Standards for Enabling Integration and Interoperability in Smart Manufacturing

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Abstract – This study focuses on the significance of standards in facilitating the integration and interoperability within the realm of smart manufacturing. The integration of information communication technology with the manufacturing sector, often known as smart manufacturing, presents novel prospects for the efficient allocation of production resources and the implementation of predictive maintenance strategies. Nevertheless, a notable deficiency exists in terms of complete standards that establish the defining attributes, technology, and facilitating elements of smart manufacturing. This article emphasizes the need of implementing cross-manufacturer standards, worldwide standardization activities, and standards pertaining to product lifecycle management and manufacturing processes. The paper also examines the significance of standards in facilitating data sharing, equipment connectivity, and product inspection within the context of smart manufacturing. The study highlights the significance of a set of standardized protocols that can effectively interoperate with one another, hence enabling efficient interchange of product data and promoting the seamless integration of intelligent manufacturing systems.

Keywords – Smart Manufacturing, Product Lifecycle Management, Manufacturing Processes, Data Exchange, Equipment Communication, Product Inspection.

I. INTRODUCTION

New information and communication technologies are being incorporated into the industrial sector, known as smart manufacturing, has emerged as a prominent trend in the global manufacturing industry. This trend is gradually permeating throughout the entire manufacturing process, leading to a significant transformation in production processes. Researchers from several countries have dedicated their efforts to the advancement of smart manufacturing, achieving notable advancements in both theoretical understanding and practical implementations. Additionally, governments have played a crucial role by providing substantial assistance to this field. For example, Tao, Qi, Liu, and Kusiak [1] argue that smart manufacturing involves the integration of advanced operations technology and information technology to exploit untapped market opportunities. Smart manufacturing is put to use in this case by optimizing furnace temperature balance in the steam methane reforming process. Furthermore, the United States Department of Energy is likewise using high-performance computing to propel research and development in advanced manufacturing [2]. The fundamental aspect of attaining integration pertains to the Cyber-Physical Systems (CPS) that has the ability to establish a connection between the tangible physical realm and the virtual network domain.

Trainor and Rapp [3] have found a range of properties, technology, and facilitating conditions that are connected with social media. Certain qualities, technology, and enabling elements have been explicitly identified as such. However, it is important to note that this is not always the situation. Therefore, Kaplan and Haenlein [4] have conducted a comprehensive review of the relevant literature to identify additional factors that might be linked to these categories. Alalwan, Rana, Dwivedi, and Algharabat [5] have proposed many social media platforms that take into account the integration of various technologies inside the system. At the facility level, SM refers to the process of integrating manufacturing systems both vertically and horizontally. Hence, it is essential for an SMS to possess knowledge on the status of its preceding machines, succeeding machines, and concurrently operating devices. A learning system that utilizes computational methods, intelligent information, integrated automation, and networked data has been used in literature to develop a Short Message Service (SMS). However, in this particular instance, the scope of SMS is restricted to calculation.

National Institute of Standards and Technology (NIST) has provided a strategic model for supply chain management (SM) that places agility as the primary objective [6]. This model is designed to be adaptable to several additional aims. The variables used for classifying SMS were agility, asset utilization, and sustainability. In addition, there exist other attributes and technological advancements that have been used in the delineation of social media (SM). There are many proposed measures that may be implemented to enhance issue-solving processes. Firstly, the establishment of forums dedicated to discussing problem definitions can facilitate comprehensive and collaborative discussions. Secondly, the development of cyber-platforms can provide a digital space for individuals to engage in problem-solving activities. Additionally, promoting data sharing among relevant stakeholders can contribute to a more informed and effective problem-solving approach. Lastly, the implementation of laws that are conducive to social media (SM) use can foster a supportive environment for problem-solving endeavors. Nevertheless, a thorough compilation of technologies, properties, and enabling elements that contribute to the intelligence of a manufacturing system has yet to be presented in existing research. The necessary components, technology, and facilitating aspects that are essential in an SMS will vary. For instance, a technologically advanced pharmaceutical system that aims to enhance the efficacy of pharmaceuticals and other medicinal products may not need the use of visual technology like augmented reality (AR). However, another system of healthcare, such as one that specializes in the development of prosthetic limbs, may potentially benefit from the use of this technology.

