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Evolution of Quality Through Industrial Revolutions

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Industry 4.0, also known as the Fourth Industrial Revolution, is fueled by a remarkable suite of emerging technologies. These encompass everything from artificial intelligence and interconnected smart devices to groundbreaking advancements in nanotechnology. Such innovations are spawning unprecedented capabilities, fostering dynamic shifts in interpersonal communications, societal relationships, business operations, and service delivery. They are also stimulating product usage diversity and heightening production flexibility.

The momentum and breadth of this revolutionary transformation are intrinsically tied to the maturation rates of these underlying technologies, which are evolving at a swift pace. Historical precedents show us that each industrial revolution has deeply influenced management sciences and practices, including those in quality management. There is no reason to assume that the Fourth Industrial Revolution will be any different—it is poised to reshape our world in ways we are only beginning to comprehend.

Established quality management systems, such as total quality management (TQM), originated in the early period of the previous century. These systems were designed in response to the needs of the Second Industrial Revolution, which was characterized by mass production. Their primary goal was to mitigate defects and nonconformities within manufacturing processes. It is undeniable that these quality systems and methodologies have proven robust over time, consistently enhancing quality. They have undergone regular upgrades to stay relevant, and they continue to be fundamental components of our contemporary operational landscape.

However, it has had no innovative changes for nearly 60 years, and many methods and tools are outdated, so they are less and less used in the field. Figure 1.1 illustrates Google search trends for quality management and Six Sigma, and they are clearly trending downward since 2004. Obviously, pursuing good quality is human nature, and it will never go out of style. It is the current quality management theories and practices that become stagnant [1–3]. It is time for a breakthrough in quality management.

Quality is an ancient, complex, and eternal concept. Throughout history, as science and technology develop, at some point, industrial revolution will happen, as a result, new production systems may emerge, and the quality paradigm usually evolves with it to keep pace with these changes. Since the central theme of this book is "Quality in the Era of Industry 4.0," it is beneficial to see how quality has been evolving through all previous industrial revolutions. It will help us to predict what is next for quality in Industry 4.0. This is the key topic of this chapter.

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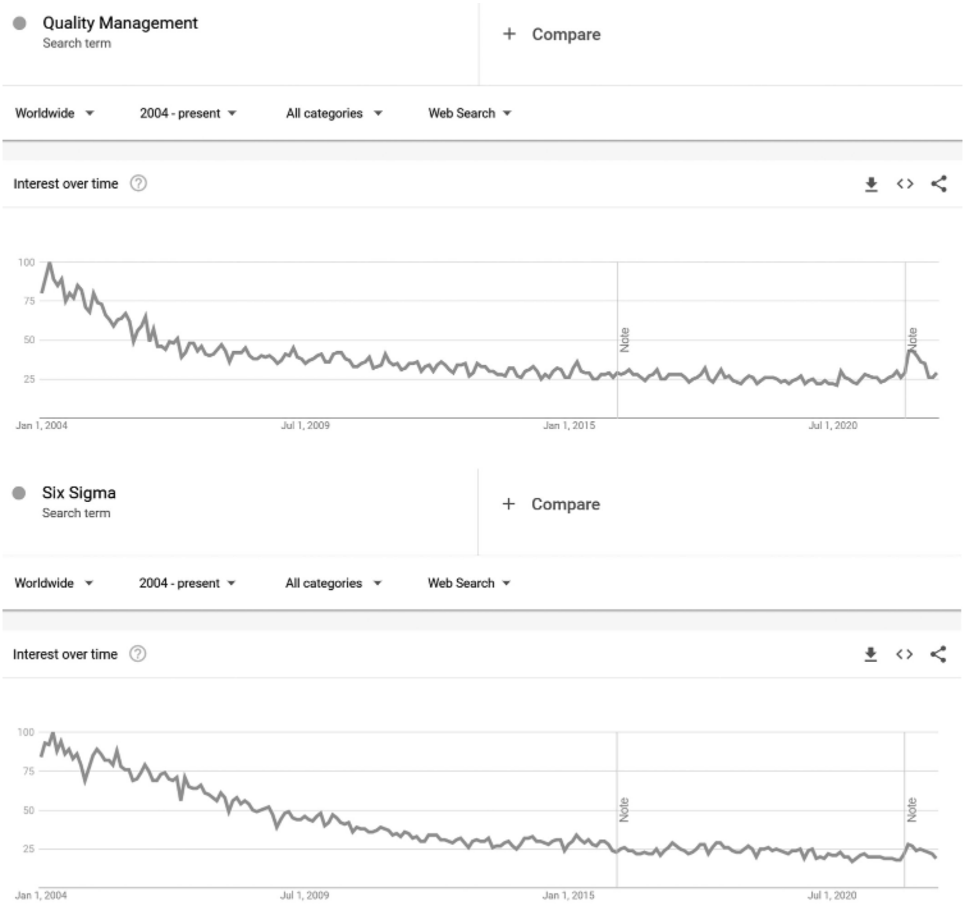


Figure 1.1 Google Search Trends for Quality Management and Six Sigma

1.1 Quality Before Industrial Revolutions

Throughout the course of history, quality has consistently manifested as an elegant, profound, yet elusive concept. The term "quality" has its roots in ancient Rome, derived from "qualis," signifying a "degree of excellence" in things or human values [4]. This concept echoes the philosophical musings of Greek thinkers such as Plato and Socrates on the subject of epistemology. Further exploration by philosophers, including John Locke, introduced the duality of quality: the objective aspect, which is inherent in the items themselves, and the subjective aspect, reflecting individual perceptions of these items [4].

With the burgeoning consumer markets that began in the 1600s, products started reaching a mass audience. This meant a diverse array of consumer expectations and needs, compounded by a wide spectrum of economic capabilities. Consequently, the interpretation of quality began to transition from an "absolute excellence" toward the concepts of "value for money" and "cost-effectiveness."

In the business realm, "value" has emerged as a critical measure of quality. In this context, value is defined as the ratio of a product's benefits to its cost. Prior to the era of industrialization, goods were predominantly crafted through craftsman production systems. In such setups, a craftsman or a team would oversee the entire design and production process, from inception to completion.

Craftsmen typically possessed high levels of skill, dedication, and self-discipline. They approached their work with an artisan's mindset, finely attuned to the client's subjective evaluation of quality or their esthetic sensibilities. These highly esteemed craftsmen were, in essence, the arbiters of quality for their products. As highlighted by Juran [5], they meticulously monitored every detail of design and production.

During this era, quality assurance relied heavily on the integrity of the craftsmen who valued their reputation highly. Consumers, too, played a role by carefully inspecting the products. In many parts of Europe, guilds implemented self-inspection and certification protocols, significantly enhancing the branding and quality assurance of artisans and their workshops. An official standard verification model was also prevalent, with government-led verification and oversight mechanisms being particularly advanced in China since the Qin and Han dynasties [5].

