basis of previously constructed control charts (Fig. 1). Control charts are graphs where x-axis presents duration time of manufactured process, and y-axis is the value of quality characteristics. They make a network of horizontal and vertical lines for plotting the measurement data. The result is a time picture of the observed process. Each control chart has plotted control limits that present regulation boundaries, that is, managing boundaries, and a centerline gained by calculating average arithmetic value of the measurement samples. If the measured values are within control limits, the process is under control; otherwise, it is out of control. All control charts have three basic components:

- a centerline, usually the mathematical average of all the samples plotted,
- upper and lower statistical control limits that define the constraints of common cause variations,
- performance data plotted over time.

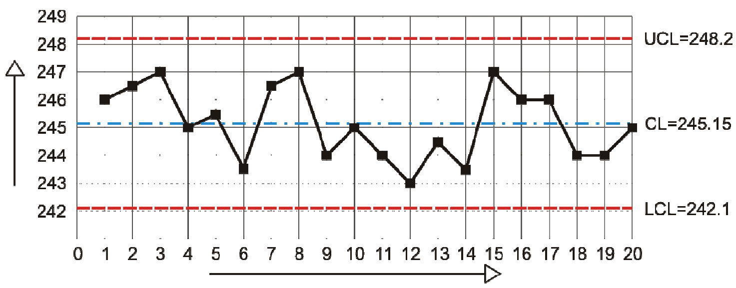


Fig. 1 Control Chart

Control charts are classified as follows (Fig. 2):

- control charts for variables (X chart, XR chart, Xσ chart, EWMA chart, individual chart),
- control charts for attribute (p chart, np chart, c chart, u chart),

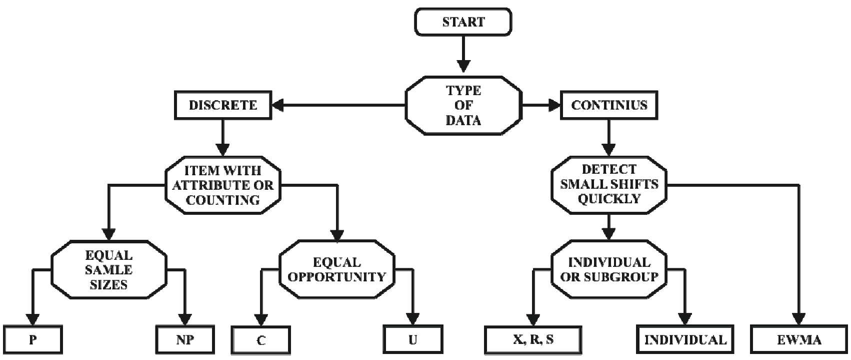


Fig. 2 Control Chart Selection

The sample size, as well as the trend and position of points in relation to the centerline and control limits influence the stability evaluation. The following diagram is suitable for evaluation of stability in any control chart. Unstable conditions can be any of the following (Fig. 3).

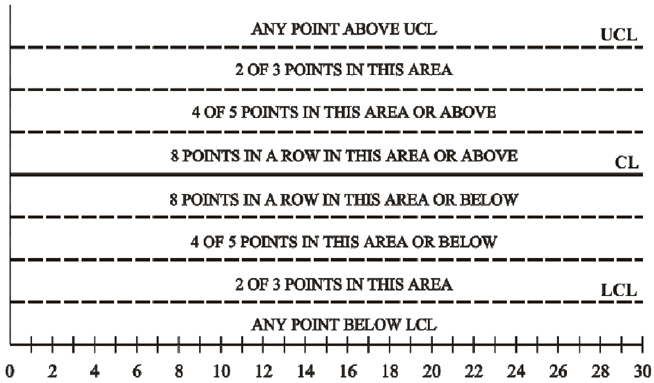


Fig. 3 Control Chart Stability

After the process is analyzed and optimized, it is time to start the statistic work on setting up the control chart. The statistic work can be done according to the seven steps below.

- step 1 - choose the test size,
- step 2 - set time intervals of tests,
- step 3 - calculate centerlines,
- step 4 - calculate control limits (lower and upper),
- step 5 - plot the graphs,
- step 6 - evaluate the graphs,
- step 7 - calculate the process stability and process capability.

Process capability is also another important concept in SPC. Being in control of a manufacturing process using statistical process control is not enough. An "in-control" process can produce bad or out-of-spec product. Manufacturing processes must meet or be able to achieve product specifications. Further, product specifications must be based on customers' requirements. Process capability is the repeatability and consistency of a manufacturing process relative to the customer requirements in terms of specification limits of a product parameter. This measure is used to objectively measure the degree to which your process meet the requirements or not. Capability indices have been developed to graphically portray that measure. Capability indices let you place the distribution of your process in relation to the product specification limits. Capability indices should be used to determine whether the process, given its natural variation, is capable of meeting the established specifications. It is also a measure of the manufacturability of the product with the given processes. Capability indices can be used to compare the product/process matches and identify the poorest match (lowest capability). The poorest matches then can be targeted on a priority basis for improvement. If we sample a group of items periodically from a production run and measure the desired specification parameter, we will get subgroup sample distributions that can be compared to that parameter's specification limits. Two examples of this are represented below (Fig. 4). The diagram on the left shows a series of sample distributions that fall inside and outside of the specification limit. This is an example of an unstable rather than capable process. The right side of the diagram shows all of the distributions falling within the specification limits. This is an example of a capable process.

