INTEGRATED PROCESS CONTROL AND ENGINEERING

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> 'The mathematicians and physics men
> Have their mythology; they work alongside the truth,
> Never touching it; their equations are false
> But the things *work*. Or, when gross error appears,
> They invent new ones.'
> Robinson Jeffers, 'The Great Wound'.

SUMMARY

The paper presents an Advanced Charting Technique (ACT) for process management with minimal risk of adjustment errors. The technique combines the Neyman-Pearson concept of control region and the Taguchi philosophy. It permits Integrated Process Control (IPC) by simultaneous testing of process stability and current quality monitoring on a twofold pooled chart. Quality control limits are of decisive importance, whereas stability limits serve for warning. Thus IPC reflects a quality-oriented approach to process control and diverts attention from dry Statistics, focusing on Quality. IPC makes for significant reduction of the risk of adjustment errors and considerably improves the efficiency of automated control by feedback adjustment. Comparison of the conventional technique and ACT is performed, using numerous case studies for different processes.

KEY WORDS

advanced charting technique (ACT), integrated process control (IPC), statistical quality control (SQC)

INTRODUCTION

Statistical Quality Control (SQC) tools can be classified in three categories: 1) Dynamic tools for continuous running follow-up (control charts); 2) Static tools for periodic detailed study under special conditions (design of experiments (DOE) and capability study; 3) Sampling or screening for detection and removal of defective products with their subsequent replacement. In our opinion, this classification is similar to the classification used in medical practice: 1) Instruments for daily observation at home (stethoscope, blood pressure monitor, thermometer); 2) Complex stationary hospital equipment for detailed examination under sterile conditions (e.g., tomograph); 3) Operating room equipment for detection and removal of diseased organs and hopefully their replacement by sound ones.

Considering the tools used either for SQC or in medicine, one can see some disparity as to the importance of the relative primitive first-category tools intended for early diagnostics compared with their second- and third-category counterparts. For example, stethoscopes and thermometers do not differ from those used in the fifties, whereas a new tomograph generation is introduced every couple of years or so. The situation is similar for SQC. The tools for off-line control activity are continuously modernized, whereas the control charts (on-line activity) devised in the 1920s are essentially no different now from what they were then (Porter and Caulcutt 1992). Meanwhile fast-advancing technology needs SQC supporting software with options for process-control equipment. The efficiency of automated process control (APC) depends on the chart decision-making method. Therefore the authors have seen their goal in the development of an advanced complex approach applicable to the quality needs of the new century instead of the rather rough Shewhart 'one-parameter-at-a-time' technique (using the DOE terminology).

CONCEPT OF CONTROL REGION AND ADJUSTMENT ERRORS

The single goal of the conventional charting technique is stability testing, i.e. comparison of process variation over time versus its 'natural' variation. The technique represents a kind of continuous procedure of hypotheses testing. The chart centerline represents the hypothesized mean value of the process parameter, the control limits represent the critical values of the two-sided test for the Null Hypothesis (H_0: the process is in the 'in-control' state) acceptance region, and each point represents a test value for the given sample. The risk of a Type I error (α) is specified (α=0.0027), whereas that of a Type II error (β) should be minimized, using run tests for pattern recognition. The decision-making method by charting is illustrated in Table 1.

	H_0 IS TRUE	H_0 IS FALSE
ACCEPT H_0	NO ADJUSTMENT	UNDERADJUSTMENT (β)
REJECT H_0	OVERADJUSTMENT (α)	ADJUSTMENT

Table 1. Adjustment Errors in Hypothesis Testing by Charting

Proceeding from the assumption that any process can be described by a normal distribution, Shewhart proposed a combination of two separate control charts for stability testing: one for averages ($\bar{x}$) to determine whether the process mean is at the standard value, and the other for sample standard deviations (s) to characterize the process variability value. Thus the Null Hypothesis was split by Shewhart into two Simple Null Hypotheses concerning mean and variance. A positive decision as to whether the process is stable is therefore based on the logical 'and' concerning these Null Hypotheses: neither the process mean nor the process variability has changed. In charting language it means that for the given sample both the average and the standard deviation are within the corresponding control limits.

