Capability Evaluation and Statistical Control of Electrostatic Separation Processes

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***Abstract*—The variability of the outcome is often deplored by the users of electrostatic separation equipment. A slight modification of the composition of the processed material, a change in the environmental conditions, or an alteration of the electrode configuration may cause objectionable fluctuation of product quality. Thus, the purity of the copper product recovered from electric cable wastes can easily diminish from 98%, which is fully acceptable for recycling purposes, to a value below the standard level of 97%. This paper is written with the aim of showing how statistical process control methods could contribute to the improvement of users' overall satisfaction. In order to validate a procedure for evaluating the short- and long-term capabilities of the electrostatic separation process, the authors carried out a series of experiments on subgroups of chopped electric cable wastes, which are similar to those currently processed in the recycling industry (95% polyvinyl chloride; 5% copper). The first set of experimental data showed that an "in-control" electrostatic separation process can easily satisfy the level of performance required by the customers (i.e., a capability index of > 1.33). The same set of data enabled the computation of the upper and lower limits of the R- and X-bar control charts. The second set of experiments was designed to evaluate the ability of these charts to detect the following typical situations of abnormal operation of the electrostatic separation equipment: 1) a change in the composition of the processed material; 2) a failed connection of the static electrode to the high-voltage supply; and 3) the accumulation of dust on the surface of the corona electrode. Based on the authors' experience as consultants for the recycling industry, the following several recommendations have been formulated: 1) Evaluate the capability of the electrostatic separation process by performing no more than ten observations and making use of the confidence indexes; 2) use moving R- and X-bar control charts to obviate the difficulty of sampling; and 3) prepare a "Corrective Actions Guide" for the operators using control charts for monitoring.**

***Index Terms*—Control chart, electrostatic separation, process capability, statistical process control (SPC).**

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I. INTRODUCTION

DURING recent years, new electrostatic separation processes have been developed for ore processing and waste recycling [1]–[4]. For each one of these applications, the quality of the products is a crucial issue. Thus, the purity of the copper recovered by electrostatic separation from electric wire and cable wastes should exceed 97%. The insulating materials recovered from the same type of wastes could not be recycled unless they contain less than 0.02% of metallic impurities [5].

The statistical process control (SPC) proved to be an effective tool for improving manufacturing quality in many industries [6]. Since the pioneer works of Shewhart, 80 years ago, the SPC methodology has been widely used for detecting nonconforming products by monitoring the process through samples. The statistical analysis of sample characteristics prompts the adjustments to be made to the process in order to keep it within the specifications.

The keywords of SPC are capability and control charts. The capability index quantifies the variability in process characteristics. A process having a high capability index will constantly respect the quality requirements imposed to its products. The control charts are graphical representations of process characteristics. They make the control of a process easier, in order to maintain or improve its capability.

This paper aims at answering the question: How can these concepts be applied to electrostatic separation processes? The variability of the outcome (quantities of recovered materials; purity of the products) is a serious drawback for any new electrostatic separation application. SPC could be a promising solution to this problem.

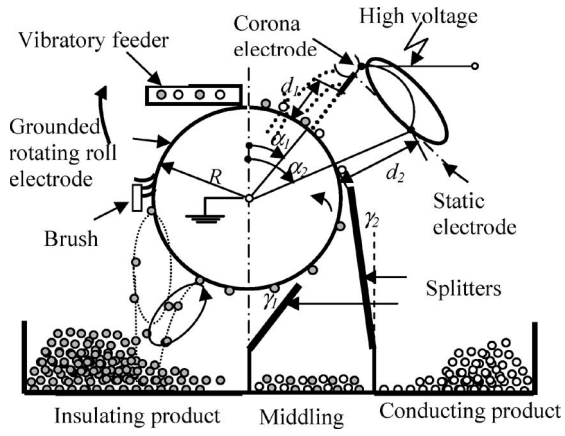

Fig. 1. Variables of an electrostatic separation process: high-voltage level U, roll speed n, angular α_1 and radial d_1 positions of the corona electrode, angular α_2 and radial d_2 positions of the electrostatic electrode, and angular position γ of the splitter.

The difficulty of the problem resides in the fact that the electrostatic separation is a continuous process, the outcome of which is a function of numerous factors: flow rate, granule size, high-voltage level, electrode configuration, and the roll speed [7]. In a typical roll-type corona-electrostatic separator [8], the granular mixture to be sorted is fed onto the surface of a grounded roll electrode, which rotates at a controlled speed. The electric field in which separation takes place is produced between this roll and one or several electrodes connected to a dc high-voltage supply (Fig. 1). The insulating particles are charged by ionic bombardment in the corona field zone and adhere to the surface of the rotating roll electrode due to the electric image force. The conducting particles, which are not affected by the corona field, are charged by electrostatic induction in contact with the grounded roll and are attracted by the static electrode.

