CONSTRUCTS AND METHODS OF STATISTICAL QUALITY CONTROL. THE ROLE OF THE ITALIAN STATISTICAL SOCIETY

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Abstract. *The paper briefly discusses the evolution of the concept of quality, aimed at assessing of the characteristics of the products in order to verify their compliance with product specifications. The original Statistical Quality Control (SQC) was chiefly concerned with a unique indicator, of an objective type, the fraction p of non conforming units. Now a possible unitary reference was found in customer satisfaction, which however is not objectively measurable being related to subjective, psychological evaluation. Moreover, the quality culture has been extended to classes of goods as well as of services, for which the assessment of customer satisfaction is particularly relevant, including such important services as medical care, education, transportation. The Italian Statistical Society (SIS) has been active in SQC with its Working Group on Statistics for Technology and Industry (1990 - 2002) and with the Coordination Group on Statistics for Enterprise (2003 - 2008). The main aim of the paper is to offer an outline of the contributions of Italian statisticians in the typical issue, with reference to the Proceedings of the SIS Meetings from the 1990's onward.*

Keywords*:* *Statistical quality control, Quality measurements, Process control, Customer satisfaction, Italian Statistical Society.*

1. QUALITY: HISTORICAL BACKGROUND AND IMPORTANCE

Quality is not a new concept in modern industry and business, contrary to common belief; it is at least as old as industry itself. In 1887 W.C. Procter, the grandson of the founder of Procter & Gamble, stated that critical issues to managers of manufacturing and service organisations are: productivity, cost and *quality*.

The nineteenth century novelty is represented by Statistical Quality Control (SQC). Statistics is a rather young science too, its history going back to seventeenth-eighteenth century. While some early applications may be found in physics, astronomy and biology, W.A. Shewhart of the Bell Telephone Laboratories is recognised as a pioneer in applying statistical methods in production control and introducing SQC in the 1920s, relying upon sampling theory. He first sketched control charts in a 1924 memorandum, then he developed his new methodology in

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a number of notes and papers, and published a pioneering book on SQC (Shewhart, 1931). Shewhart proposed the extensive use of control charts to identify quality problems in production processes and ensure consistency of products with specifications.

At that time, there was a group very active at Bell Company in developing the use of Statistics in the Statistical Process Control (SPC). Two members of this group, H.F. Dodge and H.G. Romig, pioneered the statistical theory of sampling inspection, documenting their results in *Sampling Inspection Tables.* (Dodge and Romig, 1941).

The bulk of statistical quality and control methodologies used today is based upon the pioneering work of Shewhart, Dodge and Romig and coworkers, who promoted and popularised the new methods in the United States by actively collaborating with such outstanding associations as American Society for Testing and Materials, American Standards Association, American Society of Mechanical Engineers. The production engineering community was however initially reluctant to adopt the new approach, relying instead on scientific work organisation based upon deterministic foundations. Random variation and stochastic approach simply did not fit traditional engineering framework, and they were even less appealing to foremen and plant managers. Even today applied statistics does not enjoy overwhelming popularity in engineering curricula. World War II swept away most obstacles as the U.S. military faced squarely the emergency by enrolling and exploiting at best scientific, technical and managerial capabilities, relying in the potential of the new methods. The need of procuring fast unprecedented amounts of mass produced supplies meeting strict requirements was addressed by steamroller application of scientifically designed sampling procedures, which quickly developed into an array of MIL-STD standards (e.g. sampling tables) still in use today. General Leslie E. Simon recruited a group of leading engineers from the Bell Telephone Laboratories (among others, George W. Edwards, director of Quality Assurance[3] at Bell System, H.F. Dodge, G.R. Gause, H.G. Romig) to develop sampling inspection programmes for the U.S. Army Ordinance, serving both Army and Navy.

The most important implication of military influence was the setting up of extensive educational programmes and training courses on statistical methods for

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[3] *Quality assurance* (QA) is a technical term that re lates to an overall approach to quality control. It is a system of activities whose purpose is to assure that overall quality control is being done effectively. The ANSI/ASQC Standards (1978) supply this definition of QA: *It is all those planned or systematic actions necessary to provide confidence that a product or service will satisfy given needs.*

process control. Quality control societies were created and meetings were promoted where new ideas and experience were shared. The American Society for Quality Control, created in February 1946, appointed George D. Edwards as its first president, while Walter A. Shewhart was the first honorary member.

In the United Kingdom, statistical quality methodologies development was rapid, thanks to the rise in applied statistics promoted by such giants – and sworn enemies – as Karl Pearson and Sir Ronald A. Fisher. Shewhart went to London, he was in contact with prominent British statisticians (in 1925 L.H.C. Tippet, a statistician that worked in the British cotton industry, published a paper about the distribution of the sample range from a normal distribution that Shewhart used in his book referred to above). Egon S. Pearson of University College in London had a presentation at the December 1932 meeting of the Royal Statistical Society, a survey of the use of *Statistical method in the control and standardization of the quality of manufactured products,* after visiting Shewhart in the U.S. Opposite to the slowness of the American industry in picking up the new statistical methods for quality, the response of the British industry was prompt and widespread, with applications to chemistry, to the production of coke, coal, lamps, building materials and textiles; the Royal Statistical Society started publishing the review Applied Statistics in 1952.

After World War II, quality control techniques spread to other countries. A war-torn Japan welcomed such outstanding American consultants as Joseph Juran and W. Edwards Deming (the latter was a member himself of the group of the Bell System and the most influential man in the quality revolution). Rather than concentrating on inspection, they focused their effort on improving all organisational processes through the people (the management): the Japanese Company Wide Quality Control (CWQC) model. CWQC may be defined as a set of systematic activities carried out by the entire organisation in order to provide products and services at the appropriate time and price with a high level of quality fully satisfying customers. The Total Management of Quality (TQM) is the western development of the Japanese model, consolidated and expanded by the U.S. Department of Defense. TQM may be defined as the management of initiatives and procedures aimed at achieving timely delivery of high quality products and services, its main premise being that quality of products and processes is everyone's responsibility. Hence, TQM involves management, workforce, suppliers, and even customers, in order to meet or exceed customer expectations. TQM aims at a continuous improvement of the quality at all levels, relying on four element: Vision, Principles, Practices, Techniques and Tools.