Hence, this addresses the inquiry of whether an SMS must include all the recognized technologies, traits, and enabling variables concurrently, or whether it is satisfactory to classify a manufacturing system as intelligent when just a certain subset is used. The level of social media involvement often exhibits notable disparities between small and medium-sized enterprises (SMEs) and major organizations. It is often noticed that a limited number of SMEs possess an IT-based management system of production, despite the presence of partially automated operations. Nevertheless, a significant proportion of big, international firms have already integrated information technology (IT) systems to facilitate real-time communication and several other functionalities. Among the many industries, only a limited number of high-tech enterprises, like Siemens, Samsung, LG, and Tesla, have now implemented a tailored manufacturing system that relies on the CPS and IoT.

Two standard development organizations that have recognized the relevance of standards in the field of smart manufacturing and have been actively revitalizing key standards are the International Organization for Standardization (ISO) and the American Society of Mechanical Engineers (ASME). In 2014, for instance, ISO issued ISO 10303 AP242 with the intention of easing the use of controlled model-based 3D engineering. With the publication of a new standard (ISO/AWI 23247), the groundwork for an innovative twin manufacturing framework has been laid [7]. The proposed standard aims to provide a set of standards and a reference architecture that would facilitate the implementation of Digital Twin production. This emerging practice is considered a prominent aspect of smart manufacturing. Furthermore, the technical foundation for the development of intelligent manufacturing solutions has been greatly enhanced by community-based open standards, like OPC UA and MTConnect. Given the extensive collection of industry standards specifically designed for smart manufacturing applications, it is essential to conduct a comprehensive assessment of the existing standard environment in order to provide appropriate recommendations on the effective use of these standards.

In this article, we will review the most current standards and guidelines for creating smart industrial systems. This paper reviews literature reviews that have utilized these norms to accomplish smart manufacturing goals. The subsequent sections of this work are structured in the following manner: Section II presents an overview of key concepts in this article, discussing the definition and technologies of smart manufacturing, and the significance of standards. Section III presents a detailed discussion of smart production lifecycle management requirements, where various concepts are discussed: product information exchange standards, and standards of manufacturing. Section IV presents a discussion of process monitoring requirements and practices, and discusses extensively the smart inspection requirements. Lastly, Section V presents final remarks to the article.

II. OVERVIEW OF CONCEPTS

Definition and Technologies of Smart Manufacturing

Smart manufacturing is a sophisticated manufacturing approach that integrates artificial intelligence (AI) and computer-integrated manufacturing (CIM) to enable data-driven adaptability across the entire production cycle. **Table 1** presents the relevant technologies connected to the concept of smart manufacturing. The adaptability of these technologies encompasses various stages, including product quality assurance, product design, optimization, control, and process scheduling. Two crucial strategies that facilitate the implementation of this production mode are smart scheduling and predictive maintenance. The numerous vehicles, robots, equipment, and materials used in a smart factory are conceived of as CPS within the framework of Industry 4.0 (I4.0) production systems. Sensors, RFIDs, and other edge computing gadgets serve as modern identifiers for these things in the real world. This emerging manufacturing paradigm, bolstered by artificial intelligence (AI), presents novel prospects for the efficient allocation of production resources and the implementation of predictive maintenance strategies.

The Department of Energy (DoE) and NIST (National Institute of Standards and Technology) of the United States of America have provided their respective definitions of "smart manufacturing." From the shop floor to the plant and beyond into the supply chain, the role of ICT and sophisticated information analytics is emphasized throughout these descriptions. The concept of smart manufacturing has significant promise for the industrial sector. The Internet facilitates the gradual interconnection of machines, systems, goods, ICT systems, and people, resulting in the establishment of a production network. Within this network, information carriers engage in communication, exchanging data and information in a nearly instantaneous manner.