Throughout this period, the craftsman held primary responsibility for the product. This role was sometimes played by an individual entrepreneur, at other times by a team, albeit typically a small one. The craftsman managed all aspects of the product's design, production, and delivery. When required, craftsmen liaised closely with clients to ensure a high standard of work. Given their comprehensive oversight of the entire process, they could ensure full production control, preclude coordination issues, and maintain a tight rein on product defects.

This approach remained in vogue until the onset of the Second Industrial Revolution.

1.2 Quality in the First Industrial Revolution

The First Industrial Revolution unfolded in Great Britain between the 18th and 19th centuries. The driving forces behind this revolutionary period included the use of fossil fuels for power generation and the advent of steam engines for trains and ships. These developments were bolstered by significant breakthroughs in the iron, steel, and chemical industries and the rise of machine-driven textile industry.

The First Industrial Revolution incited transformative changes across economies, societies, and lifestyles. While it did not fundamentally alter the craftsman model, it did raise the complexity of many products well beyond that of traditional handicraft items. Consequently, the teams of craftsmen expanded, giving rise to a workshop-based supplier system—commonly known as the "cottage industry." This new system provided parts, materials, and subsystems for complex products. To coordinate this growing supplier system, the inception of early versions of industrial standards was necessary [6].

The craftsman model is characterized by its practitioners being "jacks-of-all-trades"—highly skilled individuals who manage all aspects of production. However, a notable drawback of this model is the extensive training period required for craftsmen.

In the craftsman production model, the manufacturing of complex products lacks streamlining. Lengthy process transitions and preparation times lead to lower productivity, extended production duration, and consequently, higher costs. It is also important to note that the First Industrial Revolution did not significantly impact quality control methods.

1.3 The Second Industrial Revolution and the Birth of Modern Quality Management

The Second Industrial Revolution predominantly originated in the United States, spanning from the late 19th century to the early 20th century. This revolution was marked by the extensive adoption of electrical energy and the implementation of a mass production system. This system was grounded in moving assembly lines and the use of standard, interchangeable parts.

The influence of the Second Industrial Revolution on production methods and working practices was incredibly profound. It has shaped modern quality management significantly and has even influenced the definition of quality itself, a testament to its enduring impact that persists to this day.

1.3.1 Mass Production System Is a Game Changer

Since the First Industrial Revolution, scientific and technological advancements have accelerated rapidly, significantly boosting the production capacity of industrial materials. This led to the emergence of various complex new products, such as automobiles. Crafting such products via traditional craftsmen and workshops was prohibitively time-consuming and expensive, making them accessible only to a select few.

The breakthroughs in electrification infrastructure presented opportunities to expedite the production process and reduce costs. Among those seizing this opportunity was Frederick Taylor, who proposed the "Scientific Management Method," also known as *Taylorism*. This method proposed several core principles [7]:

- Break down large, complex tasks, such as automobile assembly, into numerous smaller steps—potentially in the thousands.
- Divide labor among workers, assigning each to a specific process step, with each worker performing the same task repetitively.
- Utilize stopwatches and motion analysis to determine the most efficient work practices and use these as a standard for training workers.
- Abandon the craftsman production system completely by segregating management, design, and production sectors, and by instituting an extensive division of labor and professions, marking a clear distinction between "blue collars" and "white collars."

Another pivotal figure in the Second Industrial Revolution was Henry Ford, founder of the Ford Motor Company and the originator of the moving assembly line operation and the mass production system [8]. His core contributions include:

- Full utilization of standardized, interchangeable parts across the entire industry—preceding Ford, the American firearms industry had already implemented the practice of standardized parts in the late 19th century.
- The first electrically powered moving assembly line: the assembly line comprised numerous workstations, each executing a single operation performed by one worker.
- Simplified, standardized, and interchangeable worker skills.

At its inception, the moving assembly line exhibited the following characteristics:

- The product (automobile) had a single design.
- The assembly line was a rigid yet precise process, capable of producing only one specified product through a sequence of pre-determined process steps.
- The work of product design was also highly specialized and separated from production.

Compared to the craftsman production model, this mass production model drastically reduced, if not entirely eliminated, setup and change-over times between consecutive process steps. Consequently, it markedly improved productivity and production capacity, substantially reduced the cost and sales price of products, and significantly broadened the consumer base. However, the product variety in the mass production system became quite limited, with monotonous styles and typically unimpressive esthetics.

(a)

(b)

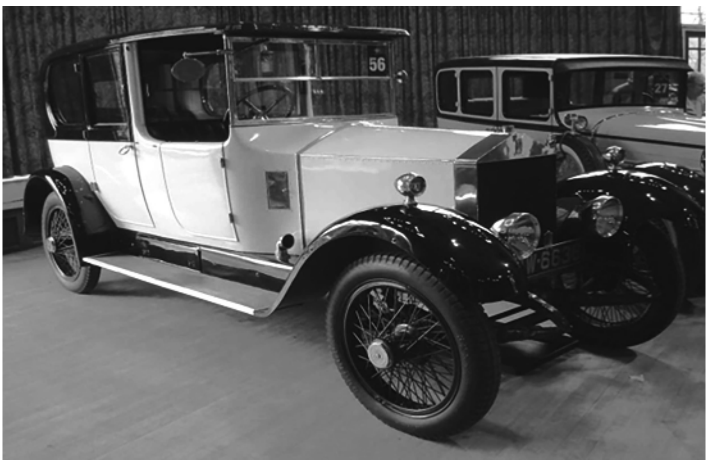


Figure 1.2 Comparison Between Cars Produced from Craftsman and Mass Production Systems. (a) Mass Production: Ford Model T, 1922 Price: U$319, 1.3 million produced per year. *Source:* Shawshots / Alamy Stock Photo. (b) Craftsmen Production: Rolls-Royce Twenty £1600, 2940 cars produced from 1922 to 1929. *Source:* Barker / Wikimedia Commons / CC BY-SA 2.5

Figure 1.2 contrasts two types of cars—one produced by a mass production system and the other by a craftsman production system. The vast differences in cost, productivity, and style between these two cars are clearly discernible.

The mass production model, or the Taylor model, had a disruptive and profound impact on the economic activities, business models, lifestyles, and corporate organizations of that era, effects that largely persist today, particularly in Western countries.

Some key effects of the mass production system include the following features:

- **The decline of the craftsman/artisan class**: Craftsmen, highly skilled and versatile individuals, once constituted the backbone of key economic activities in ancient and pre-modern times. With the proliferation of the mass production model, this class has become nearly extinct, now appearing predominantly in the luxury goods and handicraft industries.

- **Realignment of Society**: A highly specific division of labor and professions has become a common practice, extending beyond manufacturing to government, service, medical, and scientific research sectors.
- The widespread adoption of well-designed processes and standardization in all disciplines.

The mass production system also exerted a paradigm-shifting, disruptive influence on quality control. In ancient times, quality represented "the degree of excellence," and with the maturity of the mass consumer market, the concept of quality evolved to encompass "benefits versus cost" and "customer value." Compared to handcrafted luxury products, when the mass production system substantially reduced product prices, consumers, driven by cost considerations, were willing to forgo all luxurious features and decorations in favor of basic functions. For instance, the Ford Model T, available only in black color, was inexpensive, functional, and reasonably reliable, making it the most popular car model of its time.

