Quality management in the industry 4.0 era

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Abstract: In the current competitive scenario, manufacturing companies are facing various challenges related to an increasing level of variability. This variability means different sets of dimensions such as demand, volume, process, technology, quality, customer behavior and supplier attitude, and transform the industrial systems engineering domain. A new paradigm tries to solve these challenges and solutions such as "the fourth industrial revolution" or "Industry 4.0" refers to new production patterns, including new technologies, productive factors and labor organizations, which are completely changing the production processes and developing high-efficiency production systems that make it possible to minimize production costs and improve production and product quality. Manufacturing companies need to achieve a substantial improvement in performance by manufacturing high-quality products and creating highly flexible systems that make it possible to maintain their efficiency even when demand varies dramatically. Tools for the management and optimization of quality are vitally important. In this way the adoption of highly flexible cyber physical production units permits the implementation of production processes capable of guaranteeing high-quality standards in the finished product, even in the case of small production lots. Industry 4.0 provides promising opportunities for quality management therefore, the purpose of this paper is to focus on the quality management and industry 4.0 concepts and analyze the current state of literature trying to understand the implications and opportunities for quality management in the industry 4.0 era.

Keywords: industry 4.0, quality management, literature review

1.Introduction

Industry 4.0 is the integration and interaction of technologies regarding physical and digital domains, which makes it stand out from the other industrial revolutions. Manufacturing has switched from mass production to mass customization (Demartini et al. 2017). No longer it is based on scale and volume effects but on flexible and localized production situated close to customers. It manufactures "on demand" and no longer creates inventory, adapting itself to needs. It is more predictive and auto-corrective and it involves less trial and error. Its logic is now focused not on the product but on usage, and it has also switched from a rigid form of labor, inherited from Taylorism, to a flexible form (Holmström 2014). This potentially represents a complete overhaul of the operations management. Indeed, the introduction of innovative technologies and complex interconnected systems involves not only huge investments but also a significant change which influences the internal organization from production layout and interaction between robots and humans, up to transforming supply and value chains. The industrial transformation promises an increase in quality management by improving products, processes and service quality. Product quality governs the success of manufacturing companies. Efficient quality management leads to a sustainable reduction in costs and facilitates the development of quality products with a high degree of customer satisfaction (Demartini et al. 2017). Singular events, such as delayed delivery of supplied parts, or the failure of production equipment can quickly disrupt the production of an entire day. Current practice is to pre-plan as many such situations as possible and to test and optimize the production plant regarding its responses to such events. Significant savings can potentially be achieved by self-reconfiguration and self-adaptation of production equipment and production workflows based on the cyber physical production systems (CPPS) and the workpieces actual state or they can be triggered by information from factory-level systems and/or external systems. The biggest challenge in this respect is the wear and tear of production tools or a decrease of production quality, which should be discovered automatically by the production units, resulting in a self-adaptation of production behavior. The goal is high-quality production even with wear and tear, reducing unnecessary production downtime and degraded production quality. Another relevant aspect is related to the quality of raw materials (fibers, grains, etc.) or environmental conditions (humidity), which can change. However, material quality and environmental condition impacts production quality in certain industries. To guarantee a continuously high production quality, adaptation of the actual production process of the product is necessary. Today this adaptation requires explicit engineering or an operator who dynamically modifies the actual production process. Automatic adaptation of production processes or advanced decision support for operators would reduce production downtimes and waste, while preserving high quality production. Therefore, industry 4.0 can provide extensive opportunities for the quality management domain. The purpose of this paper is to focus on quality management and industry 4.0 concepts and analyze the current state of literature trying to understand the implications and opportunities in this field. The paper is organized as follows. Section 2 presents the key concepts of quality management while Section 3 describes the research methodology adopted for this paper. Section 4 depicts the literature review and finally, Section 5 provides a critical analysis based on results of the review.

2. Quality management

The quality of products and processes throughout the product lifecycle is a prerequisite for achieving company goals. Quality largely determines the competitiveness of all manufacturers, and high-quality standards require integration of quality processes in all manufacturing companies. The basis for high product and process quality is established in areas of research and development, construction and work scheduling. Figure 1 shows the common methods adopted to improve and manage quality.

