Structure and Analysis of QS 9000 : An Executive Overview

- QS 9000의 구조와 분석 -

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요 지

본 연구는 우선 QS 9000의 배경, 구조 및 인증에 따른 혜택과 적용 사례를 알아보고 ISO 9000과 적용, 내용, 문체, 접근법, 평가과정, 용어 및 요건 면에서 구조적 차이를 비교·분석·요약하며, 또한 TE supplement 및 APQP/CP의 역할에 관해 조사한다. 끝으로 QS 9000의 주요 도구인 QFD, SPC, 공정능력지수, MSA 등의 개선기법과 적용방법 등을 소개한다.

1. Introduction

As one more response to the reality of global competitiveness, beginning in the late 1980's, Ford, General Motors(GM) and Chrysler(known as the Big Three) began to realize that there was economic advantage to adopting common standards for their supplier bases[21].

As the culture in organization transforms, a strategy to acquire a quality management system must be agreed upon and implemented. In today's business environment, an effective quality management system must be internationally recognized, all-encompassing and have a proven track record. The QS 9000 standard addresses all of these issues. Specifically, this quality standard was created to reach beyond the limits of ISO 9000 by incorporating the powerful components of continuous improvement, a parts approval process, and manufacturing capabilities. It was the automotive industry that saw the success of a quality management system within a defined structure, which eventually led to the development of the QS 9000 standard.

The concept of quality management systems isn't new. Quality systems have been around for a long time and have been used by many industries. It is difficult to understand, however, what a quality system is often difficult to achieve in the exiting culture. For this reason, a company must undergo a cultural transformation, or shift to truly utilize the power of a well-defined quality management system such as QS 9000[3].

This paper provides a sound understanding of the background, structure, analysis and major tools for QS 9000 through an executive overview. We compare QS 9000 with the generic ISO 9000 and

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summirize the differences. Improvement tools as QFD, FMEA, SPC, process capability studies and MSA are considered.

2. QS 9000

2.1 Background and Purpose

QS 9000 is an industry-specific adoption and modification of the ISO 9001 standard. In 1987, several activities came about as a result of a meeting of the Automotive Industry Action Group(AIAG), the American Society for Quality Control(ASQS) and other groups in order to harmonize the approach of the Big Three to quality in the automotive industry. One result of this meeting was the development of an industry-specific standard within the ISO 9000 framework. In 1994, this new set of requirement was published and it carried the endorsement of Ford, Chrysler, GM and the heavy truck manufacturers of Freighliner, Kenworth, Mack, Navistar, Petribilt and Volvo GM. The QS 9000 quality management system requirement is for your company to develop a quality system that provides for continuous improvement, emphasizing defect prevention and the reduction of variation and waste in the supply chain. The QS 9000 standard defines the rudimentary expectation of the quality system for companies that supply production, service parts and materials to the Big Three and other subscribing companies[3].

2.2 Applicability and Deadlines

QS 9000 applies worldwide to all internal and external supplies of production and service parts and material to the Big Three and to participating truck manufactures. Requirements vary among the Big Three[39]. Table 1 shows a summary of the implementation dates[25].

Table 1. Deadlines for QS 9000 Implementation

Chrysler	· Letter to supplies issued on January 11, 1995, by Stallkamp. · Mail in self-assessment by July 31, 1995. · Third-party registration for all production and service supplies by July 31, 1997.
Ford	· Letter to supplies issued on January 16, 1995, by Carlos E. Mazzorin. · Full compliance by June 1995. · Third-party registration not required.
General Motors	· Letter to supplies issued on October 17, 1994, by Harold R. Kunker. · Begin using QSA by January 1, 1995. · Third-party registration for all new supplies by Junuary 1, 1996; all others by December 31, 1997.

2.3 Registration and Benefit

A qualified auditor is a person who holds a valid auditor or lead auditor rating from a national accreditation body and has taken the two-day course on QS 9000 and Quality System Assessment(QSA) offered through the automotive Industry Action Group. After finishing the two-day class dealing with the automotive sections of the standard, the person must pass an exam relating to the QS 9000 standard. Only after successfully completing this exam is a person allowed to conduct

qualifying third-party QS 9000 assessments[25].

Table 2 shows accredited certification bodies(registras) and other certification bodies which have applied to United Kingdom Accreditation Service(UKAS) for assessment, taking account of QS 9000 as in June 1966[10, 26].

But senior European Standards officials ware determined to reform registration practices relating to management standards such as ISO 9000 and QS 9000[31, 40].

Table 3 Shows value-adding stages to approach successful registration from the proper point of view[33].

Table 2. Certification Bodies

Accreditied certificaton bodies
British Standard Institution Quality Assurance Ltd.
Lloyd's Register Quality Assurance Ltd.
National Quality Assurance.
SGS Yarsley International Certification Services Ltd.
United Registrars of Systems Ltd.
Applicant certification bodies
Associated Offices Quality Certification Ltd.
British Approvals Service for Electric Cables.
Bureau Veritas Quality Assurance Ltd.
Det Norske Veritas Quality Asurance Ltd.
Inspec Certification Ltd.
ISOQAR Ltd.
Premier Assessments Ltd.
Professional Assessments Ltd.
Professional Environmental and Caring Services Ltd.
Vehicles Certification Agency.

To ensure a smooth and uneventful QS 9000 implementation, there are eight steps that must be followed successfully :

- Organize the effort
- Management review
- Form teams for implementation
- Establish the project plan
- Document the system and process
- Audit and improve the system
- Achieve and manage the registration
- Use and maintain the system

Once enterprise have registered to QS 9000, it will have earned a quality management system that is practical, comprehensive and effective.

The process achieving peak to peak performance using QS 9000 consists of three pervasive strategies : winning manufactruing, QS 9000 implementation and the genesis enterprise[3]. Plastic component manufactruer LINPAC GPG achieved a UK first with third party registration to QS 9000[20]. As part of Tenneco Automative, an American Cooperative, Gillet Exhaust Manufactruing Ltd. was also the first in the group to get QS 9000 certification[38].

Table 3. Value-Adding Stages

- Analysis of existing process
  - Flowchart what you're doing today related to the QS 9000 elements.
  - Construct a matrix of the elements and functional departments(optional).
  - Identify what's right and what's worng with your quality system.
- Development of revised(or new) processes
  - Simplify processes that are too complicated until they can't be simplified any more.
  - Combine and optimize processes to simplify even further.
  - Flowchart by shift on production operations.
  - Standardize procedures so that all shifts operate in the same manner.
  - Improve those processes that need it.
- Internal auditing
  - Enlist people from other functions or other plants to audit each part of the system.
  - Evaluate the new revise processes.
  - Review audit results with operating management.
  - Make assignments for corrective actions as needed.
  - Repeat this process perhaps monthly, until yor're satisfied with the results.
- Preassesment(Optional)
  - Use to verify readiness.
  - Use to calibrate internal auditors to the registrar's auditors.
  - Incorpate corrective actions where required.
- Document review
  - Supply the auditor with your quality manual and operating procedures
  - Revise any part of the documentation found to be deficient.
- Registration assessment
  - Prepare employees for auditors' visit. Remember, auditors will evaluare the system, not individuals.
  - Relax.
- Onging surveillance and continuous registration
  - Continue internal auditing process. Once a quarter is often best.
  - Continue to flowchart processes as they change.
  - Continue to document new or changed procedures.

2.4 Trends

At the present, the QS 9000 requirements are imposed on tier-one suppliers only. But, with the specific requirement to develop their tier-two suppliers, it's only a matter of time until we see the requirements being directly or indirectly imposed throughtout the industry's customer supply chain.

The government has dropped quality specifications like MIL-Q-9858A, which it has used for yeras to control suppliers, in favor of ISO 9000.

