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Commentary

Journey to Quality 6.0: Evolution of quality management across industrial revolutions

Tereza Smajdorová*

Department of Quality Management, VSB - Technical University of Ostrava, Czech Republic

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***Corresponding author:** Tereza Smajdorová, Ph.D., Department of Quality Management, VSB - Technical University of Ostrava, listopadu 2172/15, 708 00 Ostrava-Poruba, Czech Republic, E-mail: tereza.smajdorova@vsb.cz ; tsmajdorova@seznam.cz

ORCiD: https://orcid.org/0000-0002-3426-697X

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Abstract

This article explores the development of industrial revolutions and their relationship to the evolution of quality management from the first to the fifth revolution. The analysis covers significant changes in manufacturing processes, technologies, and business models that shaped the concept of quality in industry. Special emphasis is placed on the transition from manual labor to automation, the development of industrial standards, and the increasing role of quality in corporate leadership. Furthermore, the article introduces considerations about the potential form of the sixth industrial revolution, highlighting the impacts of artificial intelligence, the Internet of Things, and digitization on the future of industry. A focal point of interest is the visualization of "Quality 6.0," representing the next level of quality management in light of emerging technologies and industrial trends. This article offers a perspective on how quality management could respond to the anticipated sixth industrial revolution and what innovative quality might look like in the digital era.

Introduction

The development of quality management is closely related to the dynamic development of industry. It all started with the advent of mechanization during the first industrial revolution to the digital transformation during Industry 4.0. We are now at the beginning of the fifth industrial revolution, which is mainly connected with the interconnection of people and machines, and also a lot of attention is paid to sustainability and ecology. What awaits us in the future in the sixth industrial revolution? Will it be the connection of all systems in real-time, the development of artificial intelligence, or the development of biological materials?

This article is devoted to the historical development of the industry and the related development of quality management. It examines how the pursuit of quality management has developed hand in hand with technological innovation. How quality management has evolved from 100% control carried out by the manufacturer himself, to the introduction of various tools such as sample inspection, SPC, PDCA, Lean management tools, and more. In addition, he is also considering the future focus of Quality 6.0.

Take a journey through industrial progress with this article that reflects on the past, analyzes the present, and speculates on future possibilities.

Literature review

Industry 4.0 has a huge impact on society and social life. It is connected not only with industrial but also with social transformation. Robots, automated decision-making systems, learning machines, 3D printing, and others dominate the manufacturing process. Machines begin to play the role of a member of the decision-making team and have all the rights to make decisions. For example, 3D printing is progressing

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really fast daily necessities or even artificial human organs are being printed. The concept of smart cities is also rapidly spreading around the world [1].

The transition from agriculture to industrial society, i.e., the first, then the second, and third industrial revolutions was acknowledged and accepted by society. Similarly, also the transition to Industry 4.0 requires extensive analysis so that society will be able to understand and accept the inevitable and irreversible changes associated with it. Several elements of the changes with significant social impacts on the company are listed below [2]:

1. IoT – Technology enabling mutual communication between machines and production environment without people.
2. Autonomy – A state where machines have the right to make decisions by themselves using various sensors and cyber-physical systems.
3. Communication of machines with operators.

As far as production processes and the use of new technologies are concerned, it is not clear whether this is a new revolutionary initiative or a development of an existing concept [3].

There are several definitions of Industry 4.0. Synonymous with smart manufacturing, Industry 4.0 is the realization of a digital industry transformation that brings real-time decision-making, increased productivity, flexibility, and agility to revolutionize the way companies manufacture, improve, and distribute their products [4]. Industry 4.0 is the next step of the industrial revolution, which can potentially continue to transform the production flow and also change the communication between people and machines as the interaction between suppliers, manufacturers, and customers. It consists of nine perspective pillars and includes, for example, autonomous robots, simulation, horizontal and vertical system integration, cyber security, and augmented reality and can be further enhanced by artificial intelligence solutions [5]. The term Industry 4.0 is not just a buzzword, but a powerful tool that is spreading globally and infecting all aspects of human life today [6]. The concept and definition of Industry 4.0 focus on the automation of the industrial world. It ensures the implementation of Information Communication Technology (ICT) or the digital world as the backbone of its current existence [7]. Some people consider the dominant feature to be digitization, while others focus on autonomous production systems [8].

