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Chapter

Smart Manufacturing: Quality Control Perspectives

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Abstract

Quality Control (QC) is a guideline or set of procedures intended to ensure that a manufactured product or performed service adheres to a defined set of quality criteria or meets the requirements of the client or customer. Smart manufacturing is where the work is interfaced work pieces and associated tools that include logistics operations, Cyber Physical Systems, Artificial Intelligence, and Big Data Analytic tools. These form the norm of manufacturing operations to generate large amounts of data, which are used for analysis and prediction. Therefore, help to optimise the quality of manufacturing operations and manufactured products. The change in technologies have, however, altered the traditional way of manufacturing process as well as QC systems. Therefore, to address the challenge of data reliability, the sensors, actuators and instruments used at various levels of integration in the manufacturing process often operating under adverse physical conditions need to provide adequate levels of data accuracy and precision. Methodologically, the Chapter followed critical literature review on QC concepts and Industry 4.0 revolution, thereby culminating into conceptual framework of QC in Smart Manufacturing, which is the main contribution of this Chapter.

Keywords: Industry 4.0, quality assurance, total quality management, organisation, artificial intelligence, big data analytics, logistics management, supply chains

1. Overview

The Chapter examines the Quality Control (QC) in Smart Manufacturing or Industry 4.0 Revolution. First, the Chapter begins with an examination of the historical development of QC from the Middle Ages (pre-Industry 1.0 revolution). Second, gives an overview of evolution of Smart Manufacturing and Quality Control, with emphasis on chronological trends of Industry revolutions up to date. Third, the concept of QC from the Middle Ages to 20th century. Fourth, it conceptualised the QC in Smart Manufacturing or Industry 4.0 revolution. Fifth, the Chapter gives an in-depth evolution of QC into Smart Quality Control Systems (SQCS) or Intelligent Quality Control Systems (IQCS), benefits, and lastly, summary of the Chapter.

1.1 Introduction

Historically Quality Control (QC) can be traced back to the times of pre-Industry 1.0 revolution when the modes of productions were still in their infant stage or Iron Age. During this period Human to Machine (H2M) interactions were still not

common in the manufacturing/assembly lines. And humans were not specifically and strategically positioned within the production lines to ensure that products, which do not meet specifications are eliminated before end of the production processes. This is because the production was always manned by Artisans working with some few workers using simple and less mechanised tools of production. The manufacturing processes continued with the Artisans being solely responsible for the product quality, while the consumer was expected to apply the principle of '*Caveat emptor*' when buying products [1]. Although it should be noted that, there were some punitive measures put in place to guard against unscrupulous traders who could take advantage of the customers. This method of quality control continued until the advent of Industry 1.0 revolution, which brought some remarkable improvement on the ways and methods of productions. However, it is not possible to discuss QC without discussing how the modern quality systems have evolved. First, modern "Total Quality Management" emerged as a subset of Quality Control (QC), whose sole purpose was to ensure that entire production systems (from inputs to outputs) followed set standards. Total Quality Management (TQM) origin can be trailed to the early 1920s, the time statistical theory was introduced to product quality control. TQM's idea was further advanced in Japan in 1940s by three Americans namely Deming, Juran and Feigenbaum [2]. To date QC has followed the same standards of inspections of inputs (raw materials) before the production/manufacturing processes (assembly lines) and outputs (final products) reach the market.

The development of the present QC can be traced to the period of Hawthorne studies between 1924 and 1932, which highlighted the significance of social and psychological work climate [3]. In the same period, Shewhart also developed Statistical process control, which later became known as "Statistical Quality Process" (SQP). Statistical Quality Control (SQC) emphasised the products' design and production. Over the years though the concept of quality has developed into a discipline, a complex set of principles and assumed truths that define quality of goods and services is to be assessed, managed, delivered and assured [3]. During and until late into Industry 1.0 revolution, quality could be best described as "*caveat emptor*", which means, let "*the buyer be aware*". The manufacturers, artisans and industrialists produced goods of certain quality, but it was up to the consumer/buyer to appraise the quality of these goods. Thus, the consumer/buyer became responsible for the assurance of the goods they purchased [1, 2]. In the pre-industrial era, the quantity and quality of goods were the essential characteristics defining an economic transaction. In other words, "the qualities of the goods were known by their colour, sound, smell, taste, make, or shape [1, 4]. These forms of judgement made it problematic to differentiate the features that are the appropriate evaluators of those products. The problem is further compounded by the fact that people do differ very much; some person have clearer eyes, peculiar ears, noses, and tastes. In fact, the truth is every person having a good opinion of his/her faculties; therefore, it is difficult to find assessor to establish which is best" [4]. This approach makes quality to be more subjective and experiential. However, as progress made, through industrial evolution, and automation increased in the applications of manufactured goods, the level of product and process complexity, hence a new paradigm of quality control was borne, coinciding with a broader set of changes taking place under the realm of scientific management.