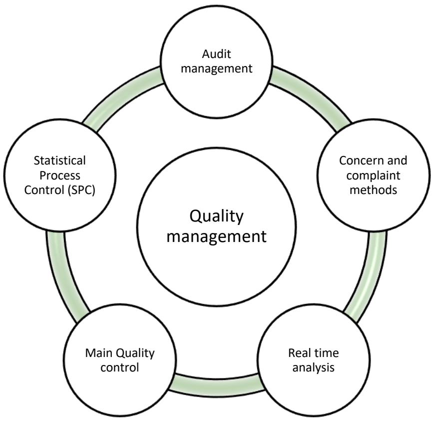

Figure 1: Most common quality management methods

Audit management is based on the execution of internal and external audits to trace working operations and improve the efficiency on project feedback.

Concern and complaint methods allow companies to optimize and align their supply chain procedures with integrated and standardized processes.

Real time analysis is based on data acquisition, which supports continuous process and product improvements and provides multi-level statistical functions.

Quality data management is based on the collection, integration and exchange of data related to customers, suppliers, products and processes in order to improve decision making.

Main Quality control reports on the current quality situation of incoming and outgoing goods in the production process.

Finally, the adoption of a *Statistical Process Control (SPC)* results in a relevant inspection of the overall product manufacturing process, including inspections during product development.

3. Methodology

Quality management in manufacturing system is not a completely new topic, but due to the current market situations and the enhancements in manufacturing technology and information systems, in the emergent digitalization process, its importance raises. Since there are many different approaches towards defining and structuring quality management, a more detailed review of new paradigms is needed. Therefore, a qualitative literature review aims at providing i) the theoretical framework for this research and ii) the definition of key terms and topics related to our study. In order to create a solid base from the best available evidence with respect to our topic, a literature review has been adopted as research methodology. Literature review is considered a rigorous scientific investigation, limiting bias and random error through pre-planned methods and strategies. These strategies imply a search of all significant papers and the adoption of a selected criteria, which can be used by other researchers. Literature review is a suitable methodology for conducting research in the operations management field, which produces a reliable stock of knowledge that can support practical applications. This literature review process is composed of two main steps: i) the relevant papers are identified and analyzed and then ii) these studies are grouped in clusters and relevant data and information are extracted.

4. Literature review

The literature review has been performed by selecting papers from Scopus. Authors chose this database for its ample coverage of articles in this field. It offers search combinations using "and" and the possibility to search for keywords. The qualitative literature review process was composed of two parts: firstly, an explorative unstructured one that had a number of different origins; and secondly, a more structured one involving searching databases using search strings and dashboards.

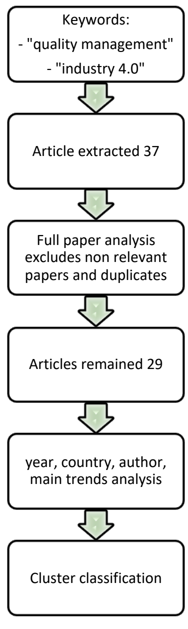

Figure 2: Structure of methodology adopted for literature review

The Authors' strategy was to identify articles that included "quality management" and "industry 4.0" as keywords in all fields. Additionally, the Authors considered various synonyms of each of these terms such as "smart manufacturing" and "smart factory". The aforementioned search technique allowed identification of 37 academic papers, which were rigorously reviewed in order to evaluate their adherence to the study. After reading all the papers, 8 were eliminated and 29 were accepted for further analysis. Of the 8 papers that were excluded, some were duplicated and some were not relevant to the study, they were focused on different fields such as Biochemistry, Genetics, Molecular Biology or Medicine. Then the selected database was analyzed according to the country, publication year, journal and their principle trends. The whole review process is summarized in Figure 2. Figure 3 shows that there is an increase in the number of papers regarding this topic, especially in the last years.

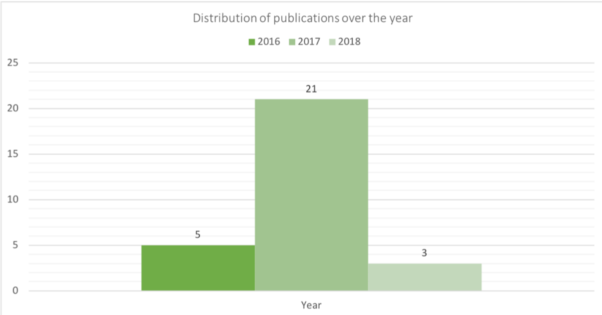

Figure 3: Number of papers by publication year

Regarding the geographical distribution of data, many different countries around the world contributed to this area of research and the papers were based on the main author's university affiliation. One country stands out, Germany. So, this topic is primarily rooted in this country, and partially in countries throughout the rest of Europe and the world. Additionally, there is a considerable contribution from scholars in China and Italy.