The transformation of production continues to grow exponentially. This transformation is driven by a number of factors, from technological innovation through changes in customer behavior to a turbulent manufacturing environment. Firms are thus under a lot of pressure to introduce new innovations at an ever-faster pace [9].

Industry is a collective term that includes many modern systems and production technologies. These are, for example, cloud systems, data mining, machine-to-machine decision-making, IoT, virtual production, or intelligent robotics [1].

Manufacturing in I4.0 systems means a system where machines offer services and share information in real-time, facilitate system monitoring and diagnostics, and are more environmentally friendly and sustainable by using more environmentally sensitive resources [1].

The First Industrial Revolution began in the second half of the 18th century and lasted until the beginning of the 19th century. During the First Industrial Revolution, machine manufacturing was introduced. The development of electrification and the increasing division of labor led to the Second Industrial Revolution at the end of the 19th century. This was followed by the Third, or Digital Industrial Revolution, which began in the late 1900s, and early 2000s. During this period of time, advanced electronics and IT increasingly contributed to the development of automation of production processes. Then an initiative called Industry 4.0 was introduced, where the ideas of digitization with a certain degree of machine automation were promoted [10].

Lucke points out the great importance of production systems and technologies that face the new challenges of ever-increasing demands for global sustainability [11].

Kowalska sees our future optimistically, stating that all objects will be connected to the Internet and will cooperate with each other anywhere in the world and at any time [12].

During the First Industrial Revolution, productivity and work efficiency improved thanks to the first steam engines. The Second Industrial Revolution then enabled the introduction of mass production thanks to electricity, and the Third Industrial Revolution was characterized by the automation of production through the development of electronics and IT [13].

Industry 4.0 involves rapid and disruptive changes including digital manufacturing, network communication, computer and automation technologies, and much more [14].

This new paradigm includes a set of technological innovations, such as IoT, robotics, Big Data, or Cloud Manufacturing, which enable an increase in efficiency and productivity [15].

Another development of the industry, which can be referred to as Industry 5.0, involves the interaction of intelligence and creativity with the cognitive properties of computer technology [16].

The I5.0 concept, introduced in 2015, enables the personalization of products and greater involvement of human intelligence in the production process. Following on from I4.0 technologies, the integration between humans and robotic technology is being strengthened [17].

The concept of Industry 5.0 was introduced to meet the increasing demands for people's personal needs. It provides highly personalized products and services. It is a revolution in which humans are getting closer to machines [16].

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Nahavandi states that the biggest problem with I4.0 is that it aims to improve process efficiency while completely ignoring the human benefit of process optimization [18].

Maddikunta says that while the main priority of I4.0 is to automate processes, thereby reducing human intervention in the process, in I5.0 we can put human power back into the production process and thus support highly skilled jobs [19].

Another significant change within I5.0, which will affect absolutely the entire world, is a change in material engineering. For example, 3D printers will start using fillings that we could only dream of until today. Houses, cars, rocket engines, weapons, furniture, and statues are already being printed. Food or artificial organs from stem cells will follow soon. The field of nanotechnology will expand. It can be assumed that a number of mineral resources will cease to be mined and they will be replaced by new materials with precisely defined useful properties. Everything around us will be made to measure, without cutting, machining, and mostly without waste [20].

How far could the industry go, what will industry 6.0 or even 7.0 look like? Soon, quantum physics will be used, which could turn the current world upside down. And the so-called biologization of industry will also have a big impact - all systems will be a combination of natural materials and materials from artificial DNA. If we want to know in which direction the industry will develop, we can be inspired by the authors of science fiction films. They have a very big imagination and many of their previously unthinkable visions are commonplace today. Long ago, in the 1985 movie Back to the Future, 15 inventions, such as drones or glasses for virtual reality appeared, of which 10 are readily available today [20].

The basic task of quality management is to ensure the competence of the organization and the ability to provide high-quality products. Although the basic ideas and goals remain the same, the paradigms for developing and implementing methods and tools change over time [21].

According to T.S Kuhn, a paradigm is a collection of basic presumptions and assumptions. Adopting a new paradigm means a revolution in world perception [22].