From Industry 1.0 to Industry 3.0 revolution, a lot of changes have been made in manufacturing lines/assemblies with the aim of producing products that meet customers specific needs. However, with the entry into Industry 4.0 revolution, organisations have moved from Human to Machines (H2M) production to Machine to Machine (M2M) intensive production, altering the way QC is managed in the manufacturing processes. Industry 4.0 revolution or Smart/digital manufacturing,

with more emphasis on Big Data Analytic, Cyber-Physical Systems, 3-D printing, interface between M2M and Artificial Intelligence in the manufacturing processes [5]. Artificial intelligence (AI) can be conceived as the simulation of human intelligence in machines that are automated to think like humans and can imitate human behaviours [6]. This term may also refer to any machine, which displays attributes related to human minds such as learning and problem-solving.

1.2 Evolution of smart manufacturing and quality control

The fourth industrial revolution, or Industry 4.0 revolution (I4.0R), has become a reality today (**Figure 1**). The political debate about the term Industry 4.0 revolution focuses equally on the important and abstract objectives. For its promoters, Industry 4.0 revolution, though coined in Germany is not only about improving Germany's international competitiveness, but also perceived as means for solving some of the urgent global problems for example, climate change that has created new demand for the increased consumption of renewable and non-renewable resources. While some of the problems are specific national challenges such as, labour supply that is ever-changing due to demographic shifts [7, 8], Industry 4.0 revolution is focused on smart products, procedures, and processes (smart production). A key element of Industry 4.0 revolution is, therefore, the Smart Manufacturing (**Figure 1**). Smart Manufacturing or Industry 4.0 revolution are Cyber-Physical Systems, physical systems integrated with ICT components. These are autonomous machines that can make their own decisions based on machine learning algorithms and real-time data capture, analytics results, and recorded successfully past behaviours [9].

The Smart Manufacturing controls the fast-growing complexity, while also boosting production efficiency. Therefore, Smart Manufacturing is about direct communication between man, machine and resources to produce Smart products and services. Furthermore, Smart products know their manufacturing process and

