Research Trends in Quality Engineering and Management

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Abstract: This expository cum review paper outlines the levels of knowledge currently held in the areas of quality engineering and management, and identifies the trend of exploratory improvements which have caught the imagination of academics and industries alike in this area. The paper also explores the frontiers of quality and its state of the art applications in both production and service sectors and identifies future potential research areas.

Keywords: Quality engineering, quality control, total quality management

1. Introduction:

The concepts of quality, its definitions, diversified applications, control and management have been matching pace with the stupendous creation of knowledge in engineering and technology. This evolutionary legacy that we intend to present aims to motivate further research leading to better practices and products. With the aforementioned intent, this expository cum review paper outlines the levels of knowledge currently held, identifies the trend of exploratory improvements which have caught the imagination of academics and industries alike, identifies the frontiers of quality and its state of the art applications in both production and service sectors, and identifies future potential areas of scholarship for catapulting inquisitive minds into active research.

The rest of the paper is organized as follows. Some important definitions of quality and how this is maturing with time are presented in Section 2. The different approaches of quality are discussed in Section 3. The developments in the three important branches of quality, viz., quality control, quality design, and quality management are presented in Section 4, 5, and 6 respectively. The future directions for quality research and applications are explored in Section 7 and conclusions are presented in section 8.

2. Quality: Maturing Definitions Through the Decades

The concepts of quality are as old as the human civilization. It had been a constant endeavor of any society or culture to design and develop finest pieces of quality in all walks of life. Quality is a performance measure of a product, service, human being or anything. Even though, it is expressed in different ways; it means the same thing, viz., performance. Its definitions also have been revised and evolved through several decades. This section briefly presents these definitions and perceptions.

“Conformance to specifications” was one of the earliest definitions of quality by Crosby [1] followed by “fitness for use” by Juran [2]. Deming [3,4] used the terms quality of conformance and performance. Feigenbaum [5] suggested a much broader definition for total quality control (TQC) to focus on “total composite product and service characteristics of marketing, engineering, manufacturing, and maintenance through which the product and service in use will meet the expectations of the customers”. Taguchi [6] opined that, quality should have monetary terms also. He introduced quality loss function. As per this the quality can be assessed by the 'loss imparted to the society from the time a
product is shipped". Crosby [7] opined: "Quality means getting everyone to do what they have agreed to do and to do it right the first time in the skeletal structure of an organization, finance is the nourishment, and relationships are the soul". Thereafter, ISO [8] defined it in a much broader sense as "the totality of features and characteristics of a product or service that bears on its ability to meet a stated or implied need". These definitions are mostly focused on the production side.

There are several definitions focusing on customers also. Some of the important definitions are: “Quality consists of the capacity to satisfy wants” by Edwards [9]; “Quality is the degree to which a specific product satisfies the wants of a specific consumer” by Gilmore [10]. Kuehn and Day [11] opined that, in the final analysis of the marketplace, the quality of a product depends on how well it fits patterns of consumer preferences. Oakland [12] said that the core of a total quality approach is to identify and meet the requirements of both internal and external customers. Some service based definitions are: “conformance to requirements” by Crosby [1], and “do it right first time” by Price [13]. Quality was also defined based on value. Some important ones are: “Quality is the degree of excellence at an acceptable price and the control of variability at an acceptable cost” by Broh [14]. “Quality is the degree to which a specific product conforms to a design or specification” by Feigenbaum [5], “Quality is to satisfy customers’ requirements continually”, and “TQM is to achieve quality at low cost by involving everyone’s daily commitment” by Kanji [15]. Newell and Dale [16] opined that quality must be achieved in five basic areas: people, equipment, methods, materials and the environment to ensure customer’s need are met.

