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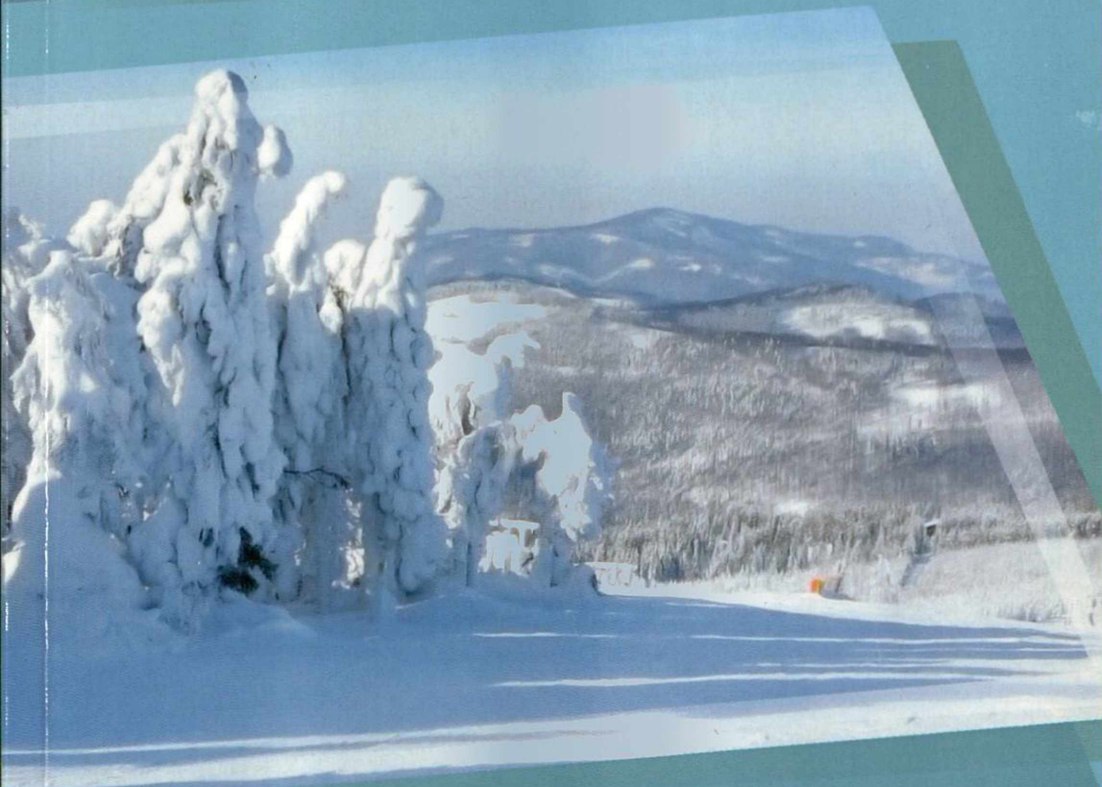

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Value Engineering of Production Processes

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THE USE OF THE ELEMENTS OF THE SPC METHOD FOR QUALITATIVE ANALYSIS OF PAPER GRAMMAGE

Abstract: An essential part of the quality management system in industrial processes is quality control. Effective way of realizing this task is Statistical Process Control (SPC). The SPC tools that allow for the practical interpretation of variables and determine whether the process is within the established production parameters are control charts. Because of their versatility those tools are used in almost every branch of industry including paper processing. An important issue concerning the process of paper production is to obtain a product with the required grammage (expressed in g/m^2) where the stability of drying operation can be controlled by a single observation card (X_i) which was the main objective of this study. Subsequently, an analysis of the equilibrium state and evaluation of capacity of the manufacturing process were performed.

Key words: control charts, paper production, SPC.

13.1. Introduction

Statistical Process Control (SPC) includes methods and techniques to ensure quality of the product. The SPC philosophy based on the Deming assumptions leads to improvement of the manufacturing processes.