Table 1: Ranking of journals by number of publications

Journal title	Publications
IFIP Advances in Information and Communication Technology	2
Lecture Notes in Business Information Processing	2
Procedia Manufacturing	2
International Journal of Quality and Service Sciences	1
Productivity Management	1
International Journal of Innovation Management	1
Computers and Electrical Engineering	1
Sustainability	1

The most prolific authors identified have similar disciplinary backgrounds in operations or supply chain management. Voigt, K.-I., Terzi S., Stjepandić, J. and Philipsen R. lead the ranking with 2 publications respectively. Table 1 presents the list of journals where researches were published. This also depicts the composition of papers; the majority are conference papers (48%) followed by articles (45%) and reviews (7%). Finally, academic papers were examined regarding their major trends, thirty-four different trends were found. As shown in Figure 4, it is fundamental to underline the primary role of digital transformation, sustainability, performance and lean production, which count for five, three, three and three papers respectively, but an important role is also played by trends such as "intelligent technologies", and "ramp up".

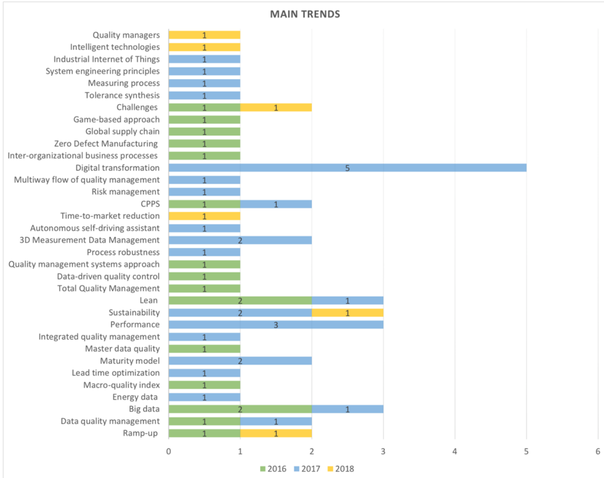

Figure 4: Number of papers by main trends

A database in MS Excel has been created to sort and categorized papers, starting from the main trends of quality management, it is possible to group these contents into five main clusters. The identified clusters are shown in Table 2:

Table 2: Identified clusters

Cluster	Trends	Publications
Digital transformation	Digital transformation, Maturity model	5
Sustainability	Sustainability	3
Lean thinking	Lean, Zero defect manufacturing	4
Performance	Performance, Measuring process, Time to market reduction, Lead time optimization, Macro quality index	6
Intelligent technologies	Intelligent technologies, CPPS, Big data, Internet of Things	5

Figure 5 shows the clusters distribution of grouped publications with reference to the research methodology adopted. Empirical papers are significant with 57% of articles. Of these articles, case studies are the most empirical assessment method (39%) although experimental design is also used (30%). Conceptual papers represent the remaining 43% proposing innovative frameworks to integrate quality management and industry 4.0. Of this 43%, theory building is the most popular research (80%).

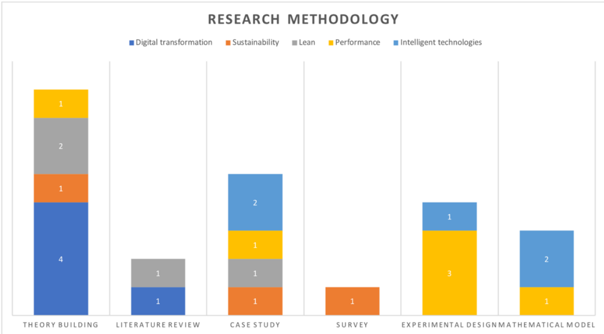

Figure 5: Number of grouped papers per research methodology

Figure 6 shows that most of papers (17) are seen to be "theoretical" studies as they do not refer to specific industrial sectors. Meanwhile of the remaining papers (6), we find that the automotive sector is studied in 50%. All the latter studies (6) focus on manufacturing-oriented sectors therefore, they are the leaders in driving quality management and industry 4.0 implementation. This reflects pressures on manufacturing companies to improve performance and increase product quality.