The idea of meeting customer requirements while maximizing profit and minimizing costs is almost as old as humanity itself. In the beginning, these were matters between the provider and the customer, and compliance was guaranteed by law and "craft honor" based on the personal responsibility of the provider. However, this situation changed dramatically with factories. The development of the division of labor and the increased proportion of machine work resulted in the impossibility of assigning responsibility for quality to a specific person. This situation resulted in a demand for the introduction of control activities, which can be considered as the origin of quality management in the company [23].

The history of the quality management system began in 1910 when F. Taylor laid the foundations of "scientific management", which aimed to increase profit and labor productivity while simultaneously reducing energy consumption. In 1924, W. Shewhart presented the method of statistical quality control. His control charts became the basis of lean manufacturing and the Six Sigma methodology. They also served as the basis for the future PDCA methodology. The American Society for Quality Control (ASQC) was founded as early as 1946, later changing to the well-known American Society for Quality (ASQ). In the fifties of the 20th century, J.M. Juran published a quality management manual, which is considered a basic source of information on quality. Juren's concept of quality is based on the Pareto principle, management theory, and his quality trilogy (planning - management - improvement). At the same time, Toyota introduced the TPS production system, which is the predecessor of lean production. In the 1960s, General System introduced the TQM concept. And the Japanese theoretician Ishikawa puts into practice the concept of quality circles, which strengthen the position of workers in the field of quality. In the early seventies of the 20th century, Toyota develops the concept of JIT as a means of satisfying customer requirements. In 1982, Ishikawa introduced his cause-and-effect diagram, which is used to identify defects. In 1986, Motorola introduced the concept of Six Sigma, which focuses on increasing efficiency and also uses the DMAIC methodology. In 2000, the International Organization for Standardization introduced a comprehensive series of ISO 9000 standards, which serve as the basis for many of today's standards. Currently, companies are moving to cloud-based solutions for enterprise quality management systems, which allow easier access to the necessary data and faster resolution of problems [24].

Research methodology

For the preparation of this article, a qualitative research method was used. This research included a detailed analysis of technical papers, scientific studies, and industry trends. The analysis made it possible to understand the context of the development of the industry and the historical development in the history of mankind, and thus also the current state of the industry. Subsequently, this analysis allowed us to predict the possible development of the industry in the future.

The first step of the analysis was a search of a whole range of databases, such as Scopus or Web of Science. The criteria for this search were the historical development of industrial revolutions, advantages, and disadvantages of Industry 4.0, the influence of the historical development of industry on changes in quality management, Industry 5.0, Quality 4.0, Quality 5.0, future development of industry, and future development of quality management. The time range of sources studied was mainly focused on the period of the last five years; however, some older publications were also included. Professional articles, contributions to the proceedings, and also book publications were included in the research. As the subject of Industry 5.0 and Quality 5.0 is a relatively new research area, information from the websites of reputable organizations such as the American Society of Quality (ASQ) has also been included.

This analysis aimed to find quality information from the field of industry development and quality management, their

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present state, and the possibility of future direction. Both theoretical articles and contributions involving quantitative and qualitative research were sought. Contributions in both English and German were included and also partially in Czech. Those articles that did not address defined areas of research or those that did not contain clear arguments for their conclusions were excluded from the analysis.

Then, an extensive analysis of the collected publications was performed. First, abstracts and introductions were screened to exclude articles that did not address the required research areas. Afterward, the entire articles were read so that their conclusions could be included in this study. And finally, references to other sources mentioned in the articles were also studied, so that other publications could possibly be included in the study as well.

The next step was the analysis of the information obtained from selected publications. Individual publications were read several times in order to sort the articles into several categories and then to compare the obtained data. The articles were analyzed in detail and the information they contained ultimately led to the determination of conclusions.

Discussion

Historical development of the industry

The industrial revolution is a radical change in the way of production. These changes were caused by social, economic, and political conditions. Very often it is related to some kind of wartime crisis that led to a lot of technological innovation. The following is an overview of the historical development of individual industrial revolutions:

1. Industry 1.0 began its journey at the turn of the 18th and 19th centuries in England. It was about the development of mechanization and the biggest technological innovation was the steam engine. This caused a significant increase in production productivity. From England, over time, this innovation spread throughout Europe and also the USA. A concrete example of an innovation within Industry 1.0 was the mechanized version of the spinning wheel. It brought up to eighteen times greater productivity. It was also the development of steamships and locomotives, which enabled the transport of goods over long distances in a short time [25]. An overview of the basic information of Industry 1.0 is shown in Figure 1.