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However, methods ensuring the quality of the product verify their compliance with the required technologies and the receiving control. They are the basis to make sure what (or who) is functioning correctly, and what or who incorrectly. This approach helps to avoid the creation of faulty products, thereby preventing problems and reducing process variability (ZYMONIK Z. 2010)

Statistical Process Control (SPC) is a method that uses the so-called. Shewhart control charts, allowing an objective assessment of the natural variability in the manufacturing process. It allows to decide if a production is undergoing correctly and does not show interference. Causes of process variation can be divided into two groups according to the theory of control charts (WISE S. 1998):

• Natural - observed throughout the duration of the operation. A lot of causes can be assigned to this group and they are constant in magnitude. Their elimination is possible only by changing the whole process. An example of natural variability is the variability of the conditions of operation, the volatility of raw materials or the accuracy of the measuring instruments carrying out the process.

• Custom (special) - do not have to appear in the production process. They cause high volatility of operation and move the average value of the measured feature, which has a direct impact on the long-term variances, their size can be variable. Examples of a custom causes of variations of the process are improper employee training or incorrect machine settings.

The use of control charts allows drawing conclusions when the process starts to behave abnormally, which enables quick response. In practice, control charts are used in industry to control the stability of operation at the time of production.

13.2. General characteristic of paper production process

Papermaking process can be divided into stages, beginning with the preparation of the pulp, by forming, pressing and drying the paper web and ending and refining of paper. At this step we can say that there is a parallel between this process and the process of preparation and purification of water. The relationships between the following steps of the process of forming the structure of paper are shown in Figure 13.1.

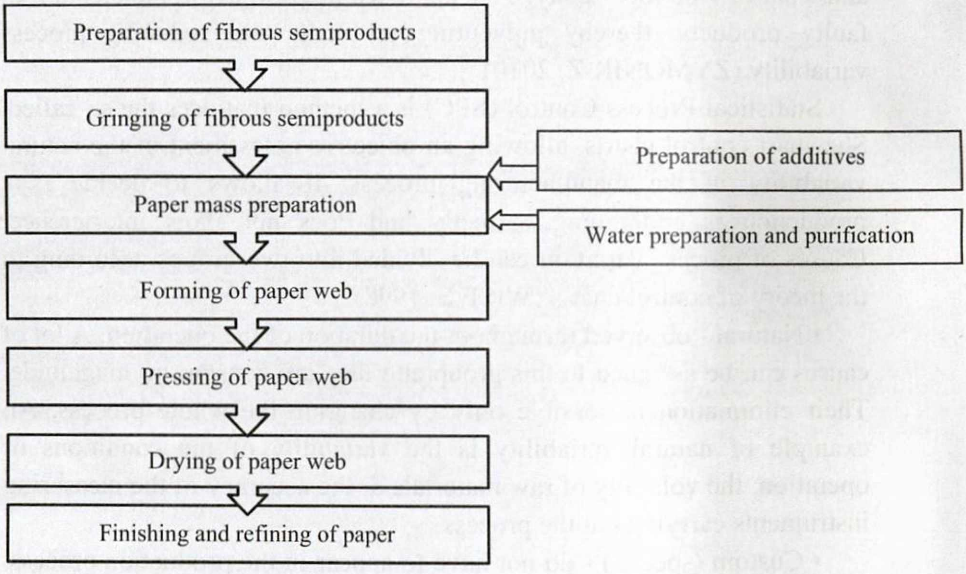

Fig.13.1. A scheme of paper production process.

Source: SZWARCSZTAJN E. 1968, PRZYBYSZ K. 1997.

The first stage of the production involves the preparation of defined amount of wastepaper and treating it with soaps of fatty acid and hot water. All of the ingredients are mixed in a special tank. This process which is called "deinking" allows the separation of fibers from each other and gets rid of the ink from the printed fibers. Other impurities are removed from the mass by means of the rotational sorter and during mass filtering. The mass is then treated in a multi-step washing process, which enables to remove more than 99% of the paint adhering to the fibers. The soaps of fatty acids are added into a vat of hot water and prepared paper-mass. Soap releases binder contained in the paint, which penetrated paper fibers during the process of fusing. Then the compressed air is recessed from the bottom of the tank. It causes the formation of soap bubbles, which attract the released fragments of paint. Bubbles rise along with the paint and form dirty foam. This foam is then removed and treated as a waste. This process is repeated several times in the tanks, to the point where pulp is clear. Next, the prepared pulp is transferred to the sieve section. At this stage formation of paper web, by means of infusion, is performed, followed by a distribution of the paper-mass on the appropriate part of the machine. In this process, it is important to establish a constant pressure at the inlet and outlet to prevent uneven filler degradation. After the initial formation of the web, water is removed in the press section. This is archived by the pressure that forms between the rollers in the presence of one or two felts (fig. 13.2). Uneven pressure on the width of the ribbon or mismatched shafts can result in uneven thickness of the paper. During press stage water is removed to approximately 50% of its' previous volume. Further drying of the paper web is carried out in the drying process (KONKOLEWSKA G. 2006, SZWARCSZTAJN E. 1968, Internal documentation of the Company).