The fact that the definition of quality has changed over the years is a reflection of the changing technology, emerging global economy, increasing competition for survival, heightened consumer awareness, surcharged regulatory provisions and the way we conduct trade. Quality could now be considered as an essential attribute to the survival of the fittest and so survivability could influence the future definition of quality. Since the concept of quality is relevant in every human activity, it will find equal contribution from other disciplines as well and not remain confined to engineering and technology. So, a progressive definition of quality could be “the characteristics of a product or service which apart from being conformant to premeditated specifications could also have adequate flexibility to adapt new specifications/requirements, at no extra cost, thus ensuring product/service survivability, maximizing both producer’s and customer’s satisfaction”. In this respect, the Japanese are the forbearers of the policy of achieving “exceptional custom satisfaction” or “exceptional customer delight”. And Kano’s QFD models did emphasize on what extra functional requirement of the customer could be met augmenting customer delight. Also, a thought on how producer’s satisfaction could be defined to benchmark achievement of a pre requisite quality level, would also point to a direction of expanding the current customer satisfaction oriented definition of quality.

At this juncture of changing economic scenario with the advent of knowledge based economy, the definitions and perceptions linked to quality with earlier affiliation to an industrialized economy needs to be revisited. Is it not fair that the definition of quality accommodate the changing requirements lest we should face another major quality related disaster to wake up to a new outlook? Also important is extruding the established concepts beyond their assumptions and limitations. It is not unusual to observe that the industries are largely depending on simple statistical tools instead of the numerous advancements which are resorted to once in a while, mostly by a hired quality consultant. The benefits of research ultimately have to whet the needs of the industry and therefore a drive to simplify
quantum of statistical quality tools for expedient practice assumes utmost importance. In the area of SPC alone more than 4000 research papers have been published, which is a huge volume of work, but its translation into standardized practices with proven profits for manufacturer and service providers seems to be rather quite limited. An excellent review on quality engineering and management is available in [17].

3. Timeline of Quality: March of Quality

Quality has evolved over several decades. In the pre-1900, the focus was on checking the fitness of a product by the operators. In the next three decades, the focus was on quality inspection using gauges on all items produced. Major paradigm shift occurred during the next four decades. Statistical tools were used for process control and sampling techniques were extensively used for application in scenario of mass production. In the next phase of about two decades the quality research was focusing on development of off-line quality concepts such as design for quality. Thereafter, the focus has been on development of strategic quality management and quality certification [18, 19].

The sojourn of quality in the last 100 years has been tabulated to establish the flow of research work and its chronological position. This would showcase the importance in the way we understand quality in terms of the approaches that eminent quality Gurus have enunciated at different points of time. Some of the important milestones in the quality journey are summarized in Table 1.

4. Quality Control: The Inescapable Tool

Statistical process control (SPC) is one of the most important developments of the 20th century. Due to its sound theoretical foundation, it can be applied for wide range of industrial and business settings. It is easy to apply and can dramatically reduce process variability. The initiative of quality control remains largely unchanged from the days of Shewhart in the sense of applying statistical tools. Therefore, the movement that started with the introduction of simple control charts employing simple statistical tools now finds itself with a huge volume of knowledge in statistical tools. Certainly, researchers have been employing evolving statistical concepts to make smarter and more effective control charts for better quality and process control. A review of the important concepts is presented in [20]. Various SPC techniques are discussed in the review paper [21]. The last decade has witnessed a lot of research into SPC in the following broad areas:

a. Evolving Different Types of Statistics or Indices for Control Charts: The effort to find better suited indices or statistics as always been at the forefront of research and concepts of fuzzy sets, auto correlated variates, multivariate influenced processes [22]. Bayesian theories, Bootstrap methodologies, have inspired research.

b. Improving the Univariate Control Chart with Robust Design: The robustness to detect parameter shifts in normal control charts can be improved through various design schemes be it univariate or multivariate charts [23].
### Table 1: The Quality Journey