In addition to control charts and sampling plans, other statistical methods previously developed, such as correlation analysis, analysis of variance and design of experiments, were added to the statistical toolbox exploited by laboratories and research departments. First adopted for research purposes (biological, agricultural, social), they were later on exploited in issues concerning with process and product control and quality assurance, thanks to their obvious potential. Response surface analysis, pioneered by George E.P. Box, introduced a systemic exploratory approach nowadays widely used in industry, embodied in the well known evolutionary operation technique (EVOP).

In recent years new quality systems have moved from manufacturing to services: healthcare, education, transport and government sectors. The economies of the most developed countries are becoming more service oriented, and customer satisfaction is the driving force towards success of both manufacturing companies and service organisations. Most of the statistical quality control methods thought up for quantitative variables should now be reconsidered for categorical variables that are peculiar for evaluating service quality.

1.1 WHAT IS QUALITY?

Unfortunately, neither business professionals nor academics agree on a universal definition of quality. Moreover, the quality concept has evolved in the course of the years. The Webster's Third new International Dictionary defines quality as a degree of excellence, a degree of performance to a standard. But some criticism arises: how and who determine a standard? Is it really necessary a high degree of excellence? Does a product have to meet the standard in every feature? An example just to explain these concepts: an inexpensive utility car has definitely fewer luxury equipments than a costly car. But if the utility car meets or even goes beyond the expectations that the customer deserves in the utility car market, it can be said to be a car of quality. Nevertheless, we mention a few definitions of the quality.

- *Quality is defined as fitness for use* (Juran,1974). This definition may fit the quality of both products and services, because it refers to a "conformance to requirements or specifications". In fact, another definition assignable to Crosby (1979) is *conformance to requirements or specifications*. A specification is a concise statement of a number of requirements (dimension, volume, mass, color, output, taste, service life,…) to be satisfied by a product or a service. There are international standards that provide formal definitions of specification. This definition was criticised because it does not take sufficiently into account the customer needs.
- *Quality is the totality of features and characteristics of a product or service that bear on its ability to satisfy given needs* (American National Standards ANSI,

and American Society for Quality Control ASQC, 1978). This definition was shortened in the 1980s by the companies in a simpler, but powerful, definition: *Quality is meeting or exceeding customer expectations*. This definition focuses on the role of the customer. The *customer* is not only the ultimate purchaser of a product or service. The customer is here referred to as *consumer*, discerning between internal and external customers. The concept of quality as customer satisfaction has been of capital importance to the Japanese business approaches. Definitely, *quality is the goodness or excellence of something. It is assessed against accepted standards of merit for such things and against the interests/ needs of users and other stakeholders* (Smith, 1993).

- There are other definitions ascribed to quality practitioners: G. Taguchi defines quality as the loss a product causes to society after being shipped, other than any losses caused by its intrinsic function; D. C. Montgomery defines quality as one which is inversely proportional to variability. Consequently, improving quality requires a sensible reduction of the variability in processes and products.

1.2 IMPORTANCE OF STATISTICS FOR QUALITY

Quality is vital not only in companies, affecting different features as increasing productivity, reduction of costs, enhancement of the expertise and skill of employees and management, but also in the society because it leaves its mark on education, cultural and moral values and on health.

That is the reason for an operational definition for quality rather than conceptualise it with definitions or list of its descriptors. The standards list quality features and characteristics of a product or service that bear on its ability to satisfy needs: physical characteristics usually expressed with continuous variables (such as length, weight, voltage, viscosity, etc.), attributes (such as sensory ones like taste, appearance, color, smell), and time-dependent characteristics (such as reliability, maintainability, serviceability). The ‘totality’ of the above features and characteristics, named quality measures, is expected to satisfy the customers’ “needs”.

The matters are: *How far does this set of characteristics and features meet the given needs*? *How to measure the above*?

Statistical methods can be employed to identify the characteristics that are highly correlated with the latent variable “quality”. Deviation from the target of a quality characteristic may be caused by uncontrollable factors known as noise factors (outer noise due to humidity, temperature, vibration, dust etc., inner noise due to wear and deterioration and in-between noise due to the material, worker etc.). The variation produced by common causes is sometime referred to as noise, because there is no ‘real’ change in process performance. Noise cannot be traced to a specific cause, and is therefore either unexplainable or uncontrollable, although predictable. The strength of these noises largely determines the amount of variability from the target; and variability can be defined and understood only in statistical terms. Hence the use of statistical methods becomes important for reducing the variability or improving quality.

- *Process Optimisation and Robustness*

  The application of experimentation to industry is aimed at ensuring that the variability in the quality characteristic caused by the process and input variables is minimal. In other words, the variability expected in the actual production process should be largely 'error' or natural or inherent variability. The design of experiments (DoE) is a statistical methodology initially developed for agricultural experiments (in fact, a number of the key terms of experimental design such as plot, treatment, etc. reflect these origins). DoE is extremely useful in identifying the key variables affecting the quality characteristics. In industrial experiments, the controllable input factors will be systematically varied and the effects of these factors on the response variables observed. The variation in the response quality characteristics is analysed using statistical models**.** Hence DoE is an off-line quality improvement tool. A product is said to be robust if it performs equally well in good and bad conditions of use. Robust experimental designs identify the optimum mix of controllable factor levels that produces a robust response to external noise factors. In other words, quality improvement implies reduction of variability in processes and products.

- *Statistical Process Control*

  Statistical process control (SPC) is the methodology for monitoring and optimising process output, in terms of both location and variability, and for judging whether changes (engineering actions) are required to bring the process back to a "state of control". W. Shewhart, the inventor of the control chart technique as described in Section 1.1, is considered the father of the SPC. He proposed three postulates: 1. All chance systems of causes are not alike in the sense that they enable us to predict the future in terms of the past. 2. Systems of chance causes do exist in nature such that we can predict the future in terms of the past even though the causes are unknown. Such a system of chance is termed constant. 3. It is physically possible to detect and eliminate chance causes of variation not belonging to a constant system. A production process is always subjected to a certain amount of inherent or natural variability caused by a number of process or input variables. This stable system of chance causes, known as common causes, belongs to the process. SPC includes many statistical tools to warn the presence of special causes of variability in a production process. Hence it is necessary for the technicians to be familiar with the statistical techniques.