This paper presents a series of experiments that enabled the authors to evaluate the capability of such electrostatic separation processes and to establish appropriate control charts. In order to show how SPC methods could contribute to the improvement of users' overall satisfaction, several typical situations of abnormal operation were simulated.

II. SPC Concepts

SPC techniques are widely used in manufacturing industries for monitoring repetitive processes to determine whether they are operating properly. The variability of process characteristic is the key concept of these techniques. Thus, the common cause of variation is the naturally occurring oscillations of system response around a long-term average value, due to inherent fluctuations of system parameters. Special cause variation is typically caused by some problem in the system and can be quickly detected with SPC techniques.

A. Capability

Process capability studies distinguish between conformance to control limits [upper control limit (UCL) and lower control limit (LCL)] and specification limits [upper specification limit (USL) and lower specification limit (LSL)]. Specifically, control limits characterize the inherent variability in a process, whereas specification limits define acceptable product characteristics. The products that are outside the specification limits represent wastes that must be discarded or reprocessed.

The difference between the USL and LSL defines the interval of tolerance (IT). The inherent variability of a process, as defined by the control limits, must be well within this IT. The process capability index C_p is defined as [9]

$$C_p = \frac{I_T}{6\sigma} = \frac{USL - LSL}{6\sigma} \tag{1}$$

where σ is the standard deviation of the process characteristic being monitored. In most cases, σ is replaced in the aforementioned formula by an estimation given by the following:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(X_i - m)^2}{n-1}} \tag{2}$$

where

$$m = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{3}$$

is the mean of n measured values $X_i, (i = 1.n)$.

The capability index shows how well a process is able to meet specifications. The higher the value of the index, the more capable is the process: $C_p < 1$ (unsatisfactory), $1 < C_p < 1.33$ (low capability), $1.33 < C_p < 1.66$ (medium capability), and $C_p > 1.66$ (high capability).

This index considers only the spread of the characteristic in relation to specification limits, assumed to be two-sided. The *process performance index* C_{pk} takes into account the position of m with respect of the two specification limits [9]

$$C_{pk} = \text{Min}\left(\frac{USL - m}{3s}, \frac{m - LSL}{3s}\right). \tag{4}$$

These two indexes should be jointly employed in order to accurately assess the capability of a process. A higher capability index can be achieved by reducing the variation in the process. The effect of shifting the mean of the process toward the target is an increase of the process performance index.

An easier way to assess the capability of a process is to use the C_{pm} index introduced by Taguchi *et al.* [10]. This indicator considers at the same time the variability of the process characteristic and the position of each measured value with respect to the target. As any variation of a process characteristic compared to the target value affects the quality of the product, Taguchi recommended to evaluate the "nonquality" by calculating the average standard deviation from the target.

The loss generated by an individual value is evaluated by

$$L = K(X - Target)^2 \tag{5}$$

where K is a constant which depends on the problem under study, and X is the value taken by the characteristic. In the case of a sample of mean m and standard deviation s, the

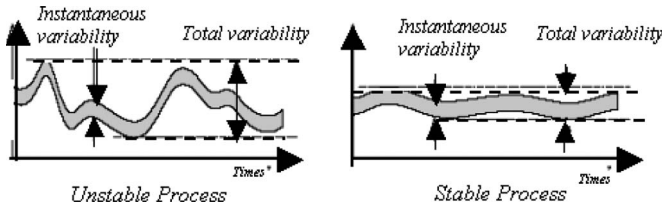

Fig. 2. Unstable and stable processes.

average loss is given by the following, known as "Taguchi's loss function":

$$L = K\left(s^2 + (m - Target)^2\right). \tag{6}$$

The C_{pm} indicator is defined by

$$C_{pm} = \frac{I_T}{6\sqrt{s^2 + (m - Target)^2}}. \tag{7}$$

Experts agree to list five elementary sources of variability, which are also the causes of low capability: machine, operator, material, method, and environment [6]. The most difficult to act on is machine variability. This residual variability, which is also designated as "natural (or common cause) variability," determines the maximum values of C_p, C_{pk}, and C_{pm} that can be attained. Therefore, a process can be characterized by two types of variability (Fig. 2): the instantaneous ("short-term") variability, caused by the machine and, to a lesser extent, by the other four factors listed earlier, and the total ("long-term") variability, which is a resultant of the variations caused by all five factors over a longer period of time. The stability of a process can be characterized by the index

$$R_S\% = \frac{P_p}{C_p} * 100 \tag{8}$$

with P_p as the long-term capability. The computation formulas of indicators P_p, P_{pk}, and P_{pm} (long term) are strictly identical to the formulas of C_p, C_{pm}, and C_{pk} (short term).