2. Industry 2.0 began in the second half of the 19th century. This revolution is connected with the development of electrification. The development of the telegraph and the telephone also played a big role. This revolution also brought great changes in transport and communication, which resulted in a better connection of the whole world and thus a faster spread of new technologies. The most famous pioneer of the Second Industrial Revolution is H. Ford. He introduced assembly lines in the automotive industry, changing the entire production process. With the help of conveyor belts, the entire production was accelerated and costs fell [26,27]. An overview of the basic information of Industry 2.0 is shown in Figure 2.

3. Industry 3.0 began in the 20th century and is associated with the development of information technology and the beginning of production automation. This revolution brought about the development of computers, the Internet, robotics, and other technologies, leading to greater efficiency and productivity in production. Transistors and integrated circuits allowed the automation of some machines, leading to reduced labor, greater accuracy, and speed of production. The rapid development of the first SW also began. An overview of the basic information of Industry 3.0 is shown in Figure 3.

4. Industry 4.0 is the dominant feature of the beginning of the 21st century and is a significant digitization, automation of production, and the use of new technologies such as the Internet of Things (IoT), artificial intelligence (AI), 3D printing, and others. This revolution allows the industry to be more flexible and respond more quickly to market changes and customer demands. The development of the Internet and communication technologies and new cyber-physical systems allow machines to communicate with each other without physical or geographical barriers. The fourth industrial revolution thus brings with it the possibility of the automatic collection of a large amount of data in real-time [28]. An overview of the basic information of Industry 4.0 is shown in Figure 4.

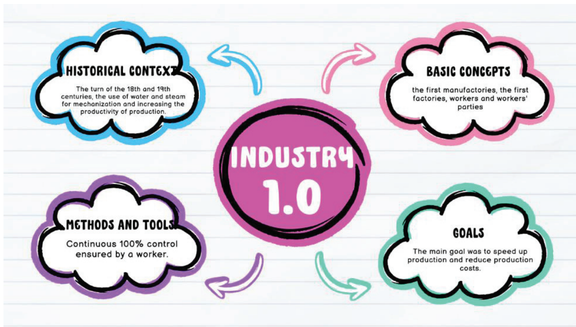

Figure 1: An overview of the basic information of Industry 1.0.

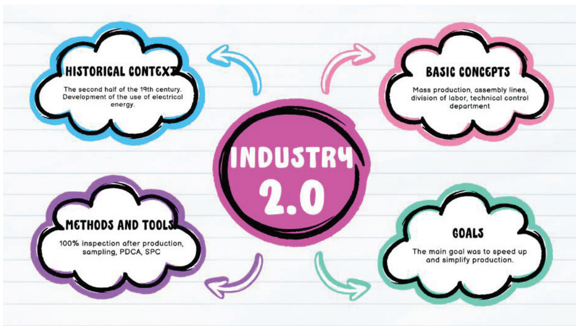

Figure 2: An overview of the basic information of Industry 2.0.

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5. Industry 5.0 is the question of today. This concept is not yet settled. The main motto of this industrial revolution is a sustainable future of re-engagement of human creativity in the world of intelligent systems and robots [29]. An overview of the basic information of Industry 5.0 is shown in Figure 5.

- Some experts suggest that the Fifth Industrial Revolution will be the development of technologies in the fields of nanotechnology, biotechnology, and quantum computing. These areas can bring new ways of manufacturing and processing materials, improvements in healthcare, and the development of new kinds of communication technologies.

- Another possibility for the Fifth Industrial Revolution is the development of so-called "green" technologies and a sustainable economy, which includes the development of new types of renewable energy sources and the use of materials with a low carbon footprint.

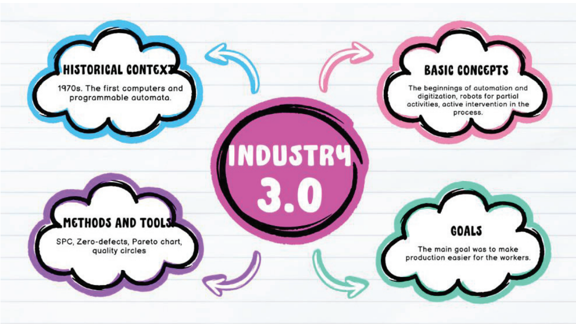

Figure 3: An overview of the basic information of Industry 3.0.