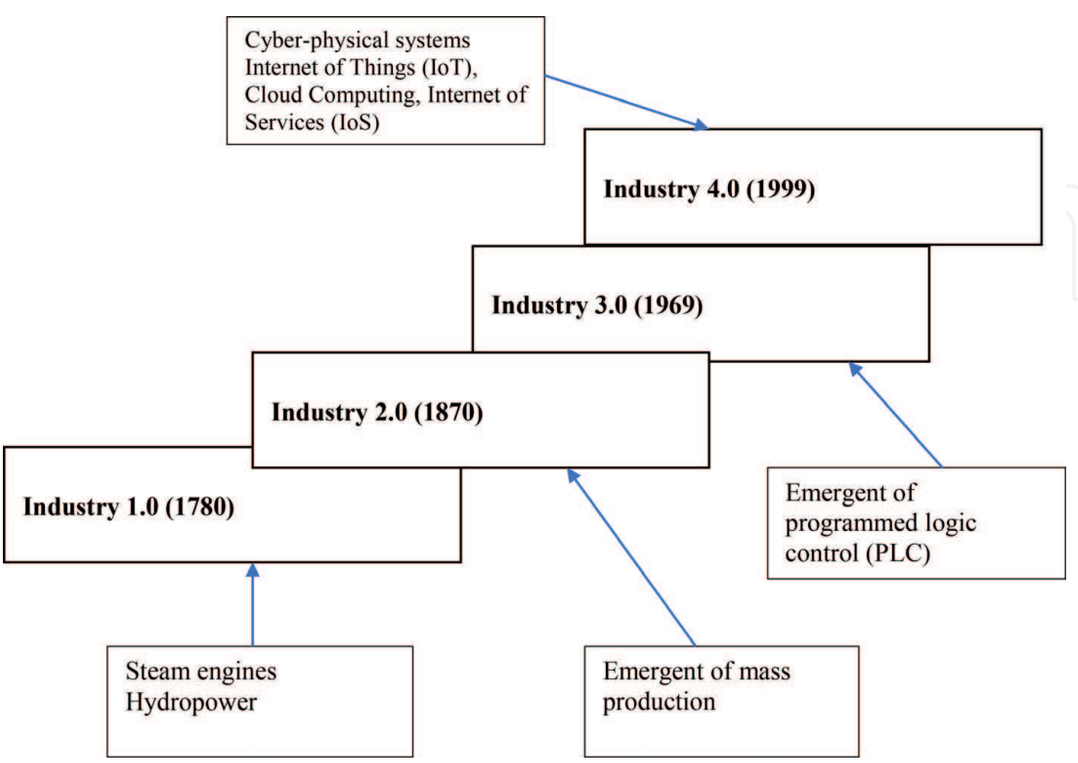


Figure 1.
Chronology of industry revolution. Source: Author's own illustration.

future applications. Equipped with these types of knowledge and intelligence, these gadgets actively support the production and documentation process. This will create value chain capable of answering questions such as ("*when was the product made, which parameters to be given to product, which destination is product intended for?*") [10, 11, 13]. These interfaces to smart mobility, smart logistics, and smart grids make Smart Manufacturing an important element of future smart infrastructures. Conventional value chains will thereby be refined, and totally new business models will become established [12, 13].

Industry 4.0 revolution concept, therefore, encompasses not only value creation, but also work organisation, business models and downstream services. It performs this by using information technology networks of production, marketing and logistics. This enables it to capture all resources, production facilities and warehousing systems. The re-organisation thus, extends from the energy supply and smart power grids through to advanced mobility concepts (Smart mobility, Smart logistics) [12, 13]. However, on the technical side the concept is based on integrating Cyber-Physical Systems into production and logistics. In this Smart environment the concept of the Internet of Things (IoTs) and services that were already devised a decade ago have actually now become a reality. This process involves developing people and capital mobility, changing modes of production, consumption, learning, working and leisure, and increasing world-wide competition. In the subsequent subsection, we try to highlight the concept of quality control in Smart manufacturing.

2. Concept of quality control (middle age to 20th century)

Quality is as old as mankind on earth. It is possible that the quality of goods and services rendered has been monitored, either directly or indirectly since time immemorial [1, 2]. In the ancient Egyptians history, a commitment to quality in their pyramids was well demonstrated, similarly with the Greek architecture of the 5th century B.C. Such quality of work was evidenced in Roman-built cities, churches, bridges and roads that inspire the modern constructions [1, 2]. From the Middle Ages up to nineteenth century, the production of goods and services were predominantly confined to Artisans, a single person or small groups. These groups were mostly family-owned businesses, hence the responsibility for controlling the quality of a product or service rested with the Artisans or small groups [1, 2].

The quality of the goods and services rather followed the principles of "*caveat emptor*" as a single person controlled both the processes, leaving the buyer to determine the of the quality. This was pre-industrial revolution period. The phase comprising the time period up to about 1900, has been labelled the "*operator quality control*" period [14]. Then, the question is, what really motivated the Artisan or worker to continue producing quality goods and services? Perhaps, the worker took pride in total control of both number of products produced and the control of quality of such limited goods, hence a feeling of a sense of accomplishment, which lifted morale and motivated the worker to the new heights of excellence [2]. Therefore, controlling the quality of the products was embedded in the philosophy of the worker because a pride of workmanship was widespread. The "operator quality control" phase covered the entire pre-industry 1.0 revolution through to Industry 2.0 revolution.

However, beginning the early twentieth century through to 1930, a second wave evolved, that was referred toas the "*Foreman quality control*" [2, 14]. With this came Industrial revolution resulting in Mass production, which was based on the principle of the division of the labour specialisation. This principle placed emphasis on putting or assigning each worker according to their areas of skills and knowledge,

for example, those workers who technicians, were grouped together, those skilled in the production were grouped also as such, and so on. That means no one person was entirely responsible for production processes, but rather a portion of it. But soon, the approach suffered some drawbacks as workers lost sense of accomplishment and pride in their work. This is because the workers could no longer control the entire production processes of the product being produced as before. Though most tasks were still not very complicated, and workers became skilled at the particular operations that they performed [2]. People were grouped together according to the tasks performed, for example, production units and assembly lines. A supervisor who directed the operation had the task of ensuring that quality was achieved. Foremen or supervisors controlled the quality of the product, and they were also responsible for operations in their span of control [2].