Table 1. List of technologies linked to smart manufacturing.

Related technologies	Literature
Three-dimensional printing/additive manufacturing	Hassan [8]: Cheng and Feng [9]
Advanced manufacturing	Han et al [10]; Ping et al [11]
Augmented reality	Jiang, Tran, and Williams [12]; Silva, Southworth, Andrews, Privitera, Henry, and Silva [13]
Big data	M. Sui et al [14]
Computer-aided manufacturing, computer-aided design, computer-aided X	Xu, Liu, Huang, and Ma [15]
Cloud computing/cloud manufacturing	Li et al [16]
Cyber-physical systems/Cyber-physical production systems	Bengler et al [17]
Cyber security	Thotadi et al [18]
Cyber-physical infrastructure	Chen, Trivedi, Abdelwahed, Morris, and Sheldon [19]
Data analytics/big data analytics	Kulkarni, Kumar, and Rao [20]
Data visualization	Zhang, Cheng, and Mueller [21]
Energy saving/efficiency	Chu, Duić, and Wang [22]
Enterprise resource planning	Vasiljeva and Berezkina [23]
Forecasting	Hao, Feng, Li, and Sun [24]
Geographic Information Science	Wu, Dong, Wu, and Liu [25]
Holograms	Howe, Tang, and Rowlands [26]
Intelligent	Yalçın, Lallé, and Conati [27]
Intelligent control	You [28]
Interface (Supply Chain Operations Research, Design Chain Operations Reference, Manufacturing Enterprise Solutions Association, ISA 95/88)	Chen, Huang, and Kuo [29]
Internet of Things/Internet of services/ Industrial Internet of Things	Alam, Ahmed, Matam, Mukherjee, and Barbhuiya [30]
IT-based production management	Grigorovich, Starikov, Voytko, Koykova, and Nekrasova [31]
Knowledge decision-making techniques	Affonso, Leite, Oliveira, and Nakagawa [32]
Machine learning	Senanayake, Fremont, Kochenderfer, Lomuscio, Margineantu, and Ong [33]
Manufacturing execution system	Shojaeinasab et al [34]
Modeling	Lyu, Mei, Zu, Liu, and Chu [35]
Operations planning	Gupta [36]
Product lifecycle management	Morshedzadeh, and Jeusfeld [37]
Predictive analytics	Agbemenou, Motamed, and Talaei-Khoei [38]
Real-time communication/data	Khaydarova, Mouromtsev, Fishchenko, Shmatkov, Lapaev, and Shilin [39]
Radio-frequency identification	Wang et al [40]
Supply chain management	Islam, Habib, and Islam [41]
Simulation	Diederich et al [42]
Smart materials	Mei, Li, Ma, Wang, Zhu, and Guan [43]
Smart product/part	Feng, Zhou, Jing, Jiang, Wu, and Jiang [44]
Smart sensors	Sivaraju, Mani, Umaamaheshvari, Divya Banu, Thangavelu, and Srithar [45]
Statistical process control	Lou, Wang, Si, and Lu [46]
Tracking and tracing	Sommer, Leeb, Weishaeupl, and Daub [47]
Virtual reality	Chen and Chen [48]

Significance of Standards

Standardization is a fundamental need for the successful integration of systems and processes, as well as for facilitating effective partnerships among them. The collaboration of various components is contingent upon the establishment of cross-manufacturer standards. Similarly, it is essential for various organizations to establish collaborative partnerships only when they adhere to standardized engineering practices. Standardization of procedures is widely recognized as a major barrier to the widespread adoption of smart manufacturing. Due to the collaborative and interconnected nature of smart manufacturing, it is essential that interfaces, data, semantics, and architectures interchange formats be standardized. This standardization is necessary to optimize business outputs across various solutions and technologies in the field of smart manufacturing. For this reason, it is crucial that open standards be adopted and interoperable interfaces developed for smart manufacturing systems as part of international standardization initiatives. There is a need for the development of standards in order to establish the collaboration mechanisms and define the information that should be communicated for the purpose of inter-company integration and intra-company automation. In a similar vein, the NIST emphasizes the insufficiency of open standards-based technologies in facilitating effective communication, interaction, information sharing, decision-making, and fault response within smart manufacturing systems.

