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A generic interface and a framework designed for industrial metrology integration for the Internet of Things

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ABSTRACT

Industry 4.0 promotes the advance of several key areas in manufacturing. Industrial metrology, and associated activities such as Quality Assurance are receiving constant pressure to enhance integration, interoperability, and availability of measurement information to other operations. This promotes a trusted Internet of Things (IoT) or Cyber-Physical Systems (CPS) environment where reliable measurement data is accurate and available to different stakeholders This work addresses the integration of measuring devices in an IoT architecture using open standards. It provides a framework, based on IEC 62264 for Quality Operations Management (QOM) and ISO 23952:2020 - Quality Information Framework (QIF) to describe the activities of Quality Assurance and Quality Control and provides a generic interface using OPC UA to receive and send information to the QOM activities, enabling the integration with upper systems such as an ERP and the creation of quality oriented Key Performance Indicators (KPIs). An experimental scenario in the steel manufacturing industry is provided, demonstrating, how the generic interface can support custom software applications by using metrology data to support, reducing product and process defects leading to Zero-Defect Manufacturing (ZDM).

1. Introduction

Classic mass production is increasingly being replaced by individual production (mass customization). This trend, in combination with the increasing variety of products and shorter product life cycles, leads to decreasing lot sizes (Koren, 2010). As a result, companies increasingly must deal with aspects such as flexibility, adaptability, changeability and reconfigurability in production. There is a clear trend towards greater flexibility. The current challenge is to transfer current manufacturing systems to the Internet of Things (IoT) or Cyber-Physical Systems (CPS) and to meet the requirements placed on such component. This means that objects, including their virtual representation, should be networked with other ones. Sensors, machines, plants, and other physical systems are connected with each another and with their virtual images (digital twin) and other virtual objects and processes, such as control systems for production control and planning, such as Manufacturing Execution System (MES) or Enterprise Resource Planning (ERP). In addition, systems must have a semantic description so that both humans and other systems can read out the capabilities of the component. This results in a variety of interfaces and communication configurations that can be used to implement these requirements. Both standardized and proprietary solutions can be found on the market. This diversity and the lack of consistency in standardization, lately means that system integration is currently associated with a great deal of effort and requires specialist knowledge (Schmied et al., 2020).

In order to reduce complexity, comprehensive modularization, broad standardization and continuous digitization are required (OPC Foundation, 2020). Current initiatives such as Industry 4.0 and IoT are trying to achieve these goals. For this purpose, the *Plattform Industrie 4.0* has developed the Reference Architectural Model Industrie 4.0 (RAMI 4.0) (DIN, 2016) with the proposal of a I4.0 component.

The communication standard of OPC Unified Architecture (OPC UA), has been available for some time, which enables uniform and standardized communication between different systems in a company. These properties distinguish OPC UA as currently the most important candidate for the implementation of IoT and CPS (Sino-German Industrie 4.0/Intelligent Manufacturing, 2018; VDMA, 2017). Although OPC UA has been standardized as IEC 62541 (IEC, 2020) in 2011, it is not yet widely used. This is due to the lack of domain-

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Nomenclature

AQDEF	Advanced Quality Data Exchange Format
CAQ	Computer Aided Quality
CMM	Coordinate Measuring Machine
CPPS	Cyber-Physical Production System
CPS	Cyber-Physical System
CWA	CEN Workshop Agreement
DMAIC	Define-Measure-Analysis-Improve-Control
DMIS	Dimensional Metrology Interface Standard
DML	Dimensional Markup Language
eQuiPP	Exchange of Quality measuring Process Plans
ERP	Enterprise Resource Planning
HTTP	Hypertext Transfer Protocol
I++DME	Inspection Plus, Plus Dimensional Measuring Equipment
IoT	Internet of Things
LIMS	Laboratory Information Management System
MES	Manufacturing Execution System
NIST	National Institute of Standards and Technology
OPC UA	Open Platform Communications Unified Architecture
PMI	Product Manufacturing Information
QA	Quality Assurance
QIF	Quality Information Framework
QMD	Quality Measurement Data
QML	Quality Markup Language
QOM	Quality Operations Management
RAMI 4.0	Reference Architectural Model Industrie 4.0
REST	Representational State Transfer
SCADA	Supervisory Control and Data Acquisition
STEP	STandard for the Exchange of Product model data
TQM	Total Quality Management
UMATI	Universal Machine
UML	Unified Modeling Language
VIM	International Vocabulary of Metrology
XML	eXtensible Markup Language
ZDM	Zero-Defect Manufacturing
ZDMP	Zero-Defect Manufacturing Platform

specific models and, also, to the skepticism of the benefits although some studies were conducted in the machine tools domain (Mourtzis et al., 2018; Liu et al., 2019) and IoT sensors domain (Morato et al., 2021).