It was shown (Bluvband, Grabov and Ingman 1995) that this decision-making method is equivalent to construction of a rectangular control region (Shewhart Rectangle) on a two-dimensional graph formed by superimposing the charts. For all sampling points falling within the Rectangle the process is considered to be in a state of control, otherwise it is in the 'out-of-control' state in terms of either the process mean or its variability. In contrast to the Shewhart approach, this work is based on the Neyman-Pearson concept (Neyman and Pearson 1928) of a 'true' control region having an oval shape and representing the result of cutting the joint ($\bar{x}$ -s sampling distribution (shown in Fig. 1) by a horizontal plane at the height corresponding to the given significance level. It can be shown (see Bluvband, Grabov and Ingman 1995) that the Oval equation is as follows

$$-\ln(\alpha) = 0.5\,\{\, n\,(\bar{z})^2 + (n-2)\,[(s^*)^2 - 2\ln(s^*) - 1\,]\}\ , \tag{1}$$

$$\text{where} \quad \bar{z} = \frac{\bar{x} - \mu}{\sigma}\ ; \quad s^* = \frac{s}{\sigma}\sqrt{\frac{n-1}{n-2}} \tag{2}$$

n - size of samples drawn from a normal universe with parameters μ and σ.

Fig. 2 presents the results of Monte-Carlo simulation (N(0;1), set of 20.000 samples, n = 5), the Shewhart Rectangle and the oval control region corresponding to the same significance level. At a glance one can see that the Oval fits the scatter diagram shape much better, so the Rectangle represents a rather rough approximation of the true control region. The Rectangle corners are practically empty (underadjustment area), whereas many sampling points have fallen outside the Rectangle (possible overadjustments). Note that the observed number of these points (177) considerably exceeds its expected value (108), which approximately corresponds to the number of the points falling outside the Oval (124). Numerical integration of the probability density function of the joint sampling distribution over the Rectangle area also shows that the actual Type I error for the Shewhart charts considerably exceeds its advertised level (by more than 20%).

To demonstrate the disparity between the Rectangle and the Oval from the power point of view, the β-value was calculated for the Rectangle and the Oval for a given shift of the universe parameters. Comparison of the regions shows that the Oval is more powerful than the Rectangle ($\beta_{rec} - \beta_{oval} > 0$) for most possible directions of process shift. Summing up, one can see that the oval control region provides a more reliable basis for judgment as to whether the process is in statistical control.

TRANSITION TO QUALITY ENGINEERING

The concept of being 'in-control' is limited to process stability without any regard to product quality. Meanwhile, process control should be aimed at quality improvement, not at freezing the statistical status