B. Control Charts

High capability indexes are obtained by limiting the variability of process characteristic being monitored. The difficulty is to distinguish between natural variations and those assignable to special causes. The adjustment of process variables is justified only in the latter case. Control charts enable the detection of this kind of situations.

To monitor the process, samplings are carried out regularly. The mean and the range of the measured process characteristics are calculated for each sample and then plotted on graphs called control charts. In this way, process evolution is visualized. The frequency of sampling is chosen so that, if special cause variation is present, the control charts can identify it [5], [6].

The control charts are established based on measurements made on n subgroups (samples), each one having a number N of elements. The experts recommend $n \geq 30$; $N \geq 3$ [6].

TABLE I
COEFFICIENTS FOR THE CALCULATION OF CONTROL CHART LIMITS

Number N in a sub-groups	2	3	4	5	6	7
A	2.574	2.282	2.114	2.004	1.924	1.864
B	0	0	0	0	0.076	0.136
K	1.023	0.729	0.577	0.483	0.419	0.373

The centerline of the X-bar chart that will be employed in this paper is the mean of the means X_i of the subgroups, expressed by the following relation:

$$\overline{\overline{X}} = \frac{1}{n}\sum_{i=1}^{n}(\overline{X_i}). \tag{9}$$

The upper (UCL_X) and lower (LCL_X) control limits of this chart are

$$UCL_X = \overline{\overline{X}} + K\overline{R} \tag{10}$$
$$LCL_X = \overline{\overline{X}} - K\overline{R} \tag{11}$$

where K is given in tables as a function of the number N of elements in a subgroup (Table I) and

$$\overline{R} = \frac{1}{n}\sum_{i=1}^{n} R_i \tag{12}$$

with R_i being the range of the values measured for the subgroup i. The upper (UCL_R) and lower (LCL_R) control limits of the R-bar chart are

$$UCL_R = A\overline{R} \tag{13}$$
$$LCL_R = B\overline{R}. \tag{14}$$

III. MATERIALS AND METHOD

A laboratory-scale role-type corona-electrostatic separator manufactured by CARPCO Inc., Jacksonville, FL, was employed for the experimental study. In order to simulate the conditions of an industrial installation, the angular and radial positions of the corona electrode ($\alpha_1 = 30^\circ$ and $d_1 = 40$ mm), the angular and radial positions of the static electrode ($\alpha_2 = 70^\circ$ and $d_2 = 70$ mm), and the angular position γ_1 of the splitter of the collector were maintained fixed for all experiments (see again Fig. 1).

The tests were carried out on three granular subgroups (S_1, S_2, and S_3), obtained from genuine chopped electric cable wastes (RIPS-ALCATEL, France). The mass of each sample was 100 g [5 g of copper + 95 g of polyvinyl chloride (PVC)], the characteristic size of the granules ranging between 1 and 2 mm. The products are recovered in three different compartments: conductor, nonconductor, and middling.

The process characteristic being monitored was the mass of the middling product, which was measured with an electronic balance (precision: 0.01 g). Laboratory studies and industrial practice have proven the pertinence of this output variable for the characterization of the overall performance of the process. Smaller quantities of middling are naturally correlated with

higher recovery and purity indexes of both conducting and insulating materials. With copper representing only 5% of the feed, the acceptable mass of middling collected after electrostatic separation should not exceed 1%.

A four-step experimental procedure was adopted.

Step 1) Identification of the optimal point of operation ($U_{\rm opt}$, $n_{\rm opt}$, and $\gamma_{\rm pt}$) by using a 17-run composite experimental design [11]. The procedure was similar to the one thoroughly described in [12].

Step 2) Assessment of the short- and long-term capabilities of the process. During one day, characterized by stable ambient conditions (20.2 °C–22.2 °C; $RH = 27.5\%$–30%), each of the three samples was subjected to 20 electrostatic separation tests (one test every half an hour, the three products of the separation being remixed after having measured the mass of the middling fraction). The tests were performed using the optimal operating conditions obtained at Step 1).

Step 3) Setup of the control charts. The experimental data obtained at Step 2) were employed for calculating the UCL and LCL of the X- and R-bar charts, using the formulas given in the previous section of this paper, with $n = 20$ and $N = 3$. Taking into account the fact that the electrostatic separation is a continuous process, sampling is not economically and practically feasible, in an industrial environment. Therefore, "moving X-bar" and "moving R-bar" control charts were set up, using only the individual measurements on sample 1.