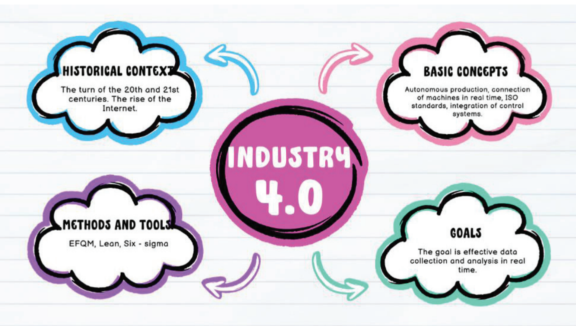

Figure 4: An overview of the basic information of Industry 4.0.

Figure 5: An overview of the basic information of Industry 5.0.

- The return of human creativity to the production process could also be part of the next industrial revolution. In the past, manufacturing processes sought to maximize efficiency and minimize human influence, leading to the introduction of machines and automated production lines. However, modern technology and the increasing need for product personalization and differentiation can lead to an increased involvement of human creativity in the production process. The inclusion of human creativity into the manufacturing process could lead to greater innovation, faster time-to-market for new products, and greater customer satisfaction. For this purpose, tools such as 3D printers are already used, which enable the rapid production of prototypes and testing of new ideas [30].

Development of quality management

Quality management focuses mainly on satisfying customer needs. These are processes and procedures that aim to ensure high product quality and try to reduce production costs. The development of methods and tools is closely related to the development of industry.

In today's turbulent world, ensuring the quality of production or services, i.e. satisfying the needs and expectations of customers, is in the first place.

The development of quality management and the development of industry go hand in hand and influence each other. At the same time, the development of quality management leads to more efficient production and higher product quality, which leads to improved competitiveness and also leads to the development of new technologies.

The current trend of quality management is increasing the efficiency and flexibility of production, reducing costs.

The development of quality management tools, as part of the Quality 5.0 concept, will probably continue in line with the trend of digitization and automation, which has been prominent in the industry in recent years. A few possible directions that could lead to further development of these tools include:

1. The use of artificial intelligence and machine learning to improve the quality of production and reduce the dependence on human labor. Machine learning algorithms can help identify poor-quality products or processes, allowing industrial companies to respond more quickly to problems and optimize production.

2. Development of real-time quality assurance tools. Industrial companies will try to minimize the time gap between identifying a problem and solving it, which can lead to the use of sensors and IoT (Internet of Things) technologies to monitor processes in real-time and detect problems immediately after they arise.

3. Greater emphasis on quality monitoring throughout the supply chain. The company will try to ensure that every supplier in its chain delivers products or services

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that meet the established quality standards. This could lead to the development of new tools for supply chain monitoring and management.

4. Greater integration of various quality management tools. The development of quality management tools will seek to provide a comprehensive overview of process and product quality, which may lead to the integration of various tools such as production monitoring, claims management, and quality management tools.

5. Increasing the flexibility of quality management tools. With the rapid development of the industry, the need for flexibility and the ability of quality management tools to adapt to different environments and requirements increases. The tools should be able to work effectively in different industries and be easily adaptable to changes in processes.

Industry 6.0:

Trends that could lead to the next, already sixth industrial revolution:

1. The development of quantum computers - One of the basic principles of quality management is decision-making based on data. In today's world, we have a very large amount of data at our disposal, but we are no longer able to process it using classic computers. Quantum computers are able to perform some calculations several times faster than classical computers.

2. New materials and technologies are the great challenge of the future. Nanotechnology has new applications in a wide range of fields, from chemistry to physics and biology, to medicine, engineering, and electronics.

3. Further development of robotics and automation - The further development of robotics combined with AI will lead to robots being able to imitate human activity much better. Robots that act and think like humans will be better able to integrate into the work process.

4. Development of biotechnology - Biotechnologies have become a common part of our lives. It is the use of biological materials to improve human life and health. It is the use of living materials or biological products to create new products for their use in various pharmaceutical, medical, agricultural, and environmental applications.