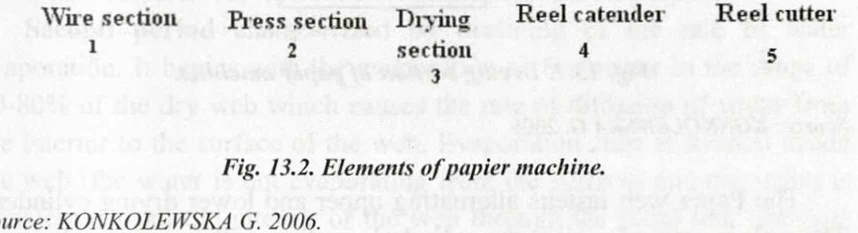

Fig. 13.2. Elements of papier machine.

Source: KONKOLEWSKA G. 2006.

Knowledge of the drying process is necessary for further analysis of its stability and to suggest ways on how to improve this stage of production. Implementation of the drying process using paper machine is made by the provision of heat, carrier of which can be one of the following: water vapor introduced into the drying cylinders, air jets flowing from the high-guard, or air injected into the space between the cylinders (ROGUT R. 2004).

The drying stage starts by transferring partially dehydrated and formed paper web of approximately 40-45% of the dry part from the press to the drying section of the paper machine. Even though the paper ribbon has right shape and structure it is characterized by low mechanical strength. As a result of physical and chemical processes occurring in the drying stage, the final shape and structure of the paper consolidates and develops its functional properties. Drying is carried out in the paper drying unit consisting of drying cylinders heated by steam. These cylinders (Fig. 13.3) are arranged alternately in two rows (KONKOLEWSKA G. 2006).

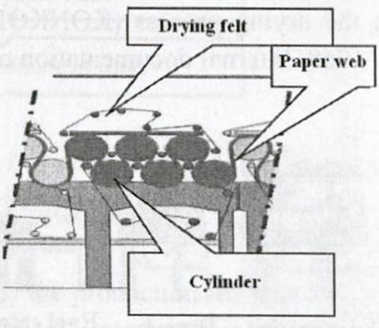

Fig. 13.3. Drying section of paper machine.

Source: KONKOLEWSKA G. 2006

The Paper web fastens alternating upper and lower drying cylinders. The web is pressed against the cylinder's surface with a specific dryer, to improve the drying efficiency and to prevent wrinkling of the paper. The steam discharged from the paper partially penetrates the dryer and condenses inside the dryer and then is discharged to the outside. The main factors influencing the drying process are (PRZYBYSZ K. 1997.): means of bringing the heat, the water content in the web, the chemical nature of the water connections of the fiber material, the structure of the web, humidity and air temperature in the dryer section.

13.2.1 The stages of drying process

The process of drying the paper webs can be divided into three periods.

The initial period involves heating the paper web. The increase of temperature and the speed of water evaporation is observed.

First drying stage consist of a constant speed and a fixed temperature of drying. During this step the evaporation of free water and partially the water coming from the capillary is achieved. Evaporation is carried out on the surface of the paper web and results in difference between the moisture content of the interior and the surface of the web and is aligned by means of diffusion of water from the interior of the web in a continuous manner. The rate of diffusion of water molecules is equal to the rate of water evaporation. The rate of drying during this stage depends on external factors such as the heating surface temperature and humidity. The boundary between the dry period and the next period is the K1 critical point beyond which the rate of evaporation of water drops (PRZYBYSZ K. 2005, Internal documentation of the Company).