As in the automative industry, other industries are using ISO 9000 as a base, then adding suppliments to develop their own industry-specific quality standards. For example, the aerospace industry has just released a new standard, ASE ARD 9000, that mirrors the general architecture and intent of QS 9000[25, 39].

2.5 Software

With ISO 9000 and the recent introduction of QS 9000, software packages are becoming increasing popular as a means for managing and controlling quality documents. Automating such activities means companies can re-engineer their processes quicker and more efficiently in an ever-changing environment[32].

3. Structrue and Analysis of QS 9000

3.1 Documentation Structrue

Figure 1 shows a full-paper figure that appears on page three of the QS 9000 standard.

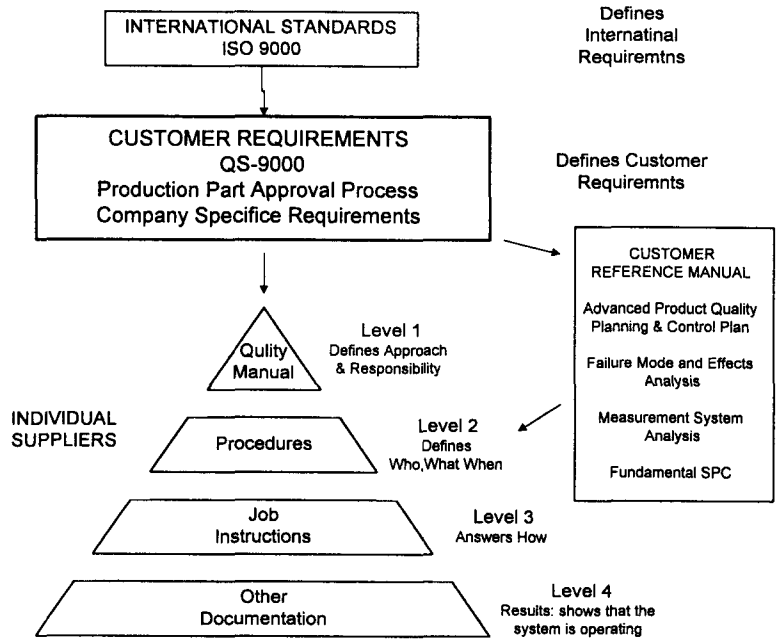

Figure 1. Quality System Documentation Progression

3.2 Comparing QS 9000 with ISO 9000

3.2.1 Differences in Applicability

ISO 9001 applies when design is required and the requirements are expressed in performance terms. It can be applied to any type of organisation. QS 9000, however, only applies to internal and external suppliers of :

- production materials
- production or service parts
- heat treating, painting or other finishing services directly to the big three or other original equipment manufacturer's customers that subscribe to QS 9000.

3.2.2 Differences in Content

QS 9000 is a book of 106 pages, several times larger than ISO 9001. In structrue it has their sections :

- Section I contains ISO 9000 based requirements. It includes the text of ISO 9001 section four and some 58 new clauses
- Section II contains sector-specific requirements and includes three additional elements, notably production part approval process(PPAP), continous improvement and manufactruing capability could have just as easily been incorporated into element 4.9(a comparison between ISO 9001

and QS 9000 in terms of numbers is given in Table 4.

- Section III contains customer specific requirements for Chrysler, Ford, General Motors and truck manufacutrers.

Table 4. ISO 9001/QS 9000 Comparison

	ISO 9001	QS 9000 sections I, II and glossary
Elements	20	23
Clauses	59	126
'Shall' statements or equivalents	138	268
'Shall' statements including lists	184	284
Procedures required	20	42
Quality records requitred	20	25

These address identification conventions, critical characteristics audits, heat treatment, material qualification, labelling and many more. There are five appendices :

- Appendix A gives an overview of the quality system assessment process
- Appendix B contains a code of practice for third party registration
- Appendix C covers special characteristic and symbols
- Appendix D is a cross reference to national equivalents to ISO 9001 and 9002
- Appendix E covers the acronyms that are used of which there are 40

At the back is a glossary of 37 terms some of which appear in ISO 8402 but have not been defined in the same way. Table 5 shows the additional clause. One of the weaknesses in the layout is that many of the additional clauses have not been numbered making referencing difficult.

QS 9000 is fundamentally a suite of documents. The documents in the suite include :

- quality system assessment guide(QSA) (38 pages)
- advanced product quality palnning and control plan reference manual (119 pages)
- potential failure mode and effects reference manual (61 pages)
- production part approval process manual(PPAP) (52 pages)
- measurement system analysis reference manual (127 pages)
- fundamental statistical process contorl reference manual (166 pages)

3.2.3 Differences in Style

The authors of QS 9000 have not perpetuated the layout and writing style of ISO 9001.

3.2.4 Differences in Approach

There are several fundamental differences in the approach :

- Third party assessments have to be carried out using the QSA.
- Registration to ISO 9000 does not give exemption from QS 9000 requirements.
- Certification bodies have to be accredited by a customer-recognised national body. There was 14 acceptable accreditation bodies.
- Certification bodies have to conform to EN45012 and accept a code of practice. Ther were 32 certification bodies approved to conduct QS 9000 audits.
- The International Auto Sector Group(IASG) sanctions interpretation to QS 9000 and issues agreed interpretations to members.

Table 5. Additional Clauses in QS 9000

4.1.2	Organisational interfaces	4.10.2	Incoming product quality
4.1.4	Business plan	4.10.3	Defect prevention
4.1.5	analysis and use of data	4.10.4	Layout inspection and functional testing
4.1.6	Customer satisfaction	4.11.3	Inspection, measuring and test equipment records
4.2.3	Advanced product quality palnning	4.11.4	Measurement system analysis
	Use of cross-functional teams	4.12	Product layout
	Feasibility reviews		Supplemental verification
	Process failure mode and effects analysis	4.13.1	Suspect product
	Control palns	4.13.3	Control of reworked product
4.4.2	Required skills	4.13.4	Engineering approved product authorisation
4.4.4	Design input supplemental	4.14.1	Problem-solving methods
4.4.5	Design output supplemental	4.14.2	Returned product test/analysis
4.4.7	Design verification supplemental	4.15.3	Inventory
4.4.9	Design changes supplemental	4.15.4	Customer packing standards
4.5.1	Reference documents		Labelling
	Document identification for special characteristics	4.15.6	Supplier delivery performance monitoring
4.5.2	Engineering specifications		Production scheduling
4.6.1	Approved materials for ongoing production		Shipment notification system
4.6.2	subcontractor development	4.16	Record retention
	Scheduling subcontractors		Superseded parts
4.6.3	Restricted substances	4.17	Inclusion of working environment
4.9	Government safery and environmental regulations	4.18	Training as a strategic issue
	Designated special characteristics	4.19	Feedback of information from service
	Preventive maintenance	4.20.2	Selection of statistical tools
4.9.1	Process monitoring and operator instructions		Knowledge of basic statistical concepts
4.9.2	Preliminary process capability requirements	II-1.1	Production part approval
4.9.3	Ongoing process performance requirements	II-1.2	Engineering chage validation
4.9.4	Modified preliminary or ongoing capablity requirements	II-2.1	Continuous improvement
	Verifications of job set-ups	II-2.2	Quality and productivity improvements
4.9.5	Process changes	II-2.3	Techniques for continuous improvement
4.9.6	Appearance items	II-3.1	Facilities, equipment and process planning and effectiveness
4.9.7	Acceptance criteria	II-3.2	Mistaking proofing
4.10.1	Accredited laboratories	II-3.3	Tool design and fabrication

3.2.5 Differences in Assessment Practice

Ther are also several difference in assessment practices :

- Auditors have to check for effectiveness as well as conformity
- The audit report format has to be based on the Road Voor de Certificatie(RVC) model
- Each auditor has to have completed QS 9000 and QSA training courses approved by the big three
- A rating system is employed to determine compliance using a pass/fail method or a variable score method.