However, the early Taylorism mass production system was highly fragmented. Workers operated separately at different stations along the assembly line without communicating with each other, contrasting starkly with the craftsman model, where one craftsman would complete the entire order from start to finish.

1.3.2 The Start of Modern Quality System

Amid the surge in complexity attributed to the large number of components and steps involved in the mass production system, the susceptibility of products to errors and defects intensified. Consequently, the critical aspect of quality assurance shifted toward managing defects by guaranteeing conformance from every supplier and each stage of the production process. This need served as a catalyst for the evolution of modern quality management systems pioneered by distinguished figures such as Shewhart, Deming, and Juran [9].

Several fundamental quality systems and methodologies, such as statistical quality control (statistical process control [SPC]) [10] and total quality management (TQM) [11], took root during the pinnacle of the Second Industrial Revolution. Notably, following the widespread adoption of Taylorism's mass production model, the working definition of quality underwent a transformation. It evolved from notions of "excellence" and "customer value," to the more tangible metrics of "defect free," "low scrap rate," and "low failure rate." This interpretation of quality has persisted to this day, with scrap and failure rates remaining the sole quantifiable quality indicators being assessed.

In conclusion, the emergence of modern quality management and quality engineering can be attributed to the pressing issue of handling, controlling, and eradicating defects and failures within mass production systems.

The transition in defining quality, from a "degree of excellence" to "free from defects and adherence to standards," is a drastic shift. To make sense of this "definition of quality," it is essential to explore the numerous studies that have debated this issue. This brief summary provides an overview. In their article, Reeves and Bednar [12] argue that perceptions of quality vary based on individual perspectives. For instance, from a consumer's perspective, quality may signify "excellence," "customer value," or "surpassing expectations." In contrast, producers perceive quality as "conformance to specifications" and low rates of scrap, failure, and defects. In the initial phases of the mass production model, a seller's market prevailed due to product scarcity, which likely influenced this differentiation.

Garvin's 1987 article [13] outlines eight dimensions of quality: performance, features, reliability, conformity, durability, service, esthetics, and perceived quality. This comprehensive overview contemplates multiple perspectives, encompassing both "objective quality" and "subjective quality." However, from then until the present, the quality community has prioritized aspects such as reliability, conformity, and durability.

Since the advent of the mass production system, the initial method of quality control involved inspecting products prior to shipping, repairing or discarding defective products, and retaining the quality ones. Large repair shops were commonplace in early automobile factories. Sampling inspection [14], involving random or full inspection to prevent defective supplier parts from reaching factories, was another common practice. If a batch failed this inspection, it would be returned to the supplier. Inspection was also used to weed out inferior products within factories before shipping them to customers.

However, this inspection approach had clear disadvantages. First, the inspection was labor intensive and time consuming, with the manual inspection proving less than foolproof. Should an issue be detected during inspection, the root cause could potentially lie anywhere within the thousands of process steps, due to worker errors, defective incoming parts, or machine failure. Identifying and eliminating these problems via end-of-production inspection proved challenging, hence their recurring nature. The production process, as shaped by the Taylor system, was fragmented and compartmentalized, complicating the swift identification and resolution of quality issues. For instance, in early 20th-century automobile plants, the repair workshop, managed by the quality department, aimed to eliminate defects. This objective clearly conflicted with the assembly plant management's goal of swiftly dispatching manufactured cars.

Since quality issues typically arise during the production process, and inspection is the last step, some argued that "quality control should move upstream." Consequently, it was deemed necessary to control quality at critical upstream process steps. In 1931, American statistician Walter Shewhart's book "Economic Control of Manufactured Product" formally defined quality control as a statistical issue and introduced the concept of the statistical process control (SPC) [15]. This method of managing key processes marked a significant shift, with numerous subsequent quality methods and indicators (such as process capability indices) deriving from it and remaining in use today.

Before World War II, the usage of control charts was not widespread among manufacturers; they were primarily utilized in Bell Labs factories. However, Edward Deming and Joseph Juran [9], who were involved with these early initiatives, later emerged as key pioneers of modern quality management.

It is noteworthy to observe the gradual evolution of the mass production system between 1920 and 1950. In the 1910s, the Ford production system epitomized the first version of the mass production system. The assembly line was virtually inflexible, producing solely the Ford Model T. Initially, due to its low price and reasonable reliability, Model T dominated the market. However, post-1920s, General Motors (GM) employed several strategic measures to outmaneuver Ford:

1) They deviated from a single product line setup, introducing several brands catering to different price points to meet varying consumer needs. Each brand operated akin to a small company, all under the GM umbrella.
2) They initiated the practice of introducing new models annually. While there may not have been significant changes each year, the presence of new features was ensured. This marked the beginning of the mass production system's gradual transition toward a flexible production system [16].

1.4 The Third Industrial Revolution and the Maturity of Modern Quality Management System

In the 1950s, Toyota's lean production system emerged, enabling greater flexibility in production and an increased variety of products without sacrificing efficiency [17]. The advent of the Third Industrial Revolution in the 1960s, powered by computer and information technology, introduced further flexibility and control over the production process [18]. It also significantly improved product design capabilities. These advancements underscored the emphasis on another critical aspect of quality: a robust focus on customer satisfaction. This series of events precipitated the comprehensive evolution of quality management systems and quality engineering.

1.4.1 Contributions of Japan to Quality Management

The initial wave of modern quality management unfolded in post-World War II Japan. Although Japan had industrialized prior to the war, its reputation for consumer goods' quality was unimpressive. The label "Made in Japan" was equated with cheap and low-quality products during this period. The Korean War transformed Japan into a critical strategic hub for the US military, necessitating the rectification of their problematic, defect-ridden, and subpar telephone communications within a stipulated timeframe. As a measure to "urge Japan to improve quality," American quality experts Edward Deming and Joseph Juran were invited to deliver open classes on quality management to Japanese corporate executives. The US military mandated the attendance of top Japanese company executives at these sessions [19].

Intriguingly, Deming and Juran had previously conducted similar lectures in the United States, but their insights garnered far less attention from American executives. However, their presentations in Japan led to significant impacts and spurred a series of follow-up activities:

- As per historical documents, the Japanese executives attending these sessions expressed significant interest in the Plan-Do-Study-Act (PDCA) or Plan-Do-Check-Act (PDSA) work process. This process entailed "identifying and defining a critical problem and persisting with it until it was resolved" [20].
- At that time, Japan was grappling with severe economic hardships in the post-war period. The nation needed to export consumer goods to alleviate these economic difficulties and sought to enhance the quality of its products to alter the reputation of Japanese goods. Consequently, many companies demonstrated considerable interest in this approach.

Following the absorption of American methodologies, several Japanese experts began propagating these principles via broadcast lectures tailored to the needs of Japanese business individuals. This marked the beginning of many Japanese experts and business professionals enhancing these quality methodologies originating from America and developing their own unique approaches.