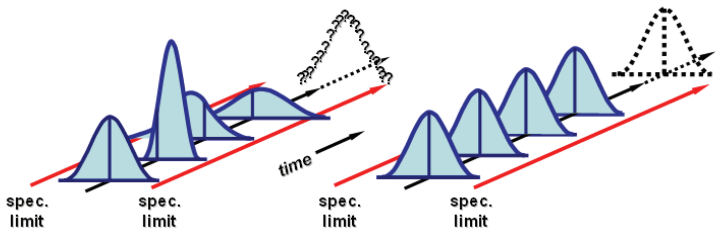


Fig. 4 Example of an Incapable and Capable Process

Process capability can be expressed with an index. Assuming that the mean of the process is centered on the target value, the process capability index C_P can be used. C_P is a simple process capability index that relates the allowable spread of the specification limits to the measure of the actual, or natural, variation of the process, represented by 6 sigma.

If the process is in statistical control, via "normal" SPC charts, and the process mean is centered on the target, then C_p can be calculated as follows (Fig. 5):

$$C_P = T / T_P = (USL - LSL) / 6\sigma \tag{1}$$

where:

- T - tolerance width,
- T_P - process width,
- USL - upper specification limit,
- LSL - lower specification limit,
- σ - standard deviation.

The process capability index shows how able the process is to meet specifications. The higher the value of the index, the more capable the process is:

- $C_P < 1$ (process is unsatisfactory),
- $1 < C_P < 1.33$ (process is of medium capability),
- $C_P > 1.3$ (process shows high capability).

While C_P relates the spread of the process relative to the specification width, it does not address how well the process average is centered to the target value. C_{PK} is often referred to as critical process capability index. C_{PK} measures not only the process variation with respect to allowable specifications, it also considers the location of the process average. C_{PK} is taken as the smaller of either C_{PKL} or C_{PKU} (Fig. 5).

$$C_{Pk} = \text{minimum}\ [C_{PKU}, C_{PKL}] \tag{2}$$

$$C_{PKU} = (USL - \mu) / 3\sigma \tag{3}$$

$$C_{PKL} = (\mu - LSL) / 3\sigma \tag{4}$$

where:

- C_{PKU} - critical process capability index at USL,
- C_{PKL} - critical process capability index at LSL,
- μ - process average
- USL - upper specification limit,
- LSL - lower specification limit,
- σ - standard deviation.

Many companies are establishing specific process capability targets. They may typically start with 1.33 for supplier qualification and have an expected goal of 2.0. If the process is near normal and in statistical control, C_{PK} can be used to estimate the expected percent of defective material.

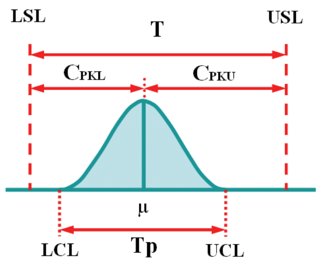


Fig. 5 Graphic Presentation of C_P and C_{PK}

3. Automation of Statistical Quality Control of Production Process

3.1. Defining the Problem

Prerequisites which are indicted by the modern market require automation of work procedure in all activities that are involved in one enterprise. Appliance effects of automation in work procedure and improvement of quality system are numerous, and they can be seen through reduction of total costs and time. In addition, modern information systems are highly capable of liberating man from his routine activities and jobs related to time-consuming execution of mathematical operations over the large number of data, and this is important in the field of quality control. As for computer appliance in field of quality control in CIM surroundings, today several approaches are present: Computer Aided Quality (CAQ), Computer Aided Inspection (CAI), Computer Quality System (CQS) and Computer Integrated Quality (CIQ). The common feature of all these approaches is that the secure quality system supported by computer represents a group of engineer activities which provide for the formation of information system about parameters for product quality in all stages of its life cycle (from product development through its manufacture to its exploitation), and all that serves to increase product quality and presents equipment availability.

With manufacture organization analysis, particularly in the quality control domain, in a great number of production systems in surroundings, it is indicated that in those systems statistical quality control is being applied. To an large percentage (85%) quality control is managed particularly in the manual way, and to some smaller one (15%) through interaction between the operator and the computer. Computer is exclusively being used for data storing (MS Exel). Measuring is manually done, as well as adequate calculations and drawing of adequate control charts. The whole job is very difficult, time-demanding and mostly depends on the operator.