The 23 elements may be classified either as a 'conforms/minor/major nonconformance status for that element' or as a 0 to 3 point rating for the element.

3.2.6 Differneces in Terminology

One of the more significant differences in QS 9000 is that only section four of ISO 9001 was embodied and therefore section three addressing definitions was omitted. When conducting assessments to ISO 9000, ISO 8402 is a requirements in voked in section three of ISO 9001. However, when conducting assessments to QS 9000, ISO 8402 is not a requirement.

3.2.7 Differneces in Requirements

The most significant additions to QS 9000 are the requirements for[12] :

- business plans, although the content is not subject to third party audit
- determining customer satisfaction, trends and indicators, benchmarking, etc.
- failure mode effects analysis
- compliance with govermment occupational safety and environmental requlations
- process capability analysis
- production part approval
- measurement system analysis
- suplier delivery performance monitoring
- continuous improvement
- mistake proofing

3.3 Tooling and Equipment Supplement

The big Three released the Tooling and Equipment Supplement to QS 9000 in late July, 1996. The system was introducted to Chrysler, Ford and General Motors Suppliers by way of a letter from the Big Three on July 26, 1996. The letter was sent to about 1500 key tooling and equipment suppliers.

The TE supplement is outlined in the Quality Systems Requirements Tooling and Equipment Supplement booklet and supported by the Tooling and Equipment Quality System Assessment(QSA-TE) booklet.

In addition, the process requires the use of the Reliability and Maintainability Guidelines for manufactruing Machinery and Equipment(Relibability and Maintainability Guidelines) as appropriate.

The four manuals listed below are suggested as reference tools[28] :

- Advanced Product Quality Planning & Control Plan
- Failure Mode and Effects Analysis
- Measurement Systems Analysis
- Statistical Process Control Manual

3.4 The Central Role of APQP/CP

The most significant way in which QS-9000 differs from the basic ISO 9001 framework is through its explicit requirement for product quality planning. This requirement is important both in terms of strengthening the quality system and in the resources required by the supplier for compliance. Although the need for the supplier to perform documented product quality planning appears prominently in several of the other Qs-9000 elements, including statistical techniques and inspection and testing, nowhere is it so pronounced as in element 4.2, the Quality System.

It is in the quality system element that the first reference to product quality planning appears: The supplier shall utilize the advanced product quality planning(APQP) and control plan reference manual. This sentence opens up an approach to quality planning and control that revolves around understanding the product and its unique characteristics. This approach centers around the mandated use of the control plan method and supporting tools, such as failure mode effects analysis(FMEA), process capability studies, and measurement system analysis.

In reviewing the requirements for product quality planning that appear throughout QS-9000, the intent of the Big Three becomes readily apparent. These manufacturers want suppliers to have technically competent, cross-functional teams that are intimately knowledgeable about both the product characteristics that are important to customers and about the influencing process characteristics. This knowledge includes an understanding of potential failure modes, the degree of

process stability and predictability, the capability to meet tolerances and targets, and the extent to which measurement variation affects observed data.

This product and process knowledge is then used to detail the designing, building, and verification activities specific to particular products. In practice, generic process control plans might be appropriately referenced within multiple product control plans, but must be supplemented with control provisions for process characteristics that are unique to the particular product, of course, all unique product characteristics are included in the product control plan.

The control plans are developed at the system, subsystem, and component and /or material levels as appropriate for the product being supplied. They also cover three distinct phases as appropriate-prototype, prelaunch, and production, and they are living documents that will be reviewed and updated as appropriate[21]. Figure 2 shows APQP/CP cycle.

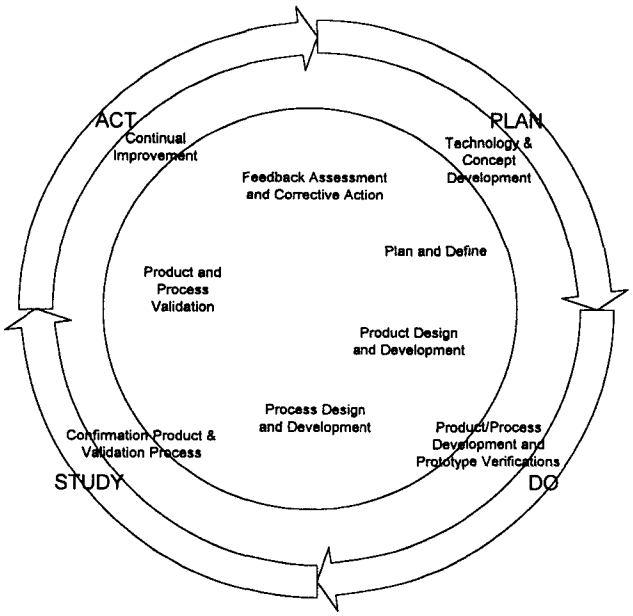

Figure 2. APQP/CP Cycle

4. Major Tools for the QS 9000

4.1 Quality Function Deployment (QFD)

Probably the most widely described and used model in the United States is a four-level model known as the Clausing model, or the ASI mdoel. ASI is the American Supplier Institute, and organization that has done much to popularized QFD. Figrue 3 depicts the model[6].

Quantitative method type Ⅲ(QMⅢ) provides an automatic method or clustering processes and data, it is possible to use judgement and observation to perform the process without automations.

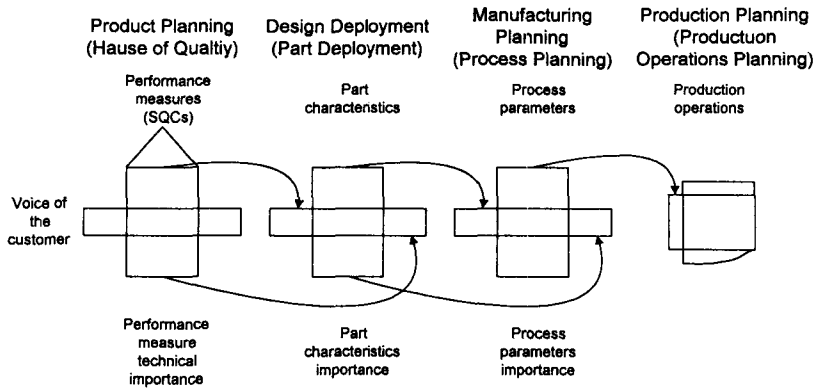

Figure 3. Four-Phase QFD Model

P_{ij} can be normalized so that all rows and columns sum to 1.0. Let x and y be the score vectors :

$$X = (x_1, x_2, \cdots, x_m)^T, \quad Y = (y_1, y_2, \cdots, y_n)^T$$

The correlation coefficient is

$$\rho_{xy} = \frac{\sigma_{xy}}{\sigma_x \sigma_y}$$

where the covariance is

$$\sigma_{xy} = \sum_i \sum_j x_i P_{ij} y_j - \sum_i P_{i\cdot} x_i \sum_j P_{\cdot j} y_j$$

the standard deviation for x is

$$\sigma_x = \sqrt{\sum_i p_{i\cdot} x_i^2 - (\sum_i p_{i\cdot} x_i)^2}$$

and the standard deviation for y is

$$\sigma_y = \sqrt{\sum_j p_{\cdot j} y_j^2 - (\sum_j p_{\cdot j} y_j)^2}$$

The QMIII maximized ρ_{xy} to classify two-dimensional data to maximize ρ_{xy}, the partial derivatives are solved with respect to x_i (i = 1, 2, ···, m) and y_i (j = 1, 2, ···, n).