1.4.1.1 Total Quality Control

Local expert Ishikawa Kaoru, a professor at the University of Tokyo, played a significant role. He translated and expanded on Deming and Juran's teachings. In 1950, in collaboration with front-line industry workers, he developed the cause-and-effect diagram (also known as the fishbone diagram). Post-1960, he posited that not only middle and upper-level enterprise managers should learn quality management, but first-line supervisors and on-site workers should as well. This belief led him to pioneer the "total quality control (TQC)" activity model and training method, which subsequently became the first practical version of the TQM system, underpinned by Ishikawa's 11 points [21].

1.4.1.2 Taguchi Method

Another local expert, Genichi Taguchi, joined Nippon Telegraph and Telephone Company (NTT) in 1950 with the aim of enhancing the quality and reliability of Japan's telecommunications industry. He later developed the Taguchi method to improve durability, stability, and reliability during product design—a method which was adopted seriously by Toyota and promoted worldwide post-1980 [22].

1.4.1.3 Quality Function Deployment

Quality function deployment (QFD) is a unique design planning methodology originating from Japan, which is focused on incorporating the customer's product expectations into the design process. The inventor of QFD, Yoji Akao, saw his concept first applied in Japan in 1966. QFD gained initial popularity in Japan before being adopted globally [23].

1.4.1.4 Kano Model

Professor Noriaki Kano from the Tokyo University of Science and Technology introduced the renowned Kano Customer Satisfaction Model (Kano Model) in the 1970s and 1980s. This model categorizes customer needs into three types (or five, according to some studies): must-have, one-dimensional, and attractive quality. Different categories of customer needs are addressed in various ways. Kano also developed a method to identify these three types of customer needs through customer surveys [24].

1.4.1.5 Affinity Diagram

Japanese anthropologist Jiro Kawakita proposed the affinity diagram methodology in the 1960s [25]. This method helps analyze data from large volumes of scattered, rambling words collected from customer surveys or brainstorming sessions. The technique can discern patterns and underlying structures within these words. It is now widely used to analyze and synthesize customer needs, serving as a fundamental technique for brainstorming and one of the seven tools of TQM.

1.4.1.6 Kansei Engineering

Originating in Japan, Kansei Engineering is a product design methodology that stems from the observation that consumers possess conscious or subconscious preferences or dislikes for specific product features based on their personal feelings. These feelings can be evoked by a comprehensive psychological state induced by the customers' five senses—sight, hearing, taste, smell, and touch. As such, designers must comprehend the correlation between these consumer perceptions and the features of the design, aiming to enhance the design's positive impression. Kansei Engineering has evolved several robust methods to capture, quantify, and analyze sensations. For instance, it uses techniques such as analyzing the gaze, attention, facial expressions, and smiles captured in video recordings of visitors during a product exhibition. The outcomes of this human perceptual analysis are translated into product design elements, and products are manufactured to align with people's preferences. Pioneering the introduction of perceptual analysis into the realm of engineering research were researchers from the Faculty of Engineering at Hiroshima University, Japan. Starting in 1970, with a focus on residential design that takes into account occupants' emotions and desires, they investigated how to embody occupants' sensibilities into engineering techniques used in residential design. Renowned expert Nagamachi Mitsuo has contributed significantly to this field, authoring works such as "Kansei Engineering of Automobiles" and "Kansei Engineering and New Product Development" [26].

1.4.1.7 Poka-Yoke

Shiego Shingo, a technical pioneer of the Toyota production system, devised key processes and techniques for quick die change and rapid process changeover to achieve zero inventory and flexible production [27]. As the Toyota production system underscores "one piece flow," conditions such as "zero defects" and "zero failures" are indispensable. This led Shingo to extensively investigate quality control, arriving at several critical observations:

1) Shingo recognized the human tendency to make mistakes, acknowledging that perfection is unattainable. However, he believed that an effective system to automatically correct errors could prevent human mistakes from turning into significant defects or flawed products.
2) He categorized the prevalent post-production inspection to separate good from bad products, often done manually, as "judgmental inspection." Shingo pointed out several drawbacks to this method, such as the inevitability of human error and its general inability to identify the root cause of a quality issue.
3) Shingo found that SPC, which originated in America and was popular in Japan, had limitations. Statistical process control relies on sampling data from production for quality-related judgment, requiring production to halt and root cause identification when the SPC charts indicate an "out of control" situation. Shingo argued that due to its reliance on sampling inspection and time lag in problem identification, SPC might miss defects and prove ineffective for retrospective investigation of root causes.
4) He advocated for three inspection methods to effectively guarantee zero defects: (i) step-by-step inspection, wherein the downstream process checks the upstream's semi-finished products, investigating any problem's source immediately; (ii) self-inspection, which involves checking the semi-finished product before it leaves the process, and tracing the source of any issue promptly; (iii) source inspection, which finds and blocks the source of a problem to prevent its occurrence.

After an exhaustive study of existing quality inspection and control methods from the United States, Shigeo Shingo proposed his Poka-Yoke (fool-proof) quality assurance method. He outlined the following guiding principles:

- To achieve zero defects, 100% inspection is necessary.
- Judgmental testing, if needed, should be objective, and not manual.
- Inspection must be low cost and automated.
- On detecting faults and defects, the root cause should be identified immediately.
- All hidden root causes should be identified and eliminated one by one.
- Upon finding the source of the problem, it needs to be blocked at the source to prevent its occurrence using an automatic detection device, termed a Poka-Yoke device.

Shingo emphasized the characteristics of the Poka-Yoke device, which should be inexpensive, capable of 100% inspection, produce real-time results, and be implemented either through technical means or process design.

Interestingly, Shingo also shared his thoughts on statistical methods and SPC. Initially, he viewed SPC and statistics as the ultimate solution to quality issues. However, he later saw SPC as a means of estimating and maintaining the current process, not necessarily improving it. He regretted that his early reverence for statistics and SPC might have delayed the perfection of his Poka-Yoke system. Despite Shingo's somewhat controversial views, both non-statistical and statistical methods have their places in quality management, varying case by case and over time.

In practical terms, Shingo Shigeo has undeniably triumphed. The modern digital Poka-Yoke system, governed by automatic sensors, facilitates automatic real-time 100% inspection and online real-time control, becoming the mainstay of online quality control [28].

1.4.2 Total Quality Management (TQM)

Starting from the 1970s, the remarkable success of Japan in multiple domains posed significant competitive pressure and challenges to industries in Europe and America. This led to introspection across various sectors in the United States. In 1980, a conversation was sparked by an NBC TV show titled "If Japan can, why can't we?" which led to heated discussions about "Japan's success and the United States' response."

Edward Deming and Joseph Juran, who were acknowledged for introducing modern quality management to Japan, were then solicited by many large Western corporations, such as Ford and General Motors, to guide their operations. In the process, Deming and Juran learned about many Japanese practices like the total quality team, which they had greatly influenced during their involvement in Japan's quality initiatives. From the 1970s onward, they published numerous works on quality management. Some examples are Deming's "Out of Crisis," "The New Economics for Industry, Government, Education" [29], and Juran's "Quality Planning and Analysis," "Upper Management and Quality" [30].

