

Review

# Classification of Industry 4.0 for Total Quality Management: A Review

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**Abstract:** The philosophy of total quality management is based on meeting quality requirements in all processes and meeting customer needs quickly and accurately through the contribution of all employees. This concept means that all the processes in an enterprise, all the technology used, and all the workforce employed represent the total quality of the enterprise, with the necessary controls and corrections made to ensure that the quality is sustainable. In this study, a detailed literature review and classification study regarding Industry 4.0, Industry 4.0 technologies, and quality has been carried out. The place and importance of quality in Industry 4.0 applications have been revealed by this classification study. In previous studies in the literature, the relationship between Industry 4.0 technologies and quality has not been examined. With this classification study, the importance of quality in Industry 4.0 has emerged, and an analysis has been conducted regarding which quality criteria are used and how often.

**Keywords:** Industry 4.0; quality; technology; quality management; sustainability



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## 1. Introduction

Companies worldwide face significant challenges due to recent environmental, social, economic, and technological developments [1]. To meet these challenges, companies need to be agile and manage their entire value chain sensitively [2]. Various innovations can be made to realize agile management. In addition, companies need physical and virtual structures to enable collaboration and rapid adaptation throughout the entire lifecycle, from innovation to production and distribution [3]. Meeting these needs is essential for value chains to be effective. In addition, companies' futures are changing with the development of digital environments, where value chains are more influenced by each other and processes are becoming smarter [4,5]. In order to keep up with this change, companies aim to reduce unnecessary costs, increase business performance and quality, and shorten cycle times.

With the advancement in technology, the systems and processes used to create value are also developing. In order to increase value production, development processes and technologies need to adapt to the new industrial revolution (Industry 4.0). Industry 4.0, known as the fourth industrial revolution, has emerged with the digitalization of the manufacturing industry [6]. Industry 4.0 is the digitization of all physical assets to create an infrastructure and the stakeholders that make up the e-value chain [7]. With Industry 4.0, which leads the digitalization era, production systems, processes, machines, and environments are all digitized [8–10].

In order to achieve digitalization, high technologies must be used. High technologies have an impact in every sector. However, the sustainability and continuity of these technologies are also important, and in this context, it is necessary to ensure the sustainability of Industry 4.0. Iyer [11] has researched developments in sustainable production processes worldwide. By performing a study in India, he examined how developing economies should transition to Industry 4.0. Environmental sustainability is becoming an essential

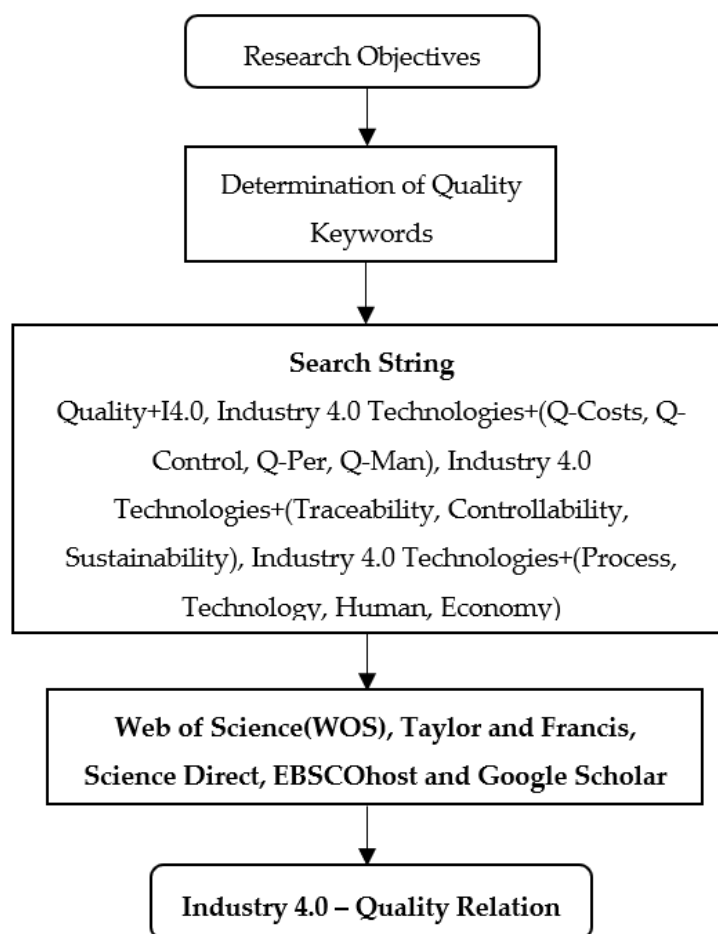
competitive factor among manufacturing companies due to economic markets and international regulatory pressures. In recent years, the increase in awareness of environmental issues by consumers has resulted in companies offering products that are environmentally monitored and certified. Papetti et al. [12] states that by sharing data between components, a structure can be created that can effectively model complex supply chains and measure the environmental sustainability of items.