Then

$$\frac{\partial}{\partial x_i} \rho_{xy} = 0, \quad \frac{\partial}{\partial y_j} \rho_{xy} = 0 \tag{1}$$

By calulating Eq.(1) becomes

$$\frac{1}{\sigma_x \sigma_y} \left[\sum_j P_{ji} y_i y_j - p_{i\cdot} \sum_j P_{\cdot j} y_j \right] - \frac{\rho_{xy}}{\sigma_x^2} P_{i\cdot} \left[x_i - \sum_i P_{i\cdot} x_i \right] = 0 \tag{2}$$

$$\frac{1}{\sigma_x \sigma_y} \left[\sum_i P_{ji} x_i x_j - p_{j\cdot} \sum_i P_{i\cdot} x_i \right] - \frac{\rho_{xy}}{\sigma_y^2} P_{\cdot j} \left[y_j - \sum_y P_{\cdot j} y_j \right] = 0 \tag{3}$$

Let $\hat{x}$ and $\hat{y}$ be normalized as

$$\tilde{x} = \frac{\{x - (I_m^T p_x x) I_m\}}{\sigma_x}, \quad \tilde{y} = \frac{\{y - (I_n^T p_y y) I_n\}}{\sigma_y}$$

Equations (2) and (3) are changes into the folowing :

$$P_{\tilde{y}} - \rho_{xy} P_x \tilde{x} = 0, \qquad P^T \tilde{x} - \rho_{xy} P_y \tilde{y} = 0 \tag{4}$$

From Eq.(4), the following formulars are extracted :

$$(P P_y^{-1} P^T - \rho_{xy}^2 P_x) \tilde{x} = 0, \qquad (P^T P_x^{-1} P - \rho_{xy}^2 P_y) \tilde{y} = 0 \tag{5}$$

These are the eigenvalue formulas with the eigenvalue

$$\lambda = \rho_{xy}^2.$$

Solve Eq.(5). Let

$$P_x^{1/2} = \text{diag}(P_i.^{1/2}) \text{ and } P_x^{-1/2} = \text{diag}(P_i.^{-1/2})$$

Then

$$(P_x^{-1/2} P P_y^{-1} P^T P_x^{-1/2} - \rho_{xy}^2 I) P_x^{1/2} \tilde{x} = 0$$

$$(P_y^{-1/2} P^T P_x^{-1} P P_y^{-1/2} - \rho_{xy}^2 I) P_y^{1/2} \tilde{y} = 0$$

Form these equations and Eq.(4), $\hat{x}$ and $\hat{y}$ are extracted. On the basis of these eigenvalues, two-dimensional data are organized[17].

4.2 Failure Modes and Effects Analysis (FMEA)

FMEA was developed during the early 1960's in the U.S. aerospace industry. FMEA was a tool used to understand the potential types of failure, what might cause them and how to prevent or contain the adverse consequences of possible failure.

There are two types of FMEA : design FMEA(DFMEA) and process FMEAs(PFMEA). The former focuses on the design of a product, whereas the latter emphasized consistent manufacture of that design. Figure 4 demonstrates the improtance of design tool capability.

Part Name and Part Function	Potential Failure Mode	Potential Effect(s) of Failure	SEVER	▽	Potential Cause(s) of Failure	OCCUR	Design Verification	DETEC	RPN	Recommended Actions(s)	Area/Individual Responsible & Completion Data	Actions Taken	SEVER	OCCUR	DETEC	RPN
Analogue Circuit used to process a sensor signal	Output stuck at either hight or low	Zero readout on instrumentation	8		Short circuit due to insufficient space allotment between conductors	1	Comupter simulation	10	80	100% test to verify validity of design rules	Product/Test Engineering	Test program written and verified	8	1	1	8
					Short circuit due to violation of design of rules	3	Computer check of schematic vs design rules	1	24	None recommended, 6-sigma effective						

Figure 4. Design Rule Exapmle.

4.3 Statistical Process Control (SPC) and Process Capability Studies

4.3.1 SPC

Lin[19] presented the paper targeted for readers who are involved in manufacturing fairly complicated products where automation is needed for efficient SPC implementation. He also considered (i) the relationship between the variable process capability indices and the attribute process capability, (ii) C_p, C_{pk}, and C_{pm}, (iii) examples of data transformations to account for nonGaussian behavior in process capability calculations and (iv) an example for combining control charts, process capabilities and distribution characteristrics to facilitate out-of-control investigation[37].

4.3.2 C_{pw}

Consider the process capability index C_{pw},

$$C_{pw} = \frac{USL - LSL}{6\sqrt{\sigma^2 + w(\mu - T)}}$$

where w represents a weight function letting

$$p = \frac{|\mu - T|}{\sigma}$$

denote a measure of off targetness, then the weight function

$$w = \begin{cases} \frac{k(2-k)}{(1-k)^2 p^2} & , \ 0 < k < 1 \\ 0 & , \ \text{elsewhere} \end{cases}$$

The weight function can also be written as a function of C_p,

$$w = \begin{cases} \frac{(6C_p - p)}{(1-k)^2 p^2} & , \ 0 < p/3 < C_p \\ 0 & , \ \text{elsewhere} \end{cases}$$

Defining

$$d = \frac{USL - LSL}{2} \text{ and } a = \mu - \frac{USL + LSL}{2}$$

$$w = \begin{cases} \left[\frac{d^2}{(d-|a|)^2} - 1\right]\frac{1}{p^2} & , \ 0 < p \\ 0 & , \ \text{elsewhere} \end{cases}$$

The general confidence interval for C_{pw} of the form

$$p_r\left[\sqrt{\frac{Q^2_{n,\lambda}\left(\frac{\alpha}{2}\right)}{n\left(1+\frac{w\lambda}{n}\right)}}\ \hat{C}_{pw} \le C_{pw} \le \sqrt{\frac{Q^2_{n,\lambda}\left(1-\frac{\alpha}{2}\right)}{n\left(1+\frac{w\lambda}{n}\right)}}\ \hat{C}_{pw}\right] = 1-\alpha$$

where, $Q^2_{n,\lambda}(x) = \sum_{i=0}^{\infty} d_i \chi^2_{n+2i}(x)$

$$p_r\left[\sqrt{\frac{\chi^2_{n-1}\left(\frac{\alpha}{2}\right)}{n}}\ \hat{C}_p \le C_p \le \sqrt{\frac{\chi^2_{n-1}\left(1-\frac{\alpha}{2}\right)}{n}}\ \hat{C}_p\right] = 1-\alpha$$

$$p_r\left[\sqrt{\frac{\chi^2_{n,\lambda}\left(\frac{\alpha}{2}\right)}{n\left(1+\frac{\lambda}{n}\right)}}\ \hat{C}_{pm} \le C_{pm} \le \sqrt{\frac{\chi^2_{n,\lambda}\left(1-\frac{\alpha}{2}\right)}{n\left(1+\frac{\lambda}{n}\right)}}\ \hat{C}_{pm}\right] = 1-\alpha$$

$$p_r\left[\sqrt{\frac{Q^2_{n,\lambda}\left(\frac{\alpha}{2}\right)}{n(1+wp^2)}}\ \hat{C}^*_{pk} \le C^*_{pk} \le \sqrt{\frac{Q^2_{n,\lambda}\left(1-\frac{\alpha}{2}\right)}{n(1+wp^2)}}\ \hat{C}^*_{pk}\right] = 1-\alpha$$

$$p_r\left[\sqrt{\frac{Q^2_{n,\lambda}\left(\frac{\alpha}{2}\right)}{\left[\frac{nd^2}{(d-|a|^2)}\right]}}\ \hat{C}_{pk} \le C_{pk} \le \sqrt{\frac{Q^2_{n,\lambda}\left(1-\frac{\alpha}{2}\right)}{\left[\frac{nd^2}{(d-|a|^2)}\right]}}\ \hat{C}_{pw}\right] = 1-\alpha$$