Then there came the period from 1920 to 1940 or World War II period, which saw the next phase in the evolution of QC. This period was known as the "Inspection quality control" [14]. The introduction of improved machines and equipment for industrial and manufacturing as a result of Industry 2.0 revolution, and increased demand for industrial and manufactured goods due to World War II, resulted in increased production volumes. However, as workers who were reporting to one foreman grew in numbers, it became apparent that these workers needed to be kept under close watch as a way to have control over the operations. This resulted in inspectors being assigned the tasks of quality check of the product after certain operations were completed [2]. Quality standards were set, and the inspectors compared the quality of the items produced against those standards. Any product found not meeting the set standards or, defective was put separately from those that met standard. The nonconforming products were reworked, if possible, or rejected altogether. It is at this period that the aspects of Statistical Quality Control (SQC) were being developed in the United States, however, it did not immediately gain wide usage in the United States industries [2]. Walter A. Shewhart of Bell Telephone Laboratories proposed the use of statistical charts to control the variables of a product, which later became to be known as "Control charts" (or Shewhart control charts). These played a vital role in Statistical Process Control. This was followed by H.F. Dodge and H.G. Romig, also from Bell Telephone Laboratories, who also pioneered work in the areas of acceptance sampling plans. These plans were to later to substitutes for 100 percent inspection [2].

The eve of 1930s saw the application of acceptance sampling plans in industry, both domestic and abroad. Walter Shewhart continued his efforts to promote to industry the fundamentals of statistical quality control (SQC). In 1929, he obtained the sponsorship of the American Society for Mechanical Engineers (ASME), the American Statistical Association (ASA), and the Institute of Mathematical Statistics (IMS) in creating the Joint Committee for the Development of Statistical Application in Engineering and Manufacturing. During these periods, the interest in the field of QC started to gain acceptance in England. The British Standards Institutions Standard 600 (BSIS-600) dealt with the applications of statistical methods to industrial standardisation and QC [2]. In the United States, J. Scanlon introduced the Scanlon plan, which dealt with improvement of the overall quality of work life [14]. Thereafter, the U.S. Food, Drug and Cosmetics Act 1938 had jurisdiction over procedures and practices in the areas of processing, manufacturing, and packaging.

The next phase of QC was the evolution process of the Statistical Quality Control (SQC), which took place between 1940 to 1960 [2, 14]. During these periods, the production of industrial and manufactured goods increased as a result of World War II and population explosion. However, because of mass production, 100 percent inspection became impossible, hence opening the way to the sampling plan [2].

In 1946, the American Society for Quality Control (ASQC) was established and immediately got renamed the American Society of Quality (ASQ). Then later on, the U.S. Military in 1950 developed a set of sampling inspection plans for attributes called MIL-STD-105A, which was modified to MIL-STD-105B, MIL-STD-105C, MIL-STD-105D and MIL-STD-105E. This was later followed by a set of sampling plans by the U.S. Military in 1957 [2].

After suffering humiliating defeat at the hands of the allied forces in the World War II in 1945, Japan wholeheartedly embraced the philosophy of SQC. This is after W. Edwards Deming visited Japan and lectured on these new ideas in 1950, which convinced Japanese engineers and top management of the importance of SQC as a means of gaining a competitive edge in the world market. The next person was J.M. Juran, another pioneer in QC who also visited Japan in 1954 and impressed upon Japanese on the strategic role top management plays in the achievement of a quality programme. The Japanese seized this opportunity and immediately realised the profound effects that these principles would have on the future of business, hence made a strong commitment to a massive programme of training and education [2].

The changes in quality swept through Industrial 1.0 to 2.0 revolutions, when the new paradigm that we all know as the '*quality control*' was borne. During this period, quality experts Edwards, Juran and Feigenbaum called upon the management to be more responsible, and responsive, to the issue of quality. [15] went further to state, "It is most important that top-management be quality minded". This sentiment was followed by [16], who echoed the significance of management commitment, "I submit that to enable QC to be really effective, we must work on making QC a member of the regular management team". Feigenbaum came up with an idea on organisation-wide efforts into the concept of "Total Quality Control" (TQC). The ideas behind TQC was that to provide genuine effectiveness, then real quality control management must start with the design of the product and end only when the product is finally with the consumer, who must remain satisfied, therefore quality was seen as everybody's business" [1, 17, 18]. However, it is worth noting that, the present QC manifested from Japanese, who revolutionise QC into the concept of "Total Quality Control". In their quest to revive home industries, after humiliating defeat in the hands Allied forces, the Japanese turned around their ailing industries after listening to Deming's lectures. Japanese TQC was manifestation of the third paradigm of the quality discipline, "Total Quality Management". This later on were embraced world over, though the concept originated in Japan.