Step 4) Simulate several "out-of-control" situations. Three sets of experiments were performed in order to simulate the following: 1) a change in the composition of the processed material (four tests with a sample containing 4% Cu and four with a sample containing 6% Cu); 2) a failed connection of the static electrode to high-voltage supply (the static electrode was disconnected from the high-voltage terminal of the electrostatic separator); and 3) the accumulation of dust on the surface of the corona electrode (three successive groups of four tests with the wire covered with starch powder on 5%, 10%, and 15% of its surface, respectively).

Each of these situations has been encountered by the authors during their activities as consultants for the recycling industry. The problem with such "out-of-control" situations is that they generate only a small shift of process outcome, which cannot be detected by plain visual monitoring of the products collected after the electrostatic separation. A disconnection of the corona electrode is an event that cannot pass unobserved, as the deterioration of the separation process is radical. This is not the case with a failed connection of the static electrode, which might arrive in installations, the electrode configuration of which is often modified for technological reasons. Such an event cannot be detected by the operator without the use of a control chart.

TABLE II
RESULTS OF THE 17 RUNS OF THE COMPOSITE EXPERIMENTAL DESIGN

n	U	γ	Insulating product			Middling-	Conducting product		
min[1]	kV	°	M_i[g]	Pu_i[%]	Rec_i[%]	M_{mim}[g]	M_c[g]	Pu[%]	Rec_C[%]
60	30	-6	94.86	98.92	99.85	0.54	3.67	99.73	73.20
90	30	-6	94.31	99.27	99.27	1.04	4.03	99.01	79.80
60	34	-6	94.63	98.68	99.61	0.63	3.47	99.42	69.00
90	34	-6	94.07	99.23	99.02	1.14	4.03	98.76	79.60
60	30	2	94.76	98.71	99.75	0.74	3.34	100.00	66.80
90	30	2	94.39	99.15	99.36	1.36	3.47	100.00	69.40
60	34	2	94.62	98.67	99.60	1.00	3.14	100.00	62.80
90	34	2	94.29	99.15	99.25	1.43	3.51	100.00	70.20
60	32	-2	94.66	98.81	99.64	0.72	3.42	100.00	68.40
90	32	-2	94.28	99.24	99.24	1.30	3.69	99.73	73.60
75	30	-2	94.48	99.04	99.45	0.95	3.63	99.72	72.40
75	34	-2	94.41	98.96	99.38	1.13	3.49	98.85	69.00
75	32	-6	94.63	98.99	99.61	0.59	3.79	99.47	75.40
75	32	2	94.65	98.90	99.63	0.90	3.43	99.13	68.00
75	32	-2	94.58	99.04	99.56	0.90	3.64	99.73	72.60
75	32	-2	94.67	99.03	99.65	0.86	3.60	99.72	71.80
75	32	-2	94.56	98.91	99.54	0.84	3.54	99.72	70.60

IV. RESULTS AND DISCUSSION

A. Set-Point Identification

The optimal values of the high voltage U, the speed n, and the angular position γ_2 were established based on the results given in Table II, which were obtained under stable ambient conditions (temperature: $T = 20$ °C–21 °C; relative humidity: $RH = 27\%$–30%). The optimal values of the control variables (i.e., those that simultaneously maximize metal recovery and insulator purity), the minimum middling mass (i.e., the target of the process), and the 95% confidence interval of this predicted value were computed with a commercial software of experimental design (MODDE 5.0 [11]), and they are as follows: $U_{\rm opt} = 31.6$ kV, $n_{\rm opt} = 75$ tr/min, $\gamma_{\rm opt} = -6°$, $Target = 0.76$ g, $T_U = 0.91$ g, and $T_L = 0.51$ g. The upper (T_U) and lower (T_L) limits of the confidence interval were adopted as USL and LSL ($T_U = USL$; $T_L = LSL$). These limits correspond to what is commonly accepted in industrial practice, for this particular application.

B. Capability Assessment

The results of the 60 electrostatic separation tests that will be employed for calculating the process capability indexes are given in Table III. From a purely statistical point of view, both the "short term" and "long term" capabilities of a process should be evaluated based on at least 30 observations. In industrial practice, this might be a very constraining requirement, taking into account the difficulty and the cost of sampling. Therefore, at this stage of the study, a comparison was performed between the capability indexes evaluated from a lower number of observations, but making use of the so-called confidence index [13]. This index is a function of the number of observations. The higher the number of observation, the closer

TABLE III
RESULTS OF 60 ELECTROSTATIC SEPARATION EXPERIMENTS CARRIED OUT WITH THREE SUBGROUPS OF CHOPPED ELECTRIC WIRE WASTES (5-g Cu–9-g PVC)