Second period characterized by declining of the rate of water evaporation. It begins with the evaporation of free water in the range of 60-80% of the dry web which causes the rate of diffusion of water from the interior to the surface of the web. Evaporation zone is located inside the web (the water is not evaporating from the surface) and the steam is transferred from the interior of the web through the pores and channels formed in the outer layers of the dried web. Following the contact of the outer layers of the web takes place and thus reduces the rate of evaporation of water. Until reaching the second critical point K2 the web temperature is maintained at a constant level and beyond K2 (from dryness level of about 89-92%) alongside the intensification of the drying rate decrease gradual increase of drying temperature can be observed (PRZYBYSZ K. 2005, Internal documentation of the Company).

During the drying stage, as a result of changes in the structure of the paper strip, the reduction in its dimension, which is called shrinkage, is observed. The web is a spatial structure consisting of the swollen fibers and fines. The free spaces are partially filled with water. During the beginning of the drying stage the free water is evaporated due to its weak connection to the paper structure. Next the water, from the spaces between the fibers, is removed. As a result of surface tension forces, closing of the ribbon structure of fiber is observed (first phase of shrinkage). The second phase consists of the evaporation of capillary water. Removing the water from the swollen fibers causes a significant contraction: diagonal coming up to 30% and longitudinal as insignificant as 1-2%. The fibers are the backbone of the spatial structure of the web and that is related to great forces being generated during drying. The shrinking fibers cannot move in relation to each other and contraction of the fibers causes the deformation (or contraction) of the entire dried web. Web shrinkage occurs in all directions: longitudinal, transverse and perpendicular to the plane of the paper. The most prominent shrinkage occurs in perpendicular direction and the volume of shrinkage in the other directions depending on orientation of the fibers in the web. Two kinds of paper can be distinguished according to shrinkage orientation and directions. Isotropic paper is a paper that has an equal shrinkage in the longitudinal and transverse directions. Anisotropic paper (longitudinal direction privileged) transverse shrinkage is predominant (KONKOLEWSKA G. 2006, Internal documentation of the Company).

13.3. Control Charts in Paper production

The data obtained during the grammage paper tests were analyzed by SPC tools in order to determine the stability of a manufacturing process.

SPC methods are used to obtain control of the final products and they are reliable ways of controlling the technological processes. These tools are also used to identify areas of potential improvement and prevent from the manufacturing the products that do not conform to the customer's specifications (ŁUCZAK, J. 2007). The data is gathered from a production process of paper of the Kraft type produced in Poland. Analysis by SPC methods allows the creation of control charts. This enables for the practical interpretation of variables to be established and to determine whether the manufacturing process is under control. The process will be considered as out of control if:

- seven consecutive points lie on the same side of the central line,
- one point exceeds the lower or upper control line,
- three of seven points are located outside of the warning lines,
- two consecutive points are above or below the control limits,
- four of five consecutive points are in the zone between the control and a warning line,
- eight consecutive points lie on both sides of the central line, but none of them near it,
- trends showing deregulation of the process occurred, a series of points manifest progression,
- ten of the eleven points are on one side of the central line (ŁUCZAK J. 2007).

Determination of the stability of the process depends on the trend line, meaning there are seven consecutive points on a control card. They define a continuous trend of increasing or decreasing. If such a trend is detected, the immediate adjustment of the process is required. If 7 consecutive points will be on one side of the center line we can observe what is called "run". The situation indicates the steady change in average which means that the process should be immediately terminated and its' regulation should be performed. Evaluation of the process and its pre-classification, before the serial production, consist of a number of products which are then subjected to measurement and analysis, on the basis of previously established procedures. If the process proves to be correct, it becomes the basis for the development of guidelines for future monitoring. These guidelines assess the capability of the process and allow creating the specification. For this purpose, the values of certain parameters such as process capability Cp and process capability index Cpk were analyzed. Indicator of capability of quality (Cp) defines the probability to fulfill the set quality requirements established by the manufacturer and fulfill the requirements of the recipient. The ability of the whole process or just selected machines can be examined (HAMROL A. 2005, KOŃCZAK G. 2000).

$$Cp = \frac{permissible\ variation\ resulting\ from\ the\ manufaturer\ requirements}{variability\ of\ the\ process}$$

Process capability:

$$C_p = \frac{(UCL - LCL)}{6\delta} = \frac{T}{6\delta}, \qquad [13.1]$$

UCL – upper control limit

LCL – lower control limit

T - tolerance

δ- standard deviation of process.