Once the above-presented problems are identified, the authors of this paper, have defined the main aim as the development of an adequate system for automation of process acquisition, preparation, statistical processing, previews and grade of observed quality characteristics in real time. During development of adequate applicative solution care is taken to make the solution easy to use, and, on the other hand, to make it compatible with the measuring equipment. Further on in the paper the operation of the developed system - applicative software is provided.

3.2. System's Functioning

Measurements are entered into the system either manually or through a measuring interface (automated). Standard equipment for automatic data acquisition consists of computer, measurement interface, one or more measuring instruments, and footswitch (Fig. 6).

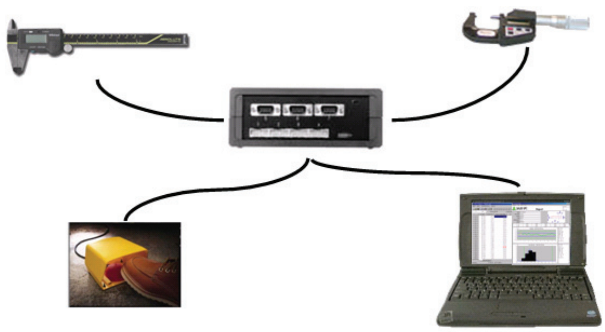


Fig. 6 Standard Equipment for Automatic Data Acquisition

If a measuring interface is used, all that has to be done is to press the trigger to record a value. However, the first thing is to select the gauge. In this case, the selected one has the cursor move after each measurement has been entered. The position of the cursor (the active cell) can be changed to any of the following (Fig. 7):

- No movement: The cursor stays in the current cell
- Down: The cursor moves down
- Right: The cursor moves to the right

- Right/New line: Move to the right until last column containing product characteristic, then jump to new line in first column
- Last in Column: Measurement is always recorded as the last measurement of the current column
- Last in Column/Right: Measurement is recorded as the last measurement of the current column, after the entry the cursor moves to the right

The cursor movement should be set according to your measurement process. For example, if a measurement for the same characteristic for all samples has to be done, then "Move Down" should be selected, but if measure for all characteristics for each sample is required, then it would be best to choose "Right / New Line".

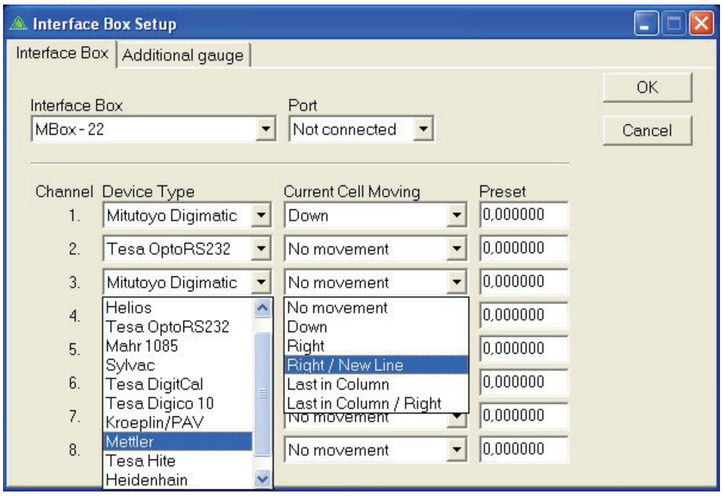


Fig. 7 Selecting Measurement Device

The next step is to arrange the working tables, that is, to arrange individual columns for entering the measures. Since for all product characteristics product name, code, working command, sample amount and sample size are identical, they are adjusted only for the first time, and then copied for all other characteristics. The name of the characteristics, nominal value and tolerance are adjusted for every characteristic individually (Fig. 8).

In the measurement, the first step is to take proper position between the measurement device and the workpiece; then, footswitch is pressed, and the measure is automatically input into the prepared cell in the working table. The measurement is performed in a way that all characteristics are measured on one workpiece; then you move to the next workpiece. Measured results are automatically written into the adequate cells in the table.

Fig. 9 shows a typical software main window with a worksheet containing measurements, the menu, toolbar and two status bars. Measurements are entered into the cells on the worksheet. Where a measurement is colored yellow, this means that it is outside reduced tolerances or outside the middle-half of the tolerance field. The red colored measurement warns of measurements outside of the predefined tolerance limits.

For each measurement, time, date and operator are recorded. Software can work on multiple worksheets simultaneously. All of the worksheets are saved in a single file.