- *Sampling Inspection*

  Sampling inspection, or acceptance sampling, is a quality assurance technique where decisions to accept or reject manufactured products, raw materials or services are taken on the basis of sampling inspection. This method provides only an indirect means for quality improvement. The fraction of nonconforming product is also adopted as an (inverse) measure of quality. Calibration of instruments to tackle measurement errors is done using statistical methods which aim at providing measurement quality assurance.

- *State of Statistical Control*

  A production process is said to be in a state of statistical control if the only variability is due to common causes, and no special causes are present. Although both common and assignable causes create variation, common causes contribute to controlled variation while assignable causes contribute to uncontrolled variation. According to Shewhart's definition: *A phenomenon will be said to be controlled when, through the use of past experience, we can predict, at least within limits, how the phenomenon may be expected to vary in the future*, prediction within limits means that we can state, at least approximately, the probability that the observed phenomenon will fall within given limits. The special or assignable causes will increase the variability beyond the level permitted by the common or chance causes. Such an increase in variability due to special causes can be detected using probability laws that model the stable state of control. The presence of special causes can be monitored by considering a control statistic. The estimated probability distribution of the control statistic can then be used to define a range for the inevitable, and hence allowable, common cause variation (*control limits*).

1.3 STATISTICAL THINKING FOR QUALITY

Statistical thinking is a philosophy of learning and action based on the following fundamental principles:

- All work occurs in a system of interconnected processes,
- Variation exists in all processes, and
- Understanding and reducing variation are keys to success.

This definition is assignable to the American Society for Quality (ASQ), Statistics Division (2004).

Every (manufacturing or non-manufacturing) activity must be regarded as a process, and there are always variations. In a manufacturing process, variation is caused by machines, materials, methods, measurements, people, and physical and organisational environment; in non-manufacturing or business processes, mainly people contribute to the total variation in addition to methods, measurement and environment. Such sources of variation, which are possibly preventable, are called assignable or special causes of variation. Assignable causes lie outside the process, giving a significant contribution to the total variation observed in performance measures. The variation created by assignable causes is usually unpredictable, however it is explainable after the variation has been observed. Statistical models based on data help us in understanding the nature of variability. The reduction of variation is done by actions such as eliminating special causes or designing a newly improved system with smaller variability.

In the mid 1980s, Motorola Corporation faced stiff competition from competitors whose products were of superior quality. Hence a resolution was made to improve the quality level to 3.4 defects per million opportunities or below. Motorola achieved the low defect level, that was to keep the process variation one-sixth of the variation allowed by the upper or lower specifications, by the *Six Sigma* process management. This management methodology is highly data driven and involves five steps: Define, Measure, Analyse, Improve and Control (acronym DMAIC). *Define* means identify the process or product that needs improvement and select the product characteristics (dependent variables); *measure* includes various activities (definition of the process map, setting up the cause and effect matrix, …) aimed at estimating the process capability. Next step is *analyse* and benchmark the important product/process performance measures, using various statistical and basic quality tools. Further, select the performance characteristics which should be *improved*, performing statistically designed experiments to set the improved conditions for the key process variables. The last step is implement statistical process *control* methods, reassessing the process capability and revisit one or more of the preceding phases, if necessary.

Motorola saved several billion dollars using Six Sigma methodology. From early nineties, Six Sigma methodology is being adopted by many multinational companies for achieving quality and hence profitability. Quality is the business of everyone in an organisation. Hence employee training in the use of technical tools and problem solving is an integral part of the Six Sigma quality management model. Trained employees are named as “black belts” and “master black belts” depending on their skill levels and experience. There are (statistical) simple Exploratory Data Analysis (EDA) tools such as histograms, scatter plots, boxplots etc. that are useful for understanding a production process.

Statistical Thinking plays an important role in the DMAIC philosophy: the variables causing quality must be identified and experimented to achieve improvements.

2. A PRESENTATION OF BIBLIOGRAPHY HEADINGS[4]

The Italian Statistical Society (SIS) has been active in SQC with the Working Group *Statistics for Technology and* Industry (WGT&I) (1990-2002), having as coordinator Angelo Zanella, and with the Coordination Group *Statistics for Enterprise* (CGE) (2003-2008), whose coordinator was Mario Montinaro. The WGT&I was composed of some local permanent units, directly connected with the University of Padua, Catholic University of Milan, Polytechnic University of Turin, the Universities of Florence, Bologna, Naples and Palermo. The spreading of the interest in the subject was provided through satellite and invited sessions at SIS scientific meetings.

We are not aware of the existence for years of a similar working groups abroad. However we have to mention the Sections *Business.& Industrial* and *Quality Improvement* of the Royal Statistical Society with the local Group Committees; the TQM movement initially centred around the Sheffield Hallam (UK) with an annual International Congress; th*e Quality and Productivity Section of the American Statistical Association* which promoted annual conferences in connection with USA universities.

This section is devoted to update, from the nineties, the book *Italian Contribution to the Methodology of* Statistics by Naddeo (1987), specifically Chapter 5 *Contributions of Italian Statisticians to Statistical Quality Control*. The bibliography which we refer to has been selected among more than 120 papers many of which were published in special issues of *Statistica Applicata*: 1991, 4; 1995, 2; 1997; 1999, 11; 2004, 4; 2006 and 2006, 2.

These papers have been selected for the purpose of giving the reader the opportunity to perceive the major evolution trends. This subjective choice was motivated by some reasons:1) we wanted to acknowledge the importance of some authors owing to their direct participation in programmes and activities of WGT&I and CGE; 2) we favoured new ideas and results of conceptual analysis, which,

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[4] We warn the reader that the quotations referring to this section follow a rule slightly different from the Journal standard. Each quotation is related to some specific comments to one of the subsections, from 2.1 to 2.7. The authors mentioned in a subsection are presented in alphabetic order, after the title of the subsection. Thus e.g. the first quotation of 2.1 *Scales and measurements* is Iuculano (1992), the second one is Monari (1992), etc.

beyond a formal treatment, may represent practical guidelines in carrying out SQC; 3) we intended to select important contributions, not only to SQC methodology but also to applications; 4) we paid attention for SQC, of which we have a first-hand knowledge.