2.1 Definition of quality control

The term 'quality' in essence means different things to different people. This is because people value different features of a product, some view quality as product package, price, colour, durability etc. However, [19] defines quality as, 'degree in which a set of inherent characteristics satisfies the requirements. The question is, what are these 'inherent characteristics' that a product must satisfy? The question can better be answered by; *first*, product values must meet or exceed the expectation of the final consumer. *Second*, overall quality- products, processes, systems, machinery and equipment must meet the statutory and contractual quality requirements [20]. Quality is not merely a monitoring tool by organisations, but rather should be viewed as a mechanism for anticipating problems, preventing them from occurring, and, ultimately, if they occur, solving them [20].

The importance of quality control ranges from good image, increase in sales volumes and competitiveness, good reputation, customer loyalty, just to mention a few. Global competition, customer heterogeneity, and technological change have

altered the way the QC should be carried out in organisations. The traditional quality control has been rendered nearly obsolete by Industry 4.0 revolution technologies such as Big Data Analytics, Artificial Intelligent (AI), Cyber Physical Systems (CPS), Augmented Reality (AR), and Robo-Mate System gave birth to Smart Quality Control Systems (SQCS) or Intelligent Quality Control Systems (IQCS) as Manufacturing processes transforms itself to Smart Manufacturing [21, 22]. In Smart Manufacturing, AR can allow production managers to view productions KPIs and have an intra-factory overview of workstations and production lines in real-time for monitoring, identifying, analysing, diagnosing and resolving problems and flaws, a thing that used to be performed by human working in the production line. In the following subsection, we discuss the quality control in Smart Manufacturing.

2.2 Concept of quality control in smart manufacturing

Although the past three Industrial revolutions had quality control (QC) well entrenched in the manufacturing and industrial complexes, the application of the QC was more routine based on sampling plans and inspections. This was due to the fact that the three industrial revolutions' manufacturing and industry were characterised by mechanisation, waterpower, and steam power (Industry 1.0 revolution); Mass production, assembly line, and electricity (Industry 2.0 revolution). The distinctive features of these two Industrial revolutions were that they were both labour intensive, therefore, division of labour with emphasis on specialisation. However, Industry 3.0 revolution was anchored on computerisation and automation, hence eliminating some manual work that were carried out by human beings. Goods produced were of high quality compared to the previous two Industry revolutions as automation and computerisation were both introduced into the manufacturing and industrial complexes to aid in QC [23, 24]. The question is how do quality control (QC) works under Smart Manufacturing? In the subsequent section, the Chapter reviews some of the current literature to conceptualise QC in the Smart Manufacturing context.

2.3 Intelligent quality control systems

The concept of Intelligent Quality Control Systems (IQCS) or Smart quality control systems (SQCS) is founded on the premise that, in Smart Manufacturing production, quality control (QC), is driven by the infusion of Big Data Analytics, Artificial Intelligence (AI), Cyber-Physical Systems (CPS), Robotics and intensity of Human-to-Machine (H2M) interactions. The concept replaces the traditional QC systems in the manufacturing processes, as automation take over most of the operations or tasks that were routine tasks performed by human. Smart quality control is mainly executed to physically manage various Smart machines or tools through a cloud enabled platform. These technologies are capable of communicating both with the products (Smart products) and their environments. They are capable of detecting any slight defects and delays that could hamper manufacturing processes, and then communicate the same to the shopfloor, using fitted sensors [22, 25]. These gadgets work autonomously to create seamless communication between themselves. For example, [21, 26] installed sensors, utilised simulation and AI techniques assist in design and implementation of automatic machine model that predicts machine health status, which in turn can diagnoses any quality defects that could results from the machining failures. This result in a cost-effective solution in monitoring the production process to improve the quality of the products based on Industry 4.0 technologies.