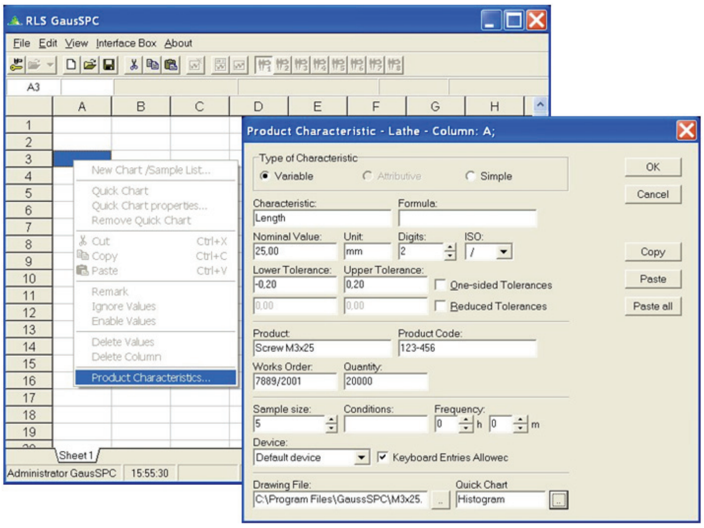


Fig. 8 Adjusting Product Characteristics

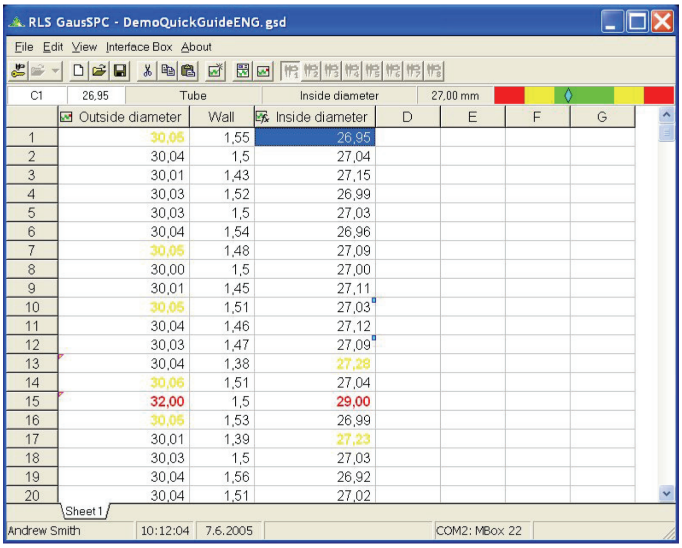


Fig. 9 Main Window of Software

Measurements can be imported to software from a number of sources including those from a custom measuring device, a coordinate measuring machine (CMM) or measurements saved in an external file (Fig. 10). Measurements can be exchanged with other applications (e.g. MS Excel) through the clipboard.

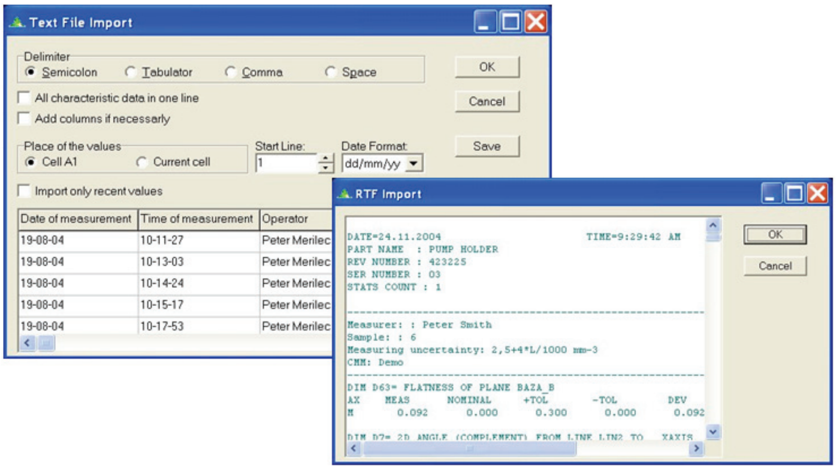


Fig. 10 Importing Data from a Text File and from Rich Text Format File Created by PC-DMIS Software

After measurement, it is necessary to adequately present the measurement results, so certain conclusions could be drawn from them. First, the automatic calculation of statistical parameters is done, and after that defining of desired previews. In developed software data can be displayed in two ways: by table or graphically (Fig. 11). For graphical data display the user defines: chart type, data range selection and characteristic filters for data display. For graphical data display the following is used: X chart, histogram, probability plot, EWMA chart, XR chart and Xσ chart. All data in spreadsheet and charts are changing in real time - during input, delete or modification.