Sub-groupe (test) N°	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
RH%	27.5	27.6	27.6	27.5	28.5	28.3	28.9	29	28.4	28.4	29.7	29	28	29.6	29.1	29.7	30	29.4	29.6	29.5
T°	20.2	20.2	20.9	20.9	20.6	21.2	21.1	20.9	21.2	21.2	21.3	22.1	22.1	21.1	21.4	20.9	20.9	20.6	20.5	20.4
S_1	0.73	0.74	0.75	0.73	0.74	0.78	0.81	0.80	0.79	0.75	0.71	0.72	0.73	0.75	0.71	0.70	0.69	0.71	0.77	0.69
S_2	0.72	0.70	0.71	0.72	0.73	0.71	0.68	0.67	0.65	0.63	0.64	0.69	0.70	0.71	0.72	0.71	0.71	0.73	0.75	0.70
S_3	0.70	0.71	0.68	0.63	0.65	0.68	0.68	0.67	0.70	0.71	0.69	0.69	0.71	0.65	0.63	0.65	0.68	0.69	0.67	0.69
X	0.72	0.72	0.71	0.69	0.71	0.72	0.72	0.71	0.71	0.70	0.68	0.70	0.71	0.70	0.69	0.69	0.69	0.71	0.73	0.69
R	0.03	0.04	0.07	0.10	0.09	0.10	0.13	0.13	0.14	0.12	0.07	0.03	0.03	0.10	0.09	0.06	0.03	0.04	0.10	0.01
$X_{(m)}$			0.74	0.74	0.74	0.75	0.78	0.80	0.80	0.78	0.75	0.73	0.72	0.73	0.73	0.72	0.70	0.70	0.72	0.72
$R_{(m)}$			0.02	0.02	0.02	0.05	0.07	0.03	0.02	0.05	0.08	0.04	0.02	0.03	0.04	0.05	0.02	0.02	0.08	0.08

to one is this index. With the data from the first ten experiments carried out on sample 1

$$C_{p(10)} = \frac{0.91 - 0.51}{6 * 0.03} = 2.3 \tag{15}$$

$$C_{pk(10)} = \text{Min}\left(\frac{0.91 - 0.76}{3 * 0.03}, \frac{0.76 - 0.51}{3 * 0.03}\right) = 1.6 \tag{16}$$

$$C_{pm(10)} = \frac{0.91 - 0.51}{6\sqrt{(0.03)^2 + (0.76 - 0.76)^2}} = 2.3. \tag{17}$$

Using the data from all the 20 experiments performed with that sample, the same indexes are

$$C_{p(20)} = 1.9 \quad C_{pk(20)} = 1.5 \quad C_{pm(20)} = 1.9. \tag{18}$$

In order to assess the capability of the process, these values were multiplied by the confidence index [[13]]. The corrected values derived from the two sets of data are

$$C^*_{p(10)} = 1.396 \quad C^*_{pk(10)} = 1.151 \quad C_{pm(10)} = 2.3 \tag{19}$$

$$C^*_{p(20)} = 1.387 \quad C^*_{pk(20)} = 1.186 \quad C_{pm(20)} = 2.3. \tag{20}$$

As $C^*_{p(10)} \approx C^*_{p(20)}$, it can be concluded that ten experiments are enough for assessing the capability of an electrostatic separation process, with the condition of using the appropriate confidence index.

Using the data of the 60 experiments, which model the long-term behavior of the process, the following indexes were computed:

$$P_p = 1.6 \quad P_{pk} = 1.6 \quad P_{pm} = 1.5. \tag{21}$$

After corrections,

$$P^*_p = 1.349 \quad P^*_p = 1.405 \quad P^*_{pm} = 1.50. \tag{22}$$

The stability of the process characteristic being monitored is very good, as

$$R_S\% = \frac{P^*_p}{C^*_p} * 100 = \frac{1.384}{1.387} = *100 = 99.50\%. \tag{23}$$

This means that the control charts can be confidently employed for supervising the process.

C. Setup of Control Charts

Using the data in Table III, (10)–(14), with $N = 3$ and $n = 20$, lead to the following values for the central line:

$$\overline{\overline{X}} = 0.71 \text{ g} \tag{24}$$

and for the UCL and LCL of the X-bar chart

$$UCL_{\overline{X}} = 0.71 + 0.729 * 0.08 = 0.78 \text{ g} \tag{25}$$

$$LCL_{\overline{X}} = 0.71 - 0.729 * 0.08 = 0.63 \text{ g}. \tag{26}$$

For the same set of data, the computed upper and lower limits of the R-bar chart were

$$UCL_{\overline{R}} = 2.282 * 0.08 = 0.19 \text{ g} \tag{27}$$

$$LCL_{\overline{R}} = 0 * 0.08 = 0 \text{ g}. \tag{28}$$

Fig. 3 shows the X- and R-bar chart setups in accordance with the aforementioned UCL and LCL. The USL and LSL are represented on the same charts, to facilitate the analysis of the situation from the customer's point of view. The plotted values are the mean and the range of 20 subgroups simulated by the 3 × 20 experiments in Table III. All the values are within the control limits. The process was under control, during those 60 experiments.