Industry 4.0 is a concept that has been studied frequently in recent years. There are many applications and classification studies compiled in the literature. Öztemel and Gürsev [13] carried out a classification study to provide an applied Industry 4.0 library to academics and to those who apply these technologies in the industry. In order to ensure the reliability of the review process, 619 studies related to Industry 4.0 were analyzed. In addition to classification, the researchers also presented a roadmap for those who want to achieve digitalization in production. Muhuri et al. [14] conducted bibliometric analyses on the latest developments in Industry 4.0 and examined how often Industry 4.0 was studied. Web of Science (WoS) and Scopus databases, which are widely used in bibliometric analysis, were preferred. As a result of the analysis, it was found that the most productive countries in Industry 4.0 are Germany and China, and the most frequently used keywords are: cyber-physical systems, Internet of Things, smart production, and simulation. Cobo et al. [15] examined the working areas of Industry 4.0. Cyber-physical methods, cloud computing techniques, innovative technologies, and supply chain comparisons were made. Researchers examined 333 studies on Industry 4.0 in the Web of Science with SciMAT software between 2013 and 2017, arguing that cyber-physical methods and cloud computing are the most preferred techniques. Culot et al. [16] analyzed the definitions of Industry 4.0 keywords in the literature. Classification was made by determining the elements for each definition. In the study of Mariani and Borghi [17], a bibliometric analysis of the potential development of Industry 4.0 in service sectors was carried out. Li et al. [18] examined the relationship between the existing literature on data, information, and knowledge dissemination in the manufacturing industry and Industry 4.0 technologies. This relationship was separated into groups and examined as \*additive manufacturing, \*cloud production, \*information transfer, \*information management, and \*information sharing. Echchakoul and Barka [19] conducted a literature review on the effects of Industry 4.0 on the plastics industry. In the study, the Bibliometrix R tool and VOSviewer software were analyzed, and “Internet of Things” (IoT) was found to be the most used keyword. It was also discovered that Industry 4.0 could also be analyzed by dividing it into clusters.

This study conducted a literature search on the definitions, application areas, advantages, and difficulties of Industry 4.0 and its technologies. In the first and second parts of the study, literature research on Industry 4.0 is included. In addition, how Industry 4.0 technologies are used on a sectoral basis is investigated. In the third part of the study, the content and scope of quality are explained. The traceability/controllability/sustainability of all the processes in the enterprise, the technology used, and the quality of the workforce employed are then examined within the scope of Industry 4.0 and the quality relationship. The flow of the study is shown in Figure 1.

In the fourth part of the study, quality and Industry 4.0 technologies (Internet of Things, cloud, artificial intelligence, big data, 3D printer, cyber-physical systems, augmented reality) are examined with the help of SciMAT and VOSviewer programs, and a classification study is carried out. The classification consists of four stages. In the first stage, 958 studies regarding quality and Industry 4.0 technologies were examined. In the second stage, quality was divided into four main titles (quality costs, quality control, quality performance, quality management), and the relationship of each subject with Industry 4.0 technologies was examined separately. The classification structure is shown in Table 1. In the second stage, a total of 226 articles were examined. In the third stage, 797 studies, in which each of the criteria of traceability, controllability, and sustainability in the quality assessment were used together with Industry 4.0 technologies, were examined. Finally, at the last stage of classification, how the relationship between process, technology, human, economy, and

Industry 4.0 technologies determines quality in Industry 4.0 was examined. At this stage, 6954 articles were scanned.



**Figure 1.** Flow-chart of the study.

**Table 1.** Industry 4.0 studies.

Study	Work
[20]	Revolutionary development in industry, literature study
[21]	Investigating which key technologies are influential in Industry 4.0
[22]	Analysis of similarities and differences in Industry 4.0 technologies
[23]	Framework proposal for Industry 4.0
[24]	Developing an Industry 4.0 model for machine tool efficiency
[25]	Industry 4.0 application guide: model for manufacturing companies
[26]	Roadmap for the transition to Industry 4.0
[27]	Smart factory transformation model for SMEs
[28]	What to do in the transition to Industry 4.0
[29]	Gradual transition plan to Industry 4.0
[30]	Simulation study on the importance of the human factor in Industry 4.0
[31]	The role of Industry 4.0 technologies in data management
[32]	Key aspects of Industry 4.0 and risks during its implementation
[33]	Investigating what skills and expertise are required for Industry 4.0
[34]	Application of Industry 4.0 in SMEs
[35]	Investigation of the effects of Industry 4.0 on SMEs
[36]	Model for the integration of lean manufacturing and Industry 4.0 to SMEs
[37]	Key benefits of Industry 4.0 adoption in SMEs examined
[38]	Comparison of Industry 4.0 applications in SMEs and large enterprises

Table 1. Cont.

Study	Work
[39]	Studying energy trends, electric vehicles, and the use of Industry 4.0 technologies in the EU
[40]	The effects of Industry 4.0 technologies on sustainable energy
[41]	Using blockchain to ensure sustainability
[42]	Agile structuring and integration of Industry 4.0 in the automotive industry
[43]	Use of blockchain in the automotive industry
[44]	The role of Industry 4.0 in the transformation and development of products
[45]	The impact of additive manufacturing on the development of smart factories
[46]	Claimed that with Industry 4.0, automation, integration of lines, and management of production systems would be more effective
[47]	Analysis of the performance of smart factories and its relationship with Industry 4.0
[48]	Concrete steps to be taken in Industry 4.0 for smart factories
[49]	The effectiveness of Industry 4.0 technologies in a smart factory environment
[50]	Improving the development processes of products with the smart virtual product development system
[51]	Applicability of Industry 4.0 for the security and protection sector
[52]	Digital transformation of supply chain and marketing processes
[53]	Use of Industry 4.0 in technology transfer in the supply chain
[54]	Smart product assessments for product quality and sectoral growth
[55]	Energy management with cloud-based web application
[56]	Managing data in the health sector with Industry 4.0 technologies
[57]	Using Industry 4.0 to reduce bicycle accidents
[58]	Production scheduling with Industry 4.0
[59]	Using Industry 4.0 to predict bottlenecks
[60]	Using process mining as one of the stages of Industry 4.0
[61]	Digitization of existing manuals