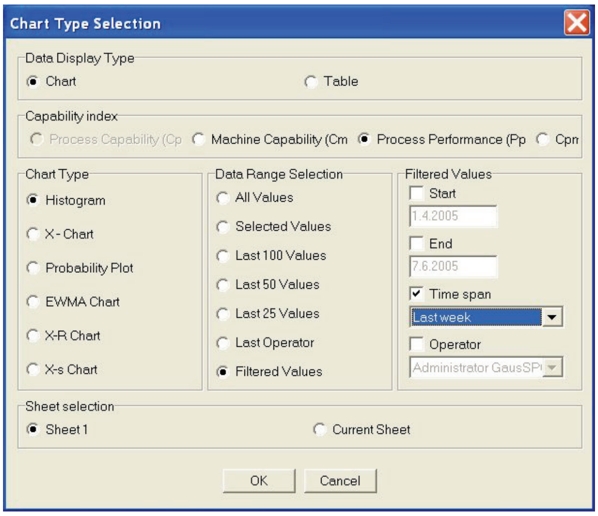


Fig. 11 Chart Type Selection

3.2.1. Graphical Data Display (Preview)

The X chart displays single measurements in the same order in which they were recorded. For each measurement there is one point on the graph. Two green horizontal lines limit the tolerance field of the characteristic. Two blue lines define the control field. The width of the control field is either one half of the tolerance field or it equals the reduced tolerance field (if reduced tolerances have been set). In the Chart Properties dialog box, display graph points can be set and whether control limits and/or the trend line will be displayed. (Fig. 12).

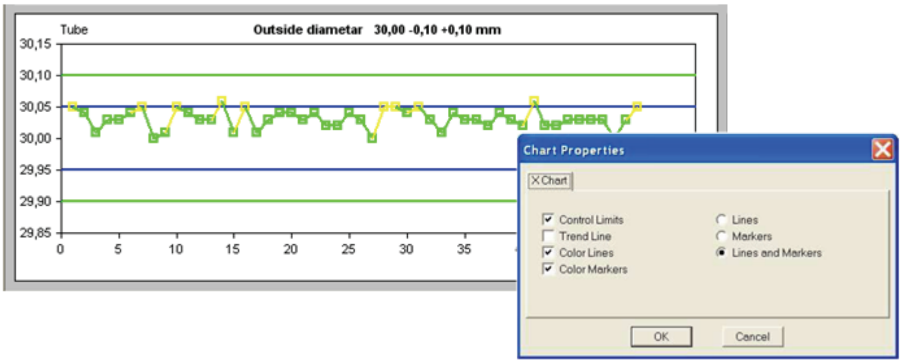


Fig. 12 X Chart

Histogram - Software groups single measurements into divisions. The default number of divisions is a rounded square of the number of selected measurements. The two vertical green lines depict the upper and lower tolerance limits. The blue curve is the Gauss curve with the same average and same standard deviation as the measurements. The number of divisions, display of the Gauss curve and the Cumulative curve can be set. The bars can either be colored or hatched (Fig 13.).

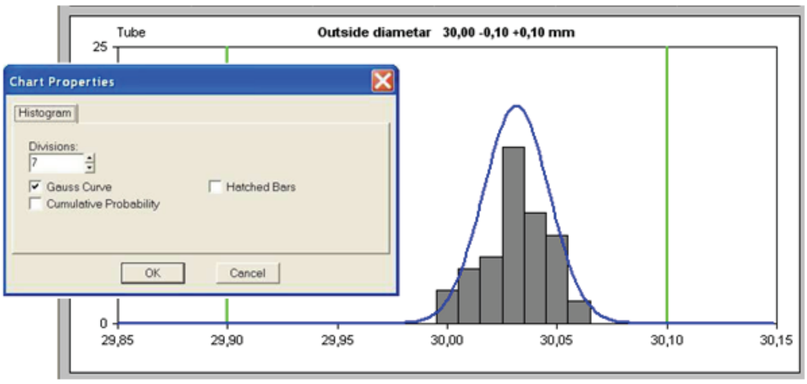


Fig. 13 Histogram

The probability plot is different from the histogram in that instead of number of measurements in a single division on the vertical axis, there is a cumulative frequency by divisions expressed in terms of standard deviation. From this chart it is possible to quickly see the average value and ratio between the range and the tolerance field. In addition, changes are possible for number of points on the graph and show/hide the trend line (Fig. 14).