2.1 SCALES AND MEASUREMENTS

We quote from Monari (1992) the definition by Bertrand Russell: "The measurement of characteristics, in the most general sense, is any method by which a corresponding homomorphic – that is univocal and reciprocal-function exists between the characteristics of a given kind and some or all numbers.........". The assignment of a number to any characteristic of an experimental unit can be viewed in an axiomatic way. To be more precise, given a finite set A, a binary comparison relationship $\Re$, a logic linking rule $\odot$ which is assumed to comply with the equivalence conditions (reflexive, symmetric, transitive) and to lead to a strict ordering when anti-symmetric, it is possible to define a homomorphic function $\phi(\cdot)$ from A to the real numbers $\mathbb{R}_n$, with $\Re$, corresponding to >, $\odot$ corresponding to +, which transforms the empirical relationships into real numbers according to the basic representation theorem. Consequently, if f is a strictly monotone function, the composite function $f(\phi)$ defines equivalent measurements of the ϕ's, i.e. another "admissible transformation". When dealing with measurable quantities, a realization of one of these can be assumed as a reference unit (e.g. a segment for lengths, etc.) and we may come to ratio scales, defined except for the scale unit, or to interval scales for which the admissible transformations are linear, with a possible arbitrary origin. So we obtain metric variables or measurements.

Considering characteristics whose categories can only be ordered, we come to ordinal scales which are defined except for a strictly monotonic f. The correspondent problem is to find, under suitable conditions, a transformation f of the category scores, so that the transformed scores can be considered on a metric scale which allows to use typical statistical methods as the regression analysis, etc.

In Zanella and Cantaluppi (2004), the approach of Thurstone, named *Threshold Method*, (Bollen, 1989), is extensively examined. It assumes the existence of a latent random *variable* underlying any categorical attribute, whose inverse cumulative probability distribution function is the function f used to transform the ordinal scores. The paper deals with the conditions required to use Thurstone's method for simultaneously transforming a set of observed random categorical variables into values on interval scales. The method is generalised assuming that the latent underlying variables, besides the normal distribution, may have a probability distribution *reducible to a location-scale type.* An application to the logistic-Weibull distribution is illustrated.

Three main sources of errors are mentioned in Monari (1992): a) inadequacy of the fitted model; b) *repeatability error*, due to the measurement process when independent test results are obtained with the same method, on identical test items, in the same laboratory by the same operator, using the same equipment, during short time intervals; it has zero mean and variance σ_r; c) a further zero mean random error with variance σ_R^2 due to different equipment and different operators using the same method. The two above mentioned error sources lead to *reproducibility error*, according to an additive model whose variance is $\sigma_r^2 + \sigma_R^2 + 2\,\mathrm{cov}(\varepsilon_r, \varepsilon_R)$, with obvious notations. This is the framework of this subsection. Specific aspects of the electric and electronic equipments are considered in Iuculano (1992). Compatibility intervals for pairs of measurements are defined for an assigned confidence probability in Zanobini *et al.* (2000). The paper by Vicario and Barbato (2000) deals with measurements operated by coordinate measuring machines, used in industry to check dimensions and shape of manufactured parts. They may be considered as "statistical" machines as the part surfaces are probed in a sample of points. The authors of the former article present a method for parameter estimation and uncertainty assessment of a circular shape, resorting to the maximum likelihood criterion under the hypothesis that the joint distribution of the *x* and *y* coordinates errors of the measured points is bivariate normal.

We finally quote the book by Franceschini (2001), which is an excellent monograph, on the scales of measurement. Starting from the classical theory related to physical quantities, the treatment is extended to the modern relational approach to measurement. This allows obtaining, in the same conceptual framework, the notion of measurement in keeping with the requirements of cognitive and social sciences. Thus, in the perspective of evaluation of service quality, nominal, ordinal, *SERVQUAL* scales of measurement and also fuzzy scales, which express ambiguous uncertainty, are clearly and rigorously presented.

2.2 ACCEPTANCE SAMPLING PLANS

The aim of this subsection is to examine the contributions devoted by Italian scholars to improve the current use of attribute sampling plans, typically carried out according to the well-known standards MIL STD 105D. Basic parametric indicators are the Acceptable Quality Level (AQL), expressing the fraction of nonconforming units to be considered, still acceptable, mostly by the customers, e.g., AQL=p=0.01 and the Average Outgoing Quality (AOQ), e.g., it could come out AOQ=0.009. In Zanella and Maggi (1991) a simple random sample of size n is taken from a lot of N units without replacement and the lot is accepted if and only if $x \le c$, with x the number of nonconforming unit, c a fixed non-negative constant. It is assumed that the lot corresponds to N independent trials of an elementary Bernoulli random variable assuming the value 1 if the unit is nonconforming (defective), otherwise 0, with probabilities p, $0 < p < 1$, and $1-p$, respectively.

Adopting an empirical Bayesian point of view, p is regarded as varying at random from each lot according to a beta distribution. Two measures of performance, concerning the residual portion of defective elements of a lot $Z= Y/(N-n)$, are considered: the *posterior operating characteristic function*, which, for the chosen prior distribution beta, conditionally to the number x of defective items in the sample, gives the probability that Z does not exceed a given AQL value; and the *predictive tolerance limit* which is the value not exceeded by Z, under the same conditioning, with a given probability $1-\eta$. Since Z, under the preceding conditions has a posterior beta-binomial probability distribution, the paper by Barsotti and Paroli (1991) completes the above paper with suggestions related to the estimation of the parameters needed for determining the posterior distribution.

The paper by Pistone and Rogantin (1991) is focused on the other index of production quality AOQ.