They asserted that in a mass production system, the assurance of quality can only be achieved through comprehensive control and continuous improvement in all key process elements throughout the entire product lifecycle. Since all actions are performed by people, everyone needs to receive proper quality training and be empowered to take responsibility. They saw quality as a meticulously planned and executed systematic endeavor by the whole organization, a concept they referred to as TQM.

This concept of TQM received varying degrees of response and support from the governments and industries of Europe and America:

- Beginning in 1984, the United States, initially with the military and with the Department of Defense, and then with the US federal government, embraced the concept of TQM.
- From 1987 onward, the United States has annually evaluated and bestowed the Malcolm Baldrige National Quality Award [31] upon select outstanding companies and entities.
- Since the 1990s, many European countries have standardized TQM, leading to the creation of ISO 9000 certification, which is now issued to companies worldwide.

1.4.3 The Third Industrial Revolution and Its Impact on Quality Management

The Third Industrial Revolution [18] marked a transition from mechanical and analog electronic technology to digital electronics. This shift, which began in the latter half of the 20th century, was characterized by the adoption and proliferation of digital computers and related information technology. These advancements had profound impacts on the manufacturing industry as sensors, computers, and information technology were continuously integrated into the production process. Consequently, important parameters in industrial processes, such as workpiece dimensional measurements, temperatures in chemical reactors, and real-time pressure measurements in containers, could be collected in real time.

The technological developments of the Third Industrial Revolution had several significant impacts on quality management and quality engineering, particularly within the manufacturing industry:

1) **Widespread Application of Automatic Sensors, Detectors, and Digital Poka-Yoke Devices/Systems in the Production Process**: Starting from the 1980s, numerous manufacturing companies invested billions of dollars in installing these devices and systems in their factories. Their implementation significantly reduced production failures and assembly quality issues, leading to a marked improvement in production quality.
2) **Computer-Aided Design (CAD) and Computer-Aided Analysis (CAE)**: A multitude of quality issues are attributed to poor design, affecting not only performance, esthetics, and features but also resulting in malfunctions, hidden safety concerns, and low reliability. Addressing these problems typically requires a significant investment of manpower, materials, and time. However, from the 1980s onward, the extensive use of CAD and CAE for simulation testing, product modeling, and virtual reality exercises on computer platforms allowed engineering teams to detect and rectify design issues quickly and inexpensively. Consequently, CAD and CAE significantly improved both the quality and speed of design.
3) Advances in computer capabilities facilitated the widespread application of numerous rigorous scientific methods. These included scientific modeling, statistical analysis, ultrafast computing, and the handling of vast digital data storage. These advances simplified the use of powerful quality tools such as SPC, design of experiments (DOE), and statistical modeling and analysis. Some advanced industrial companies were even capable of integrating sophisticated statistical methods with engineering disciplines such as mechanics and materials science, along with other specific sciences, to implement in-depth and accurate process modeling. This process facilitated the monitoring, control, and optimization of manufacturing processes. These advancements in computer capabilities also served as a key enabling factor for the Lean Six Sigma initiatives in the quality community.

1.4.4 Lean Six Sigma

1.4.4.1 Overview of Lean Six Sigma

Six Sigma [32], which was first pioneered by Motorola, is a business operating system initially aimed at eliminating manufacturing defects. The term "Six Sigma" originates from the statistical field of process control, signifying the capacity of manufacturing processes to generate a substantial proportion of output within specification. In short-term operations, processes running with "six sigma quality" are projected to yield long-term defect rates below 3.4 defects per million opportunities (DPMO).

The concept and movement of Six Sigma were initiated as early as 1986 at Motorola and later spread to various manufacturing companies in the 1990s. In 1995, General Electric (GE) officially launched the Six Sigma movement. Due to the immediate benefits it brought about such as quality improvement, cost reduction, and profit enhancement, Six Sigma rapidly expanded across the entire Western manufacturing industry. The primary components of Six Sigma include:

1) The concept of continuous improvement through reducing scrap rate, costs, and waste.
2) **Establishing an Organization and Team**: The company's top management and administrative team must shoulder the responsibility of leadership and implementation, while also selecting and recruiting technical teams. An improvement project team, the administrative team, and the technical team collaboratively select projects for the project team.
3) Each project must establish specific goals and timelines, such as "reducing the paint shop scrap rate by 50% within three months." Each project must also undergo the Six Sigma (DMAIC)

process (a digitized PDCA). Upon completion, the project's cost and return are reviewed by the finance department.

4) Both the administrative and technical teams should receive bespoke training. The executive team learns the concepts of TQM and Lean, while the technical team should grasp more comprehensive quality methods and lean techniques.

It is noteworthy to mention that Six Sigma's initial goal in the early 1990s was to minimize the "cost of poor quality" with an extremely low scrap rate, signifying 3.4 defects per million (3.4 ppm). From the 1990s to the 2000s, several influential books on the Toyota production system and lean manufacturing were published in the West, including "The Machine that Changed the World," "Lean Thinking," and "Toyota Way" [33–35]. The Toyota system gained popularity due to its clear concept, limited mathematical components, wide applicability, and immediate impact on efficiency improvement and waste reduction. Given that Lean and Six Sigma address different problems—efficiency and quality, respectively—they complement each other. Incorporating Lean into an already established Six Sigma team enhances its effectiveness. Thus, Lean Six Sigma has become a standard business improvement operating system. After manufacturing, Lean Six Sigma quickly spread to other industries, including services, medical, financial, and government sectors.

In summary, Six Sigma has evolved into an unprecedentedly large-scale, high-intensity, and far-reaching mass quality movement, which continues to progress.

1.4.4.2 Limitations of Lean Six Sigma

In 2004, the number of Google searches for "Six Sigma" peaked, and has been gradually decreasing year on year since then. Similarly, the number of individuals mentioning Six Sigma in their LinkedIn job search biographies has declined each year thereafter. The stock value of GE, a cornerstone of Six Sigma, hit US$600 billion in the mid-2000s, making it the world's largest at that time. It now stands at less than US$60 billion. Since 2010, GE no longer designates Six Sigma as its "company-wide guiding philosophy." While Lean Six Sigma remains popular and is still utilized by many companies, its peak popularity has waned. Are there any limitations or flaws in Six Sigma? [36] We identify the following points:

- Six Sigma processes and methodologies originate from traditional manufacturing industries (mechanical, electrical, etc.) and are effective within these contexts. However, they may not be fully applicable to certain industries, such as the emerging software industry and the internet sector, where these working methods may be seen as too rigid.
- Six Sigma heavily depends on statistical analysis and its existing quality methods. While these methods can address some issues, they are not infinitely applicable. Take GE as an example. After implementing Six Sigma for five years, the model's effectiveness reached its zenith within GE. Its utility started to decline thereafter.
- Many companies rigidly adhere to Six Sigma, enforcing uniform processes and providing identical training across the board (a potential issue that might also plague ISO 9000). Many businesses report that this rigid adherence to Six Sigma stifles creativity. For instance, Mikel Harry, one of the founders of Six Sigma, proposed the "three iterations of Six Sigma": "The first is to reduce waste (which we have done), the second is to reduce costs (which GE has accomplished), the third iteration should be a system of *Value Creation* that benefits everyone." However, Mikel Harry admitted that the existing Six Sigma model could not achieve this goal. Mikel Harry passed away in 2017.
- All in all, as an increasing number of companies succeed in reducing their scrap rates to minimal levels, low scrap rates no longer serve as a competitive edge. Now, other quality aspects such as cost-effectiveness and innovation have gained greater importance.