5. Increasing emphasis on sustainability and environmental consideration - One of the most important topics nowadays is sustainability. Today, the organization strives to minimize its carbon footprint, reduce greenhouse gas emissions, and stop global warming. Circular economy and efforts to minimize waste are also modern terms.

All of the above trends can and probably will lead to a new sixth industrial revolution, which will follow the fourth and fifth revolutions [31,32].

Quality 6.0 concept:

As the industry has developed over time and the methods and tools of quality management have also developed along with it, even with considerations of the sixth industrial revolution, it is necessary to think about possible changes and the future direction of quality management. So what could quality management 6.0 look like:

1. **Total quality:** Emphasis will need to be placed on the entire supply chain, from the production of primary raw materials (or the effort to recycle raw materials as much as possible) to the delivery of the final product to the customer, or only after its recycling and reuse of materials.

2. **Life cycle quality:** Quality 6.0 includes the quality of all stages of the life cycle of a product or service, including development, production, distribution, use, and disposal.

3. **Digital transformation:** Digital transformation will also continue, which will aim to bring out new opportunities for improving the organization's performance.

4. **Sustainability:** Not only economic, but also social and especially environmental aspects will play an important role, and every organization will have to think about the effects of its business on the environment.

5. **Innovation and cooperation:** quality will no longer be the responsibility of only one department, every employee of the organization will have to advocate for quality, mutual cooperation between individual departments of the company and between partners and suppliers of the organization will be important.

6. **Quality based on data analysis:** quality is already based on data analysis today, but there is and will be more and more data, and with current technologies, it will no longer be possible to analyze it correctly and use it for improvement. Therefore, the involvement of artificial intelligence will be necessary.

What other technologies could be part of quality 6.0:

1. **Conscious Machines and Autonomous Quality Systems:** Autonomous quality control systems that continuously monitor and evaluate product quality. New technologies using AI could lead to self-awareness and self-learning of machines, which will lead to control systems being able to optimize products themselves. And that depends on constantly changing external factors, on customer demands for dynamically changing markets. In cooperation with people, they will be able to monitor, evaluate, and improve product quality in real time.

2. **Quantum Quality Analytics:** For advanced analyses, it will be possible to use quantum computers and simulations that can handle the complexity and ambiguity of systems that classical computers could not handle.

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Quantum machine learning is also in development, which should provide faster and more perfect machine learning. Optimization is also an important component of quality management. Even optimization takes on a new dimension in the world of quantum analysis. It will be possible to run optimization algorithms and search for new solutions that are currently unimaginable.

3. **Holographic Quality Visualization:** Holography is no longer an unknown concept nowadays. However, the future possibilities of using 3D holographic imaging will completely change the possibilities of quality control. It will be possible to view the entire product as if it were a physical copy. Already today, VR and AR allow us a certain degree of simulation, which allows us to make faster decisions and improve quality. In the future, 3D product presentation could completely change the design and development phase.

4. **Neuro-Quality Interfaces:** Quality 6.0 pioneers neuro-quality interfaces that directly interface with human cognition. Brain-Computer Interfaces (BCIs) interpret quality-related neural signals, enabling intuitive quality control and feedback. A Brain-Computer Interface (BCI) is a hardware and software communications system that permits cerebral activity alone to control computers or external devices [33]. Neural networks integrated with quality management systems optimize user experiences based on neuro-feedback, ensuring products resonate with subconscious quality preferences. The central element in each BCI is a translation algorithm that converts electrophysiological input from the user into output that controls external devices [34-39].

Conclusion

One of the main objectives of quality management is the continuous improvement of products and processes. And the future associated with new technological challenges will offer many interesting opportunities to ensure this improvement.

It is necessary to adapt to new trends such as IoT, AI, and autonomous systems. These new technologies will offer new ways of quality assurance. The future goal of quality management will not only be to ensure quality products, but the focus will be mainly on flexibility, personalization, shared economy, sustainability, and ecology.

Future success will require organizations to invest in training their employees, new technologies, openness to innovation, and quick response to new technologies. The future of quality management will depend on the adaptive approach of companies to new trends. This article can be an insinuation and an open window into the future of quality management 6.0.

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Declaration for the use of AI-assisted technology: ChatGPT version 3.5 was used for some parts of this article. All output has been reviewed and edited by the author. The author assumes full responsibility for the content of the publication.

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