In this study, a classification study was conducted by considering Industry 4.0 in terms of quality. There are many classification studies related to Industry 4.0 in the literature, but these studies are mostly classified in terms of technology and method. In addition, there are also classification studies carried out on a sectoral basis. However, there is no study in the literature that classifies quality, integrating it into Industry 4.0, and classifying the two together, as we have done in this study. In this sense, the study is original.

## 2. Literature Review

Industry 4.0, which also means digital transformation, is a concept that represents increasing capacity with technology, data exchange, and cyber systems. It plays a vital role in creating smart factory systems that aim to automate and remotely monitor all physical systems [62]. Many modern automation systems are the most important distinguishing elements of Industry 4.0 and include data exchange and production technology [63,64].

### 2.1. Smart Technologies in Industry 4.0

Industry 4.0 refers to the organization of production processes based on technologies and devices that communicate autonomously with each other throughout the value chain [65]. It creates production ecosystems driven by intelligent systems with autonomous features, such as self-configuration, self-monitoring, and self-development [66]. From the procurement process to the production process, applications are made with Industry 4.0 technologies in many smart factories, with more efficient work at maximum capacity being supported. Along with technological development, the way the factories work has also changed. With developing technologies, smart factories have begun to be used. The leading Industry 4.0 technologies are smart production, smart product, and smart supply [62,67]. In smart factories, processes at any stage of production can be renewed and improved using automation [68], work [69], and control [70]. Smart factories are used to provide an integrated data exchange between the physical world and the virtual world [71].

Bibby and Dehe [7] aimed to measure the application level of Industry 4.0 technologies in three dimensions in the evaluation model they developed. These dimensions were: \*factory of the future, \*people and culture, and \*with strategy. Using Industry 4.0 applications, there could be seven technologies in future factories. These are: \*Internet of Things and cyber-physical systems, \*big data, \*cloud computing, \*blockchain, \*autonomous systems and robots, \*additive manufacturing (3D printers), and \*augmented reality [62,72,73]. Simulation and some system integration tools also support the implementation of Industry 4.0 [74]. Connecting tangible assets to the internet makes it possible to access data remotely and to control objects. Synergetic systems such as the Internet of Things are needed to consolidate existing data on the internet [75]. With the increasing use of 4G-LTE (fourth generation long-term evolution) wireless internet access and wi-fi technologies, it has become essential to reach communication networks at any time [76]. With the spread of the internet, new paradigms have emerged, with one of the most prominent being the Internet of Things technology [77]. The term Internet of Things has become widespread and can be defined as an intelligent network structure in which objects communicate using techniques without manual data entry [76,78–80]. The Internet of Things means that addressable objects communicate with a specific protocol [81]. Smart devices used for the internet can identify themselves, establish networks, and transfer the collected information to public cloud services that can store and analyze it [82].

### 2.2. Big Data in Industry 4.0

Determining a data-based strategy is important for businesses to survive and gain a competitive advantage [83]. Big data technology ensures that many and various data are used effectively. Big data is a concept that defines and analyzes very different and large volumes of data that current database technologies fail to analyze [84]. The usage area for big data is quite wide; for example, it can be employed in national security [85], business and economic activities [86], entertainment, manufacturing [87], education [88], health [89], and transport and energy sectors [90]. Big data is a term used to describe datasets that are beyond the storage, management, and processing capacity of programs. Big data performs various operations, such as combining multiple unrelated datasets, processing large amounts of unstructured data, and collecting confidential information in a limited time [91].

### 2.3. Cloud Computing in Industry 4.0

The analysis of large volumes of data is essential, as is the storage and follow-up of the areas where it is used. For this reason, it is necessary to make use of technologies to carry out this follow-up. Information processing technology provides convenience in tracking when and by whom data is stored, along with instant intervention [92]. Cloud computing technologies are used in education to monitor individuals' data/instant data and to control the education processes received [93]. Cloud computing also reduces information technology costs for individual users, small businesses, and office workers [94]. Cloud computing is a network model that usually includes certain services and offers them to the user with flexible configurability. Three essential services are offered in this network model: software, platform, and infrastructure services. A software service is a service that users benefit from by accessing applications from any platform connected to the internet without any installation [95]. A platform service offers its users the opportunity to develop, test, and distribute their software and applications online, and control and manage only the peripherals required to host this software [96]. An infrastructure service accesses the processor, storage, network resources, and other host components it needs, installing any operating system on them, and developing and running applications [97].