1.5 Current Challenges and Difficulties for Quality Management

1.5.1 Industry 4.0 Is Coming

The Fourth Industrial Revolution, also known as Industry 4.0, [37, 38] is currently transforming the world. This technology-driven industrial revolution relies heavily on the maturity and rapid advancement of various digital technologies, as depicted in Figure 1.3. The breadth of Industry 4.0, in terms of both its core technologies and its areas of application, is vast. These technologies span from the Internet of Things (IoT) to highly interconnected smart machines and devices, powered by tools such as 5G wireless technology, artificial intelligence, scalable analytics (Big Data), and augmented reality.

The integration of these technologies into sophisticated cyber-physical systems signifies the present state of Industry 4.0 applications. We are still progressing toward a mature, steady state of implementation that offers a return on investment for businesses and society at large. The applications of Industry 4.0 are not confined to manufacturing. They reach into every sphere of human activity, encompassing energy, agriculture, healthcare, government, and services, and extending to all facets of social interaction.

Among all the techniques associated with Industry 4.0, such as cloud computing, big data, and additive manufacturing, the IoT plays a crucial role. The two key components of IoT technology are IoT devices and IoT platforms. The IoT devices are everyday objects and physical devices equipped with internet connectivity through the embedding of nonstandard computing devices. Examples of IoT devices include smart TVs, wearable technology, and smart appliances. Unlike

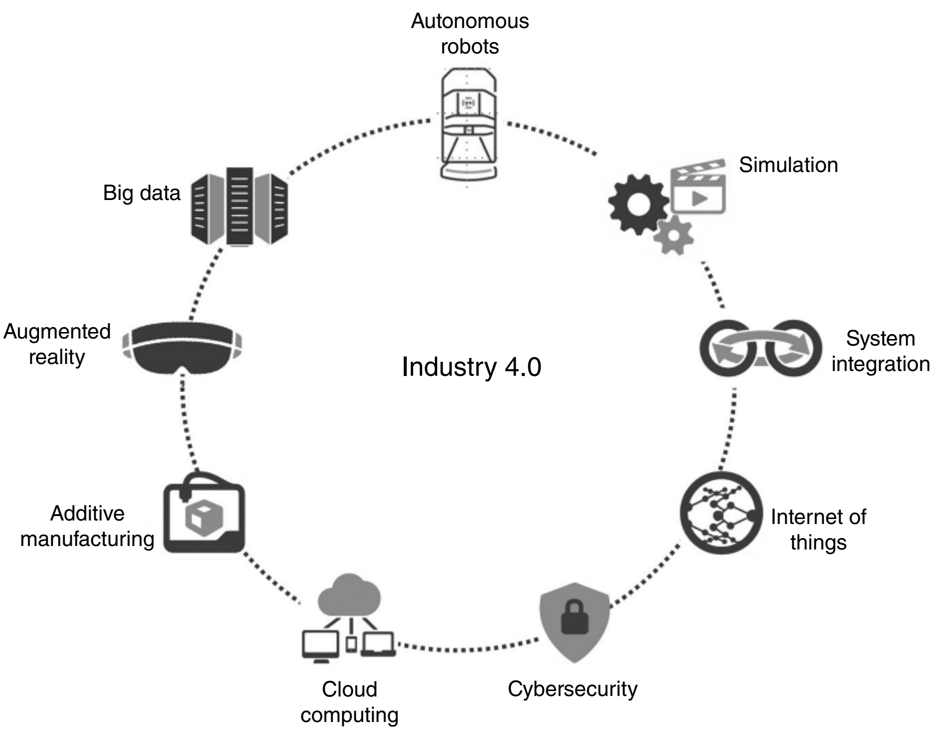


Figure 1.3 Key Industry 4.0 Technologies

traditional devices, the IoT devices can transmit data, communicate, and interact over the internet, and can be remotely monitored and controlled by IoT platforms.

With the advancement of Industry 4.0 technologies, an increasing number of products, as well as their production equipment, infrastructure, and tools, are becoming IoT embedded, evolving into smart products, smart factories, and smart suppliers. Moreover, all stakeholders of products, such as customers, producers, and suppliers, are equipped with internet-enabled computers, smartphones, tablets, and the like. In summary, our business world is progressively transforming into numerous internet-embedded dynamic ecosystems that thrive, adapt, and interact within various market environments, which is vastly different than in the past.

1.5.2 Customers in Industry 4.0 Age and Their Expectations

In today's world, customers have access to an abundance of information about any product they are interested in, including its functionality, price, and reputation, thanks to online resources. They engage in various social networks and interact with each other. What's more, customers' desires and needs continually evolve along with social and technological trends, as well as personal preferences. Figure 1.4 illustrates the evolution of customers and manufacturers over the past 150 years [39].

Before the advent of the Second Industrial Revolution, the craftsman production model was predominant. This model was based on individual customer orders and production, characterized by high costs and low efficiency. The Second Industrial Revolution, which began in the early 20th century, heralded the golden age of mass production from 1913 to 1955. During this period, product variety was low, and volume was high. Henry Ford famously said, "Any customer can have a car painted any color that he wants so long as it is black."

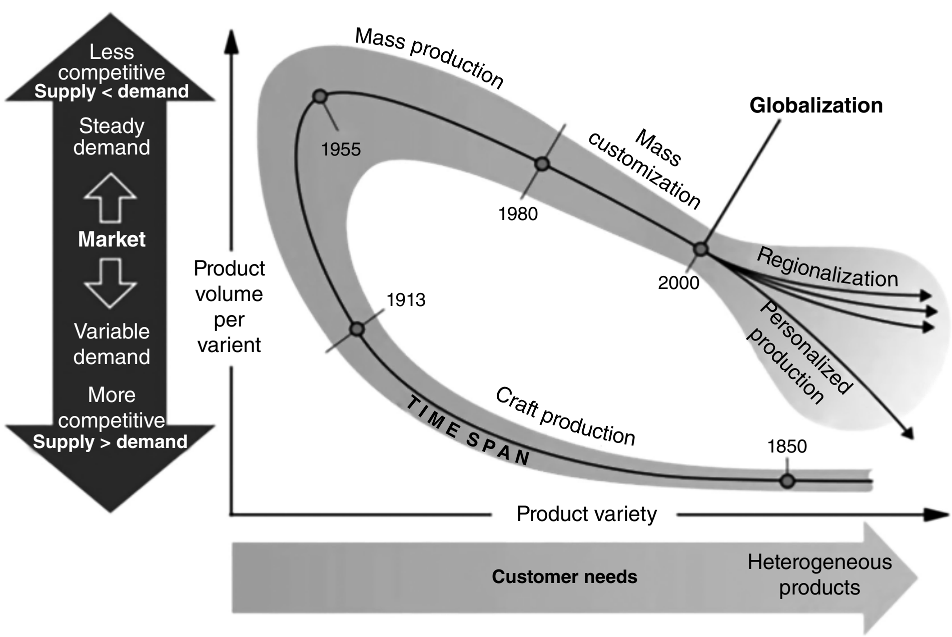


Figure 1.4 Evolutions of Customers and Manufacturers

With the gradual advent of the Third Industrial Revolution, characterized by digital control, sensors, and information technology, the production of small batches with greater variety became economically feasible. Currently, as we progressively embrace the Fourth Industrial Revolution, the trend is moving toward an even greater variety of products, more customization and individualization, but with higher efficiency and lower cost. This corresponds to the last segment of Figure 1.4.