These indices can also be described by a more generalized C_{pw}[34].

$$C_{pw} = \frac{\min(USL - T,\ T - LSL)}{3\sqrt{s^2 + w(\mu - T)^2}}$$

4.3.3 C_{pm}

The estimator of C_{pm} is

$$\hat{C}_{pm} = \frac{USL - LSL}{6\sqrt{s^2 + \frac{n(\bar{x} - T)^2}{n-1}}}$$

The p-value asssociaed with the Bayesian approach[35], is

$$p = pr(C_{pm} > c \mid \hat{c}_{pm}) = 1 - \Phi\left\{\frac{\left[\frac{(n-1)c}{n\,\hat{C}_{pm}}\right]^{1/3} - \left[1 - \frac{2}{9n}\right]}{\sqrt{\frac{2}{9n}}}\right\}$$

4.3.4 Test

The test statistic for comparing two C_p indices has an F-distribution when the two C_p indices are equal.

To compare the capability of two processes, we will test $H_0 : CPU_1 \geq CPU_2$, $H_1 : CPU_1 \leq CPU_2$. Calculate the values of $\hat{C}PU_1$, $\hat{C}PU_2$, and A where

$$\hat{C}PU_1 = \frac{USL - \bar{x}_1}{3s_1}$$

$$\hat{C}PU_2 = \frac{USL - \bar{x}_2}{3s_2}$$

and

$$A = \left[\frac{2}{(a\,\hat{C}PU_1^2+2)^{1/2}(a\,\hat{C}PU_2^2+2)^{1/2} - a\,\hat{C}PU_1\,\hat{C}PU_2}\right]^n$$

where $a = \frac{9n}{n-1}$

If $\hat{C}PU_1 < \hat{C}PU_2$, and $A < e^{-\chi_1^2 \frac{(1-2a)}{2}}$, then reject H_0[5].

Cheng[4] provided all the statistical theory about process capability indices. Table 6 shows the procedure.

Table 6. The Procedure

C_p	C_{pm}
1. Decide the definition of "capable"[i.e., the value of C(normally set at 1 or 1.33)] and the α-risk (normally set at 0.01, 0.025 or 0.05), the chance of wrongly concluding an incapable process capable. 2. Calculate the estimated value of the index from the sample, that is, $\hat{C}_p$. 3. Adjust the value of $\hat{C}_p$ to obtain W by $W = \hat{C}_p / C$. 4. From the appropriate table (depending on n), find the p-value based on W. 5. If the p-value is less than α, conclude that the process is capable; otherwise, state that we do not have enough information to conclude that the process is capable. Note. If W is less than the smallest value in the table, then conclude that the process is not capable; if W is larger than the largest value in the table, then conclude that the process is capable.	1. Decide the definition of "capable"[i.e., the value of C (normally set at 1 or 1.33)] and the α-risk(normally set at 0.01, 0.025, or 0.05), the chance of wrongly concluding an incapable process capable. 2. Calculate the estimated value of the index from the sample, that is, $\hat{C}_{pm}$. 3. Adjust the value $\hat{C}_{pm}$ to obtain W by $W = \hat{C}_{pm} / C$. Calculate the value $Q = (\bar{x} - T)/s$(only when you deal with case that the target or nominal value, T, is not equal to the process mean μ). 4. From the appropriate table(depending on n and Q), find the p-value based on W. 5. If the p-value is less than α, conclude that the process is capable; otherwise, state that we do not have enough information to conclude that the process is capable. Note. If W is less than the smallest value in the table, then conclude that the process or not capable; if W is larger than the largest value in the table, then conclude that the process is capable.

The following describes the mathematical origin of the tabulated values. With this information, other cases not covered in the tables here can be obtained.

To test H_0 : The process is not capable

vs H_1 : The process is capable

Let $CI = C_p$ or C_{pm} ,

then $H_0 : CI \leq C$ vs $H_0 : CI > C$.

If the observed value of the test statistic $\hat{C}I\ (= \hat{C}_p) = W_p$ (or W_m if $\hat{C}_{pm}$ were used for $\hat{C}I$), then

p-value = $P(\hat{C}I \geq W_p \mid CI \leq C)$.

When $CI = C_p$

p-value = $P(\hat{C}p \geq W_p \mid CI \leq C)$.

$$= P\left\{ \chi^2_{n-1} < \frac{C^2}{W_p^2}(n-1) \right\} ;$$

when $CI = C_{pm}$

p-value = $P(\hat{C}_{pm} \geq W_m \mid CI \leq C)$.

$$= P\left\{ \chi_n^2 < \frac{C^2}{W_m^2}(n-1) \right\} .$$

If $\mu \neq T$,

p-value = $P(\hat{C}_{pm} \geq W_m \mid CI \leq C)$

$$= P\left\{ \chi^2_{n,\lambda^*} < \frac{C^2}{W_m^2}(n-1)\left[1 + \frac{\lambda^*}{n}\right] \right\}$$

where $\lambda^* = n\left[\frac{\bar{x} - T}{s}\right]^2 = nQ^2$.

Solving for C_t(high)/ C_t(low) and C gives

$$\frac{C_p(\text{high})}{C_p(\text{low})} = \frac{\chi^2_{(N-1)}(1-\beta)}{\chi^2_{(N-1)}(\beta)}$$

$$C = C_p(\text{low}) \frac{(N-1)}{\chi^2_{N-1}(\alpha)}$$ [15].

Table 7 summarized the standard errors of many capability indices[30].

4.3.5 Bayesian Approach

$$\hat{C}_{pk} = \frac{d - (\bar{x} - m)\, sgn(\bar{x} - m)}{3s}$$

where sgn($\bar{x}$ - m) = 1 if $\bar{x}$ - n $\geq$ 0 and sign($\bar{x}$ - m) = -1 if $\bar{x}$ - m < 0. For $\hat{C}_p$ it is shown that $E(\hat{C}_p) = (b_f)^{-1} C_p$, where b_f is a constant known as $b_f = \left\{\frac{2}{n-1}\right\}^{1/2} \Gamma\left[\frac{n-1}{2}\right] \left\{\frac{\Gamma(n-2)}{2}\right\}^{-1}$.

Alternative forms for $\hat{C}_{pk}$[29] may be written as

$$\hat{C}'_{pk} = \frac{d - (\bar{x} - m) sgn(\mu - m)}{3s}$$

$$\hat{C}^*_{pk} = \frac{d - (\bar{x} - m) I_A(\mu)}{3s}.$$

Table 7. Standard Errors of Process Capability Indices

Statistic	Standard Error
$\bar{x}$	$\frac{s}{\sqrt{n}}$
s	$\frac{s}{\sqrt{2(n-1)}}$
$\hat{c}_t$	$\frac{\hat{c}_p}{\sqrt{2(n-1)}}$
$\hat{c}_{pk}$	$\left[\frac{C_{pk}^2}{2(n-1)}+\frac{1}{pn}\right]^{1/2}$
$\hat{c}_{pm}$	$\frac{\hat{C}_{pm}}{\sqrt{n}}\left[\frac{\frac{1}{2}+\frac{(\bar{x}-T)^2}{s^2}}{\left[1+\frac{(\bar{x}-T)^2}{s^2}\right]}\right]^{1/2}$

4.3.6 Bivariate Capability Index

It is well known that contours of constant density are ellipses centered at m.

$$(x-\mu)^T\sum^{-1}(x-\mu) \le \chi_2^2(\alpha)$$

$$T^2 = (\bar{x}-\mu_0)^T\left(\frac{s}{n}\right)^{-1}(\bar{x}-\mu_0) \qquad (6)$$

where Hotelling's T^2 and follows a $\left[\frac{2(n-1)}{n-2}F_{2,n-2}\right]$distribution.