The standard deviation is calculated from the below formula:

$$\delta = \frac{\sqrt{\sum_{i=1}^{n}(xi - XAVR)^2}}{n-1} \qquad [13.2]$$

This indicator shows the capacity and stability of the process and determines the width of the range of tolerance in relation to the range of variation.

Process capability index (C_{pk}):

$$C_{pk} = \frac{(X_{AVR} - DLT)}{3\delta} = \frac{(UCL - X_{AVR})}{3\delta} \qquad [13.3]$$

X_{AVR} – is the indicator of the centerline of the process, which in general is unknown. We replace it with a target or the average of all the data.

C_{pk} defines centering of the process. It is called the corrected process capability as it takes into consideration the location of the average value in relation to the tolerance limits. If the C_{pk} is not equal to C_p, the process is under the influence of a constant factor, which can result in the average value being different from the characteristics of the tolerance field.

The papermaking is a continuous process, it is impossible to take samples of products without interruption. The analyzed data is based on the value of grammage of paper in a particular place and time of the entire bale of paper, rather than taking a single sheet into consideration. For this reason, the cards X (medium) or Xm (median) cannot be used. Single observation X_i card is the perfect solution for bypassing the problem. Therefore, for analysis of the data X_i is used. However this approach is sensitive to random disturbances in the process. In this case to avoid unexpected errors all performed tests must be carried out under the same conditions. It can be assumed that the paper bale is a homogeneous product. Thanks to that performing of one measurement will be representative of the entire product.

To create this type of card chart the following parameters are required R_{AVR} - the range between two consecutive measurements and X_{AVR} (central line) - the average of the measurements.
The R_{AVR} is calculated using the formula

$$R_{AVR} = \frac{\sum_{i=1}^{n} \max(x_1 ... x_n) - \min(x_1 - x_i)}{n} \qquad [13.4]$$

The average X_{AVR} is calculated by the following formula:

$$X_{AVR} = \frac{x1+x2+xn}{n} \qquad [13.5]$$

The value of (LCL/UCL) is calculated by the following formula:

$$LCL/UCL = X_{AVR} \pm 2{,}66 * R_{AVR} \qquad [13.6]$$

13.4. Material and methods

Kraft paper should have a grammage of 150 g/m^2. According to the manufacturer's assumptions a batch shall be considered as defective if it does not present value in the range of 148-152 g/m^2, which is the so-called disqualifying defect. Determination of the paper's grammage is made according to PN-EN-ISO-536 Paper and board - Determination of grammage. Weight (or grammage) of cardboard is expressed as the weight of one square meter of board (g/m^2) (BIELECKI A. 2011). It is a standardized parameter but can be also classified by the manufacturer. For the proper determination of weight, sample must be conditioned (temperature 23 ± 1°C and relative humidity of 50 ± 2%). Permissible weight variation can be adjusted on the basis of agreements between the manufacturer and the customer as the existing Polish and international standards are not mandatory. The data obtained from the measurements were analyzed using Statistica program.

13.5. Data analysis and results

To determine the control charts the equitations [13.1] [13.2] and [13.3] were used. To determine the upper and lower warning limit (the limits of intervention) 148g/m^2 and 152g/m^2 values were chosen. The values were specified by the plant, as the limits of acceptability. Control charts and histograms as well as the range of grammage are shown in Figures 13.4, 13.4 and 13.6.

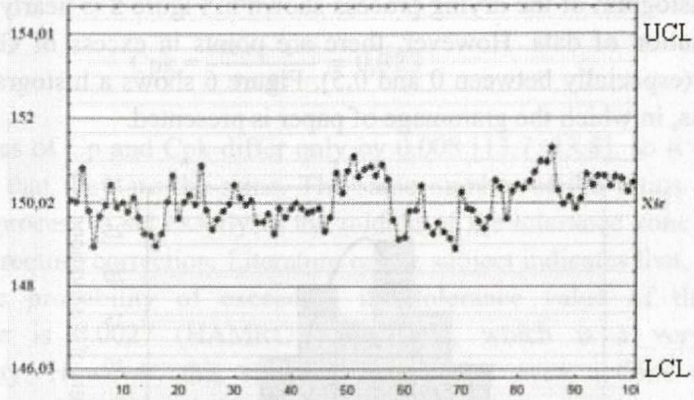

Fig. 13.4. Control chart.