Smart Manufacturing Dimensional Standards

The topic of smart manufacturing is characterized by very dynamic standardization operations, whereby several multinational initiatives are actively engaged in the development of standards pertaining to smart manufacturing. According to Li et al. [49], there exists a comprehensive collection of over 300 standards pertaining to the domain of smart manufacturing. Due to the complexity of the situation, it is impossible to establish a single set of conclusive requirements for smart manufacturing. Standards in the smart manufacturing industry have been the subject of many studies, each with its own unique focus and set of recommendations. The main aim of this article is to examine the standards that facilitate the integration of systems, particularly highlighting representative standards for the process of integrated product creation and the administration of smart factories.

III. SMART PRODUCT LIFECYCLE MANAGEMENT REQUIREMENTS

The achievement of smart manufacturing necessitates the collaboration of dispersed manufacturing enterprises in order to meet the demands of highly personalized product creation. One such situation is the concept of “design anywhere, build anywhere.” in order to accomplish this objective, it is essential for manufacturing businesses and associated software packages to possess the capability to seamlessly exchange product data across the whole of the product advancement lifecycle, without encountering any interoperability challenges. The abundance of standards in this domain presents difficulties in establishing a unified vision inside an organization. This study centers on a set of standards that facilitate efficient communication and minimize interoperability risks, hence enabling seamless interchange of product data throughout different phases of the product lifecycle.

Product Information Exchange Standards

The International Organization for Standardization (ISO) 10303, more often referred to as STEP, is a globally recognized standard that has been developed to facilitate the seamless interchange of product data across computer-aided design (CAD) systems. This standard employs a neutral data format, ensuring compatibility and interoperability between different CAD platforms. The STEP standard is divided into many components. These sections include many aspects such as the introduction of the standard, the application protocols, implementation designs, resource information models, and conformance testing. Methods for describing, modeling, implementing, and verifying compliance are known as “application protocols,” “information models,” “description methods,” and moreover “implementation methods,” each. **Fig 1** depicts the organizational scheme of the STEP standard. The components of STEP may be categorized according to their respective types in the following manner. The parts are assigned numerical values in order to group together parts of the same kind within a certain range of numbers. The range is shown below subsequent to the classification. There exists a multitude of modules of application, numbering in the hundreds. An application protocol may be constructed by including a substantial quantity of modules of application. The utilization of application modules represents a very contemporary architectural methodology as compared to the utilization of application interpreted structures, and has the potential to supplant the latter.

In [50], a big step was taken forward in the improvement of STEP AP242 for “Managed Model Based three-dimensional Engineering.” To do this, we combined AP204 and AP203 and placed special focus on accurately representing PMI (Product Manufacturing Information), geometric tolerance, and 3D model data. The introduction of this innovation was made with the intention of easing international cooperation in the design and production phases. The STEP AP242 data model allows for the straightforward transmission of machine-readable product design requirements between design and manufacturing companies. As a result of this communication between businesses and systems, no more 2D drawings will need to be interpreted. STEP AP242's capacity to provide semantic Product descriptions is a major success. Manufacturing Information, which has the potential to enhance the intelligence of manufacturing systems. The AP 242 standard enables the automated integration of Tolerance & Geometric Dimensions (T&GD) data with various downstream applications, including Coordinate Measuring Machines (CMM), Computerized inspection, tolerance control systems, and Computer Aided Process Planning (CAPP).