The importance of continuous and online data acquisition is increasing, therefore there is a growing need for error-free and reliable data acquisition with low time expenditure. The task of industrial metrology consists of collecting data about quality characteristics of an object. These specified inspection characteristics must be verified during and/or after manufacturing to reduce the likelihood of scrap being delivered to the next manufacturing activity (an internal customer) or the end customer. The very common scenario, of the importance of metrology in a manufacturing process, considers: a) in-process, in-line and end-of line part measurement (Gao et al., 2019) for quality assurance; b) tool measurement in machining processes for process-monitoring to optimize productivity and minimize costs (Xu et al., 2020); and c) measurement and monitoring the condition of critical or sensitive machine components with sensors in, to detect degrading conditions and avoid breakdown by preventive actions (Schmitt et al., 2010).

The activities of Industrial Metrology are within the domain of Quality Assurance (QA). Companies rely on continuous improvement philosophies to improve quality and reduce costs, by the application of different approaches like the Plan-Do-Check-Act (PDCA) cycle (ISO, 2015), the Juran approach (Juran and Godfrey, 1999), Kaizen - part of Total Quality Management (TQM), the Taguchi approach (Roy, 2010) and Hewlett-Packard's best practices (Walter, 1985), among others. Customer requirements are also driving the implementation of continuous improvement philosophies. The ISO 9000 standard is used by companies that want to state that each area, responsible for quality, is dedicated to continuous improvement. The automotive industry had its own path in this subject, with the implementation of Ford's Q-101 (Dietrich, 2019) in the 1980s that involved suppliers in quality assessment. Statistical Process Control (SPC) (AIAG, 2005) was introduced for production monitoring and control using Shewhart's control charts (Shewhart, 1931). The evolution of Ford's Q-101 to QS-9000 (Chrysler, 1998) was performed by the American Automotive Industry Action Group (AIAG) in the 1990s. In Europe, the German Association of the Automotive Industry (VDA) developed an equivalent system with VDA 4 and VDA 6 (AIAG, 2019) being followed by local French and Italian initiatives until in 1999, the International Automotive Task Force (IATF) harmonized the various documents, using ISO 9001 as a basis to create the IATF 16949 standard (Hoyle, 2005). This automotive specific standard provides continuous improvement, highlighting defect prevention and waste/variation reduction in the supply chain. It additionally stresses the use of core tools like Failure Mode and Effects Analysis (FMEA) (AIAG, 2019), Statistical Process Control (SPC) (AIAG, 2005), Advanced Product Quality Planning (APQP) (AIAG, 2008), Production Part Approval Process (PPAP) (AIAG, n.d.) and Measurement System Analysis (MSA) (AIAG, 2010). SPC plays an important role in continuous improvement by providing the mechanisms to detect variation in each process. SPC is applied to process characteristics that are known to affect the process outcome to reduce deviation from a target value. When applied to product characteristics, the same principles are used, but the concept is better known as Statistical Quality Control (SQC). The process capability index (Cpk) is the commonly used metrics to evaluate how well a particular process can deliver quality characteristics within specification limits (in conformance). The data-driven improvement process DMAIC (Define-Measure-Analysis-Improve-Control) (ISO, 2011), also based on statistical tools, serves as support for one of the most well-known production improvement programs: Six-Sigma. This approach is based on statistical methods developed in the 1980s and states that a Six-Sigma process allows only 3.4 defective parts per million critical quality attributes.

1.1. Research questions and main contributions

Based on the requirement for continuous measurement data acquisition addressed above and integration of measuring devices for not only performing data acquisition but also to support control activities, the following research questions arise:

- what is the appropriate framework to vertically integrate measuring devices and provide seamless communication to multiple system entities?
- considering that each device and system entity has an interface (proprietary or standard), is there a common interface, preferably a standardized one, able to semantically describe the system entities within the domain of quality assurance?