1.5.3 Challenges for Modern Quality Management Brought by Industry 4.0

Historically, every industrial revolution has brought about significant changes in quality management practices, and Industry 4.0 is expected to be no exception. As we discussed in previous sections, the current quality management and quality engineering systems were developed to meet the demands of the Second Industrial Revolution, which focused on managing, controlling, and eliminating defects in mass production systems. However, two industrial revolutions (Industry 3.0 and 4.0) have since unfolded, bringing with them considerable changes and posing significant challenges to the quality community. Some of these challenges are discussed in the following subsections.

1.5.3.1 The Limitations of Traditional Quality Management Practices

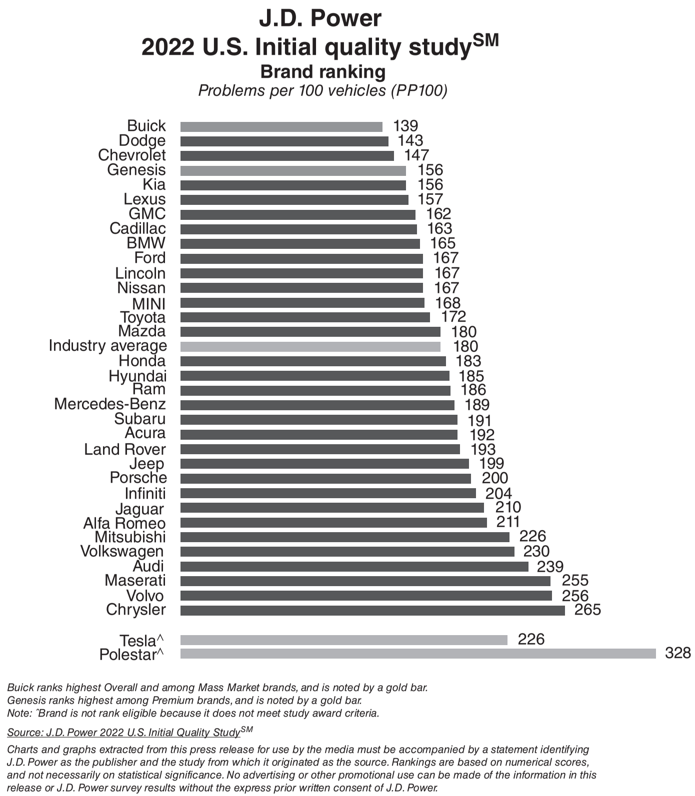
The "traditional" quality management focuses on "defects reduction." As previously discussed, traditional quality management was initiated to address the need for controlling defects, also referred to as conformance quality. However, high conformance quality has now become commonplace and widely accessible, due to technological advancements as we discussed earlier. Here the automotive industry can provide a useful example.

Figure 1.5 shows J.D. Power's initial quality rating and market capitalization data for the automotive industry in 2022.

J.D. Power, an American consumer research, data, and analytics firm established in 1968, has become a gold standard for the automotive industry. Conducting nearly 200 benchmarking studies annually, J.D. Power derives insights from consumer behavior and market data across various industries. Since the 1980s, their quality ratings have been featured in over 350,000 television commercials and two billion print advertisements.

Recently, an apparent paradox has arisen. Data from February through March 2020 showed Tesla ranking last in J.D. Power's initial quality survey among 32 major brands. The J.D. Power initial quality rating is based on the number of problems experienced per 100 vehicles (PP100) during the first 90 days of ownership, with a lower score indicating higher quality. Essentially, this is a measure of conformance quality. At the same time, however, the company topped the list in J.D. Power's APEAL study, which measures the emotional attachment and excitement of customers toward a new car [39, 40]. This paradox was addressed in an October 2020 editorial in Automotive News by Professors Siegel and Yang [41]. They posited that the J.D. Power initial quality survey measures traditional manufacturing conformance quality and is thus blind to the actual subjective customer experience (emotional appeal).

This leads us to a critical conclusion: the traditional relationship between manufacturing conformance and consumer-based measures of quality is starting to break down. These divergent rankings, coupled with Tesla's market capitalization surpassing all other automakers, are indicative of the limitations of traditional quality management—the minimization of defects—in enhancing perceived business competitiveness.



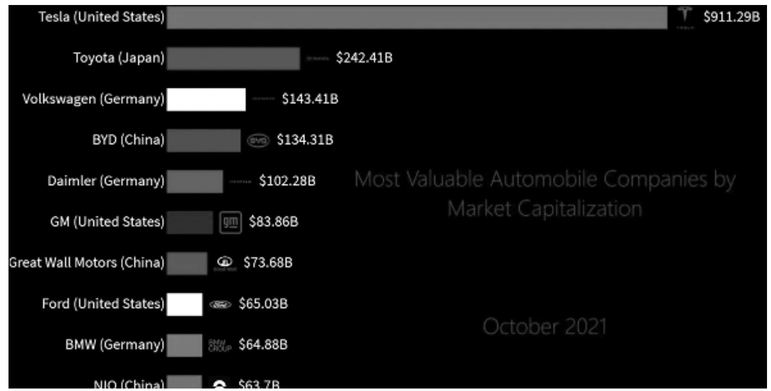


Figure 1.5 Initial Quality Rating and Market Capitalization of J.D. Power for Automotive Industry

1.5.3.2 Changing Realities in a Connected World

In our increasingly connected world, fundamental aspects such as customers, products, and business environments have significantly transformed. Customers today are well-informed and interconnected, possessing personalized, rapidly evolving needs influenced by iterative experiences. This is particularly true for Generation Z, the cohort born between 1995 and 2010, who are digital natives deeply influenced by the internet, instant messaging, and social media. A McKinsey report in 2019 revealed that 77% of Gen Z consumers prefer products and services tailored to their personal needs. A Target Group Index (TGI) (Figure 1.6) study further disclosed that superior user experience is the most crucial factor in Gen Z's purchasing decisions.

The advent of the Third Industrial Revolution introduced products with embedded electronic and IT components, replacing the one-time, buy-and-sell transactions of the past. The ongoing Fourth Industrial Revolution has further integrated IoT technologies into products, which includes two critical elements—IoT devices and IoT platforms. The IoT devices—like smart TVs, wearables, and smart appliances—are physical objects with internet connectivity through embedded non-standard computing devices. These devices can transmit data, communicate and interact over the internet, and can be remotely monitored and controlled by IoT platforms.