### 2.4. Blockchain in Industry 4.0

With developments in technology, it is no longer necessary to keep data in central systems. High-speed and secure communication can be established by duplicating the

desired data set and sharing this data with a limited number of people [98]. In an environment with more than one user, the data added to the system must have a standard. Blockchain technology is supported to update, protect, and share data with the desired person/department in the digital world [99]. Blockchain can be defined as a shared, immutable ledger that facilitates the recording of transactions and tracking assets in a business network. An asset can be tangible (house, car, cash, land) or intangible (intellectual property, patents, copyrights, branding), and almost anything of value can be traced and traded on a blockchain network, reducing the risks and costs for everyone involved [100]. A blockchain consists of a data block that is produced based on the theory of cryptography [101,102]. The blocks are recorded in a distributed ledger according to the consensus rules agreed to by the network partners [103]. In addition, the system offers the opportunity for trading between individuals without the need for a trusted third party. All individuals can view the entire transaction history. The completeness of the transaction history also ensures the validity of each virtual transaction, and all virtual transactions can be traced from the moment they are created.

Blockchain also prevents the modification of existing records; thus, the need for management is reduced [104]. Blockchain technology can be used internally or in transactions with customers, suppliers, shareholders, or the government. It is used in e-commerce, international payments, lending, and microfinance [105]. Blockchain applications can be found in many areas; for example, in the supply chain process in production [106], in the follow-up of patients by creating a digital identity in health services [107] and inpatient intervention in emergencies [108], in the storage of student notes and the protection of personal data in education [109], and between suppliers and businesses. It is used to provide data communication [110], secure money transfers, and use bitcoin in finance [111].

#### *2.5. Cyber-Physical Systems in Industry 4.0*

Industry 4.0 applications often include cyber–physical systems, combining data exchange/processing in cyber–physical systems, information technologies, and electrical devices [75,112]. With the development of technologies, information technologies and the importance of cyber–physical systems are emerging. The development of cyber–physical systems, together with technology, has affected the development of machines and increased the role of machines in human life. Machines make people’s work easier in many industries; for example: in autonomous systems and robots in the defense industry [113], assisting people with disabilities in healthcare, surgical interventions [114] and assisting nurses in inpatient care [115], in quality control to increase productivity in production [116], in education (helping with laboratory work) [117], and in geodetic surveying and spatial decision support work in the mining industry [118].

#### *2.6. 3D Printers in Industry 4.0*

Three-dimensional (3D) printing, one of the most fundamental Industry 4.0 technologies, is a technology that was developed due to the interest of entrepreneurial individuals, rather than large-scale businesses. Three-dimensional printers enable the information stored on computers to be transformed from virtual to natural objects [119]. This technology, which enables 3D production, is also called additive manufacturing in the literature [120]. Additive manufacturing is a modern manufacturing technique in which the materials used with 3D data are added layer by layer, and the production of geometric parts is carried out swiftly [121]. It has application areas in many sectors; for example, Giannatsis and De-doussis [122] investigated the benefits of additive manufacturing in preoperative planning studies for patient-specific implants in the healthcare industry and examining the human skeleton. In addition, 3D printers are frequently used to produce parts that are difficult to produce for vehicles such as aircraft and ships [123], and prototype products in R&D units [124].

### 2.7. Augmented Reality in Industry 4.0

Technology to increase image quality with graphics, sound systems, and animation is frequently used in augmented reality technology, which switches between the real and virtual world [125]. For example, augmented reality technology is used in astrology [126,127], in simulator training for trains [128,129], and in the analysis of planetary interactions with each other. Augmented reality has been suggested for use in the conversion of manuals [61] and in a newly developed CPR (cardiopulmonary resuscitation) training system in healthcare to measure the effectiveness of training [130], reduce costs [131], and control situations that employees may encounter in departments [10].

Studies on Industry 4.0 definitions, technologies, roadmaps for transition, applications in different sectors, and integration with different management styles are examined and summarized in Table 1.

## 3. Quality

Quality is the degree to which a service or product meets its characteristics or possible needs. Quality means customer satisfaction [132]. Increasing quality is possible with the participation of the employees involved in the process at all stages [133], including the participation of senior management employees and all team members. The efforts of employees to achieve this goal in line with a common goal increase the quality of the business in every field [134]. With the industrial revolutions and changes in management philosophies, quality is also diversifying. The development of quality has developed in parallel with the industrial revolutions. In Industry 4.0, the quality criteria determined to evaluate the quality of an enterprise are also considered in the revolutionary development of quality. Each quality revolution is evaluated using traceability, controllability, and sustainability quality criteria.

### 3.1. Quality Costs in Industry 4.0

The cost of quality arises from existing poor quality or measures taken to prevent potential poor quality [135]. Quality cost is one of the critical criteria that reflects the quality level of an enterprise [136,137]. Businesses should be able to predict their quality costs and plan accordingly. All quality costs should be kept to a minimum to maximize the impact of quality systems on earnings. Quality costs can be managed by measuring these costs effectively [138]. Industry 4.0 technologies can facilitate the measurement of costs more effectively; for example, it is possible to measure financial quality with the blockchain method by calculating costs for suppliers [139].

### 3.2. Quality Control in Industry 4.0

Quality control can be defined as mastering quality by taking precautions against situations that may reduce the quality efficiency of the process [140]. The primary purpose of quality control is to ensure continuity at the economic level by developing and implementing production plans that can meet customer expectations and the strategic goals of enterprises [141,142]. Quality control is an indispensable part of the processes in manufacturing companies. Proper quality control will reduce production costs and increase customer satisfaction [143]. In the case of unexpected changes during production, quality control ensures that the situation is detected and corrected immediately. Advanced technologies can be used for effective quality control, and many Industry 4.0 technologies can be used in the quality control of processes; for example, Alberts et al. [144] uses cloud technology to control products in the supply chain.