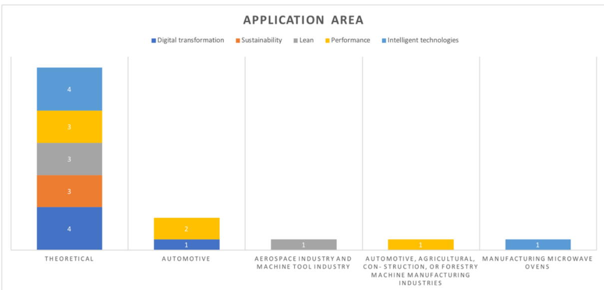

Figure 6: Number of grouped papers per application area

4. Discussion

The first cluster "Digital transformation" is composed of 5 papers (De Carolis et al. 2017; Cattaneo et al. 2017; Emmer et al. 2017; Nienke et al. 2017; Schlüter and Sommerhoff 2017). Schlüter and Sommerhoff describe changes in quality management related to digital transformation, arguing that "a new and agile form of quality management" is mandatory to face the current instable situation influenced by the fourth industrial revolution and the increasing variability. Particularly, they depict the necessary evolution of quality managers who need to be ready for the digital transformation, otherwise they risk becoming "obsolete". Roles in quality management and quality assurance are distinguished by:

- *Top management:* refer to the most senior managers and their extended role.
- *Quality strategist:* is a very creative and formative role, working on quality design and development.
- *Management system administrator:* plans and develops the system architecture and has extensive rights within this context and delegates rights to others.
- *Management system auditor:* this role, which inspects and assesses, needs a special position within the organization with an assumption of neutrality and incorruptibility.
- *Q method expert:* works at the level of process operator and has a methodical and practical approach to solving problems.
- *Q specialist:* is very operative and generally focuses on a narrow, clear range of tasks. Some specialists are mainly focused on suppliers and others on external clients.

Cattaneo et al., underline that the digital transformation results in a more effective integration of a product's life cycle thanks to the real time information acquisition. However, the scope is to understand how this quality data can be used to improve industrial productivity. The answer is to collect information, which can be displayed at the right moment in the right format. Considering the explanation above, the Digital twin (DT) tries to solve the problem of handling large amounts of data that is accessed concurrently and has numerous internal semantic dependencies. The common understanding of the DT is that it is a virtual representation that provides engineering, simulation, or runtime products, with a virtual reflection of the real world throughout multiple phases of the product or plant lifecycle. It stores a broad range of different types of data including operational parameters, behavioral, structural and process models that allow users and machines to find and access the right data at the right time in a secure way (Damiani et al. 2018). De Carolis et al., develop a maturity assessment method to "measure the digital readiness of manufacturing firms", specifically to understand if they are ready for the digital transformation. The maturity levels are: i) Initial, ii) Managed, iii) Defined, iv) Integrated and Interoperable and finally v) Digital oriented. The five levels are assessed analyzing different areas such as design and engineering, production management, quality management, maintenance management and logistics management. The company's digital readiness is assessed through a questionnaire. For example, an assessment factor related to quality management is "how many times the company perform reviews of problems related to product test and quality".

The second cluster is about "Sustainability" and it is composed of three papers (Kiel et al. 2017; Müller, Kiel, and Voigt 2018; Schlüter and Sommerhoff 2017). Kiel et al., focus on the industrial internet of things (IIoT) as the enabling technology which can improve sustainable value creation. What's more, this technology can increase the connectivity throughout manufacturing value chains resulting in increased quality and reduction of costs. Specifically, IIoT provides benefits in terms of:

- Quality optimization of process and product;
- Higher productivity;
- Lower scrap and failures;
- Waste reduction;
- Self-optimization of production lines.

The same topic is analyzed also by Müller et al., who claim that the fourth industrial revolution provides many challenges and opportunity to improve sustainability as well as quality management. Indeed, due to the adoption of innovative business models higher efficiency and quality performance can be achieved. For this, smart products and machines (CPPS) are necessary to increase the company competitiveness. CPPSs can do computations, storing data, communicating and interacting with their environment, monitoring critical process parameters as well as variations in quality autonomously. This high-quality analysis can be done through artificial intelligence abilities, comprising of i) the ability of knowledge creation and reasoning, ii) the ability of automatic scheduling and iii) the specialization and generalization ability. Indeed, the knowledge creation and reasoning ability enables the CPPS to understand the reason for a problem and to find a solution to it.