Source: personal resources.

Figure 13.4 presents a control chart including data concerning grammage from the paper drying process. The average value is 150.02 g/m^2. Values do not go beyond the upper and lower warning and limit line (UCL, LCL), however the clusters of 10 and more points on the same side of the center line are observed.

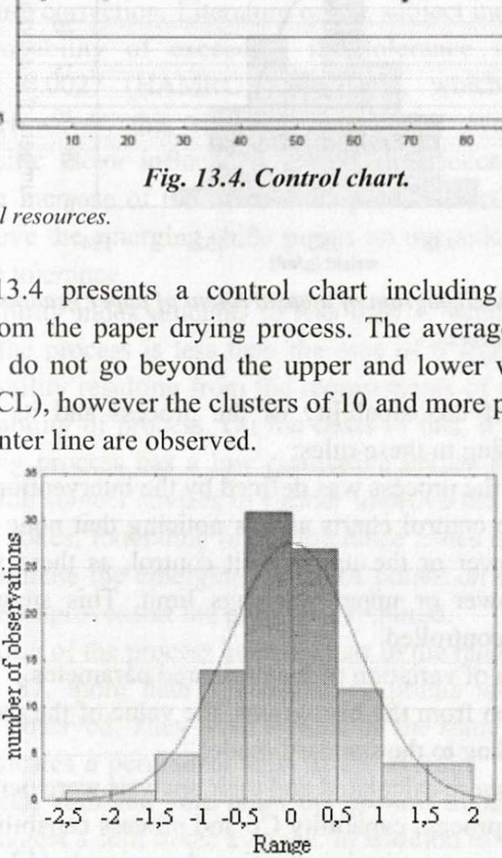

Fig.13.5. Histogram of rang of paper grammage.

Source: personal resources.

Histogram of the drying process shown in Figure **5** is nearly standard distribution of data. However, there are points in excess of Gaussian's curve (especially between 0 and 0.5). Figure 6 shows a histogram of the process, in which the grammage of paper is presented.

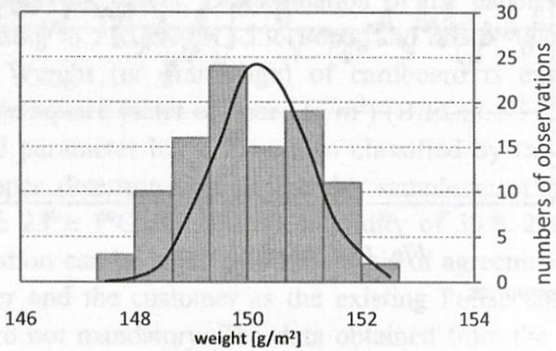

Fig. 13.6. Histogram of measurement of paper grammage.

Source: personal resources.

Verification of the capability of the process and its stability was carried out according to these rules:

a) stability of the process was defined by the intervention limits

Analysing the control charts allows noticing that none of the points go beyond the lower or the upper limit control, as there was no value outside of the lower or upper warnings limit. This suggests that the drying process is controlled.

b) distribution of variation of the measured parameter

As can be seen from the histograms, the value of the paper weight is distributed according to the standard model.

c) Cp, - Cpk were calculated and their analysis were performed

The value of process capability Cp and process capability index Cpk were established using equitation mentioned previously [13.1] and [13.3], were accordingly:

$$Cp = \frac{152-148}{6*0,82} = 0,815 \qquad [13.7]$$

$$Cpk = \frac{150,02-148}{3*0,82} = 0,823 \qquad [13.8]$$

Values of Cp and Cpk differ only by 0.008 [13.7, 13.8], so it can be assumed that they are the same. The same number of the ratios means that the process is set exactly in the middle of the tolerance zone and it does not require correction. Literature on the subject indicates that, in this case, the probability of exceeding the tolerance value of the test parameter is 0.0027 (HAMROL A. 2005), which is a very low probability. However, this situation means that even actions of the smallest specific factor influencing the process (occasional or regular) can cause the increase of the of non-compliance fraction. Even a slight factor can move the emerging shifts points on one side of the center line to beyond the tolerance.