The vertices of the rectangle are determined by solving the system of equations of first derivatives of equation(6).

$$\text{Max}\left\{1, \frac{|UPR_1-LSL_1|}{USL_1-LSL_1}, \frac{|UPR_1-USL_1|}{USL_1-LSL_1}, \frac{|UPR_2-LSL_2|}{USL_2-LSL_2}, \frac{|UPR_2-USL_2|}{USL_2-LSL_2}\right\}$$

When this index is equal to 1, then the entire process rectangle falls within or on the specification rectangle. When it is greater than one, then some or all of the process rectangle falls outside of the specification rectangle[13].

4.3.7 Geometric Dimensioning and Tolerancing (GDT)

The multivariate capability index MC_{pm} is defined as

$$MC_{pm} = \frac{\text{Volume of a modified tolerance region}}{\text{Volume of a scaled 99.79\% process region}}$$

$$= \frac{\text{Vol. (modified tolerance region)}}{\text{Vol.}\left((x-\mu)'\sum_T^{-1}(x-\mu) \le K(q)\right.}$$

A call-out which specifies a target value for the pin diameter corresponding to the midpoint of allowable pin sizes and the allowable tilt of the pin depends on its size.

$$\hat{MC}_{pm} = \frac{\left(\frac{4\pi}{3}\right)R_UR_L(U-L)}{\frac{4}{3}\pi|\hat{\sum}|^{1/2}K(g)^{2/3}\left[1+\frac{n}{n-1}(\bar{x}-T)'\hat{\sum}^{-1}(\bar{x}-T)^{1/2}\right]}$$

A call-out specifies a noncentered target for the pin diameter and the allowable tilt of the pin depends on its size.

$$V_1 = \frac{\left(\frac{4\pi}{3}\right)R_T R_L(T_z - L)}{2} \quad \text{when} \quad T_z < \frac{U+L}{2}$$

or

$$V_2 = \frac{\left(\frac{4\pi}{3}\right)R_T R_U(U - T_z)}{2} \quad \text{when} \quad T_z > \frac{U+L}{2}$$

where $R_T = 2\left[\frac{R_L - R_U}{L - U}\right](T_z - L) + R_L$

A call-out which has no target for pin diameter and yet the allowable tilt of the depends on its size.

$$AME = \begin{cases} \frac{d_t + d_b}{2} + p & \text{if } \frac{|d_b - d_t|}{2} < p \\ \max(d_t, d_b) & \text{if } \frac{|d_b - d_t|}{2} \geq p \end{cases}$$

where AME is called actual mating envelope and $p = \sqrt{x^2 + y^2}$[16].

4.3.8 Spherical Tolerance

In three dimensions, any part with an axis of the feature lying outside the spherical tolerance zone is nonconforming.

$$mfn = \int_u^{\infty} \hat{f}(\lambda)\, d\lambda$$

In the three dimensional case

$$mfn = 1 - Erf\frac{U}{\sigma\sqrt{2}} - \left(\frac{U}{\sigma}\right)\sqrt{\frac{2}{\pi}}\, e^{\frac{-U^2}{2\sigma^2}}$$

In the two-dimensional case

$$mfn = e^{\frac{-U^2}{2\sigma^2}}$$

If the spread ratio, R, is defined as U/σ for a featrue produced by a particular process, the minimum fraction nonconforming produced by that process is

$$mfn = 1 - \left\{Erf\frac{R}{\sqrt{2}} - R\sqrt{\frac{2}{\pi}}\, e^{\frac{-R^2}{2}}\right\} \qquad \text{(Three Dimensions)}$$

$$mfn = e^{-\frac{R^2}{2}} \qquad \text{(Two Dimensions)}$$

Current measures of process capability are provided in time of either a process capability index or the nonconforming parts per billion (NCPPB) produced by the process [7].

4.3.9 Lattice Data

Boyles [1, 2] presented three illustrative examples involving multiple dimensional measurements where the within-part inspection plans are structures like lattices in rectangular idealized geometry for the wall thickness data, or in polar idealized geometry for the passage location data.

4.3.10 Normality Test

A probability plot is constructed by placing data that have been ordered from the smallest to the largest values onto cumulative normal probability paper.

$$y=\frac{i-0.375}{n+0.25}\times 100$$

$$y=\frac{i-0.5}{n}\times 100.$$

If the data fall along the best fit line that is drawn through the data, it is considered normally distributed.

Skewness, commonly designated by $\sqrt{b_1}$, is

$$\sqrt{b_1}=\frac{\sum_{i=1}^{n}(X_n-\overline{X})^3/(n-3)}{S^3}$$

Many statisticians prefer to determines a standardized coefficient of skewness by dividing the skewness value by $\sqrt{b/n}$.

Kurtosis, designed by b_2 , is

$$b_2=\frac{\sum_{i=1}^{n}(X_n-\overline{X})^4/(n-3)}{S^4}\ .$$

The standardized coefficient for kurtosis is determined by subtracting, from the kurtosis value and dividing by $\sqrt{24/n}$.

The Shapiro-Wilk w test is

$$w=\frac{(b)^2}{s^2}$$

where

$$b=\sum_{i=1}^{k}a_{n-i+1}(X_{n-i+1}-X_i)\ ,\quad k=n/2\text{if n is even}$$

$$k=(n-1)/2 \text{ if n is odd}$$

The chi-square value is calculated using

$$\chi^2=\sum_{i=1}^{k}\frac{(\text{Observed}_i-\text{Expected}_i)^2}{\text{Expected}_i}$$

A method for combining the skewness and kurtosis values are :

$$y^2=x^2\sqrt{b_1}+x^2(b_2)$$

where x is the transformation function for the standardized normal equivalent. With the use of the contours, the procedure is simply to verify that the coordinate represented by $(b_2,\sqrt{b_1})$ falls within the confidence interval.

A number of references are available for further information on these and other normality test statistics :

$$A^2=\left[\frac{\sum_{i=1}^{n}(2_i-1)[\ln(z_i)+\ln(1-z_{n+1-i})]}{n}-n\right]\left[1+\frac{0.75}{n}+\frac{2.25}{n^2}\right]$$

$$\pm b_1\left[\frac{1}{2}(1-(1-\alpha)^{\frac{1}{2}}\right]\text{and}\pm b_2\left[\frac{1}{2}(1-(1-\alpha)^{\frac{1}{2}}\right]$$

$$D=\sqrt{n}\ \max\left|\frac{r}{n}-F(x_r)\right|$$

$$u=\frac{\sqrt{(n-1)}(y_n-y_1)}{\left[\sum_{i=1}^{n}(y_i-\overline{y})\right]^{1/2}}$$

$$D = \max_i \left[\frac{i}{n} - \sum_{j=1}^{i} (n+2-j)(C_j - C_{j-1}) \right]$$

$$WCM = n \int_0^1 [F_n(y) - F(y)]^2 \frac{dF(y)}{F(y)(1-F(y))}$$

$$CM = n \int_0^1 [F_n(y) - F(y)]^2 dF(y) \quad [41].$$

Fang et al.[8] showed that NPP can help detect symmetrical distributions that pass the test for symmetry and even appear to be normal to the eye, such as the t with small degrees of freedom.

Data which is normally distributed :

- The data set has 100 data points.
- The Histogram displays a bell shaped curve.
- The NPP is best represented by a straight line.
- The Boxplot is symmetric.
- The Correlation is greater than the required correlation.
- All of the four tests are acceptable[9].