Therefore, QC in Smart Manufacturing or Industry 4.0 revolution seem to take a different route as Industry 4.0 revolution is envisaged to leverage on a holistic automation, business information, and manufacturing execution architecture to improve industry with integration of all aspects of production and commerce across company boundaries for greater efficiency [27]. Industry 4.0 revolution is a complete departure from past three predecessors in several ways. First and foremost, Industry 4.0 revolution has come with Smart factories, Industrial Internet of Things, Smart Manufacturing, and Advanced Manufacturing, which were not experienced or witnessed in the past three successive Industrial revolutions. Second, Industry 4.0 revolution workplace emphasises so much on the Smart workers, Cyber Physical and Robotics in all the sphere of its Manufacturing and Industrial operations. The Internet of Things (Smart manufacturing, Additive Manufacturing, AI) have transformed the traditional production process of assembly lines with the introduction of asynchronous systems where predetermined workflows based on production work orders are running enterprise business systems [27]. Hence, making production steps that are centrally in communication to each Manufacturing station, which is harmonised with the assembly line.

In contrast, asynchronous manufacturing is based on I4.0 revolution concept in which components in the production flow using auto-identification technology to inform each machine and operator on what needs to be done to produce customised end product. This activity takes place at each step of the production process. In this process, the machines are more flexible, which make them adaptable to the requirements for the part being made at each production steps. This entire concept is a product of Industry 4.0 revolution. The systems assist in achieving a highly flexible, lean, and agile production process that allow for a variety of distinctive products to be produced in the same production facility. The process is based on the premise of profitable mass customisation that enables the production of small lots (even as small as single unique item). This is due to the ability to rapidly configure machines to adapt to customer-supplied specifications and additive manufacturing [27]. **Figure 2** below gives a snapshot of Manufacturing production process and the quality control under Smart Manufacturing. Inputs- denotes Smart raw materials, and Smart workers that are capable to communicating with Robotics to execute the tasks. Such systems comprise production facilities, storage systems and smart machines which trigger actions, exchange information complete autonomously and are able to control each other independently [8, 28].

Smart raw materials will be detected by machines without necessarily having to be verified or inspected as the case in the past. The machines fitted with sensors will be able to differentiate between quality inputs (Smart raw materials) and defects, if possible reworked, or discarded all together, a thing that was formerly done by human beings in the traditional manufacturing set up (see, **Figure 2**). Inputs will have Smart workers, who are capable of interacting with computers and Robots. The Smart Manufacturing is fully equipped with actors, sensors and CPS where

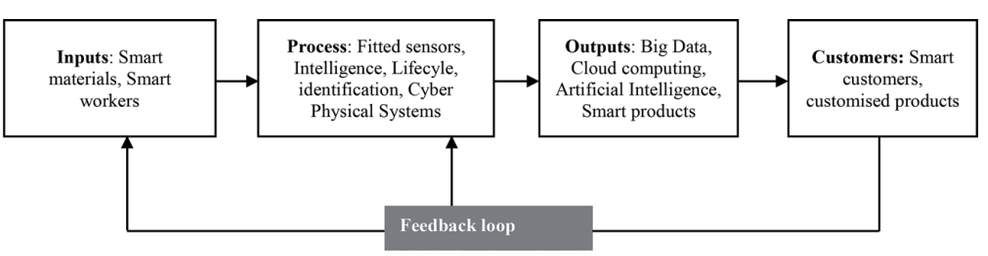


Figure 2.
Intelligent quality control Systems in Smart Manufacturing. Source: Author's own illustration.

"human beings, machines and resources communicate with each other as naturally as in a social network" [8, 28] as shown in **Figure 2**.

In **Figure 2**, Smart Manufacturing process begins with the input as smart material (because these materials are fitted with microchips, sensors), which enable them to be recognised and detected by the intelligent machines. The fact is, the material can be configured or reconfigured according to the Smart Manufacturing requirements, if found not to meet the specific product manufacturing specifications, then it can be discarded or reworked. This allows for the smooth flow of manufacturing process. This results in an improved finished product quality and reduced level of production errors [5, 25]. The implementation in the technology production process namely, ICTs, sensors technology and robotic technology, have the ability to record the production process in each element (instead of sampling and control) and detecting errors that occur during the process [25]. If errors occur or are detected, the machines can be adjusted in real time accordingly.