The flow of lots corresponds to a sequence of periods $t = 1, \ldots, T >> 1$ and from each lot a random sample is taken as above, but the number of observed nonconforming elements is assumed to follow a Poisson distribution with parameters λ_t, which, according to the Bayesian approach, are regarded – conditionally to some prior distribution – as coming from independent gamma distributions. AOQ is defined as the expectation of $\sum(\lambda_t°/M-°)$, where the sum concerns the means $\lambda_t°$ of the accepted lots whose number is $M°$ in the total period T. Particular attention is paid to the case when λ_t is considered belonging to a mixture $\alpha \cdot \gamma_1 + (1-\alpha)\gamma_2$, $\alpha \in (0,1)$, with γ_1, γ_2 two different gamma probability distributions, whose parameters together with the α proportion, are assumed to be easily available from the inspection of the process.

2.3 PROCESS CONTROL

The ten papers in the References that refer to "quality control" may be divided into two groups: a first group of papers focusing on aspects of process control when this is based on the use of control charts; and a second group dealing with stochastic process control, linked with the models and techniques of the time series analysis and typically implemented through automatic devices.

In Guseo and Panizzon (1991) the aim is the comparison – under the hypothesis that the observations are normally distributed – between the control charts for means, with the usual two simple control limits, and the control charts with other two added *warning* limits. The comparison is carried out on the basis of the power of the two procedures. The conclusion is in favour of the charts with two control limits, that is, they have to be preferred to the four-limit scheme. In Zanella and Deldossi (1992) a multivariate case is considered with the proposal of a predictive approach based on the optimum predictor of future values of the vector ***X*** to be controlled, under the hypothesis that the true underlying stochastic process is an integrated moving average vector process of order 1, $IMA_{11.}$ The process represents a rupture alternative to the in-control state of the process when it is assumed that the components of ***X*** are independent and normally distributed.

In Masarotto and Capizzi (1995) a survey of problems facing theory and structure of a control chart is presented and discussed; in particular, charts with variable sampling intervals and control schemes for autocorrelated observations are considered.

In Magagnoli and Zappa (2000) the important notion of *process capability* is discussed. In the one-dimensional case its definition moves around the indicator $Cp = (U - L)/6\sigma$, with U and L being the upper and lower specification limits, σ the standard deviation which, for centered normally distributed variabIes, is a monotonically decreasing function of the probability of having an out-of-control element. The notion is extended to the multivariate case under the hypothesis that the components of the vector ***X*** of the variables subjected to control follow a multivariate normal probability distribution.

In Galante and Lombardo (1991) a model for the automatic control of a manufacturing process, characterised by a non-deterministic evolution, is described. In particular, a software has been implemented which is able to determine the optimum feed minimising the marginal costs.

In Fassò (1990), with regard to stochastic process control, a specific vector $1 \times k$, ARMA model is considered as apt to describe the in-control process. A statistical test is defined to assess whether a rupture has occurred – e.g. due to the coming out of a different ARMA model – which is asymptotically χ^2 distributed when the number of the observations tends to infinity. The validity of the test is also discussed.

In Bordignon and Boari (1995) the "error equation dynamic model" is considered, where the observed process looks like a linear autoregressive one that also includes process corrective variables. This is a positive simplification feature of the model which renders it appropriate when moving the first steps from classical Shewart process control to stochastic control into which forecasting and corrective actions are incorporated. Correspondingly, the production process is considered when operating in closed loop condition and special attention is paid to the problem of identifying optimal control rules.

In Zanella and Cascini (1999), the variation of product quality, owing to an aging effect in a real chemical process, has been studied by means of a linear stochastic transfer function model, which allowed the authors to define a forecasting procedure concerning the quality of the outgoing product to be delivered to customers.

The paper by Pistone, Boari and Rogantin (1992) concerns the statistical software related to manufacturing and production control. It tries to comply with the need, largely felt by people, to be properly informed about the statistical software useful to implement the statistical methods. The paper emphasises the systematic use of statistics in the framework of TQM and presents a critical overview of the software available in the area. Packages like BMDP, GLIM, SAS, SPSS and others are briefly examined with suggestions of possible improvements.

Finally, in Ferreri (1991) there is an attempt to define a stochastic model for the rising of industrial injuries, matter of crucial importance in the industrial context.

2.4 TAGUCHI APPROACH

In Magagnoli and Vedaldi (1990) a thorough investigation of the optimisation of a manufacturing process according to Taguchi methodology is presented. Its essential aspects are the following: a) the products and their manufacturing processes are conditioned not only by factors controllable by the designer, but also by *noise* factors that randomly affect the response of the experiment; they express the effect of the random changes in the environmental conditions as well as raw material properties, customers' use methods, etc.; b) the variability in the product quality characteristic (the response) is obviously related to the noise factors variability; the Taguchi novelty is that there may exist controllable factors x which affect the response variance, too. Thus, Taguchi suggests to choose the setting of the controllable factors x so that it optimises an average *loss function*. An example of loss function may be the mean square error $\mathrm{MSE}=\sigma^2_Y(x)+[\mu(x)-\tau]^2$, i.e. the sum of two components: the variance of the response $\sigma^2_Y(x)$, and the squared departure of the mean response from its target value. It has to be stressed that the Taguchi methods require to statistically designing the experiment. The combined array approach – assumes that the noise factors can be reproduced as controllable factors in laboratory or on a pilot plant. Thus, all factors can be considered in a unique designed experiment: this aspect is fully examined in Zanella and Deldossi (2003). A testing procedure is proposed to ensure that the true effects remain distinguishable, conditionally to the laboratory experiment, against the variability produced by the real noise factors.

Two papers, one by Pistone (1990) and another by Barbagallo *et al.* (1999), are devoted to applications of the Taguchi methodology to real industrial processes.

In Zanella and Cantaluppi (2000), there is an attempt to extend the Taguchi approach to adaptive stochastic control concerning a simplified model for feedback adjustments of both mean and variance, assuming that the random error behaves as an autoregressive conditionally heteroscedastic (ARCH) process.