Table 8. shows Gaussian functional transformations[19].

Table 8. Gaussian Transformations

Transformation	Detransformation
$\log\left[\frac{1}{x+1}+1\right]$	$\left[\frac{1}{e^x-1}-1\right]$
$\sqrt{x+\frac{3}{8}}$	$x^2-\frac{3}{8}$
$\sin^{-1}(\sqrt{x})$	$\sin^2(x)$

The formula relies on a normal approximation to the sampling distribution of C_{pk}

$$C_k \approx \hat{C}_{pk}\left\{1 - Z_{1-\alpha/2}\left[\frac{n-1}{n-3} - \frac{n-1}{2}\left[\frac{\Gamma[(n-2)/2]}{\Gamma[(n-1)/2]}\right]^2\right]^{1/2}\right\}$$

$$C_k \approx \hat{C}_{pk} - Z_{1-\alpha}\left[\frac{1}{9n} + \frac{\hat{C}^2_{pk}}{2n-2}\right]^{1/2}$$

Levison[18] defined an equivalent CPL or CPU that describes the process' ability to meet the specification:

- Estimate P such that the non-normal process has 100 p% of its population within the specification limit.
- Find CPL or CPU such that a normal distribution would have 100 p% of its population within the specification limit. This is the point estimate for the non-normal process' equivalent CPL or CPU.
- Find a lower 100 r% confidence limit for p.
- The corresponding normal CPL or CPU is the lower 100 r% confidence limit for the equivalent CPU or CPU[18].

4.3.11 Tolerance Limit

We are give a confidence coefficient r, a proportion, p, and a sample size n. We are asked to

find a limit $\bar{x}+ks$(where k is given in table) so that we can be 100 r% sure that at least 100 p% of the sampled population is below $\bar{x}+ks$. This is the form for an upper tolerance limit. For a lower tolerance limit, we can be 100 r% sure that at least 100 p% of the sampled population is above $\bar{x}+ks$.

For two-sided limits which control both tails of the sampled distribution, we can be 100 r% sure that at most 100 q_1% of the population is below $\bar{x}-k_1s$ and at most 100 q_2% of the population is above $\bar{x}+k_2s$, where k_1 and k_2 are read from Table[27].

It is possible to construct nonparametric(or distribution-free) tolerance limits that are valid for any continuous probability distribution. For two-sided tolerance limits,

$$n \simeq \frac{1}{2} + \left(\frac{2-\alpha}{\alpha}\right)\frac{x^2_{1-r,4}}{4}$$

For one-sided tolerance limits,

$$n = \frac{\log(1-r)}{\log(1-\alpha)}$$

4.3.12 Setting Specification Limit

If the natural tolerances of the assembly are defined so that no more than a% of the assemblies will fall outside these limits, and $2W$ is the width of the specification limits, then

$$\sigma_y^{2*} = \left(\frac{W}{Z_{\frac{\alpha}{2}}}\right)$$

$$\sigma^{2*} = \frac{\sigma_y^{2*}}{n}$$

In some problems[24], the dimension of interest may be a nonlinear function of the n component dimensions $x_1, x_2, \cdots, x_n$ say

$$y = g(x_1, x_2, \cdots, x_n)$$

$$= g(\mu_1, \mu_2, \cdots, \mu_n) + \sum_{i=1}^{n}(x_i-\mu_i)\frac{dg}{dx_i}\Big|_{\mu_1, \mu_2, \cdots, \mu_n} + R$$

neglecting the terms of higher order, we have

$$\mu_y = g(\mu_1, \mu_2, \cdots, \mu_n)$$

and

$$\sigma_y^2 = \sum_{i=1}^{n}\left(\frac{dg}{dx_i}\Big|_{\mu_1, \mu_2, \cdots, \mu_n}\right)^2\sigma_i^2$$

4.4 Measurement System Analysis

4.4.1 Nested Design

One of the major uses of designed experiments is in isolating and estimating the source of variability in a process. Such a design would be called an m-stage nested design[23].

4.4.2 Gage R&R

Expressed mathematically,

$$\sigma^2_{total} = \sigma^2_{product} + \sigma^2_{gage}$$

where

$$\hat{\sigma}^2_{total} = s^2$$

$$\hat{\sigma}^2_{gage} = \frac{\overline{R}}{d_2}$$

$$\frac{P}{T} = \frac{6\hat{\sigma}^2_{gage}}{USL - LSL}$$

$$\frac{\hat{\sigma}^2_{gage}}{\hat{\sigma}_{product}} \times 100$$

$$\sigma^2_{measurement\ error} = \sigma^2_{gage} = \sigma^2_{repeatability} + \sigma^2_{reproducibility}$$

where $\hat{\sigma}_{repeatability} = \frac{\overline{\overline{R}}}{d_2}$

$$\hat{\sigma}_{reproducibility} = \frac{R_{\bar{x}}}{d_2}$$

SPC manual[9] showed the procedure for studying measurement systems with/without set-up variation.

Like every process, the distribution that can be used to describe the measurement system's variation can be characterized by:

		1			2			3			4			5			APPRAISER AVG.
APPRAISER TRIAL #		MAX	MIN	RGE	MAX	MIN	RGE	MAX	MIN	RGE	MAX	MIN	RGE	MAX	MIN	RGE	
1. A	1	.68	.58	.10	1.07	.93	.14	.87	.78	.09	.97	.83	.11	.58	.42	.16	
2.	2	.67	.57	.10	1.08	.92	.16	.85	.77	.08	.96	.81	.15	.59	.40	.19	
3.	3		-			-			-			-			-		
4. Average (All)		.625			1.000			.8175			.8925			.4975			.7665
5. Range		.01	.01	0	.01	.01	.02	.02	.01	.01	.01	.02	.01	.01	.02	.03	
6. B	1	.59	.51	.08	1.08	.92	.16	.82	.73	.09	.84	.71	.13	.49	.31	.18	
7.	2	.60	.50	.10	1.07	.93	.14	.81	.75	.06	.85	.70	.15	.48	.32	.16	
8	3		-			-			-			-			-		
9. Average (All)		.55			1.00			.78			.78			.40			.7005
10. Range		.01	.01	.02	.01	.01	.02	.01	.02	.03	.01	.01	.02	.01	.01	.02	
11. C	1	.56	.49	.07	1.10	.95	.15	.84	.77	.07	.87	.74	.13	.56	.36	.17	
12.	2	.55	.47	.08	1.08	.94	.14	.84	.76	.08	.88	.73	.15	.57	.38	.19	
13.	3		-			-			-			-			-		
14. Average (All)		.52			1.02			.80			.80			.48			.7225
15. Range		.01	.02	.01	.02	.01	.01	.00	.01	.01	.01	.01	.02	.01	.01	.02	R_o = .066
16. Part Average		.565			1.001			.799			.824			.459			R_o = .55
17. Ave. of WIV		.09			.15			.08			.14			.17			$R_{\bar{X}WIT}$ = .09
18. $\overline{R}_{REPEAT} = \frac{\text{sum RANGE(LINES 5, 10 \& 15)}}{\text{\# RANGE READINGS}} = \frac{.35}{30} = 0.0117$ (MAX/MIN RANGES ONLY)																	
19. {Max $\overline{X}$ = 0.7665} - {Min $\overline{X}$ = 0.7005} = $\overline{X}_{DIFF}$ = 0.065 = 0.07																	
20. { $\overline{\overline{R}}$ = } × { D_4^* = } = UCL_R																	
21. { $\overline{\overline{R}}$ = } × { D_3^* = } = LCL_R																	