The capability index amounts to less than 1, which implies that the tolerance of the process is less than the area of 6 sigma. Therefore, the allowed variability resulting from the requirements of the process is less than the variability of process. On the basis of this, it can be concluded that the drying process has a low qualitative ability for that reason the literature on the subject advises to further improve the process or extend the tolerance zones. Extending of the tolerance zones is not possible that is why to eliminate the emerging trends of points on either sides of the center line the improvement the process is required.

Examination of the process control chart in the range of: 34 - 47, 48 - 57 and 79 - 87, more than 7 consecutive points measured one after another were observed. They were located on the same side of the center line. This indicates a permanent shift in the average. The shift is called "Run". Between 78th and 86th point the upward trend is clearly visible which also suggest a shift in the average. In addition to that, between 34th and 48th, and 90th and 100th measuring point, 10 of 11 points are located on one side of the mid-line.

It can be said that the process violates the assumptions of the processes' stability, which have been adopted. Despite the fact that the values of grammage do not go beyond the warning lines, the drying process does not seem to be under control. The disturbances with unknown character acting on the process making it work worse than could be assumed from its natural abilities. This thesis is confirmed by the process capability Cp and process capability index Cpk, which suggest that the process has low quality ability.

13.6. Conclusions

As it is clear from the conducted research the drying process is not under control. Firstly it is necessary to continue monitoring and then improving the process. According to process description (see p. 13.2) the highest impact on the tested parameter has the temperature and the duration of drying. Therefore, the suggested way of grammage correction is to find better settings of temperature of the drying vapor and time. After changes are implemented, the stability and capability of the drying process should be checked.

Optymalization of drying can also be achieved by controlling the tension of the paper machine drying sieve. According to Datzma (Datzma M. 2010) there is a direct relationship between tension of drying sieve and area of contact of drying cylinder with paper web. Heat flow from the cylinder to the web is improved by increasing the tension of the sieve, which reduces the steam consumption and increases production efficiency. While performing the process at low tension of dryer sieve, air layers reduce web contact with the cylinder surface, which subsequently reduces the evaporation rate. By increasing the tension the air squeezes and the paper receives enhanced contact with the surface area of the cylinder and increased energy flow. Higher tension dryer sieves cause better heat transfer and hence a more efficient drying and consequently, increasing the drying speed of the machine. Increasing the tension may cause stabilization of the drying process and thus the grammage of the paper.

One other issue should be considered as a source of possible distortion of paper web grammage. The process of pulp infusion could cause interference seen as paper weight heterogeneity. The infusion distributes precisely, an equal amount of pulp to the next sections, where the paper web is formed. The incorrect settings of infusion pneumatic pressure may cause inequality of paper webs and thereby its grammage. The infusion settings should be checked to make sure that the drying step results in the observed errors in grammage distribution.

It is required to verify the two other sections: pressing part and drying felts and its down-force. Infusion and press are controlled electronically, but in the absence of adequate processes control a disturbance at these stages could happen. Stuff following the procedures is an important aspect of the process. Although the process is mostly automated failure to comply with certain guidelines could result in the observed discrepancies.

Statistical Process Control (SPC) is a method of quality management, enabling the assessment of natural variability in production processes. On this basis, one can determine whether the operation or process is under control or if there are any interferences appearing. Through the use of Shewhart control charts, SPC enables the assessment of the variability of production processes. Through statistical analysis, control charts clearly show when the action starts to behave abnormally, which in practice allows for quick response. Industry uses the cards to control the stability of the current processes. Control charts are based on the idea of proclaiming that the process variability is caused by random causes and special causes. In order to facilitate the monitoring of changing parameters on the control charts central lines (that determine the average) and control lines (illustrated by the range of tolerance of natural variability, variability induced random causes) are applied.

To assess the capability of the drying process, the specific factors were determined and analyzed. Precise evaluation of the process shows that the operation is not under control. Despite the fact that the analyzed values do not exceed the scope of the warning lines, the trends of series points located on one side of the center line were observed. The other possible locations of errors and intervention at the various stages of paper production were also indicated.

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