2.5 DESIGN OF EXPERIMENTS FOR PROCESS IMPROVEMENT

The paper by Giovagnoli (1992) offers a concise but comprehensive account of the principles underlying the modern theory of optimal design of experiments, starting from Kiefer's proposal of 1959.

The well-known D-optimality criterion – which in the one-dimensional response leads to minimise the volume of the confidence ellipsoid of the least squares estimates of the linear regression coefficients with normal error components – is extended by Guseo (1991) to the case of a vector response where the error components are jointly homoscedastic normally distributed.

The title *Computer Experiments: Promising New Frontiers in Analysis and Design of Experiments* of the paper by Vicario (2006) points to the subject. Since the physical experimentation may be awkward to perform or prohibitively expensive in a number of instances, the numerical experiments are currently resorted to at both design and analysis stages. In recent years, general availability of comprehensive computing facilities and progress in software development made numerical simulation of complex systems an attractive alternative option. In the last decade, a great deal of research activity has been conducted in this area, called Design and Analysis of Computer Experiments (DACE) or, simply, computer experiments. Unlike physical tests affected by intrinsic uncertainties, computer runs are exactly repeatable and consequently the error term lacks. If present, the error term is conveniently used in assessing significance of effects. In stochastic simulation, random variables are therefore introduced explicitly as model inputs. A way to introduce randomness in computer experiments – conducted on non-stochastic simulators proposed in literature – considers the deterministic response as a realisation of a stochastic process: differences between response values and the regression model, though deterministic, are considered as a sample path of a stochastic process. A minor variant proposed is that a Bayesian prior Gaussian process is assumed and predictions are made using the posterior process, given the observed responses. In absence of pure error (simulation output being substantially deterministic), lack of fit is exploited to enable statistical analysis. However, the typical complexity of most of the simulators provides another way to introduce effects equivalent to random noise: in complex codes, a number of parameters and discretisation options offer the user as many degrees of freedom to introduce variability into simulation and gather at the same time valuable information.

2.6 ENVIRONMENTAL SURVEILLANCE

Environmental surveillance represents a substantially new chapter of SQC. At present, the evaluation of the quality of a product has to be linked also to environment indicators related to production conditions liable to undergo corrective actions. In Cocchi (2002) a clear review of the related problems is presented, with some hints for further promising research work. The main points are: 1) identification of situations requiring systematic monitoring and control; 2) understanding the effects of pollution agents firstly on vital resources as air and water in their different forms (rain, basins, lakes and rivers). Special attention is deserved to people health, with the aim of setting definition of environment indicators and corresponding guidelines and *standard* values; 3) statistical analysis must consider the data with two exogenous dimensions: space and time. The use of several measurement processes, of explanatory models and of standards is mandatory. The statistical analysis requires methodologies proper to large data-banks of the experimental results, often provided by automatic devices; 4) definition of standards that make sense from the statistical point of view, considering that some regulations are compulsory, e.g., those concerning water and air, others are only recommended; 5) the Standard ISO 14000, even if not compulsorily, sets a very useful framework for the environment surveillance. It is pointed out that the required statistical analysis deals with a multivariate context; thus, additional research work is demanded, specially to find out new convincing graphical representations of multidimensional data.

In Cardamone and Deldossi (2002) the International Standards for Environment Management Systems, known as ISO 14000, and the European Regulation for Eco-Management and Audit Scheme (EMAS) are discussed in order to analyse the statistical methods pointed out as useful instruments to design an environment management system. The authors refer the experience of a multinational corporation that obtained the ISO 14000 certification and EMAS validation, first in Italy. The paper also tackles the use of capability indices when dealing with correlated data. The paper by Deldossi (2004) faces this last topic in detail. A review of the most important statistical SPC methods for autocorrelated data is acquainted, starting from the principle that SPC assumes that consecutive observations are stochastically independent, assumption that may fail in the environmental context. Nonlinear models, like ARCH and MSAR (Markov Switching Autoregressive), are also mentioned, which devise to capture environmental dynamics. Some suggestions related to statistical quality control are forwarded and two real cases are discussed.

2.7 SUBJECTIVE EVALUATIONS AND CUSTOMER SATISFACTION

Before presenting the contribution of the Italian statisticians to this subject, we cannot avoid to mention the basic methodological paper by Parasuraman, Zeithalm and Berry (1988). *SERVQUAL* assumes that there are five dimensions of service quality to be assessed by a respondent through pertinent indicators: Tangibles, Reliability, Responsiveness, Assurance, and Empathy. It measures the gap between customer expectations and experience. Given a random sample of n respondents, we can come to sets of data, on 7-point conventional scales, concerning the ratings of perception, the ratings of expectation statements, for each one of the five dimensions, and the weights, which sum up to 100, of each dimension. The measure of overall customer satisfaction (CS) suggested by *SERVQUAL* is the weighed arithmetic mean of the observed discrepancy between perceived and expected satisfaction. More precisely, if we have a random sample of n respondents we come to the following sets of data x_{ijs}, z_{ijs}, which refer respectively to corresponding ratings – on a 7-point conventional scale – of perception (x) and of expectation statements (z), in connection with the *i-th* dimension, i=1,2,3,4,5, through the s-th dimension indicator, s=1,2,…, S_i, owing to the j respondent, j=1,2,..,n , while w_{ij} expresses the weights, summing to 100, attached to each dimension. The measure of overall customer satisfaction proposedd by *SERVQUAL* is the weighed arithmetic mean y of all observed discrepancies of satisfaction $y_{ijs} = (x_{ijs} - z_{ijs})$:

$$\bar{y} = \left[\sum_{ij} w_{ij} \cdot \sum_{s=1}^{S_i} \left(y_{ijs} / S_i\right)\right] \Big/ n.$$

Croning and Taylor (1992) argue that the service quality is better described by explicitly ignoring the expectation term in the *SERVQUAL* model, which leads to the *SERVPERF* paradigm.