### 3.3. Quality Performance in Industry 4.0

Quality is one of the essential strategic tools in businesses [145], and businesses are aware that quality is the main factor in product and service development for sustainable success [146]. Therefore, improving quality performance is essential in product and service development. Some criteria are also taken into account in the measurement of quality

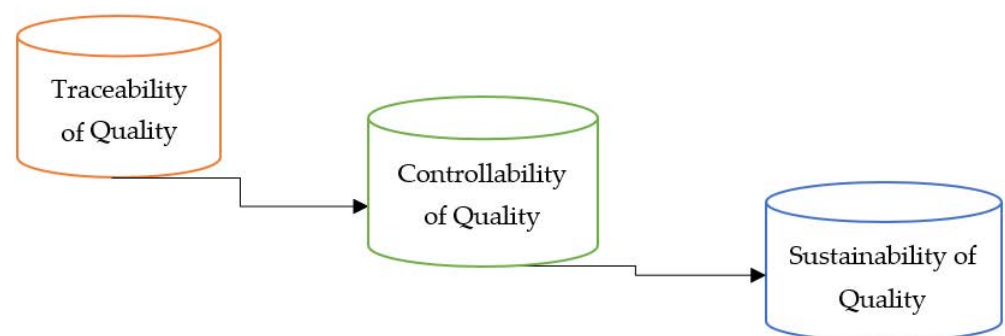
performance, such as product performance, product/service quality, on-time delivery, product suitability, product standardization, total warranty cost, and suitability of product design [147]. These criteria used in measuring quality performance are also very effective in total quality management practices [148]. Performance measurement is also a measurement of the effectiveness of quality. With the smart technologies that entered our lives with Industry 4.0, quality performance is increasing. Smart factories, smart products, and the Industry 4.0 technologies that are used positively affect quality performance; for example, the quality of processes in departments can be measured using the Internet of Things [47].

### 3.4. Quality Management in Industry 4.0

Quality management is the act of controlling all the activities and tasks that must be performed to maintain the desired level of excellence [149]. The effect of quality management becomes even more critical when strategies are applied in businesses, especially when unexpected situations are encountered [150]. Quality management facilitates the control of all processes and data used in businesses [151,152]. In order to better manage quality, studies have been carried out using Industry 4.0 technologies; for example, IoT technology [153] has been used for planning capacity in manufacturing, and big data [154] has been used to manage the health records of healthcare workers.

The development of quality has occurred in parallel with the industrial revolutions. The quality criteria determined to evaluate the quality of enterprises in Industry 4.0 were also considered in the revolutionary development of quality. Each quality revolution has been evaluated using traceability, controllability, and sustainability quality criteria. With the development in technology, it is becoming increasingly important to integrate these technologies into businesses and to reach a certain level of quality [155].

In this study, traceability, controllability, and sustainability criteria were used to evaluate the level of quality met. In Industry 4.0, for each business function, quality was evaluated according to each criterion. For example, while Industry 4.0 was being applied in production activities, an evaluation was made regarding the traceability of quality, the controllability of quality, and the sustainability of production. In Industry 4.0, Industry 4.0 technologies are used to ensure the traceability, controllability, and sustainability of quality. If the quality of the activities in an enterprise are mentioned, the quality must be traceable, controllable, and sustainable. Figure 2 shows the quality criteria.



**Figure 2.** Quality criteria.

### 3.5. Quality Criteria

#### 3.5.1. Traceability of Quality

With the traceability of the quality improvement process, businesses will be able to perceive any coordination problems [156]. These criteria monitor whether the process is carried out using the correct method/at the right time/the correct cost, considering the quality expected from the process. Assistance is received from Industry 4.0 technologies in monitoring, and with this follow-up, it is possible to intervene at the right time. For each business function, the quality of the processes can be monitored using Industry 4.0



technologies. Blockchain technology can be used to ensure the traceability of quality. With blockchain technology, accessibility between authorities and designated stakeholders is also determined, and confidentiality is ensured with information protocols. As blockchain technology records all data, both businesses and stakeholders ensure the traceability of products [102].

### 3.5.2. Controllability of Quality

With the quality traceability criteria in Industry 4.0, the tracking of processes has become more accessible. However, it has become essential to audit and control these processes, and make corrections if necessary [157]. The process should remain confidential, and only relevant persons should access this information. The decisions to be taken in line with this information, obtained as a result of the controls, should only be made by certain individuals [158]. It is not enough to simply follow the processes. With controllability, the efficiency of the monitored processes is controlled, and the possibility of intervention is provided. In addition, it is necessary to check whether the process should continue in the desired line and whether it progresses at the desired quality. Industry 4.0 technologies can be used for quality control, and it is essential to establish an information protocol in controllability, as with traceability. Quality controllability can be achieved with blockchain technology.