<table>
<thead>
<tr>
<th>Year</th>
<th>Tools</th>
<th>Events</th>
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<tbody>
<tr>
<td>1901</td>
<td>Standardization</td>
<td>Sir John Wolfe-Barry – the man who designed London’s Tower Bridge – instigated the Council of the Institution of Civil Engineers to form a committee to consider standardizing iron and steel sections [24].</td>
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<tr>
<td>1911</td>
<td>Scientific Management</td>
<td>Frederick W. Taylor published ‘The Principles of Scientific Management’ [25].</td>
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<tr>
<td>1924</td>
<td>Control Charts</td>
<td>Walter A. Shewhart, a statistician at Bell Laboratories developed the control charts, and principles of statistical process control. [26].</td>
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<tr>
<td>1925</td>
<td>ANOVA</td>
<td>Sir Ronald Fisher published the book, Statistical Methods for Research Workers, and introduced the concept of ANOVA [27].</td>
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<tr>
<td>1937</td>
<td>Pareto Principle</td>
<td>Joseph Juran introduced the Pareto principle as a means of narrowing on the vital few [28].</td>
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<tr>
<td>1940</td>
<td>Acceptance Sampling</td>
<td>The acceptance sampling plan was developed by Harold F. Dodge and Harry G Roming [29].</td>
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<tr>
<td>1943</td>
<td>Fish Bone Diagram</td>
<td>Kaoru Ishikawa developed the cause and effect diagram (also known as fishbone diagram) [30].</td>
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<tr>
<td>1946</td>
<td>ISO, ASQC</td>
<td>The International Organization for Standardization was founded in Geneva. ASQC was formed in Switzerland [31].</td>
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<tr>
<td>1947</td>
<td>Deming visiting Japan</td>
<td>Edwards Deming visited Japan to help Japanese rejuvenate their industries [32].</td>
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<tr>
<td>1950</td>
<td>TRIZ</td>
<td>Genrich Altshuller developed the theory of inventive problem solving (TRIZ) [33].</td>
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<td>1960</td>
<td>Kaizen Quality Circle</td>
<td>The concept of Kaizen developed The first “quality control circles” were formed in Japan and simple statistical methods were used for quality improvement [32].</td>
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<tr>
<td>1961</td>
<td>Poka Yoke</td>
<td>The concept of Poka-Yoke developed by Shingeo Shingo [32].</td>
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<tr>
<td>1966</td>
<td>QFD</td>
<td>Yoji Akao, introduced QFD Methodology [32].</td>
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<tr>
<td>1969</td>
<td>Quality Tools</td>
<td>Ishikawa emphasized the use Seven Quality Tools</td>
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<tr>
<td></td>
<td>Total Quality</td>
<td>Feigenbaum uses the concept of total quality [31].</td>
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<tr>
<td>1969</td>
<td>SMED, JIT</td>
<td>Shingo Shigeo, as part of JIT, pioneered the concept of Single Minute Exchange of Dies [34].</td>
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<tr>
<td>1970s</td>
<td>QLF</td>
<td>Taguchi promoted the concept of Quality Loss Function [6].</td>
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<tr>
<td>1979</td>
<td>BS 5750</td>
<td>BS 5750 was issued. This was later replaced with ISO 9001:1987. Philip Crosby published his book “Quality is Free” [1]</td>
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<td>1980</td>
<td>Kano Model TQM</td>
<td>Professor Noriaki Kano developed the Kano model which classifies customer preferences into five categories: Attractive, One-dimensional, Must-Be, Indifferent, Reverse TQM [35].</td>
</tr>
<tr>
<td>1982</td>
<td>Deming’s 14 points</td>
<td>In <em>Out of the Crisis</em>, originally published in 1982, Deming offers a theory of management based on his 14 Points for Management [3].</td>
</tr>
<tr>
<td>1986</td>
<td>Six Sigma</td>
<td>Six Sigma formulated by Bill Smith in Motorola [36].</td>
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<tr>
<td>1987</td>
<td>ISO Standards I</td>
<td>ISO issued the first version of the ISO 9000 series [8].</td>
</tr>
<tr>
<td>1994</td>
<td>ISO Standards II Q 9000</td>
<td>ISO issued the second version of the ISO 9000 series [8].</td>
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<tr>
<td>1995</td>
<td>Six Sigma at GE</td>
<td>General Electric (GE) launched the Six Sigma initiative [37].</td>
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<tr>
<td>1999</td>
<td>ISO/TS 16949 1st Edition was released</td>
<td>ISO/TS 16949 specifies the quality system requirements for the design/development, production, and (where relevant) installation and servicing of automotive-related products [38].</td>
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### c. Making the Control Charts more Adaptive and Flexible:

The utility of control chart would be greatly enhanced if some degree of optimal adaptability in terms of varying components could be available, also the space to introduce inbuilt measures
into the control chart to resist false alarms would make them flexible enough to be variedly applied. Additionally, schemes of simultaneous monitoring of parameters built into a control chart would bring about a similar adaptability in the functioning of the control chart [39].