* D_4 = 3.27 for 2 trials and 2.58 for 3 trials. D_3 = 0 for up to 7 trials; UCL_R representas the limit of individual R's circle those that are beyond this limit. Identify the cause and correct. Repeat these readings using the same appr... r and unit as originally used or discard values and re-average and recompute R and the limiting value from the remaining observations

Note. _____

Figure 5. Gage Repeatability and Reproducibility Data Sheet - Including Within-Part Variation

Part No. & Name :
Characterisitcs :
Specification :
From data sheet : $\overline{R}$ = 0.0117

Gage Name :
Gage No :
Gage Type :
$\overline{X}_{Diff}$ = 0.07

Data :
Performaed by :
R_p = 0.55

Measurement Unit Analysis | **%Total Variation (TV)**

Repeatability - Equipment Variation (EV)

$EV = \overline{R} \times K_1$
$= 0.0117 \times 4.56$
$= 0.0534$

Trials	K_1
2	4.56
3	3.05

% EV = 100 [EV/TV]
= 100 [.0534/1.178]
= 4.2%

Reproducibility - Appraiser Variation (AV)

$AV = \sqrt{[(\overline{X}_{DIFF} \times K_2)^2 - (EV^2/nr)]}$
$= \sqrt{[(0.07 \times 2.70)^2 \times (0.05^2/5 \times 2)]}$
$= 0.178$

Appraisers	2	3
K_2	3.65	2.70

% AV = 100 [AV/TV]
= 100 [0.178/1.178]
= 15.3%
n = number of parts
r = number of trials

Repeatability & Reproducibility (R&R)

$R\&R = \sqrt{(EV^2 + AV^2)}$
$= \sqrt{(0.05^2 + 0.18^2)}$
$= 0.187$

Parts	K_3
2	3.65
3	2.70
4	2.30
5	2.08
6	1.93
7	1.82
8	1.74
9	1.67
10	1.62

% R&R = 100 [R&R/TV]
= 100 [.187/1.178]
= 15.9%

Part Variation (PV)

$PV = R_p \times K_3$
$= 0.55 \times 2.08$
$= 1.144$

% PV = 100 [PV/TV]
= 100 [1.144/1.179]
= 97%

Within-Part Variation (WIV)

$$WIV = \overline{X}_{WIV} + \left\{ \frac{\sqrt{(R_{\overline{x}WIV} \times K_3)^2 - \frac{(EV_{WIV})^2}{n_{WIV} \times r}}}{2} \right\}$$

$$= .126 + \left\{ \frac{\sqrt{(.1572)^2 - \frac{(.076)^2}{3 \times 2}}}{2} \right\} = .218$$

$$\overline{X}_{WIV} = \frac{\sum \overline{X}_{WIV}\ (LINE\ 17)}{\#\ \overline{X}_{WIV}\ READINGS} = \frac{0.63}{5} = .126$$

WIV = # APPERAISERS, r = # TRIALS

$$EV_{WIV} = \left(\frac{\sum R_{RGE}(LINES\ 5,\ 10\ \&\ 15)}{\#\ R_{RGE}\ READINGS} \right) \times K_1 = \frac{.25}{15} \times 4.56 = .076$$

% WIV = 100 [WIV/TV]
= 100 [0.22/1.179]
= 18.7%

Tatal Variation (TV)

$TV = \sqrt{R\&R^2 + PV^2 + WIV^2}$
$= \sqrt{(0.18)^2 + (1.144)^2 + (0.218)^2}$
$= 1.178$

Figure 6. Gage Repeatability and Reproducibility Report - Including Within-Part Variation

- Location
  - Stability : $\overline{x}_{t_1} - \overline{x}_{t_2}$
  - Bias : Observed average-Reference value
  - Linearity : $y = b + ax$ where x = reference value, y = bias
- Width or Spread
  - Repeatability
  - Reproducibility

Figure 5, 6 show gage repeatability and reproducibility date sheet and report including within-part

variation. Table 9 represents d_2^* values for the distribution of the average range[22].

4.4.3 Measurement Errors

The general model relating to μ_k is

$$x_{ik} = \alpha_i + \beta_i \mu_k + \varepsilon_{ik}$$

where x_{ik} = observed measurement value for item k, method i

μ_k = true but unknown value for item k.

- The models are said to have common precisions of if σ_i^2 is the same for i.
- If $\alpha_i=0$ and $\beta_i=1$, the method i is said to be unbiased.
- If $\alpha_i \neq 0$ but $\beta_i \neq 1$, method i is said to have a constant bias.
- If $\alpha_i \neq \alpha_j$ but $\beta_i = \beta_j = 1$, methods i and j are said to have a constant relative bias.
- If $\beta_i \neq 1$, method i is said to have a nonconstant bias.
- If $\beta_i \neq \beta_j$, method i and j are said to have a nonconstant relative bias.

As long as the μ_k values are not known, one can never obtain estimates of the α's and β's, but only of their differences or ratios[14].

Table 9. d_2^* Values for the Distribution of The Average Range

		m													
		2	3	4	5	6	7	8	9	10	11	12	13	14	15
g	1	1.41	1.91	2.24	2.48	2.67	2.83	2.96	3.08	3.18	3.27	3.35	3.42	3.49	3.55
	2	1.28	1.81	2.15	2.40	2.60	2.77	2.91	3.02	3.13	3.22	3.30	3.38	3.45	3.51
	3	1.23	1.77	2.12	2.38	2.58	2.75	2.89	3.01	3.11	3.21	3.29	3.37	3.43	3.50
	4	1.21	1.75	2.11	2.37	2.57	2.74	2.88	3.00	3.10	3.20	3.28	3.36	3.43	3.49
	5	1.19	1.74	2.10	2.36	2.56	2.73	2.87	2.99	3.10	3.19	3.28	3.35	3.42	3.49
	6	1.18	1.73	2.09	2.35	2.56	2.73	2.87	2.99	3.10	3.19	3.27	3.35	3.42	3.49
	7	1.17	1.73	2.09	2.35	2.55	2.72	2.87	2.99	3.10	3.19	3.27	3.35	3.42	3.48
	8	1.17	1.72	2.08	2.35	2.55	2.72	2.87	2.98	3.09	3.19	3.27	3.35	3.42	3.48
	9	1.16	1.72	2.08	2.34	2.55	2.72	2.86	2.98	3.09	3.18	3.27	3.35	3.42	3.48
	10	1.16	1.72	2.08	2.34	2.55	2.72	2.86	2.98	3.09	3.18	3.27	3.34	3.42	3.48
	11	1.16	1.71	2.08	2.34	2.55	2.72	2.86	2.98	3.09	3.18	3.27	3.34	3.41	3.48
	12	1.15	1.71	2.07	2.34	2.55	2.72	2.85	2.98	3.09	3.18	3.27	3.34	3.41	3.48
	13	1.15	1.71	2.07	2.34	2.55	2.71	2.85	2.98	3.09	3.18	3.27	3.34	3.41	3.48
	14	1.15	1.71	2.07	2.34	2.54	2.71	2.85	2.98	3.08	3.18	3.27	3.34	3.41	3.48
	15	1.15	1.71	2.07	2.34	2.54	2.71	2.85	2.98	3.08	3.18	3.26	3.34	3.41	3.48
	15	1.128	1.693	2.059	2.326	2.534	2.704	2.847	2.970	3.078	3.173	3.258	3.336	3.407	3.472

5. Summary

This paper has shown that QS 9000 moves more towards a total quality management standards than ISO 9001 and requirements for continuous improvement covering quality, delivery and price, zero defects on attribute data, business plans, QFD, FMEA, SPC, MSA and many more important aspects make it a much more stringent standard.

QS 9000 will give the motor industry a much better set of requirements to work and to secure not only product quality but continuity of supply and competitive prices. There are moves to apply QS 9000 to other automotive companies.

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