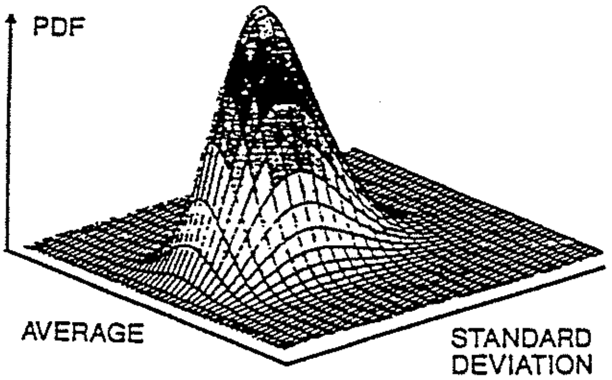

Fig. 1. Joint $\bar{x}$-s Sampling Distribution

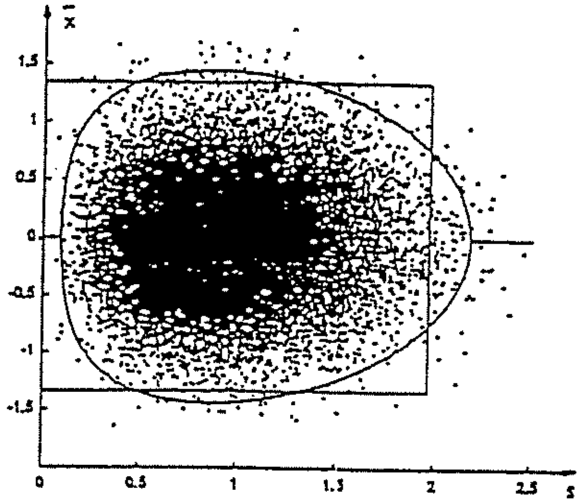

Fig. 2. $\bar{x}$-s Graph Presenting the Simulation Results:
• - Sampling Data, 1 - Shewhart Rectangle, 2 - Oval

quo. The customers select the winners among the manufacturers according to their quality (i.e. their ability to consistently deliver acceptable products); they are not particularly interested in whether the process is stable, but rather in whether its quality is stable. J. Johnson, the former director of research at US Steel, said: 'The possibility of improving the economy of steel to the customer is largely a matter of improving its uniformity of quality...' (Marker and Morganstein 1988, 23). A state of virtually uniform product can be only achieved through on-line quality control and we cannot control quality unless we measure it. For quality monitoring we proposed a loss estimator (LE-statistic) closely resembling the Taguchi Expected Loss (EL)

$$LE_i = \frac{1}{n}\sum_{j=1}^{n}(x_{ji} - \mu)^2 = \sigma^2\left[\frac{n-2}{n}\left(s_i^*\right)^2 + \left(\bar{z}_i\right)^2\right] \tag{3}$$

where x_{ji} denotes the j-th reading of the i-th sample.

Thus the LE-statistic depends on both unit-to-unit variation and process deterioration (wear-out, shift, etc.). The main difference between the LE-estimator and EL is that the former characterizes the on-line activity and uses the sample statistics, whereas the latter characterizes the off-line activity and uses population parameters. The control limit for the LE-statistic can be established from the extreme loss for the process 'in-control' state. This value represents a quality measure of the inherent process variability for a given characteristic. It seems unprofitable to adjust a process for which the loss estimate does not exceed a level under random statistical behavior. Firstly, such an adjustment increases the process variability, so that quality does not improve, but actually gets worse. Secondly, every adjustment reduces productivity, because nothing is produced while a process is being adjusted. This costly mistake of overadjustment contradicts the main idea behind Quality Engineering: cut production cost by eliminating indiscriminate adjustment and leave only that which is absolutely necessary to creation of the quality product. Note that practitioners criticize feedback controllers operating in conjunction with the Shewhart charts for overadjustments (Box and Kramer 1992). So the IPC slogan is: stop tinkering with a process, leave it alone until Quality Problems appear! Continuing the medical analogy: when you have a common cold (assignable cause in the SQC terminology) you usually wait and see whether it develops into flu. Rushing to the doctor with a common cold is a 'serious overadjustment'.

Comparison of the losses due to inherent process variability shows that the extreme loss value corresponds to the right vertex of the Oval with the coordinates $\bar{z}=0$ and s^*_{rv} (Bluvband and Grabov 1994). Thus the 'loss control' region on the $\bar{z}$ -s* graph is bounded by the iso-loss Semiellipse given by

$$\frac{n-2}{n}(s^*)^2 + (\bar{z})^2 \leq \frac{n-2}{2}(s^*_{rv})^2 \tag{4}$$

The area under the $\bar{x}$ -s graph is subdivided by the Oval and the Semiellipse into three zones (Fig. 3) used for process analysis. For points falling within the Oval, the process is considered to be in the 'in-control' state. For the points between the Oval and the Semiellipse it is in the 'warning' state. In this state the process needs to be watched carefully. An unstable process can 'explode' in any direction and what is remarkable is that all these directions usually lead to poor-quality product yields. So a warning signal is used to prompt process investigation without work stoppage. Outside the Semiellipse the process is in the 'non-uniform' state, which precedes the 'out-of-tolerance' situation. But once again, it is the appearance of a Quality Problem, not trouble with stability, that calls for immediate adjustment. IPC policy is aimed at taking the steps necessary to stabilize a loss level. IPC is thus a cost-effective approach for assuring product quality and for early detection of quality problems.