In Montinaro and Chirico (2006) a review of the principal methods of measuring CS is presented according to two approaches. The first relies on a one-dimensional measurement, i.e. a single variable represents the overall satisfaction of the good or the service; as in the case of *SERVQUAL,* the other approach relies on a multidimensional measurement, taking into account all the major dimensions characterising the complex construct of CS. This last approach is characterised by linear structural relationships among latent variables: the endogenous, i.e. related to the inner structure of the investigated concept and including quantification of overall CS, say vector $\boldsymbol{\eta}$, and the exogenous ones, say vector $\boldsymbol{\xi}$, whose origin is outside the structure. More precisely the inner linear model has the form $\boldsymbol{\eta} = \mathbf{B}\boldsymbol{\eta} + \boldsymbol{\Gamma}\,\boldsymbol{\xi}+\boldsymbol{\delta}$ here **B** and $\boldsymbol{\Gamma}$ are suitable matrices of unknown parameters, $\boldsymbol{\delta}$ is a vector of random errors with zero means. The former relationships are completed by the measurement part of the model which allows linking the construct between the unobservable variables $\boldsymbol{\eta}$ and $\boldsymbol{\xi}$ and some observable indicators $\boldsymbol{Y}=\boldsymbol{\Lambda}_y+\boldsymbol{\varepsilon}_y$ $\boldsymbol{X}=\boldsymbol{\Lambda}_x+\boldsymbol{\varepsilon}_x$, with $\boldsymbol{\Lambda}_y$, $\boldsymbol{\Lambda}_x$ matrices of unknown parameters, $\boldsymbol{\varepsilon}_y$, $\boldsymbol{\varepsilon}_x$ random errors, with zero mean, uncorrelated with each other and with the errors $\boldsymbol{\delta}$**.**

The approach is used in the definition of indices that offer large scale applications like, in the first place, the ACSI (American Customer Satisfaction Index) and the more recent ECSI (European Customer Satisfaction Index). The paper examines these important indices in some detail, comparing their dimensions: perceived quality, expected quality, perceived value, claims, loyalty and image.

In Zanella (1998; 1999), a probabilistic adaptation of the SERVPERF paradigm is attempted. The proposed model explains the observed overall CS Y as a function of nonnegative latent variables $X_1, X_2, \ldots, X_I$ and $W_1, W_2, \ldots, W_I$, corresponding to I dimensions, supposed known, and to its weights. To the former variables there correspond groups of observable ordinal variables (indicators) $X_{1s}, X_{2s}, \ldots, X_{Is}$, $s=1,2, \ldots, S_{i,}$, $S_{i,}$ being the number of indicators of dimension *i.* As usual, in what follows, small letters indicate the values of the variables. It is assumed that a random sample of n elements has been drawn from a population and that the *j-th* respondent, $j = 1, 2,\ldots, n$, expresses his assessments of the overall customer satisfaction y_j, on a m_y point rating scale, and of his satisfaction with regard to a specific dimension. The weights are determined as arithmetic means of the scores obtained from the *n respondents* on distinct m_x, m_w point ordinal rating scales:

$$\bar{x}_{ij} = \sum\nolimits_{S} \left(x_{ijs}\right) \big/ S_i, \qquad \bar{w}_i = \sum\nolimits_{j} \left(w_{ij}\right) \big/ n.$$

The model assumes that y_j has been transformed to a quantitative metric measurement:

$$y_i = \sum\nolimits_{i} \beta_i \left(x_{ij} w_{ij}\right) + \varepsilon_j,$$

where ε_j are "small" random errors with zero mean and common variance σ^2, β_i 0 are unknown real parameters; $j=1,2,\ldots n$, $i = 1,2,\ldots, I$ according to the previous notations. The true latent values x_{ij}, w_{ij} are estimated by applying the Thurstone's or the threshold method resorting to the cumulative observed frequencies of $\bar{x}_{ij}$ and of $\bar{w}_i$, assuming a suitable latent probability distribution. The logistic Weibull – multivariate normal is discussed and recommended since its marginal distributions, of the logistic Weibull type, are nonnegative and allow for distribution skewness. Referring to all unknown parameters of the model the least squares estimates are discussed and in Zanella (1999) their asymptotic consistency is proved for $n \to \infty$.

Important methodological aspects are examined in Lauro *et al.* (1997). Starting from the well-known *SERVQUAL*, the Author shows how its performance can be improved by means of a non-symmetrical version of Principal Component Analysis. The paper by Erto (1997) deals with the quality of television programming, proposing a suitable probabilistic model. The main features are: a) modeling the purchasing contacts between customer and supplier with a truncated Poisson process; b) evaluating the probability of satisfactory contacts by a binomial distribution. The model allows to assess the probability that service delivery and customer satisfaction occur simultaneously and to use it as a quality index for examining both an elementary service and the whole set of services offered by a company. The maximum likelihood estimation method of the unknown parameters is adopted in the practical application.

In Amenta and D'Ambra (2003) the multivariate analysis of data related to health service evaluation is considered. The paper assumes that clinical variables can be typically expressed on an ordinal scale. The article presents in a concise form the possible techniques with the help of two tables: the first refers to possible transformations of ordinal variables to obtain values on an interval scale; the second table summarises some proposals for the statistical analysis of dimensions of clinical data, applying partial least squares, ordinal correspondence analysis. etc.

The contribution by Brasini and Tassinari (2004) faces a possible refinement of the conceptual CS construct, a subtle matter. Especially, the authors put forward a possible link between CS and brand loyalty. A couple of empirical studies are presented with the purpose of explaining the satisfaction-loyalty relationship. In the customer satisfaction response, which is the contribution of the loyalty within a customer satisfaction response and vice versa? The customer is aware of the connection between satisfaction and brand loyalty, even if their relationship is not straightforward. The authors get to the conclusion that satisfaction is a necessary step for the development of loyalty, but it becomes less significant when conscious mechanisms begin to play a role.