In recent years, a number of challenges have arisen in relation to the ISO 10303 standard. These challenges stem from the significant magnitude of the standard and the need to keep pace with emerging technological advancements. The latter task is challenging due to the complex nature of the ISO standardization process, which entails extensive efforts to reach worldwide agreement and requires long review and balloting processes at several stages during the creation of each standard specification. As a result, many strategies are being used to achieve the recognition of documents as International Standards. Currently, the whole framework of the STEP standard is undergoing modification with the aim of expediting the development process and enhancing flexibility, while reducing the need for extensive paperwork. These modifications will further facilitate interoperability across various components of the standard, enabling, for instance, the integrated use of a mechanical engineering advanced placement (AP) course with an electrical engineering AP course. Another significant factor in the present endeavors within the STEP group is the synchronization with emerging standards in interconnected domains. One such instance is to the current focus placed on using XML as a mechanism for recording and exchanging STEP information.

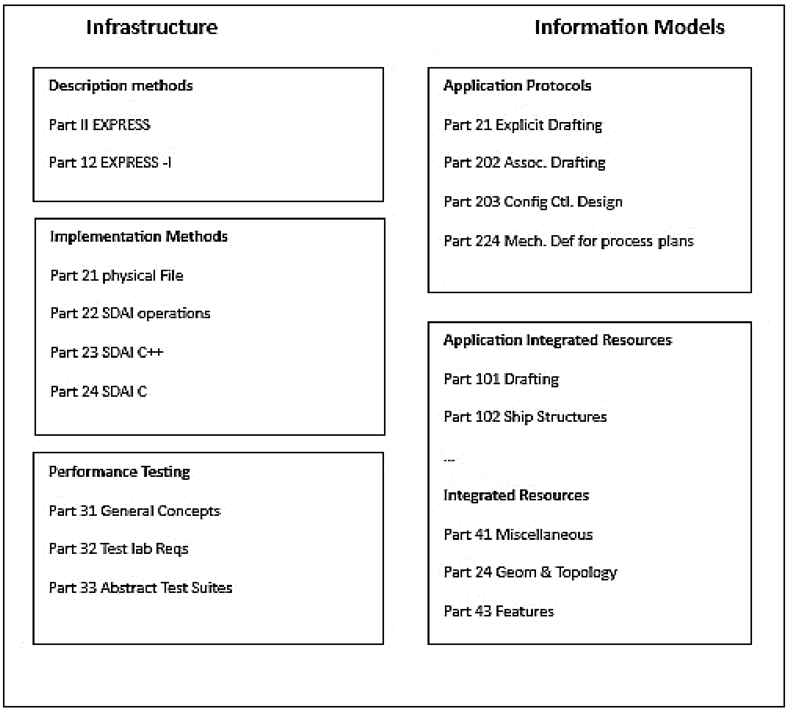

Fig 1. STEP standard structure

Standards for Manufacturing

The inclusion of standards in the design and execution of manufacturing processes is an essential component of smart manufacturing. Within this particular section, we use a limited perspective on manufacturing, whereby it is seen as the process of transforming raw materials into finished products in accordance with precise product specifications. In the current age of advanced manufacturing, the primary emphasis is on achieving a production model known as "batch size of 1." This model involves the integration of many fabrication techniques, including robotic machining, additive manufacturing, and numerical control (NC) machining, to collectively optimize the manufacturing process. In order to achieve adaptable organization of manufacturing activities in the face of changing conditions, it is necessary to establish interoperability between manufacturing systems. In addition, manufacturing machinery needs the semantic interpretation capability to read a CAD file and produce an appropriate production strategy.