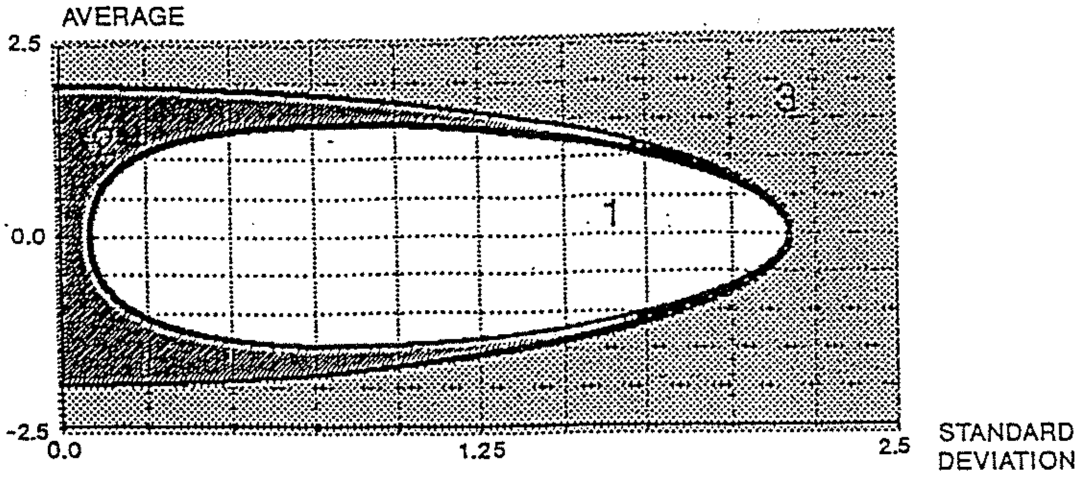

Fig. 3. The Area under $\bar{x}$-s Graph Subdivided by the Oval and the Semiellipse

ACT: DECISION MAKING & MAPPING

In principle, combining the oval and semiellipse control regions gives us an adequate tool for complete process analysis. The main disadvantage here is that on-line process surveillance is practically impossible. This shortcoming can be remedied by the equations for the Oval and Semiellipse that bound the control regions. Recalling that $\bar{z}_i$ and $\bar{s}_i^*$ for the boundary contours are related by expressions (1) and (4), and choosing the sample standard deviation as the basis for follow-up analysis, one can set up a chart for the averages with variable control limits depending on the s-value. It can be seen that the dynamics of the limits reflects the fluctuations in the standard deviation.

Since both Oval and Semiellipse yield a pair of control limits, a pooled chart with double variable control limits will be set up. The pair of quality limits will be outward relative to that of stability limits, as the Semiellipse includes the Oval and touches it only at the right vertex. Both setting up and analysis of the pooled chart can be simplified by normalization, i.e. by a procedure yielding a standardized chart with zero centerline, constant (±1) outer quality control limits and variable inner stability limits. The reader can find a detailed description of the algorithm and setting-up procedure for the pooled chart (in both non-standardized and standardized forms) in a publication on the method (Bluvband, Grabov and Ingman 1995).

An example of a standardized pooled chart is presented in Fig. 4. The chart calls for immediate adjustment at points 9 and 21 due to serious Quality Problems, whereas at points 6 and 12 the chart alerts on a problem with process stability. Thus the proposed quality-oriented pooled chart (in any of its forms) represents a simple graphical mean indicating when a process should be examined for trouble. The process is to be left alone for points falling within the inner limits. A point between these limits and the outer ones is only an alert signaling process instability, where an adjustment may be needed in the future (the quality level is still satisfactory). Appearance of a point outside the outer limits is a strong reason to believe that something serious has occurred, i.e. the process has gone astray and therefore immediate adjustment is required. The program supporting the proposed approach yields a colored pool chart with green points within the inner limits (nothing to worry about), yellow points between the inner and outer limits (attention, please!) and red points outside the outer limits (pull out all stops!).