d. **Improving Control Charts using Neural Networks:** The use of Neural Networks is an upfront idea and the tools which would be needed for application in SQC/SPC are an area of active research [40].

e. **Expanding the Scope of Univariate to Multivariate Control Charts:** The need to extend monitoring or control on multiple variable can best be achieved through multivariate control charts. Newer multivariate charts with better quantitative monitoring characteristics or indices are being researched in this area [41].

f. **Univariate Process Capability Indices (PCI) to Multivariate PCI:** The need to extend monitoring or control on multiple variable can best be achieved through multivariate control charts. Newer multivariate charts with better quantitative monitoring characteristics or indices are being researched in this area [42].

g. **Rethinking on Assumption of Normality for Assignable Causes of Variation:** The research which orients itself to questioning the very assumptions of control charts needs more impetus. It is in this direction that a new approaches to develop control chart in non-normality situations needs to be explored. The assumption of normality is not a universal phenomenon and so there is a lot of deviation in reality of observed events and data from this utopian notion of normality [43, 44].

h. **Improving Performances of Existing Control Charts, Economic Design of Control Charts for Optimization of Quality Cost Functions:** The cost of quality control is often felt prohibitive by many manufacturers until a discernable advantage in terms of profit is established. Therefore, the economic design takes centre stage to attract manufacturing or service firms to quality control using control chart [45].

i. **Integrating Different Control Charts into a Single Chart:** The concept of permutation and combination to achieve better results applies to control charts as well. It’s therefore no surprise that researchers have tried to evolve more knowledge into this area integrating available control charts [46].

j. **Process-Product Specific Control Charts:** The research on control chart is definitely as diverse as the diverse processes that exist in the world today. The number of process - product specific control charts are proliferating and research is also thriving due to the industrial sponsorship that is available to researchers [47, 48, 49].

k. **Sensitivity Analysis of Control Charts Employed in Production:** The research into the area of sensitivity analysis of control charts seems to have been limited. The knowledge creation in this area has essentially been overlooked owing to a feeling within the research community that the best test of effectiveness of any control chart is in visible variability reduction and the benefits accrued there in. However, there is a gap area which needs further exploration [50].

l. **Non-Parametric Methodologies to Evolve Control Charts:** The underlying assumption of distribution whether normality or of non-normality has been the traditional approach which can be transcended with more non parametric approaches provided they yield comparable or better results than the distribution based
approaches. With simplicity in processing such chart can hold a better potential for application in industries [51].

m. Improving Acceptance Sampling Plans for Variables [52].

n. Improving Acceptance Sampling Plans for the Use of Control Charts or any other Statistical Methodology [53].

5. Quality Assurance and Engineering: The Smart Choice

In the evolution of quality program, the shift from detection and control was eventually followed by more proactive approach of assuring quality through product and process engineering. It is in this spirit that Controllerate of Quality Assurance finds itself present in every major public sector unit (PSU). This shift into design process is best described by the concepts of DOE, Taguchi methods, and QFD. In the last decade, thriving research into this area has ensured identification of optimal design of processes or products. Montgomery (2008) has provided a good overview of the resources and potential for DOE /DOX (Design of Experiments) in which he mentions that about 58% of these papers were concerned with finding the important factors influencing the system, what we refer to as screening or characterization; 33% dealt with optimization and response surface methodology, and 9% involved robust parameter design. The latest areas of research are indicated as under:

a. Construction and Validation of Mathematical Models for Process Engineering:
The modern industrial economy could not have existed without the engineering process at its very centre. Therefore quality engineering derives its momentum from process engineering. The challenge in the present world is how to bring the processes in the field of exact mathematical understanding through their modeling with an aim to reduce variability, so that the very need to control variability is obviated. Towards this, research in terms of identifying parameters to a very high level of precision and developing process specific methodologies for modeling is the need of the hour. Readers may refer [54, 55 and 56] for more details.

b. Optimization using Design of Experiments and Taguchi Methods:
Every designed process would have to ultimately take the road of optimization as the strength of the process sustainability would largely depend on optimization of its process parameters in conjunction with economic parameters. It is also pertinent to note that optimization is a highly process/product specific activity and hardly would a universal method is evolved which is a global optimization solution. The tools of DOE, QFD, and Robust Design can well be employed for optimization. There is also a growing interest in non-parametric form or simple numerical methods of optimization. Some good references are [57, 58, 59, 60, 61, 62, and 63].