### 3.5.3. Sustainability of Quality

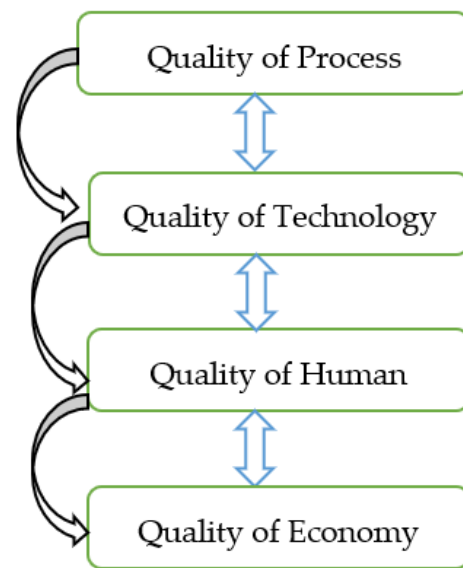
It is necessary to ensure the continuity of the quality improvement process. Quality improvement processes must be at a certain level and should meet expectations. The desired quality will be achieved by ensuring the continuity of assets in an enterprise [159]. The sustainability of the quality of processes in business functions is essential. Economic growth planning must be done correctly [160]. While achieving sustainability, it is necessary to ensure economic and environmental sustainability, the effective use of an environmental management system, and innovations [161,162]. Sivas et al. [163] examined the studies in which sustainable product development and quality management approaches were used together. They identified four areas that showed quality management's support of sustainable product development (\*supporting sustainability with the integration of management systems, \*supporting the implementation of quality and environmental management systems, \*sustainability, and \*stakeholder management and customer orientation). Bastas and Liyanage [164] described the critical themes for the sustainability of product quality: leadership, customer focus, supply chain integration, relationship management, and evidence-based decision making. While operating business processes, this study focused on adaptation to the economy, adaptation to the environment, adaptation/orientation to technology, compliance/directing customer expectations, and not losing knowledge to provide environmental/social security. Industry 4.0 technologies were used while achieving these goals.

In the third stage of the classification, which is the second main subject of this study, the publications in which Industry 4.0 technologies and quality keywords are studied together were searched.

In order to discuss quality in an Industry 4.0 enterprise, it is necessary to look at the quality of the processes. Whether the operation of the processes is progressing in line with the determined quality requirements should be monitored. The quality of the existing technologies preferred also directly affects the quality of the enterprise; technology alone is not enough. The quality of the employees will increase the quality in every unit of the enterprise. As it is essential to increase the quality of an enterprise financially, it is also essential to increase the quality of the economy.

### 3.6. Quality Components

The quality components are process, technology, human, and economy, as shown in Figure 3.



**Figure 3.** Quality components.

### 3.6.1. Quality of Process

A quality process can be measured if it is controlled, repeatable, reliable, and stable [165]. Increasing the quality of processes will positively affect the overall quality of the units. However, to comment on the increase or decrease in the quality of a process, the quality must be measurable. There are studies in the literature that include the measurement [166], structuring [167], design [168], quality evolution [169,170], and service quality [171] of the process. However, there is no study in the literature that measures the quality of the process with Industry 4.0 technologies.

### 3.6.2. Quality of Technology

With each industrial revolution, technology development has accelerated. The use of high technology directly affects product quality. With advanced technology, product quality can respond to demands better and more quickly, thus increasing the quality. In the literature, many studies involve the integration of Industry 4.0 technologies with the technologies used in the production and management activities in enterprises (e.g., Internet of Things technology [172] used in product development in R&D and the use of big data in the processing of suppliers). With information on purchasing [173], cloud computing technology has been used to keep personnel information records for human resources departments [174], and cloud computing technology has been used for remote access to production information in production [175]. However, no study has been found that measures the traceability, controllability, and sustainability of the technology used with Industry 4.0 technologies.

### 3.6.3. Quality of Human

To develop technologies to be used efficiently, it is necessary to employ individuals who can adapt to these technologies. Although technology and machinery are widely used in many sectors, qualified personnel are always necessary. In the literature, there are many studies that examine integrating the characteristics of the personnel involved in the enterprise processes and Industry 4.0 technologies. For example, cloud computing technology has been employed for keeping information regarding personnel employed in R&D [174], big data [176] has been used for product records in purchasing, cloud computing [177] has been utilized for accessing personnel information in human resources, and big data [178] has been applied for use with product records in production. The quality of Industry 4.0 technology processes can be improved by measuring the traceability, controllability, and sustainability of the employed personnel.

### 3.6.4. Quality of Economy

It is possible to measure how strong a firm can be using various cost analyses. Increasing the technology and workforce used in all corporate processes is vital to obtaining the appropriate quality while producing products or services. However, this increase has an economic cost for the business. For this reason, while the quality of the processes increases, “economy” is seen as a constraint. The quality of an economy can be measured using Industry 4.0 technologies for the traceability, controllability, and sustainability of the economy.

In Industry 4.0, criteria such as process, economy, technology, and people can be used to measure quality in business activities. For this reason, in the fourth stage of the classification study, Industry 4.0 technologies and the publications in which these quality keywords are studied together will be examined.

## 4. Classification

In the classification part of the study, the classification made with Industry 4.0 and quality studies was carried out in four stages. The keywords used in the classification are shown in Figure 4.



Figure 4. Keywords.

In the first stage of classification, the Industry 4.0 technologies (Internet of Things (IoT), cloud computing (C), artificial intelligence (AI), big data (BD), and 3D printer (3D)) used in quality studies were examined. In the second stage of Industry 4.0 and quality research classification, the concept of quality was detailed under four main headings (quality costs, quality control, quality performance, and quality management).