The third cluster is "Lean thinking" which includes four papers (Eleftheriadis and Myklebust 2016; Jayaram 2016; Mrugalska and Wyrwicka 2017). Eleftheriadis & Myklebust, develop a method "to reach a "near zero" perfection in product and process development". Today's industries are faced with an increasing demand for adaptable production systems. Therefore, to quickly respond to market demands, production systems need to be extended or downsized dynamically without shut-down, and production systems must rapidly adapt to produce new products or product variants. Statistical tools and data collection are traditional methods that can improve the quality; however, due to the increasing amount of data generated by IIoT, CPPS, DT new methods have to be developed in response to the fourth industrial revolution. The scope is to adopt intelligent monitoring of vital process parameters (VPP) to predict undesired process conditions and suggest process corrections as well as real-time adaptive processing for a large range of manufacturing processes. This approach, thanks to the implementation of sensors and monitoring systems, provides detailed documentation of any event occurring during the process. Mrugalska & Wyrwicka, aim to understand if concepts such as Lean thinking and industry 4.0. can coexist and what's more, increase quality, reduce costs and lead times. Examples related to i) smart products, ii) smart machines and iii) augmented operators are presented to support the link between lean manufacturing and industry 4.0.

- *Smart products:* these can gather information about production cycles, quality requirements, waste production from their sensors and actuators.
- *Smart machine:* self-monitoring units reveal degradation of production quality, wear of tools, and analyze the root causes of the problems and trigger appropriate response actions.
- *Augmented operators:* these can reduce the time between failure occurrence and notification by an alert signal on a smart watch. It provides information about both failures and errors on the production line and records it in a database.

Cattaneo et al. claim that lean thinking has great potential in the industry 4.0, as it supports information visualization, problem solving techniques, quality management and employee involvement. Thus, not only can they coexist but their integration can also provide benefits and opportunities. However, they underline that further research is necessary to address several uncovered areas: i) machine-human interaction; ii) industrial productivity in digitalized lean thinking and iii) data management.

The fourth cluster is "Performance", it includes six papers (Brauner et al. 2017; Dossou and Nachidi 2017; Emmer et al. 2017; Li, He, and Zhu 2017; Štofová, Szaryszová, and Vilámová 2017; Szabó 2018). Štofová et al. develop a model of the integrated quality management system based on three levels of decision making in the supply chain: i) strategic, ii) tactical and iii) operational. Furthermore, this model has an evaluation system which includes internal and external environmental conditions as well as Key Performance Indicators (KPIs). Improvement actions are provided in response to the current state measured through the aforementioned KPIs. Indeed, performance measurement is a fundamental tool to detect faults and critical problems. The model uses the Balance score card (BSC) and by grouping KPIs according to the company strategy, it is possible to monitor the effectiveness in the automotive industry. This approach results in an identification of internal and external environmental factors which can vary the quality performance of the company, therefore, the goal is to continuously monitor and control these indicators. Case studies show that a firm can measure its level of efficiency against other companies and understand the impact of their business operations on the BSC. Dossou & Nachidi underline that due to the innovative and technological push of industry 4.0, which provides an increase in production quality while reducing lead times, waste and costs, a process standardization is needed to enhance these improvements. They propose a formalism related to performance criteria, underlining that indicators are the simplest tool to measure the current state of the company and compare it to its desired future state. Specific attention is paid to lead time to improve global supply chain performance. Lead time considers several phenomena and nonlinear changes with production type, scheduling and human/technical resources. Therefore, a proper approach allows representing, predicting and controlling the supply chain lead time to improve a manufacturer's reputation. A model-based control is implemented using an artificial intelligent based method which aims at predicting lead times, increasing the level of automation and taking into account employees' ergonomics. Szabó focuses on the ramp up concept. The parallelization of product and production development results in frequent changes of production processes in the initial phases of production. In particular, changes in product design regularly require changes in arrangement and configuration of production equipment. Current practice is to start with a mostly manual production organization and then continue with automation once production is in a stable state. Such practice leads to an increase of manufacturing ramp-up fixed costs of 10% - 15%. In mass production, these costs are quickly absorbed, but with self-adaptation in response to changing production demands, these costs can be further reduced. Plug & Produce capabilities and DT of future production equipment can result in faster installation and commissioning of production lines, with corresponding savings in engineering costs and a faster ramp-up of the actual production.