The diagram shown in **Fig 2** illustrates the many stages of the manufacturing life cycle, including the process of design to fabrication. Furthermore, it highlights the intended use of ISO 14649 within this cycle. The design phase yields Computer-Aided Design (CAD) data, namely ISO 10303-203 geometry, which encompasses the representation of the physical shape and structure of the object. Additionally, this phase involves the specification of all the component characteristics according to ISO 10303-224. The process planning step is responsible for generating the resource needs for component fabrication, using ISO 10303-213, as well as producing additional outcomes that are appropriate for integration into a MES. The process planning procedure involves the division of the manufacturing characteristics outlined in ISO 10303-224 into distinct groups that are appropriate for different processes like electrical discharge machining (EDM), turning, and milling, and inspection. It is worth noting that ISO 10303-219 is also used in the inspection process. During the CAM process, the feature sets defined by ISO 10303-224 are implemented. This procedure generates ISO 14649 files, which are read by CNC machine tools for processing. Standard Data Access Interface (SDAI) allows several controllers to access ISO 10303 integrated resources simultaneously during program execution. This allows for a seamless integration of ISO 10303 data with machining processes.

The data model is OOP-based, with a focus on manufacturing qualities rather than the explicit recording of axis movement sequences and tool operations. In this context, we focus on data related to industrial activities and the characteristics of the products they produce. This in no way suggests that the language supports object-oriented features like inheritance, methods, or classes. Instead, the language provides a procedural technique for linking together a collection of feature objects.

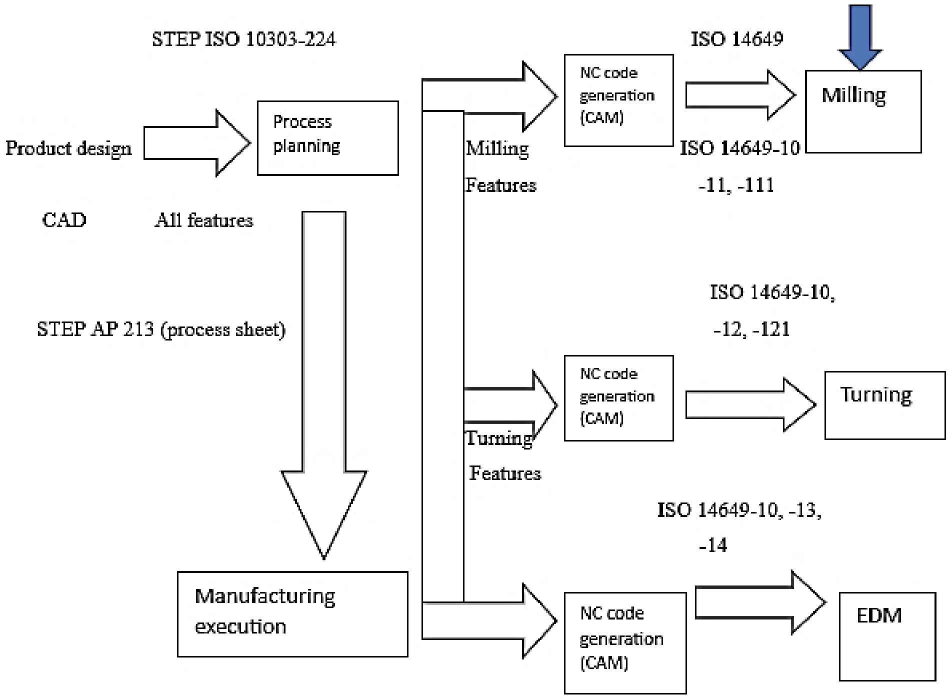

Fig 2. The whole manufacturing cycle, including the stages of design to fabrication, and intended use of ISO 14649

IV. MONITORING REQUIREMENTS

Process Monitoring Requirements and Practices

Data collected from various pieces of industrial machinery housed on the plant grounds is essential to the digital manufacturing process. Modern business systems, including those used for decision making and analysis, need the use of reliable and efficient communication channels. With the aim of easing CNC machine integration, MTConnect, a widely used standard for simplifying communication among network-based equipment, was developed. Linking and Embedding Objects in Process Control Using the United Architecture (OPC-UA) is another important standard that helps advance remote communication in the industrial sector. In order to facilitate communication between the manufacturing floor and the rest of the business, the OPC Foundation created this standard as a successor to the original OPC. With MTConnect, manufacturing machines and other devices may be linked so that data can be gathered in a centralized location. When it comes to facilitating plant-wide data interchange, however, OPC-UA is a game-changer.