The characteristic lines of the moving X- and R-bar charts in Fig. 4 were computed in a different way, which simulates in a better way, the condition in which SPC could be applied in an industrial environment. Thus, 18 moving means X_i and 18 moving ranges R_i were computed using the 18 subgroups of three consecutive values of the middling mass measured for S_1.

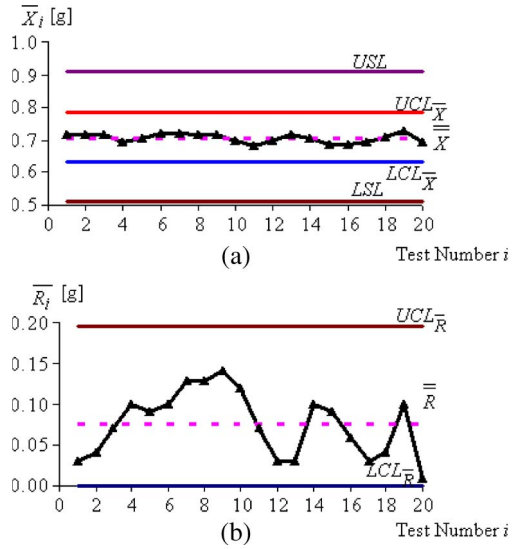

Fig. 3. (a) X- and (b) R-bar control charts for the electrostatic separation process simulated by the tests $i = 1, \ldots, 20$ in Table III.

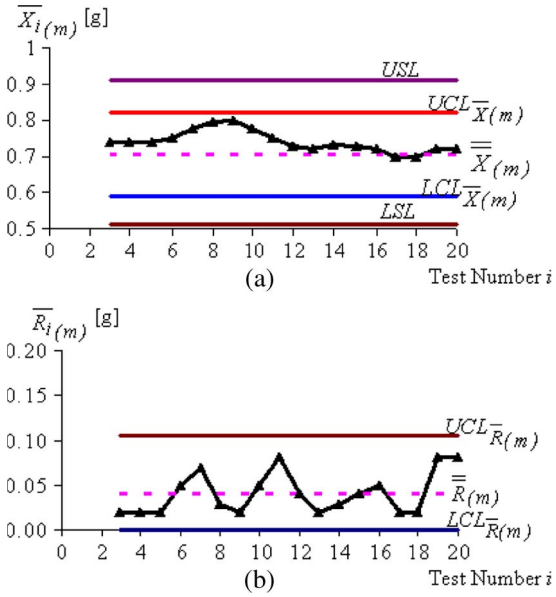

Fig. 4. (a) Moving X- and (b) R-bar control charts for the electrostatic separation process simulated by the tests $i = 3, \ldots, 20$ on sample S1 in Table III.

The values are given in the two bottom lines of Table III and served for the computation of the centerline

$$\overline{\overline{X}} = 0.71 \text{ g} \tag{29}$$

and for the UCL and LCL of the X-bar chart

$$UCL_{\overline{X}(m)} = 0.71 + 3 * 0.04 = 0.82 \text{ g} \tag{30}$$
$$LCL_{\overline{X}(m)} = 0.71 - 3 * 0.04 = 0.59 \text{ g}. \tag{31}$$

For the same set of data, the computed upper and lower limits of the R-bar chart were

$$UCL_{\overline{R}(m)} = 2.822 * 0.04 = 0.11 \text{ g} \tag{32}$$
$$LCL_{\overline{R}(m)} = 0 * 0.03 = 0 \text{ g}. \tag{33}$$

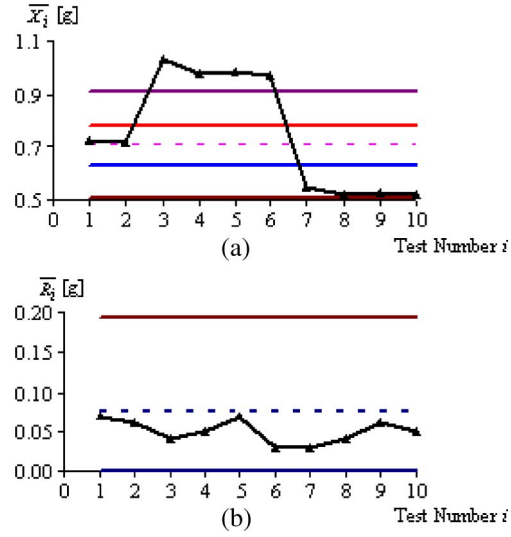

Fig. 5. Detection of the variation of metal concentration in the feed, by using (a) X- and (b) R-bar control charts.