Industry 4.0, CPS and IoT are putting metrology and QA on the verge of new requirements with additional functions in a renewed architecture. Now, as the traditional automation pyramid is evolving (DIN, 2016), also is the case of industrial metrology and quality assurance, by the provision of services. Fig. 1 shows how the vertical integration is achieved in a company, by the provision of an

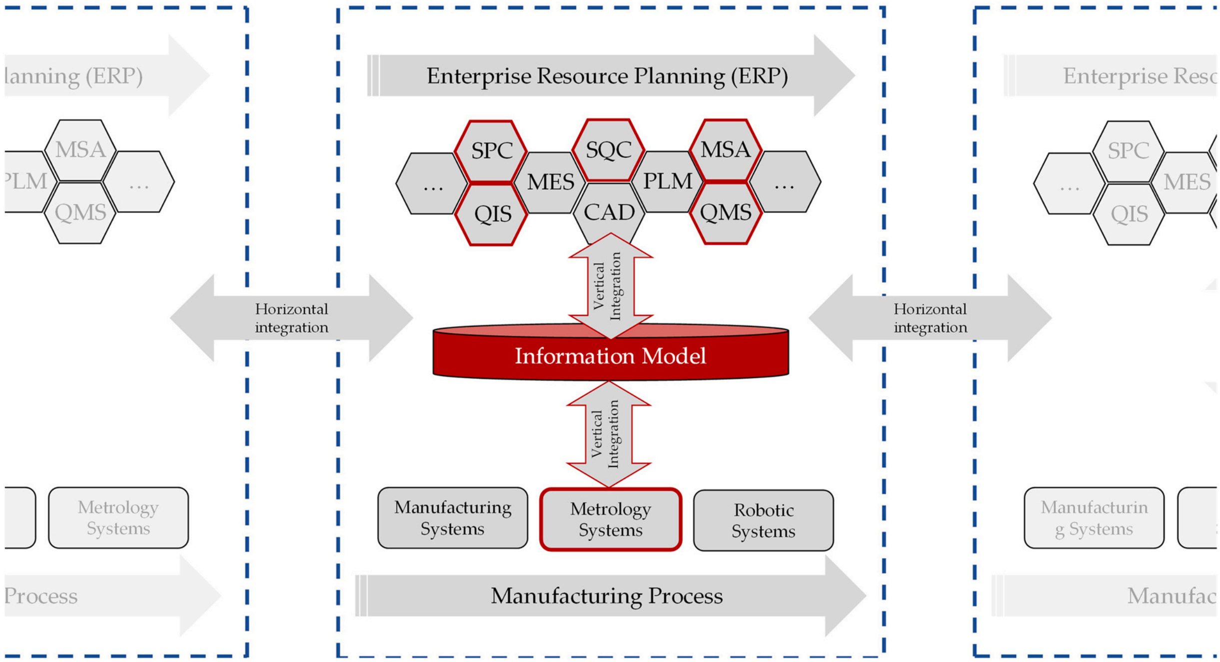

Fig. 1. Information architecture in a factory.
(adapted from (VDI, - Blatt 3 / Part 3, 5600, 2013; Flad et al., 2017; Vogel-Heuser et al., 2009)).

information model, capable of sharing information within the domain of quality assurance.

Following the above considerations and the research questions, this article addresses the design and realization of a *Common Interface for Metrology device Integration* (CIMetroI). This common interface is an attempt to provide a standard based interface for (dimensional) metrology devices and associated information to make such information available to different applications in a dedicated platform.

The proposal described in this article can be synthesized in the following points:

- proposal of a generic, quality assurance focused information model, where the basic elements represent the fundamental vocabulary of said domain;
- realization of such information model as a core component of a generic IoT architecture based on standards;
- application of said information model in a communication standard suitable for the description of *Instance* information (Production) (DIN, 2016), i.e. OPC UA;
- contextualization of said OPC UA based information model in a prominent IEC standard for enterprise-control system integration;
- Exploitation of the framework and information model in the context of and industrial use case framed in EC H2020 project for Zero-Defect Manufacturing (ZDM).