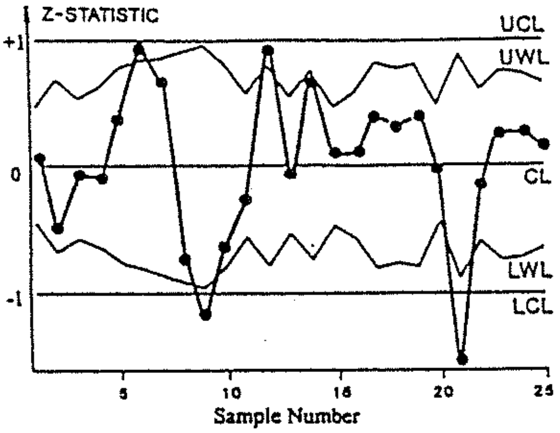

Figure 4. Standardized Pooled Chart

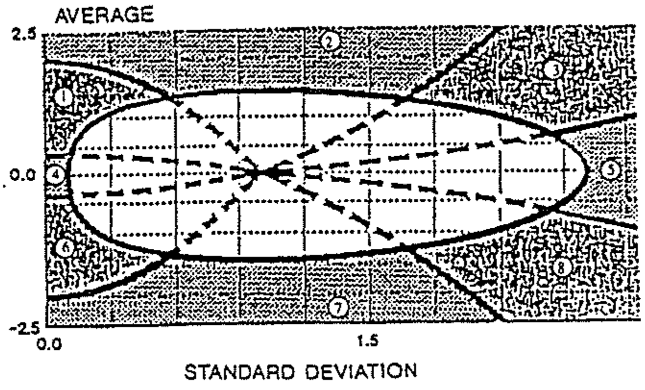

Figure 5. Decision Mapping for Oval Control Region

The suggested technique also permits us to perform correct diagnostics of the assignable causes of the process 'out-of-control' state. The above mentioned Shewhart Rectangle with the continuation of its sides divides the area under the $\bar{x}$ -s graph into 9 different zones: one 'in-control' and 8 'out-of-control' zones (see Table 2). This concept is logical and can also be accepted for our approach (the zones are shown in Fig. 5). But compared with the Rectangle the zone boundaries represent the curves of the gradients perpendicular to the oval contour of the control region. This decision mapping/making method provides an easy distinction among the different assignable causes of process disturbance. The zone boundaries of the conventional and proposed approaches do not coincide. Proceeding from the assumption that the oval region is true, one can see that the conventional approach may misinform a person concerning the assignable causes of the process 'out-of-control' state.

The decision mapping method developed here may be very useful for APC by feedback adjustment, where the signal that an appreciable process change has occurred triggers a control action to restore the process to its correct level of performance. The signal is produced by a software module supporting a given charting technique. Some of the more sophisticated APC systems deal with the problem of process adjustment by developing a process model and using it for transformation of the monitoring variables (mean value and variability) to the input parameters. So the gradient equations corresponding to the lines of the 'steepest descent' to the oval control region seem to be very important for feedback control, because they actually describe the optimal path (in terms of process mean and variance) towards the desired state. Thus ACT is not only a problem-finding technique such as the Shewhart one, but also a kind of problem-solving technique.

	INCREASE σ	σ IN CONTROL	DECREASE σ
INCREASE μ	ZONE 1	ZONE 2	ZONE 3
μ IN CONTROL	ZONE 4	'IN CONTROL' STATE	ZONE 5
DECREASE μ	ZONE 6	ZONE 7	ZONE 8

Table 2. Decision Mapping Zones

CASE STUDIES

The conventional and proposed approaches were compared on 50 practical cases (listed in the Appendix) described in literature. Only cases where at least one of the Shewhart charts indicated an excessive process variation were taken into consideration. For all cases n=5. In order to fit all cases into a single picture, the data totaling 1374 samples were normalized using Eqs. (2). The normalized sampling data, the Rectangle, the Oval and the Semiellipse as well as the boundaries of 'out-of-control' zones corresponding to the competing approaches are presented in Fig. 6. Results of the analysis are presented in Table 3.