In the third stage of classification, the studies in which Industry 4.0 technologies were used and the quality keywords (traceability, controllability, and sustainability) were examined. Finally, in the fourth stage of classification, studies in which process, economy, technology, and human criteria were used together with Industry 4.0 technologies were examined. The flow-chart of the classification is given in Figure 5.

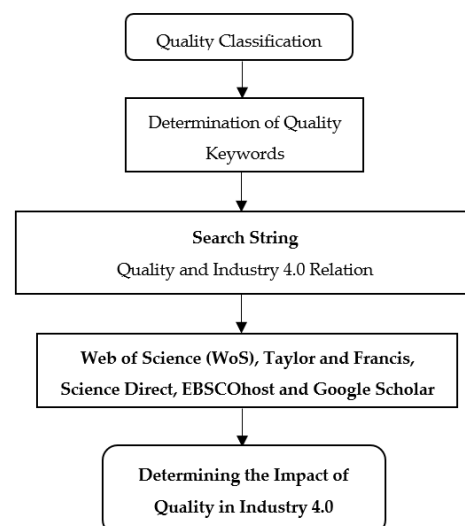
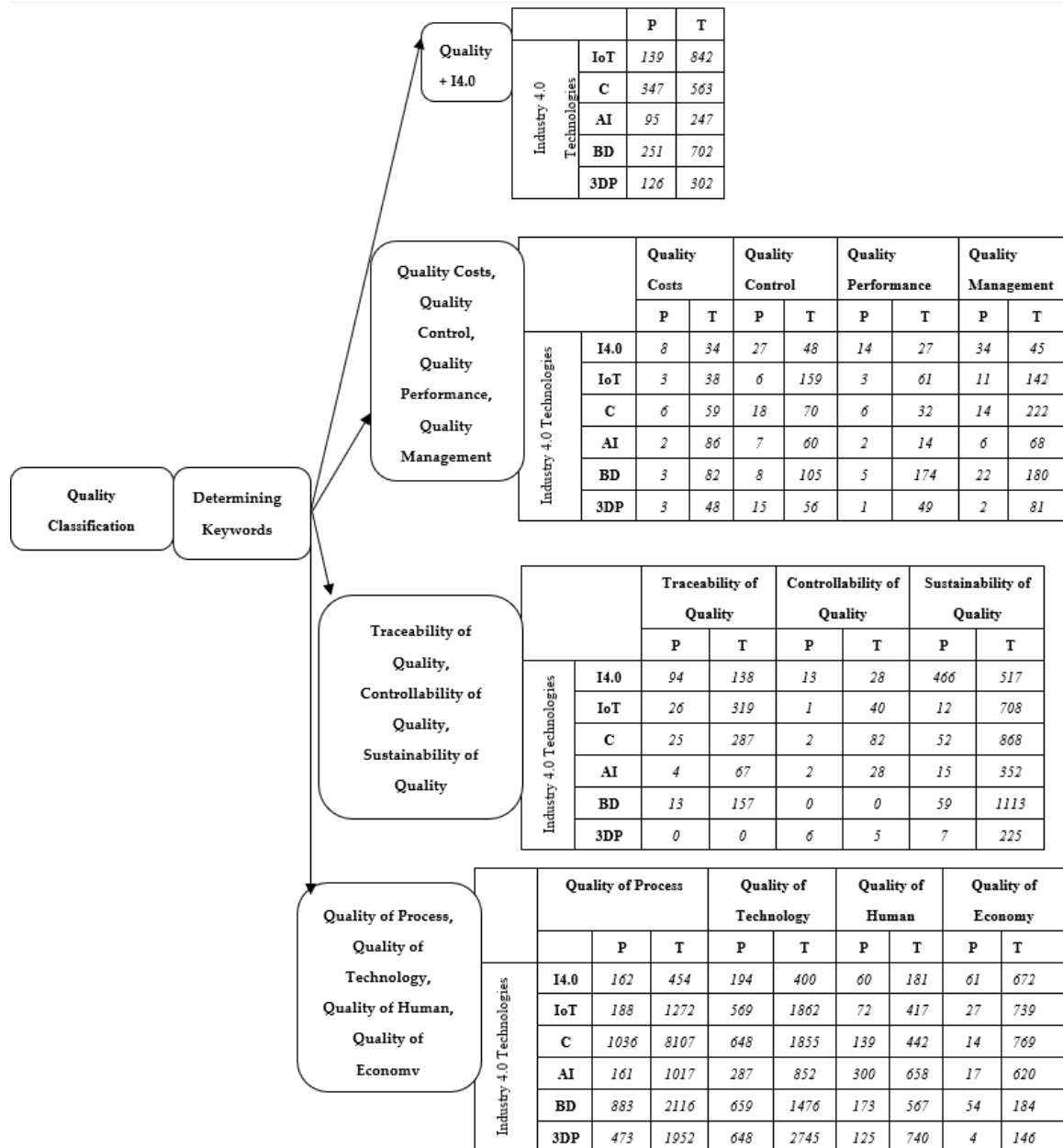


Figure 5. Flow-chart of classification.

In conducting the classification study, studies in engineering, management, and production from the last five years were examined in the databases of WoS, Taylor and Francis, Science Direct, EBSCOhost, and Google Scholar. In addition, the studies were examined using the VOSviewer and SciMAT programs. The classification details are shown in Figure 6 (P represents the number of publications on the research, and T is the number of times the relevant keyword is repeated in the publications).



P: number of publications in the research; T: number of times the relevant keyword is repeated in the publications.