MTConnect is a royalty-free, open communication standard that facilitates the exchange of data between manufacturing The MTConnect Standard is a freely available and non-proprietary standard that serves as a semantic language for manufacturing equipment. It enables the provision of structured and contextualized data without any associated royalties or restrictions on use. A basic MT Connect application has five core components, namely the device, adapter, agent, network, and client. OPC UA is an open standard, as defined by Ladegourdie and Kua [51], that governs the flow of information within the realm of industrial communication. Machine-internal components, machine-to-machine transmission, and machine-to-system transmission are all under its purview. The field extensions that are delineated by the Field Level Communication (FLC) effort are grounded on the OPC UA Framework. The architecture presented herein offers suppliers an autonomous platform that facilitates the safe and dependable transmission of information.

Client/server services, protocols, and publish/subscribe (PubSub) models and protocols are all supported by the OPC UA framework. Different client and server system architecture are supported by OPC UA (see **Fig 3**). A PubSub scenario involves a server publishing data to a network and a client receiving that data based on their subscription to the data. Signature, authentication, and encryption of data are given considerable weight in both the client/server and PubSub models of the OPC UA standard.

Smart Inspection Requirements

Inspection of completed items is an essential aspect of any productive product development process, occurring at many points from the time raw materials are received until the time they are packaged and sent. There is currently a balance between offline and online post-processing techniques for inspection. Nonetheless, making highly customized products in small batches efficiently requires a web-based in-process inspection system that is integrated with the production process.

The Quality Information Framework (QIF) is a standard developed by the American National Standards Institute (ANSI). Throughout the whole process of manufacturing quality measurement, it provides a complete range of XML information formats for sharing metrology data. Reports must be submitted, products must be manufactured and distributed, inspections must be planned and carried out, and results must be evaluated. As part of a QIF-compliant metrology process, Hallmann, Goetz, and Schleich [52] explain how CAD and PMI data are used to generate QIF Model-Based Design (MBD) product models. Using the imported product model, quality planning systems create measurement plans that adhere to the specified quality standards and production procedures. At this moment, the guidelines regarding inspection resources are being evaluated. Programming systems are used to input measurement plans in order to generate programs that are unique to Dimensional Measurement Equipment (DME). Dimensional measuring equipment is responsible for executing programs and assessing the outcomes of measurements. In the last stage, analysis systems ingest individual component results and produce statistical data in the form of QIF analysis for multiple part batches.

The primary objective of the Smart Quality Inspection (SQI) method is to enhance the performance of models and effectively tackle many issues that impact the process of visual inspection. By using automation in the process of inspection, it becomes possible to exert a certain level of control over the impacts of various work elements, environmental factors, and individual factors. The strategy presented for the development of SQI is instructive in its proposal of a methodology for the implementation of AI-based visual inspection inside a shopfloor setting. **Fig 4** illustrates the several phases included in the implementation of SQI within the manufacturing or production domain. The process has six distinct steps, commencing with the receipt of the product at the designated inspection region and culminating in the use of artificial intelligence (AI) for inspection purposes, followed by the documentation of the obtained outcomes. The following sections delineate the procedures and protocols included within each respective phase.