With the proliferation of such technologies, an increasing number of products are evolving into smart products, with functionalities largely defined or delivered by software (as illustrated in Figures 1.7 and 1.8).

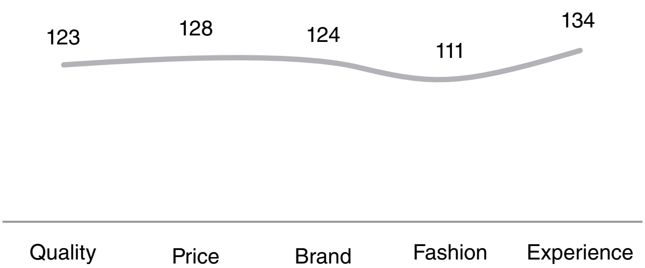


Figure 1.6 Target Group Index for Gen Z Consumers

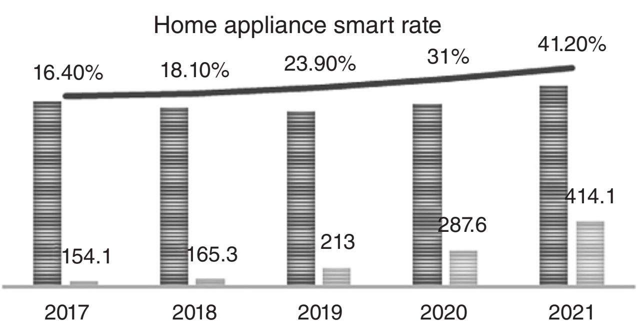


Figure 1.7 Increasing Shares of Smart Products in Appliance Market

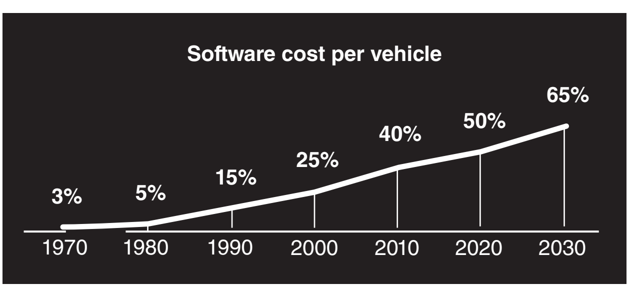


Figure 1.8 Increasing Software Contents for Automotives

These smart products have drastically reshaped the relationships between producers and consumers:

- The relationship is no longer a single transaction; producers can now access vast amounts of product usage data after the sale. These data can inform after-sales services, consumer behavior analysis, and product evaluations for future improvements. Producers can also provide over-the-air software updates to continually enhance existing products without the need for replacement or recall. Customers can interact wirelessly with producers to provide feedback and request personalized after-sales services. Consequently, the relationship between producers and customers extends throughout the product's lifecycle.
- Beyond the connection between producers and consumers, customers are more connected to other entities like social media, related services, and businesses, while producers are more integrated with other partners. These constant interactions have created an evolving business ecosystem, breaking away from previously siloed professions and business sectors. For example, clothing producers and consumers might interact with lifestyle social groups and sports clubs.

1.5.3.3 Smart Producers, Old Quality Management

As a result of the rapid development of Industry 4.0 technologies, world-class producers are now able to work with increased speed and flexibility. Pervasive sensing and connectivity allow for real-time data generation, capture, aggregation, and sharing from any location. Furthermore, IoT platforms facilitate collaboration among stakeholders—including innovators, engineers, suppliers, and customers—in iterative and concurrent product development. This enables innovative ideas from anywhere in the world to be quickly incorporated into the product. Smart factories are now capable of producing a wider variety of products with nearly zero changeover time. All of these advancements have significantly shortened the product development cycle compared to a decade ago.

However, many current quality management practices, such as certification, accreditation, and regulatory approval, have remained too slow and rigid, thereby becoming bottlenecks in the quest for efficiency.

1.5.3.4 Quality and Innovation

Quality and innovation must increasingly function in tandem in today's rapidly evolving business landscape. Evidence of this is ubiquitous, as observed in the tremendous success of highly innovative companies such as Google, Amazon, and Tesla Motors. In our earlier discussion, we mentioned the perception among many organizations that Six Sigma practices have had a stifling effect on creativity. Furthermore, the current quality management and quality engineering systems do not possess a clear framework for seamless integration with innovation activities. This represents a significant gap in modern quality practices that needs to be addressed.

1.5.3.5 Quality and Risk Management

As technology evolves, so do the inherent risks. A key responsibility of the quality management system is to guarantee the reliability and dependability of products or services. Various effective methodologies, such as Failure Mode and Effects Analysis (FMEA) and fault tree analysis, have been developed and implemented to meet this goal. However, with the advancement of Industry 4.0—the emergence of embedded products and superconnectivity—systems have become exponentially more complex and vulnerable. Consequently, the need for improved risk management strategies has never been more critical.

Table 1.1 Evolution of the Quality Concept in Step with the Different Industrial Revolutions

Timeline	Production System	Quality System	Types of Products
Pre-industrialization Ancient time to late 18th century	**Craft production system** Craftsman or team does all the work	Craftsmen interact with users to know their needs, have a deep commitment to excellence, work like artists, apply workmanship	Custom made, high quality, very expensive
Industry 1.0 From 1784 to late 19th century, the steam engine, and mechanization	**Craft production system** Cottage industry (suppliers), some industrial standards	Similar to craft production, but products become more complex and supplier chains must be managed	Custom made or batch produced
Industry 2.0 From 1870s to 1930s, electric power, and petroleum assembly line	**Mass production system** Standardization, rigid processes, division of labor, and silos	Top priority of quality is defect reduction, emergence of modern quality systems such as statistical process control and total quality management (TQM)	High volume, low cost, little or no variety
Industry 3.0 From 1970s to 2010s, automation, computers, and sensors	**Flexible, lean production system**	Application of TQM, customer centric design, elaborate data analysis, lean Six Sigma	Low cost, more variety some customization
Industry 4.0 From 2010 to present artificial intelligence times, IoT, and big data	**Business ecosystem** Smart, connected, innovative, and knowledge-based production	Quality 4.0. lifecycle data tracking	Smart products

1.6 Summary

In this chapter, we have traced the evolution of quality management from ancient times through the four industrial revolutions, summarizing our findings in Table 1.1. The prevailing theories and practices of Quality Management and Quality Engineering (QM and QE) were initiated after the Second Industrial Revolution, fulfilling the need to control defects and maintain conformance in mass production processes. The Third and Fourth Industrial Revolutions, however, brought about significant changes in lifestyle, business operations, and society as a whole, posing substantial challenges to our existing QM and QE practices. However, these technological revolutions also present tremendous opportunities for the evolution of QM and QE. In subsequent chapters, we will discuss the new generation of QM and QE in the era of Industry 4.0.

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