The paper by Zanella, Boari and Cantaluppi (2002) aims at defining an overall indicator suitable for assessing the degree of compliance of a quality management system – in principle designed according to the ISO standard – with the requirements of the standard (system effectiveness). A structural model with latent variables is proposed including the main features of the model suggested by the ISO 9000: 2000 and their causal connections especially with the system effectiveness concept. Each latent variable is made operative through a reflexive relationship with manifest variables. The scores on a conventional rating scale are obtained from the answers to a questionnaire administered to a group of employees of the quality management system. The statistical analysis is carried out according the Wold's Partial Least Squares approach, currently used in computing national customer satisfaction indices. A real case, based on a sample of 100 respondents, is examined, for evaluating the relevance of the model. It was proved that, besides leading to the desired overall indicator, the model is able to assess possible discrepancies between a given quality management system and the ideal ISO standard model. Moreover, it is possible to point out appropriate improvement actions, which could be fruitfully employed when a company aims at obtaining the system certification.

Some further remarks are suggested by the last contributions referring, in particular, to customer satisfaction, loyalty and system effectiveness. In such context a stable or increasing purchase request of goods/services is a necessary end goal, which, in the framework of TQM, is ensured by an effort of the company as a whole. This points out the requirement of process optimisation which means an attempt to optimise many coordinate sets of actions, i.e. elementary processes. This leads to consider, besides indicators with a clear subjective component like customer satisfaction and loyalty, some others showing whether the organization is running well or not in all its crucial operations, with the possibility of corrective actions. This may concern technological aspects directly as compliance with operation procedures, service effectiveness, plant maintenance, good relationships with the suppliers, etc. The paper aims at integrating some indices, that often are evaluated on qualitative scales, with the classical SQC, which is concerned with the technical control of the production lines, and, in general, is based on aspects that can be led back to quantitative measurements.

In Alvares (2000), a brief account is given of what has been done in an important national chemical company. In particular, the capital index quality cost is considered. It is defined as "cost for a product unit" and is based on a complex accounting effort.

Magagnoli and Raggi (1999) explicitly refer to an important pharmaceutical company, however their paper has a general validity. The authors face the features of the Global Process Quality Index (GPQI), that have to be provided. For its construction technical aspects, connected with manufacturing, are to be considered. For a chosen production phase, GPQI requires to agree with what can be considered an anomalous event in a given production period, e.g. one month. On the basis of past experience management can establish the typical number of anomalous events

x_o in a chosen production period. If we indicate by x the number of the anomalous events in an observed period of the chosen type, the global process quality index is defined as a ratio. Precisely, if we consider the actual number of anomalous events x for a same output in a period and the typical constant number of anomalous events in the same time interval, when the process is running properly, the ratio is GPQI=I_t=x/x_o. The interpretation is based on the empirical Bayesian approach since the number x of anomalous events is assumed as a realisation of a Poisson random variable with an unknown parameter λ, which changes at random from a period to another according to a Gamma prior distribution. Therefore, it follows that we obtain – from a period to another – a Gamma–Poisson mixture. Control charts are proposed where the observed value I_t^* of the I_t is compared with the extremes of a credibility interval based on the posterior probability of realising a value I_t, conditionally on the observed I_t^*.

A remarkable book has been published recently by Kenett and Salini (2012). The book is a collection of articles, mostly written by Italian authors, that focuses on statistical aspects, models and techniques useful in measuring customer satisfaction.

Another book by Iannario and Piccolo (2012) considers the CUB models (CUB is the acronym of Combination of Uniform and shifted Binomial random variables) related to an approach and an interpretation of subjective choices which have to be considered truly innovative. In customer satisfaction studies, respondents are conditioned by their global experience of some definite product or service and by their expectation, for instance by observing the gap between their expected and experienced performance. A more general and abstract psychological mechanism is considered at the basis of subjective choices. Quoting from the paper: "The discrete choice from a limited ordinal list of *m* alternatives is the result of human decisions which we synthesize by *liking or attractiveness towards the item* and *fuzziness surrounding the final choice* (external circumstances). We will define such unobservable components as *feeling* and *uncertainty*, which are the result of several factors related to the life of a person.

If we look for a discretisation of this component, we may refer to the support $\{1, 2,.., m\}$ and introduce the shifted binomial random variable, characterised, for a given *m, by the probability parameter* ξ leading to the probability of having r successes, r=1, 2,…, *m.* Regarding *uncertainty* the simplest solution is having recourse to a uniform random variable $U_r(m) = 1/m$. A fundamental issue in the proposed model is the assumption that we are modeling a single respondent's behavior. Each respondent includes in his decision a proportion π of *feeling* and a proportion (1- π) of *uncertainty* and we come to the conclusion that the choice brings to a realisation of a mixture with weights π and (1- π) respectively of a shifted binomial and a uniform random variable."

3. CONCLUSIONS

The paper is aimed at focusing the main principles underlying SQC and at presenting some contributions to this topic due to Italian statisticians since the 1990. Some final conclusions and remarks are required.

- The importance of the subject derives from an abstract conceptual notion, of which some reflection immediately shows its relevance and validity. In fact, whichever the manufacturing process or the service, the observations are affected by random variability and the final purpose of CSQ is the reduction of this variability.
- The *value* of quality of goods and services is obvious to anyone. If, as the origins of CSQ are related to mass production and to its technical problems, we currently notice a move from technology – perhaps owing to automation facilitating the production systems – to organisation control.
- CSQ includes indices related to dimensions not directly measurable, such as customer satisfaction, loyalty, compliance with organisational standards, etc. SQC combines current technical measurements with indices based on qualitative and subjective assessments. It forces the large companies to face squarely these developments because of their typical awareness for new technologies, new information devises and organisation systems. This is supported by the real cases to which some of the bibliography items are related: 3M (Zanella and Cascini, 1999), ENICHEM (Alvares, 2000), STMicroelectronics (Cardamone and Deldossi, 2002), GLAXO (Magagnoli and Raggi, 1999). But what happens in the small or medium companies, which are the majority in Italy, is not clear so far.
- Further investigation is necessary concerning *methodological aspects* (adapting the essential definitions of repeatability and reproducibility to the categorical (ordinal) variables, through, in particular, computer experiments); *applied methodologies* (standardisation of the quantitative assessment of CS of goods, as it was done with SERVQUAL for services, assessing compliance of a quality system with the ISO standard, representing a current reference for official certification, which is a marketing recognition at present greatly yearned; *systematic fostering of new areas* (environmental control, the monitoring of health and risks caused by accidents at work, a brand-new research topic in Italy).

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