The first impression is that the zones corresponding to reduced σ are practically empty and the points outside the picture (probably due to measurement errors) are exceptions proving the rule. In our opinion, it proves once again the Second Law of Thermodynamics: entropy cannot decrease (without external force); on the contrary, the inexorable tendency of the universe to slide towards a state of increasing disorder creates numerous points falling into the zones corresponding to increased σ. Further, as was expected, the cases of μ increase and decrease are balanced. The data also proves the fact, known to everybody who is familiar in practice with SQC, that mean shifts in the course of routine operation are more probable than variance increase. Detailed frequency analysis of the salient points in the different zones is beyond the scope of this paper but may be useful for models of process-failure mechanism.

	Reduced σ	Reduced σ, Increased μ	Increased μ	Increased σ and μ	Increased σ	Increased σ Reduced μ	Reduced μ	Reduced σ and μ
RECTANGLE	0	0	81	5	38	7	72	0
OVAL	0	5	68	26	16	61	7	0

Table 3. Table of the Salient Points

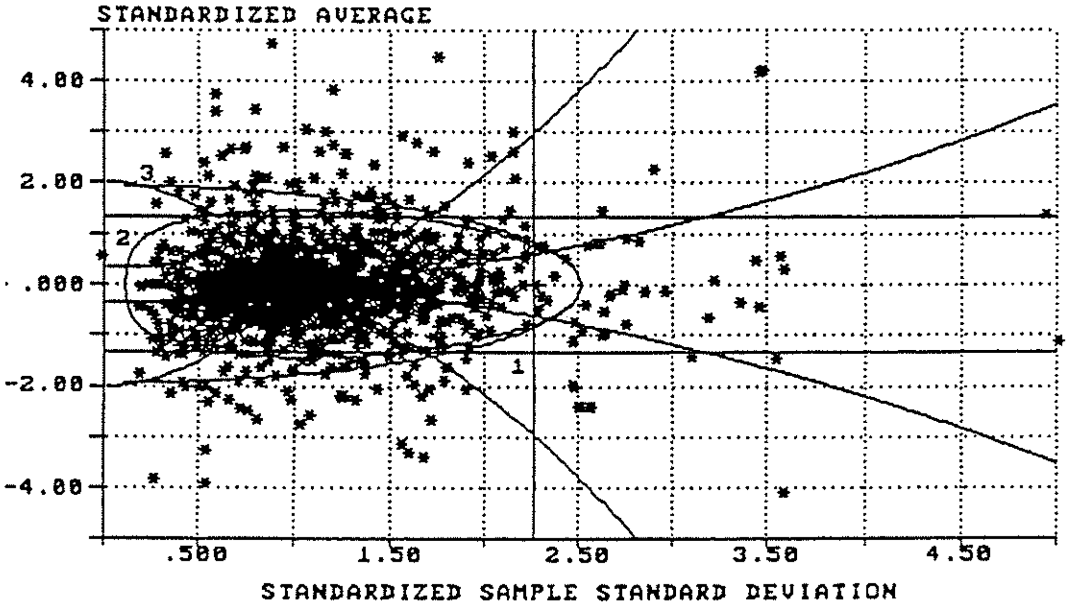

Fig. 6. Case Studies: * - Sampling Data, 1 - Rectangle, 2 - Oval, 3 - Semiellipse

Comparative analysis of the competing approaches shows that the total number of salient points is almost the same for the Rectangle and the Oval: 203 and 199, respectively (or 14.77% and 14.48%), only 171 of them coincident. Thus, proceeding from the assumption that the Oval represents the true control region, one can conclude that Shewhart charts gave about 30 false warning signals and on more than 20 occasions failed to give the necessary warning signal (rather oppressive statistics!).