In the manufacturing process, there are Smart machining, Smart monitoring, Smart control, and Scheduling (**Figure 2**). Cyber-Physical Systems enable Smart machine tools to capture the real-time data and send it to a cloud-based central system so that machine tools and their twined services could be synchronised to provide to Smart Manufacturing solutions. While, Smart monitoring, monitors the operations, maintenance, and optimal scheduling of manufacturing systems. Smart monitoring assist in Smart Manufacturing by giving warnings/alerts if some abnormality occurs to machines/tools. In addition, Smart control, though can be executed to physically manage various smart machines or robot through Cloud enabled platform [5] but do allow the end-users to switch off a machine or robot via their Smartphones [29]. This allows the decisions to be reflected in frontline manufacturing sites such as robot-based assembly lines or Smart machines (**Figure 2**). Then finally, Smart scheduling which includes advanced models and algorithms draw on data captured from sensors [5]. These data-driven techniques and advanced decision architecture is used in smart scheduling. **Figure 2**, with the assistance of data input mechanisms, the output resolutions are fed back to the parties through various means (feed loop) [5, 30]. **Figure 2** for example, comprises Big Data, Clouding Computing, Internet, Simulation, Artificial Intelligence, and System Integration, which represent technologies, such as Additive Manufacturing, Autonomous Machines, and Human -to-Man (H2M) integration. These produce faster, stronger and more consistent than workers with a combination of new sensors and actuators and extensive data analysis [25].

In **Figure 2** above, process represents transformation process of Smart raw materials into final products. Industry 4.0 revolution comprises a high-resolution, adaptive production control (APC) such as Smart Control that can be achieved through development of Cyber-Physical production control systems [10]. In addition, Smart control is mainly executed to physically manage various Smart machines or tools through a cloud enabled platform [31]. End-users (Smart customers are able to get a smart product, which are tailored-made according to their personalised needs. In addition, smart customers are able to interact with smart products from smart manufacturing and could easily identify with such products. And if the product fails to meet their specifications [29], the decisions could then be timely reflected in frontline manufacturing sites such as robot-based assembly lines or smart machines [32], as shown in **Figure 2** above. For instance, the Smart quality control in Smart Manufacturing is well illustrated by Changying Precision Technology Company's factory in Dongguan city. This is the first unmanned factory run by computer-controlled robots, numerical control machining equipment, unmanned transport trucks, and automated warehouse equipment. It is said that about six hundred human assembly-line workers were replaced with this automation alone. The result

was a fivefold reduction in manufacturing errors and an increase in production of more than 250 percent [27, 33]. This is a typical example of how quality control (QC) in Smart Manufacturing has been operationalised.

Smart Manufacturing or Industry 4.0 revolution is built around the concept of self-control or managing production processes requires open software and communications standards that allow sensors, controllers, people, machines, equipment, logistics systems, and products to communicate and cooperate with each other directly [5, 27]. This simply means the use of human beings in the manufacturing process particularly in the production/manufacturing processes as quality control inspectors, is minimised, if not eliminated. However, to embrace Smart Manufacturing in sustainable way, require that Manufacturing industries adopt technologies transformations with training and development programmes in order to fit their workforce with the new workplace requirements, such as new tools and technologies [11, 34]. This will ensure that gaps in skills and knowledge created by the Smart Manufacturing technologies do not have serious impacts on the workforce work life. Therefore, the implementation of Smart Quality Control Systems (SQCS) or Intelligent Quality Control Systems (IQCS) in Industry 4.0 requires further employee skills and competencies, such as ICT know-how, interdisciplinary competencies and special personality traits [34, 35]. This is because Human-to-Machine (H2M) collaboration that is necessary as some production tasks are too unstructured to be fully automatised.

In the production assembly/manufacturing assembly, Virtual Reality (VR) and operator create 'cognitive interaction'. For example, VR technology provides a combination of interactive reality and advanced simulations that can replicate a design, assembly, or manufacturing environment and allow the smart operator to interact with any (Machine tools, production line, hand-tool, a robot, a factory), with reduced risk and real time feedback as shown in **Figure 2** [11]. In addition, VR, at product assembly stage, CAD models of parts, hand tools, and assemblies can be transformed into interactive simulations (assembly sequence). This can be used in the training of operators working in a complex assembly tasks, and at product manufacturing stage. [11] opine that VR brings to life the "virtual factory" as an integrated simulation model of the major subsystems of a factory layout (such as arrangements of machinery, equipment and inventories for smooth flow of work, material and finished products). These arrangements form continuous communication between humans to machines and products during the production process. This is enabled by Cyber-Physical Production Systems (CPPS) in order to execute its tasks. The overall aim is to decrease cost, time efficiency, and improve product quality, which requires a broad understanding of the enabling technologies as well as methods and tools [13].

Products in Smart Manufacturing are 'Smart', with embedded sensorics that is used via wireless network for real-time data collection for localisation, for measuring product state and environment conditions [9]. In **Figure 2**, Smart products have control and processing capabilities, thus control their logistical path through the production and even optimise the production workflow. In addition, Smart products are capable of monitoring their own state during the whole lifecycle, including their lifetime or application [9].