Finally, the last cluster takes into account "Intelligent technologies" including CPPS, IIoT and Big Data (Kiel et al. 2017)(Stojanovic et al. 2016)(Brauner et al. 2017)(Li et al. 2017)(Song et al. 2017). Song et al. claim that CPPS sets a significant challenge in relation to data quality and therefore their focus is on developing effective policies to manage this data. With this in mind, they develop a "two-stage optimization model for data quality". The model defines optimal resource configurations in error types and probabilities. It employs workflow-nets to view model behavior, facilitating the capture of the static and dynamic attributes of data errors. They provide a quantitative analysis of control costs and the risks associated with data errors. Stojanovic et al. pay attention to Big Data, they develop an approach for data driven quality management to provide multidimensional analysis to detect failures and anomalies in real-time. The model is composed of two main steps: i) understanding the normal system's behavior and ii) identifying anomalous behaviors. They underline the importance of real-time data processing in order to understand variations/deviations in a process/product parameter that can lead to a decrease in the quality. This process is established in the SPC. Then the usual behavior of the system is defined through data clustering, which identifies groups of similar objects. Furthermore, based on the past data it is possible to identify clusters of usual behavior and use their characteristics as thresholds required for real-time processing. Kiel et al. in their work show a structured view of IIoT using a multiple case study approach. They claim that the IIoT aims at optimizing quality through intelligent testing and control loops, which once again results in higher productivity, machine availability and production process robustness. In addition, lower scrap and failure rates can reduce production delays and downtimes creating more robust output rates. Smart processing of supply chain quality data allows an increase of process flexibility, space and stock reductions and self-improving procedures (Burger et al. 2017). IIoT is particularly beneficial for those companies that focus on efficiency and operational excellence such as the automotive sector, and through its virtualization and simulation possibilities it priorities cost reduction potentials of complexity, quality, maintenance and inventory.

The cluster analysis shows that automatic adaptation of the production process has been identified as an area with considerable potential. For example, in response to a reduced quality of material, an adjustment of the production process can guarantee continuous product quality. Thus, thanks to the adoption of innovative technologies such as CPPS, it is possible to have a clear vision of how they can change today's production technology, mostly in the areas of quality, production planning, ramp-up, optimization, and disturbance scenarios. CPPS can observe the quality of their actual production, if a degradation of the production quality is observed, the unit checks if this degradation can be mitigated by adding additional "repair" production or changing configuration parameters of subsequent production or processing steps. In addition, CPPS learn to predict the expected performance of their own production, analyzing relevant KPI like production time, costs, and quality. Several key deductions can be made from the quality management and industry 4.0 integration literature review including:

- The relationship between sustainability, quality management and industry 4.0; only three papers cover this area and therefore it needs to be explored in more depth;
- Quality management and industry 4.0 can provide relevant benefits to improve the overall supply chain performance. This is demonstrated as being the most covered cluster with six papers;
- The "digital transformation" and "intelligent technologies" clusters are identified as an area with considerable potential for quality management as these technologies can produce huge amounts of data related both to production and product quality;
- The integration between digital technologies and lean thinking seems to be reasonable and beneficial, but more research is necessary to understand how this matching can improve productivity and quality;
- The high percentage of conceptual papers fails to grasp the practicality of digital transformation and therefore the implementation of these enabling technologies remains at a "conceptual level".

5. Conclusions

In this paper, a review of the quality management and industry 4.0 has been performed with the aim to explore unrevealed potential for integration. 29 papers were identified as relevant to this review between 2016 and 2018. Therefore, this topic started to be studied in more depth over the last two years. Nevertheless, it must be said that only 29 articles have been identified, therefore it can be assumed that there is a lack of knowledge on this topic and that the integration of quality management and industry 4.0 is an emerging area. The current industry 4.0 trend, that characterizes quality management, can be recognized as "Digital transformation", "Sustainability", "Lean thinking", "Performance" and "Intelligent technologies" clusters. Industry 4.0 embraces various technologies and presents different application fields, many of which, will influence quality criteria of the next generation production systems. Indeed, through the machines connection and the product and components traceability, an intelligent network has to be built to autonomously control production processes in quantitative and qualitative terms. This work aims to provide an insight into the rising opportunities for quality management combined with Industry 4.0 and presents an in-depth analysis for further research in this area based on the study of the relevant trends that are emerging. The aim is that both researchers and practitioners can benefit from this review to understand the future directions in this continuously developing field.

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