c. Simulation Combined with Design of Experiment Techniques:
The DOE/DOX approach is a confirmatory tool in the hands of researchers to design experiments and fathom sufficient evidence to support the results of the simulation, in the situation of lack of adequate mathematical modeling or where the process knowledge is still outside the realm of exact understanding. With the advent of a number of Simulation and Engineering software, integration of these software tools with DOE is surely the beginning of more advanced ways in quality engineering [64, 65].

d. Taguchi Robust and Related Design Methodologies:
The design approach to meet objectives with quality, reliability could at best be thought of as methodologies with a huge scope for improvement. Perhaps more inherently robust designs are yet to be
researched and used for meeting not only objectives of quality in functionality but also in reliability.[66, 67, 68] and others have contributed in these areas. The new directions for research is not to further refine models that cover known situations but it is challenging to come up with architectures for future systems that can also handle situations currently unknown [69]. It is in this spirit that research needs to be carried out.

e. Analysis of Designed Experiments: The data and the results emanating out of the designed experiment need to be appropriately analyzed with suitable statistical methods. The importance of the analysis is foremost to base deductions or inferences that would stand the test of meeting the objectives for which the experiment was designed. Besides, an analysis must measure up to the level of providing strong evidence in support of the quality being targeted. With the former in view, research on methodologies of data analysis could vary as per the need. The Bootstrap Analysis method [70], and the Factorial Design and Multivariate Analysis [71] are used for studying Continuous Process.

f. Product Life Cycle Development and Quality Modelling: The product development cycle is a rich area of quality initiatives and a number of researchers have targeted various phases of product development and have proposed various quality models. There is a large scope for simulation and modelling applications to this area in both hardware and software [72, 73 and 74] of all kinds of products.

6. Quality Management: An Edifice of Knowledge Economy

The quality revolution that had gained momentum due to the strong patronage of leading multinationals in the late 1970s with the concepts of TQM has matured over the years with further novel concepts of the ISO series and Six Sigma through the preceding three decades[75, 76]. Now, quality management is indeed the buzzword, the mantra for sustained profitability and growth. With some knowledge bank of quality management in place, efforts are on by researchers to either refine existing methods or bring fresh perspectives in the new environment of the knowledge based economy. Therefore, an attempt to identify gap areas of research in quality management is absolutely essential. The direction of research in Quality Management can be broadly identified as under:

a. Research Areas Related to TQM and its Further Refinement and Application:
The majority of research into TQM post 2006 has been focused on expanding application to nontraditional areas like service sector: education [77, 78], environment protection, health care [79], telecommunications [80], Software industry [81], hospitality industry [82], and e–Governance [83]. Also, there has been more research into the qualitative and quantitative methodologies of quantizing benefits accrued from the practices of TQM: from the viewpoint of TQM manager’s performance, customer related performances [84], and innovative performances [85]. The practices of TQM have laid the foundation for ERP systems [86] and their effectiveness in comparison to ISO standards have also been debated [87]. There also has been research into combining TQM with other tools like TPM [88]. Besides, the effect of TQM practices on Organizational behavior and Employee Job Satisfaction [89] have also been researched lately. Further prospective areas of research could be application of TQM practices in governance, Quantitative measures of TQM assessment, applications in
retail sector, Productive Farming and Animal Husbandry. The review paper [90] deserves special mention to understand its dimension.

b. **Scope of Research in ISO Quality Management Systems**: More companies are engaged in the process of attaining ISO certification due to globalization. The current research in QMS-ISO series too has expanded their purview to include their use in reducing accident rate in Motor Carrier Industry [91], improving quality in Food Industry like Winery Industry [92], understanding impact of ISO 9000 on manufacturing [93], quality assurance in supply chain [94], application of Environment Management System [95], use of AHP to identify critical factors in ISO application [96], actuarial benefits accrued from the perspective of technology coherence [97], comparing other models of environment management system with that of ISO [98], introducing international standard under ISO for social responsibility [99], combining TQM and ISO approaches for greater benefits [100], understanding financial impact on standard stringency [101], and the benefits of ISO certification on construction firms [102].