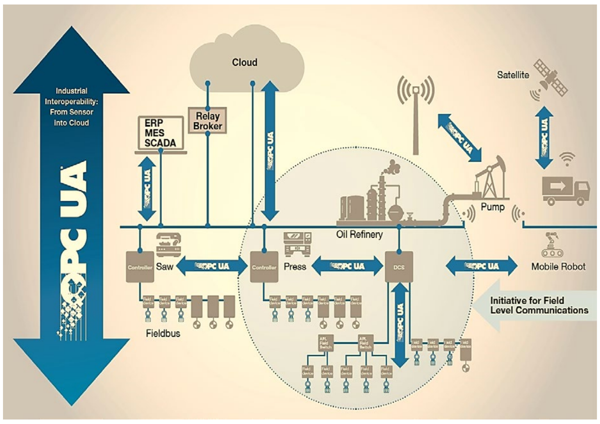

Fig 3. OPC UA FLC system architecture

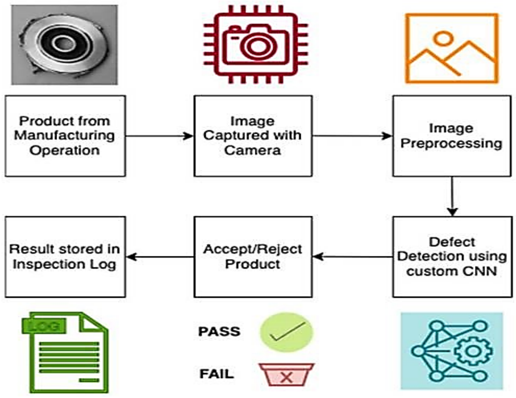

Fig 4. A methodology for smart quality inspection that is based on artificial intelligence

Fig 4 depicts Stage 1, which represents the point in time when the manufactured product is delivered to the area of inspection. During the first phase, the product produced by the assembly line is transported to the designated location of inspection. The object is positioned in a certain area to begin the process of examination. During Stage 2, an advanced camera of superior quality is used to collect photographs of the product while it undergoes the inspection process. The measurement of lighting conditions and distance from the object is contingent upon factors such as the size of the product and the camera equipment being used. During Stage 3, the appropriateness of grayscale or color photographs is determined depending on the availability of computing resources and the required accuracy and precision of forecasts. At this step, various operations such as flips, shears, rotations, shifts, whitening, and contrast modification are performed to supplement or change the data.

The detection of faults in pictures is accomplished in Stage 4 via the use of a customized Convolutional Neural Network (CNN) architecture. The architectural design exhibits adaptability in accommodating many image forms with little modifications. The model is trained on a dataset that includes both defective and normal product images so that it may learn to correctly represent those features. The inspection procedure has been simplified thanks to the defect detection model's incorporation into a shop-floor application. In Step 5, the product is inspected by the operator using the defect detection algorithm, and the results are sent to the operator as soon as possible. A decision as to whether or not to accept the product is made in light of the results. A spreadsheet is automatically updated with the results of the inspection operation when they are submitted into the SQI shop floor application in Stage 6.

V. CONCLUSION

Smart manufacturing encompasses the whole of the value chain and product life cycle, spanning from the initial conceptualization and design phase to the actual production, distribution, and final recycling processes. Additionally, it involves the seamless integration of user or customer input and feedback in real-time. The subject matter pertains to agile, adaptable, and intelligent processes. The overarching objective is to establish interconnectedness throughout all stages of the manufacturing process. Factories are now engaged in the implementation of technical systems integration on an unprecedented scale, including various disciplines, hierarchical structures, geographic regions, value chains, and life cycle stages. The successful implementation of this integration is contingent upon the technology being underpinned by internationally recognized standards that are established via a consensus-driven process at a global level. This article takes a look at the available standards for smart manufacturing integration, data exchange, and communication across the many stages of the product lifecycle. There is a compelling need to carefully review and adjust these standards as required so that they correspond with the expectations and demands of smart manufacturing, despite the fact that they have demonstrated promising application scenarios for allowing smart manufacturing. Future research should prioritize the examination of the practicality and execution evaluation of established protocols for intelligent manufacturing.

Data Availability
No data was used to support this study.

Conflicts of Interests
The author(s) declare(s) that they have no conflicts of interest.

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Competing Interests
There are no competing interests.

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