Already in use is the intelligent Quality Control Systems (IQCS), which has replaced the traditional QC in the manufacturing processes. In Smart Manufacturing, all aspects pertaining to products quality control are first defined. In the first step, the technical requirements for the quality control system in development are defined and documented. In addition, the final document is intended for as a working-document supporting the requirements process during the development of the quality control systems [13]. The introduction of intelligent-based

quality control necessitates integration steps within and outside the manufacturing industry. It affects sensors and actuators as well as general manufacturing processes, like information and documentation flows. Furthermore, manufacturing partners or customers have to be integrated into the development as they are all part of the overall value chain (see **Figure 2**).

2.4 Benefits of intelligent quality control systems

IQCS brings with it several benefits to those organisations that will be able to adapt the new technologies in Smart Manufacturing processes compared to traditional quality control has been part of the manufacturing processes in the previous three industrial revolutions. Such benefits are summarised as follows:

- "Time to market" to develop, produce and market new products and services, requiring higher and faster innovation capability [36]. This is due to the cutting-edge technologies such Additive manufacturing, Industrial Internet of Things (IIoTs), Augmented Reality and Virtual Reality. These have eliminated wastes that were formerly associated with human errors hence creating lean production of products that are competitive globally. Augmented Reality (AR) assist in reducing defects, rework and redundant inspection by offering intuitive information and combining operator intelligence and flexibility with error-proofing systems to increase efficiency of manual work steps, while improving the quality of work [9, 11].

- Increased "customisation" to satisfy individual consumer demands, in a buyer' market, not anymore a seller's one, leading to higher product individualisation; meaning products may not need to be produced in mass as before, because the manufacturers will be able to produce very small series (single product if needed). This technology provides fast configuration of machines and production process, as well as their adaptation to customer requirement [25].

- Higher "flexibility" with faster and more versatile production processes able to produce smaller lot quantities with high quality and a cost-effective way [9, 22, 36].

- "Decentralised" decision making with fewer organisational hierarchies be reduced.

- Increased resource "efficiency" by using more efficient and closed loops, regenerative, and restorative physical and economic cycles, where products and raw materials retain their physical characteristics and value as much as possible [9, 36].

3. Summary

Quality control (QC) has evolved from the Middle Ages to the present time, with the changes in manufacturing industries. As industrial revolutions transformed itself, so is the QC systems. First QC started as '*caveat emptor*', whereby the control was entirely in the hands of Artisan, and it was the responsibility of the customer to ensure that the product is of quality. This was followed by punitive measures imposed on the Artisan who produces inferior products. From there came the '*operator quality control*' (OQC). The operator was to ensure that a product meet

certain standards of the quality. Due to the failure of the two and the emergence of industrial 1.0 revolution, another QC principle was adopted, '*foreman quality control*' (FQC) fill the void that could not be filled by the two concepts. On the onset of Industry 2.0 revolution, there emerged '*Statistical Quality Process*', which later turned to be known as '*Statistical Quality Control*' (SQC). The discovery of electricity paved ways for complex machineries and industrial complex, hence the need to use data in the manufacturing processes. Then from middle of Industry 2.0 revolution to the end of Industry 3.0 revolution, QC transformed itself from just merely a control tool, to '*Total Quality Management*' (TQM) with emphasis on the entire manufacturing processes.

However, in contrast to the previous Industrial revolutions, Industry 4.0 revolution or Smart Manufacturing has completely revolutionised how QC in manufacturing processes is practiced. Traditional QC systems has now given birth to Smart Quality Control Systems (SQCS) or Intelligent Quality Control Systems (IQCS), where machines have taken over most of the roles performed by human in the manufacturing. Technological development has made production/manufacturing processes to be more complex and complicated, yet simple in terms of networked processes created by the application of Cyber-Physical Systems, Additive Manufacturing, Artificial Intelligent, Augmented Reality, and Virtual Reality. These networked technologies assume the tasks and roles that were manually performed in the manufacturing processes, thereby eliminating human errors that were common in the products design and development. The use of 3-D or 4-D printing now enable manufacturers to produce prototypes and proof of concept designs, which simplify and speed up the processes of new product design and manufacturing [24]. Hence, resulting in the following benefits to the organisations; lower production costs, low logistic costs, and quality management costs, and others are improved customer responsiveness, customisation of mass production without significantly increasing production costs, more efficient use of natural resources and energy, and more friendlier working environment. These are some of the benefits of IQCS as Smart Manufacturing.

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