c. **The Frontiers of Research in Six Sigma**: “While Six Sigma is increasingly implemented in industry, little academic research has been done on Six Sigma and its influence on quality management theory and application [103]” - this observation is thought provoking for a researcher in this area. Post 2006, in the implementation of Six Sigma processes, the importance of goals on improvement teams [104] was researched into. Research in terms of empirical studies on project successes [105] optimal portfolio identification and selection of firms for implementing Six Sigma [106], the effectiveness of DMAIC process from the perspective of problem solving [107], improving healthcare services as in operation theatres [108], and the effects of Six Sigma practices on firms' performance and innovation [109] have also been done. Also, context and elements of a project that best contributes to success in a Six Sigma project have also researched [110]. The focus lately has also been on researching on similar lines into Lean Six Sigma practices which includes its application to computer manufacturing management [111], health care sector [112], besides researchers are looking into whether six sigma processes are suppressing creativity [113]. It is thus felt that further researches in these areas have huge potential.

d. **New Concepts and Methodologies for Quality Management**: The ubiquitous management concepts of TQM and Six Sigma have given rise to a lot of allied concepts and triggered parallel thought processes for sustaining quality management in firms throughout the world. The concepts of ERP and JIT are examples of offshoots of the quality revolution. It would be of sure interest to academicians, researchers as well as entrepreneurs worldwide to keep abreast of the latest thought process in this area. Amongst the leading concepts are DFSS (Design for Six Sigma), LEO (Learn-Enrich-Optimize) [114], augmenting resource productivity [115], BPR and zero defect concepts.

7. **The Way Forward**

The foregoing discussions have brought out several aspects of quality concepts, its evolution over a century, theoretical developments, industrial applications, the lessons learnt, recent developments, and its applicability in other aspects of industrial, academic and social spears. Following are important topics for future research work. HR-related practices for the successful implementation of TQM and TPM, application of Lean Six Sigma for small and medium sized enterprises, investigating whether ISO/TS16949...
efforts mediate the relationship between TQM and organizational performance, rough set approaches for estimating correlation measures in quality function deployment, impact of the project and organizational specific risks on project payoffs prevalent in the Six Sigma projects, the causes and consequences of quality failures in terms of time and cost overrun, incorporate quality concepts into project scheduling problems and automated monitoring systems, model for supply chain design considering the cost of quality, compare the fuzzy group AHP approach with the fuzzy group Cognitive Network Process (CNP) in the areas of Software Quality Assurance management, and utilization of information technology in engineering quality control system are future topics for research.

Use of the FEM and simulation in combination with a DOE analysis, artificial neural network (ANN) and adaptive network based fuzzy inference system (ANFIS) may be used for DOE analysis, DOE for structural quality, robust design using goal programming, desirability function, and compromise programming, investigating the selection of partial replication on non-regular designs, such as symmetric or asymmetric orthogonal arrays of two-level and three-level factorials, using the Taguchi techniques to reduce product development cycle time, combining Taguchi methods, neural networks, simulated annealing, particle swarm and GAs for parameter optimization, development of control charts for detecting two-sided mean shifts of a variable or shifts in both mean and variance, optimizing the integrated model by EWMA control chart such as pattern search, GA, simulated annealing, and threshold acceptance algorithm, and fuzzy logic based assignable cause diagnosis using control chart patterns have research potential as well.

8. Conclusions

Quality concepts are now well matured and have tremendous scope for improving not only businesses but also human lives in a more sustainable way. It is a never ending process and has wide ranging applications and research potential for developing better products, processes and services. It is hoped that the ideas presented here motivates researchers.

As for the nonce, there is an urgent need to improve processes through design and engineering to eliminate internal failures. The zero defect concepts must be attained internally, not in the market alone. Also, the traditional long term perspective and investment strategy to benefit from quality is debatable and more importantly the quality policy for products with shorter life cycles merits further investigation. Designing proper quality parameters for the service sectors such as retail, transportation, outsourcing, hospitality, healthcare, education, maintenance, insurance, government departments, agriculture and food processing are the need of the hour.

References


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