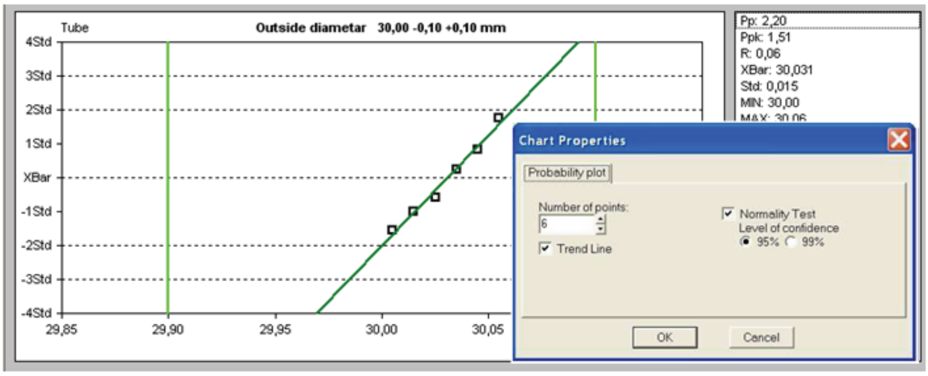


Fig. 14 Probability Plot

EWMA (Exponentially Weighted Moving Average) chart is used when quick detection of smaller shifts in the process needs to be done. The position of the point for a single sample depends also on the values of previous samples whereby a larger weight is given to the more recent samples. The weight of previous samples is defined by the value of the Lambda parameter (e.g. Lambda=0.2 means that the current sample contributes 20% to the current point, while the contribution of all previous samples amounts to 80%). The usual choice of Lambda parameter is between 0.1 and 0.3. In the chart properties dialog box setting is possible for the Lambda parameter (Fig. 15).

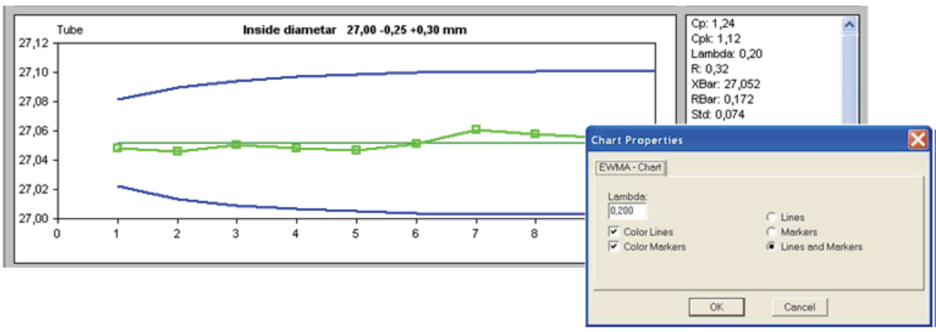


Fig. 15 EWMA Chart

The XR chart consists of two graphs. In the upper graph a point corresponds to the average value of the sample and in the lower graph a point corresponds to the range of values in the sample. Each sample is represented by one point on each of the graphs. Control limits are calculated based on the measurements and the sample size (Fig. 16).

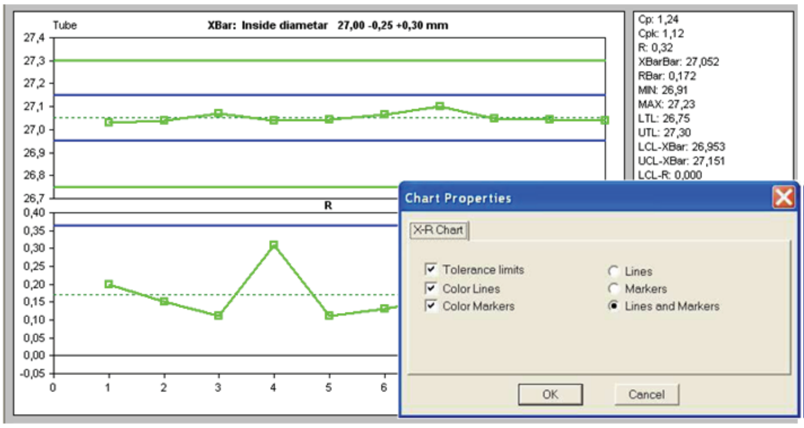


Fig. 16 XR Chart

The Xσ chart is similar to the XR chart except that instead of the range of values there is a standard deviation of a sample shown in the lower graph (Fig. 17).