Figure 6. Relationship between Industry 4.0 and quality.

In the classification, the Internet of Things (IoT), cloud computing technology (C), artificial intelligence (AI), big data (BD), and 3D printer (3DP) were the preferred Industry 4.0 (I4.0) technologies. The quality classification included quality cost, quality control, performance, and management. As seen in Figure 5, the most repeated subject in the classification for joint publications of quality and Industry 4.0 technologies, which was the first stage of classification, was the Internet of Things technology and quality joint studies, with

842 repetitions in 139 publications. On the other hand, it can be seen that cloud computing technology and quality were the most studied subjects with 347 publications. Therefore, the second stage of classification was for publications where Industry 4.0 and quality cost, quality control, quality performance, and quality management were used jointly.

## 5. Discussion

When examining the literature, many studies on Industry 4.0 can be found. The focus of these studies is on existing technologies and the sectors where these technologies can be applied. Although there are some publications related to Industry 4.0 manufacturing technology that indirectly address quality, there are only a few publications that focus solely on quality or that conduct a classification study to increase quality in general in Industry 4.0, such as [179,180]. In this sense, this study is original. In this study, the classification of quality is discussed in terms of Industry 4.0. The results can be discussed as follows:

- (1) Regarding quality costs, while the term Industry 4.0 had 34 repetitions in 8 publications, it was seen that cloud computing technology was studied in a maximum of 6 publications.
- (2) With regard to quality control, while the term Industry 4.0 was repeated 48 times in 27 publications, it was found that cloud computing technology works were carried out in a maximum of 18 publications.
- (3) Concerning quality performance, while the term Industry 4.0 was repeated 27 times in 14 publications, cloud computing technology was studied in a maximum of 6 publications.
- (4) With reference to quality management, while the term Industry 4.0 was repeated 45 times in 34 publications, it was seen that big data technology was studied in 22 publications at most. In this study's third stage of classification, traceability/sustainability/controllability criteria and publications in which Industry 4.0 technologies were used jointly were examined.
- (5) As a result of the examination, with regard to traceability, the term Industry 4.0 was found to be repeated 183 times in 94 publications, with the most used technology being the Internet of Things in 26 publications.
- (6) As for controllability, while the term Industry 4.0 was repeated 28 times in 13 publications, the most used technology was 3D printing technology with 6 publications.
- (7) On the sustainability of quality, while the term Industry 4.0 was repeated 517 times in 466 publications, big data technology was the most studied technology with 59 publications. In the final stage of classification, the publications in which process, technology, people and economy, and Industry 4.0 technologies were used jointly were examined.
- (8) Regarding the quality of the process, while the term Industry 4.0 was repeated 454 times in 162 publications, the most studied technology was cloud computing technology with 1036 publications.
- (9) Concerning technology quality, the term Industry 4.0 was repeated 400 times in 194 publications, and big data technology was studied in 659 publications.
- (10) With regard to human component, the term Industry 4.0 was repeated 181 times in 60 publications, with artificial intelligence technology ranking first as the most studied technology with 300 publications.

In the last component, economy quality, the term Industry 4.0 was repeated 672 times in 61 publications, and the most studied technology was big data technology with 54 publications.

## 6. Conclusions

Process management has an important place in the philosophy of total quality management. Process management is a discipline that forms the basis of, and manages, processes to improve the performance of businesses. As Industry 4.0 applications are increasingly being used in the business world, it is impossible for quality management and process management to stay removed from digitalization. The concept of quality in Industry 4.0 aims to digitize all business processes in terms of quality to increase the use of Industry 4.0 technologies. The quality of the technology used in businesses and the quality of the work-

force, especially the processes, are monitored in quality management, which are created using Industry 4.0 technologies to ensure the traceability/control/sustainability of the quality of all the processes that businesses need in order to continue their activities. This follow-up/increase is aimed at improving the economic quality.

First, keywords were determined for this classification study, which was the second main subject of the study. Studies in which Industry 4.0 technologies (Internet of Things (IoT), cloud computing technology (C), artificial intelligence (AI), big data (BD), and 3D printing (works using 3DP)) and the word “quality” were used together were examined. In the second stage, studies in which Industry 4.0 technologies were determined and quality costs, quality control, quality performance, and quality management worked together were investigated. In the third stage of this study, traceability/controllability/sustainability and Industry 4.0 technologies were examined together. In the last stage of the classification, the quality of the process, technology, people, and economy were examined together with Industry 4.0 technologies. It covers the classification of quality in Industry 4.0 and the literature review of the relationship between quality and Industry 4.0 technologies.

As can be observed from this classification study, there are publications in the literature where Industry 4.0 and quality issues have been studied together. However, as can be seen when examining quality in Industry 4.0, no study has used Industry 4.0 technologies to ensure quality monitoring/control/sustainability in the processes of all institutions, in all technologies used, and in all workforces employed. There are only a few studies in the literature that have explored the importance of quality in Industry 4.0. Therefore, this classification study reveals the need for studies that emphasize quality in Industry 4.0.

## 7. Future Research

In this research, a classification study was conducted by examining the relationship between Industry 4.0 and quality. In future studies, the scope of the study could be expanded by adding new criteria, such as real-time data and the circular economy. Again, as a result of the subtitles created for classification in this study, a new quality model could be created and integrated into Industry 4.0.

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