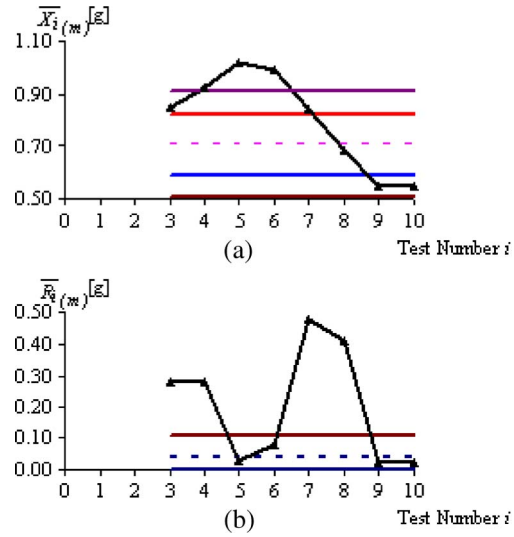

Fig. 6. Detection of the variation of metal concentration in the feed, by using moving (a) X- and (b) R-bar control charts.

The values shown in Figs. 3 and 4 represent the result of a laboratory simulation of an industrial process. Sample 1 contained a slightly higher content of copper than the others, which can explain the higher values recorded on R-bar chart in Fig. 3(b), and the values beyond the mean on the moving X-bar chart in Fig. 4(a). A correction was done after test #10, in order to center the process on the target.

D. Simulation of "Out-of-Control" Situations

1) Variation of Metal Concentration in the Feed: The results of the experiments are shown in Figs. 5 and 6 (tests #1 and #2 were pertained with a 5% Cu sample, tests #3–#6 with samples containing 6% Cu, and tests #7–#10 samples containing 4% Cu). The "out-of- control" situation could be easily detected on any of the control charts employed. Fluctuations in the composition are likely to be detected by a series of points oscillating on one side and the other of the centerline of the

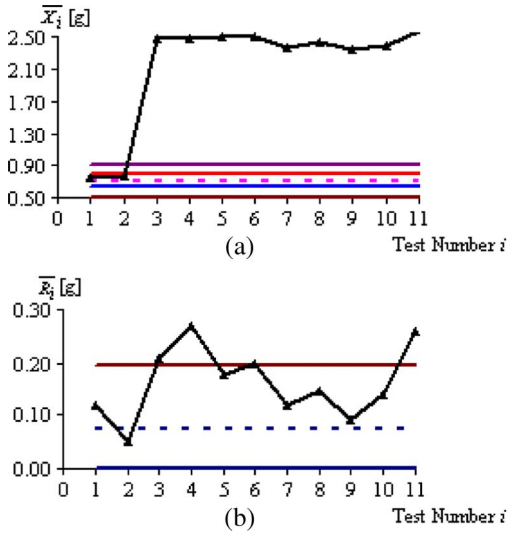

Fig. 7. Detection of a failed connection of the static electrode, by using (a) X- and (b) R-bar control charts.

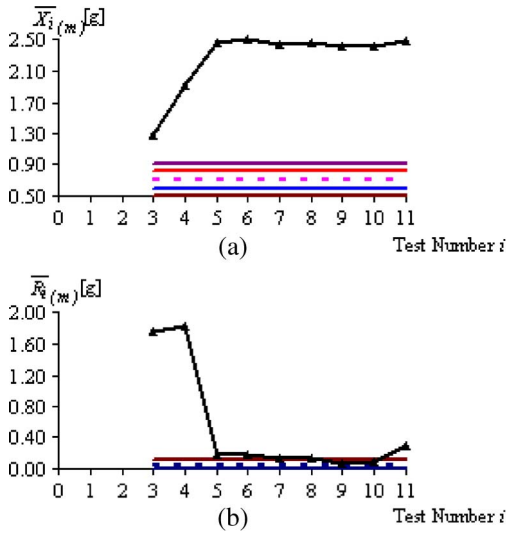

Fig. 8. Detection of a failed connection of the static electrode, by using moving (a) X- and (b) R-bar control charts.

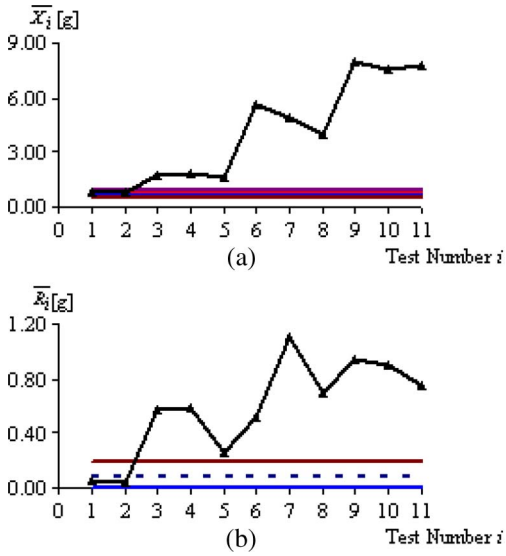

Fig. 9. Detection of dust accumulation on the corona electrode, by using (a) X- and (b) R-bar control charts.