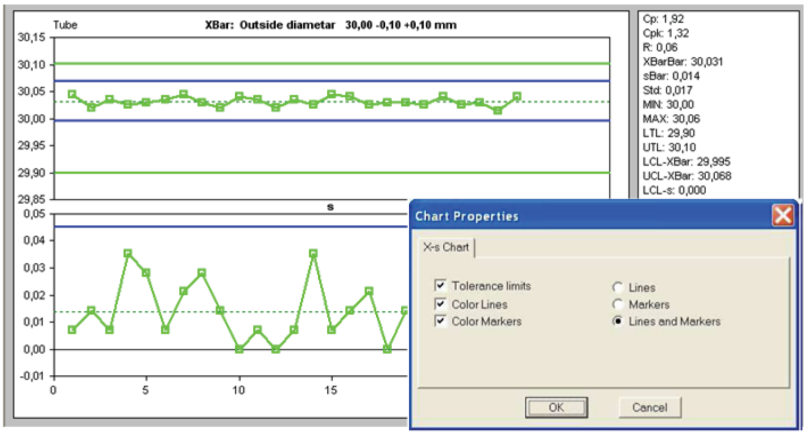
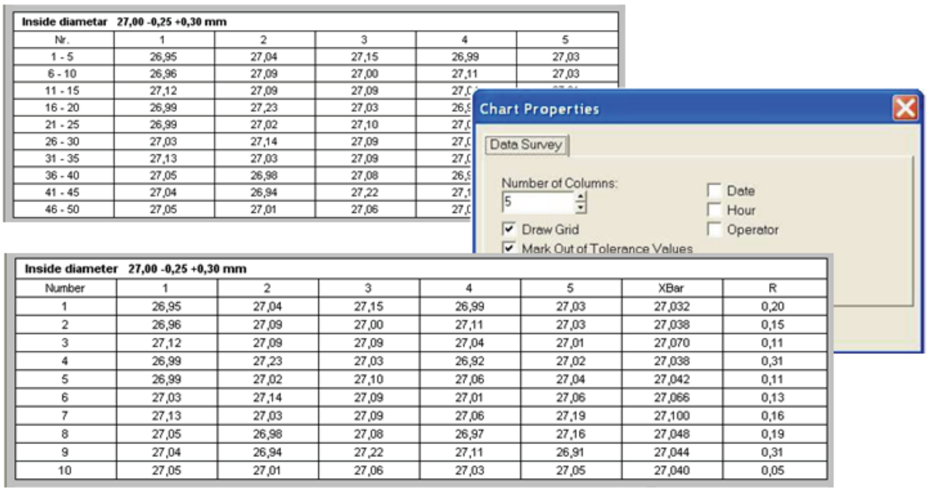


Fig. 17 Xσ Chart

3.2.2. Table Data Display (Preview)

If Table has been selected as the Data Display Type in the Chart Type Selection dialog box (Fig. 11), measurements will be shown in the form of a table. The table on Fig. 18 above is an example of a table where the Chart Type is X chart, histogram or probability plot. In the Chart Properties dialog box setting is possible for the number of columns, show/hide gridlines and selection if marking the measurements which are outside tolerance limits needs to be done. It is also possible to select whether to show the date and time of the measurements and the operator who entered them. For XR, Xσ and EWMA charts measurements are grouped by samples. Two columns are also added which display the average value and range (Fig. 18 below).



Inside diametar 27,00 -0,25 +0,30 mm					
Nr.	1	2	3	4	5
1 - 5	26,95	27,04	27,15	26,99	27,03
6 - 10	26,96	27,09	27,00	27,11	27,03
11 - 15	27,12	27,09	27,09	[illegible]	[illegible]
16 - 20	26,99	27,23	27,03	[illegible]	[illegible]
21 - 25	26,99	27,02	27,10	[illegible]	[illegible]
26 - 30	27,03	27,14	27,09	[illegible]	[illegible]
31 - 35	27,13	27,03	27,09	[illegible]	[illegible]
36 - 40	27,05	26,98	27,08	[illegible]	[illegible]
41 - 45	27,04	26,94	27,22	[illegible]	[illegible]
46 - 50	27,05	27,01	27,06	[illegible]	[illegible]

Inside diameter 27,00 -0,25 +0,30 mm							
Number	1	2	3	4	5	XBar	R
1	26,95	27,04	27,15	26,99	27,03	27,032	0,20
2	26,96	27,09	27,00	27,11	27,03	27,038	0,15
3	27,12	27,09	27,09	27,04	27,01	27,070	0,11
4	26,99	27,23	27,03	26,92	27,02	27,038	0,31
5	26,99	27,02	27,10	27,06	27,04	27,042	0,11
6	27,03	27,14	27,09	27,01	27,06	27,066	0,13
7	27,13	27,03	27,09	27,06	27,19	27,100	0,16
8	27,05	26,98	27,08	26,97	27,16	27,048	0,19
9	27,04	26,94	27,22	27,11	26,91	27,044	0,31
10	27,05	27,01	27,06	27,03	27,05	27,040	0,05

Fig. 18 Table

3.2.3. Output Documentation (Report)

Output from system is report which represents a combination of graphical and/or table previews (Fig. 19). There can be one ore more inputs of graphical and table previews in the report. Adequate statistical parameters are being written automatically in report: process capability index (Cp), critical process capability index (Cpk), range of measurements (R), average value (XBar), standard deviation (Std), minimum value (MIN), maximum value (MAX), lower tolerance limit (LTL), upper tolerance limit (UTL), number of measurements (N), number of measurements below the lower tolerance limit (X < LTL), number of measurements above the upper tolerance limit (X > UTL), number of measurements within tolerance limits (Passed), etc.

At the top of the report there is a header with title, logo, report number and the date. Below these are Header Lines where you can put other information such as product codes, tools used, order number, etc. Under the header there are charts (e.g. our example above shows a histogram with a list of statistical parameters to the right). The list depends on the chart type and it contains basic statistical parameters for the range of data shown. At the bottom of the report there is a field with the name of the operator and a field for their signature.