Finally, applying the iso-loss Semiellipse for decision making, one can conclude that there were only 141 salient points requiring immediate adjustment from the quality point of view. In our opinion, the above provides clear evidence that process management based on the Shewhart charting technique may lead to serious adjustment errors. This is especially true of overadjustment. Its exclusively negative influence on product cost and other aspects of manufacture has already been analyzed.

CONCLUSION

A comparative analysis of the Shewhart and the proposed techniques (see Table 4) shows that in all respects the latter is superior. The only undoubted advantage of the conventional technique is that it represents a familiar standardized procedure, whereas the new technique is only pulled out of hiding by the authors before the jury of public opinion right now.

It is the authors' opinion that the proposed approach yields a more effective procedure for process monitoring and control than the conventional method. It diverts attention from dry Statistics and focuses it on Quality, i.e. it listens to the 'voice of Quality'. It represents a transition from dull statistical routine to Quality Engineering, i.e. it bridges the gap between Statistics and Quality Engineering. It provides an early warning of impending quality problems, improves the consistency of product quality, and significantly reduces both the risk of adjustment errors and the manufacturing costs.

	CONVENTIONAL TECHNIQUE	ADVANCED CHARTING TECHNIQUE
1. NUMBER OF CONTROL CHARTS	2	1
2. STABILITY EVALUATION	+	+
3. CURRENT QUALITY ASSESSMENT	-	+
4. RISK OF ADJUSTMENT ERRORS	Significant	Minimal
5. CAUSE RECOGNITION	Numerous Incorrect Decisions	Correct Diagnostics
6. FEEDBACK OPTIMIZATION	-	+

Table 4. Comparison of the Competing Techniques

APPENDIX

The following items were included in the case studies: distance from back of rheostat knob to far side of pinhole, weight in canning of tomatoes, 'on' temperature at which thermostatic switch operates, pH of liquor, slot width of terminal block, muzzle velocity (Grant and Leavenworth 1988, 14, 33, 70, 92, 138, 548, respectively); mica thickness data, depth of cut for air-receiver magnetic assembly, component content in a plastic monomer (Ott and Schilling 1988, 31, 61, 80, respectively); vial weight, fill data for paint cans, cut circuit board length, hardness depth of camshaft (Gitlow, Gitlow, Oppenheim and Oppenheim 1989, 180, 203, 298, 440, respectively); weight of molded instrument display panel, surface finish of cast aluminum part, inside and outside diameters of the cylinder bore, weight per bag of dog food (DeVor, Chang and Sutherland 1992, 99, 101, 165, 186, 190, respectively); inside diameter of forged piston ring, diameter of hole drilled in composite material, cigar lighter detent (Montgomery 1991, 212, 267, 272, respectively); viscosity of chemical component (Lindgren and McElrath 1969, 135); cut-off length of stud (Feigenbaum 1983, 411); length of harness clamp (Hart and Hart 1989, 97); engine crankshaft characteristic, computability of a mold sand, surface flatness, coating thickness, gear hole TIR, hardness of iron casting, surface finish measurements of inside of reamed bore, depth of hardness measurements (Kane 1989, 76, 84, 85, 85, 88, 144, 158, 298, respectively); shaft diameter (Duncan 1974, 460); bag-weight of powdered material, machine direction strength (Feller 1988, 19, 43, respectively); length of rotor pin (Hutchins 1991, 83); shaft diameter (Hansen and Ghare 1987, 203); resistance of box (Messina 1987, 126); percentage of chromium in iron alloy (Jamieson 1982, 141); diameter of tread (Breyfogle 1992, 295); thickness of zinc sheet (Johnson and Leone 1977, 413); resistance of coil (Mitra 1993, 197), length of machined valve (Belz 1973, 329); hardness of plastic material (Clark and Schkade 1969, 338); vane opening (Hines and Montgomery 1990, 586); express-teller transaction time (Levin and Rubin 1994, 473); weight of filled container (Betteley, Mettrick Sweeney and Wilson 1994, 203); plastic strength (Wetherill and Brown 1991, 90); critical dimension of part of power transmission, length of lithographic plate (Oakland 1987, 97, 107, respectively).

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