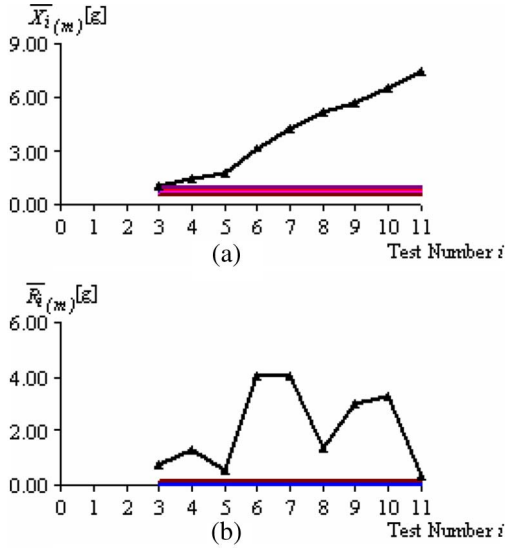

Fig. 10. Detection of dust accumulation on the corona electrode, by using moving (a) X- and (b) R-bar control charts.

X-bar and moving X-bar charts, and by points beyond the UCL on the R-bar chart.

2) Failed Connection of the Static Electrode: The control charts in Figs. 7 and 8 illustrates this "out-of-control" situation: The measured middling mass passes from 0.74 g under normal operating conditions to 2.57 g when the static electrode was disconnected from the high-voltage terminal of the electrostatic separator.

3) Dust Accumulation on the Corona Electrode: The possibility of detecting this event on the control charts is evidenced by the results shown in Figs. 9 and 10. As the first simulation was done with 5% of the wire surface covered by starch powder, the results of the measurements were all outside the control limits. The separation results worsen with the quantity of dust accumulated on the wire. Therefore, this special cause of variation can be detected by a series of points beyond the centerline and a trend of increase in time.

A "Correction Action Guide" could provide suggestions to the operators using control charts to monitor an electrostatic separation process. In some cases, the task of the operators is simple, as they can recognize the likely assignable cause of the "out-of-control" situation by examining the behavior of the process as displayed in the control charts. For instance, a series of points beyond the centerline, and a trend of increase in time, is typical for dust accumulation on corona electrodes. In other cases, the operator has to examine several possible causes of "out-of-control" situations. A point beyond the UCL in the X-bar chart may indicate a failed connection of the static electrode to the high-voltage supply, but also a change in the humidity content of the probe or an altered position of the splitter between conductor and middling product. A series of points oscillating on one side and the other of the centerline of the X-bar and moving X-bar charts is likely to reflect uncontrolled fluctuations in the composition of the feed but

also changes in the relative humidity of the ambient air or in the velocity of the rotating roll electrode. In such cases, if an elementary corrective action does not have the estimated effect, it means that the "out-of-control" situation is the association of several adverse factors, and the process cannot be restored without involving an expert capable to make use of more refined diagnosis tools.

V. Conclusion

The application of SPC to electrostatic separation of granular materials could reduce the variability that affects the output of such processes and limits their industrial application. This paper validated a three-step procedure, consisting in the following: 1) set-point identification, using design of experiment techniques; 2) capability assessment; and 3) setup of X- and R-bar control charts.

The data presented in this paper demonstrate that capability studies can be performed with no more than ten observations, if good use is made by the confidence index recommended by the SPC experts. For the particular process investigated in this paper, both "short-term" and "long-term" capability indexes were higher than 1.33, indicating that the level of performance satisfies customers.

Sampling difficulties impose the use of moving X- and R-bar control charts for monitoring electrostatic separation process characteristics. Choosing the UCL and LCL in accordance with the recommendations of SPC methodology is a guarantee of the fact that all deviations in performance can be readily detected, to prevent a more severe deterioration of the process that could yield products outside the specification limits.

The study was performed for a well-defined category of processed materials (wastes of chopped electric cables), but a similar approach could be adopted for a range of electrostatic applications of separation. At this time, only several "out-of-control" situations that were considered to most frequently cause user dissatisfaction could be examined. Deviations from optimal set points of the high voltage, roll speed, splitter position, ambient temperature, and relative humidity are other common sources of "assignable cause" variation in the electrostatic separation process and deserve a distinct study.

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