Also in report it is possible to make following activities: change the chart type or the range of data, define the chart properties, change general graph settings, change font, delete chart, select statistical parameters to be displayed to the right of the chart, show/hide spc parameters, show/hide notes under the chart, insert page break (the chart will be moved to the beginning of a new page), change the position of the chart, etc.

Fig. 19 displays example of outgoing report from the software.

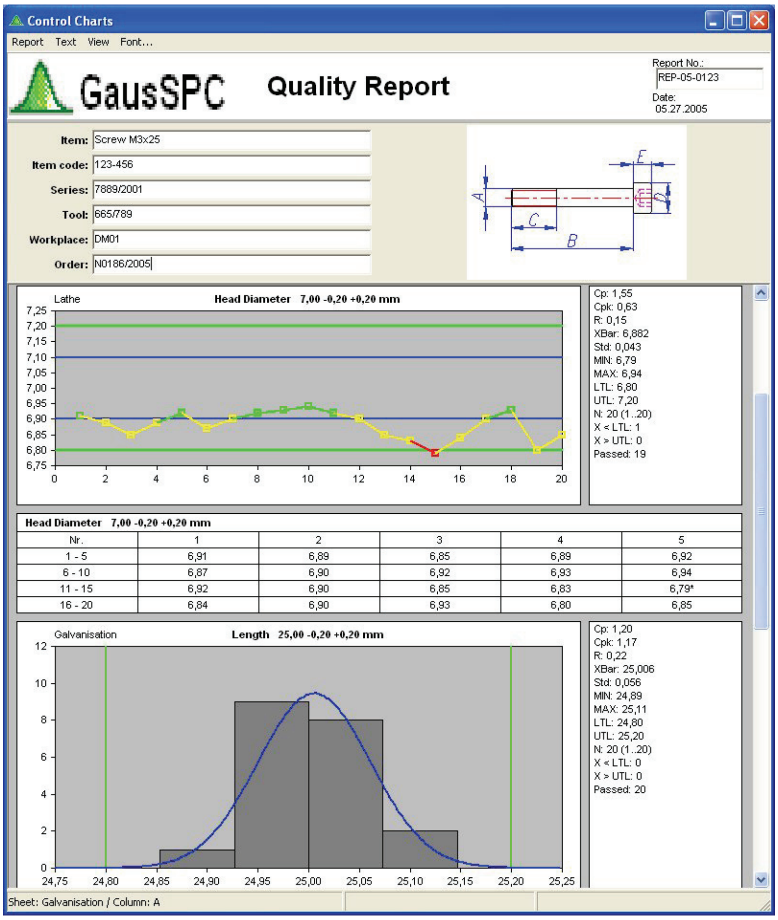


Fig. 19 Output Documentation - Report

4. CONCLUSION

Working with developed software is quick and easy. Logical, intuitive - and therefore simple work-flows have been developed through working with people from the shop-floor. Software is a complete solution that provides everything from automatic data acquisition to generation of reports. Therefore it is also an ideal tool for process control and improvement at the level of work groups, quality circles, and similar.

In accordance with the conditions at the market considering continual rise in quality level and consumers' satisfaction degree, tough competition, and new technologies, it is necessary to provide highly qualitative production. It does not imply only the aspiration towards production with zero rejects, but also achieving quality characteristics variation as close to the limits as possible. Therefore, it is necessary to continually monitor all process parameters, which, among other things, imply monitoring process stability, that is, measuring process capability. Under the conditions of market manufacturing, where all prerequisites for quality are high and the delivery deadlines are ever shorter, this is possible only by applying modern automation systems for designing, manufacturing, control, and its integration in CIM systems.

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RAZVOJ SISTEMA ZA STATISTIČKU KONTROLU KVALITETA PROIZVODNIH PROCESA

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Sprezanjem računara i mernih uređaja stvaraju se informacioni merni sistemi, čiji su osnovni zadaci automatizovano merenje i kontrola kvaliteta proizvodnihh procesa, matematička obradu rezultata meranja u realnom vremenu, memorisanje mernih rezultata, dokumentovanje rezultata merenja, upravljanje procesima, itd.

Statističke metode za ocenu kvaliteta omogućavaju analizu proizvodnih procesa a na osnovu iste i sprovođenje odgovarajućih preventivnih i korektivnih mera u cilju podizanja ukupnog kvaliteta proizvodnje. U radu je istaknut značaj primene statističkih metoda kontrole kvaliteta za ocenu stabilnosti i sposobnosti proces. Prikazana je struktura i finkcionisanje razvijenog aplikativnog sofvera za statističku kontrolu procesa. Na kraju su dati odgovarajući zaključci.

Ključne reči: *statistička kontrola procesa, stabilnost procesa, sposobnost procesa*