1.2. Relevant work

Industrial metrology research has been evolving due to the introduction of Industry 4.0, IoT and CPS. The VDI/VDE Society for Measurement and Automatic Control has proposed a roadmap for faster, more accurate, safer and more flexible industrial (manufacturing) metrology (Berthold and Imkamp, 2013) which points out the importance of the qualification of instrument operators on the accuracy of the results and the impact on the usefulness for production improvement and evaluation. It also stresses the importance of flexibility in the domain and thus delivering more information regarding the process. In Imkamp et al. (2016), the concept of "Measurement Technology 4.0″ is presented, and emphasizes the importance of metrology for Industry 4.0 as not as a simple provider of data but the element linking together the digital and virtual worlds in a Cyber-Physical Production System (CPPS). In Schmitt and Voigtmann (2017) the concept of "sensor information as a service" is introduced, again stating the central role of metrology for future CPPS, pointing out the homogenization of data formats and interfaces as one of the main challenges of the domain. A multi-agent system is proposed in Peres et al. (2018) that describes, in a data model within the domain of quality control, the concepts of quality test, quality measurement and other relevant data in AutomationML and uses Message Queuing Telemetry Transport (MQTT)[1] protocol for data exchange. In Batchkova et al. (2017) a modification of the IEC 62264 models for QOM using the RAMI 4.0 is proposed to achieve full benefit of IoT. Model Based Definition (MBD) and Model Based Engineering (MBE) research addresses interoperability in the domain of industrial metrology (Rui and Guijiang, 2018). Several studies were conducted to report the "as-measured" status of a component using a Quality Information Framework (QIF) (ANSI/DMSC, 2018) format and "as-executed" machine status provided by installed sensors using MTConnect (Kwon et al., 2020; Hedberg et al., 2021; Feng et al., 2017; Helu et al., 2018; Bernstein et al., 2018). The usage of open standards is widely researched by the National Institute of Standards and Technology (NIST), referring Standard for the Exchange of Product model data (STEP) AP 242, MTConnect and QIF as the main standardization initiatives for the collection and usage of manufacturing data (Hedberg et al., 2021, 2020, 2017; Feng et al., 2017; Helu et al., 2018, 2017; Bernstein et al., 2018; Helu and Hedberg Thomas, 2020; Horst et al., 2019; Trainer et al., 2016; Michaloski et al., 2016; Helu and Hedberg, 2015), although focusing mainly on the end-to-end integration aspects and not in vertical integration such as the scope of this work. Likewise, the works presented in Liu et al. (2019), Emmer et al. (2018), Jaimes and Álvares (2018) use current standardization initiatives such as QIF to improve interoperability in the domain of industrial

[1] https://mqtt.org/

metrology, focusing on end-to-end integration and closed loop manufacturing/inspection. The works described in Hu et al. (2018) target vertical integration by using QIF (to model a caliper), OPC UA (to model an industrial robot) and MTConnect (to model a three-axis milling machine) to perform shopfloor data acquisition and interacting with a mobile smart device.

1.3. Article outline

The state of the art and pertinent standardization activities for the domain are described in Section 2 right after a brief introduction to the topic, and the motivation for this work. This includes the description of the relevance of IoT and CPS, the modeling approaches of IoT systems and relevant product and metrology information models.

Section 3 describes the applied methodology to achieve the described framework in Section 4. This includes the requirements definition and some fundamental concepts.

Section 4 describes the CIMetrol, i.e., a generic OPC UA information model, based on QIF, and a generic architecture for metrology device integration.

Section 5 describes the validation approach in the context of project Zero-Defect Manufacturing Platform (ZDMP).[2]

2. State of the art and relevant standards

The following section provides a description of the state of the art of IoT and CPS, modeling approaches for IoT systems and relevant product and metrology information models.

2.1. Internet of Things (IoT) and Cyber-Physical Systems (CPS)

Industry 4.0, the fourth industrial revolution, is the latest concept and a broad initiative to make an innovative contribution to the manufacturing sector. The term "Industry 4.0" was first introduced in Germany in 2011 at the Hannover Messe trade fair as "Industrie 4.0" (Vogel-Heuser and Hess, 2016; Da Xu et al., 2018) and was later followed by global initiatives in the U.S. as "Industrial Internet" (2011), in the European Union as "Industry 4.0" (2014), in China as "Made in China" (2015) and in Japan as "Industrie 4.0" (2014). Similar initiatives are underway in other countries.

In addition to Internet of Things (IoT) there are many concepts such as Cyber-Physical Systems (CPS), Industrial Internet of Things (IIoT), Machine-to-Machine (M2M), Smart Manufacturing, among others, that describe similar or related systems and concepts. There is so much overlap between these concepts, particularly CPS, IoT, and IIoT, that CPS, IoT, and IIoT are often used interchangeably. CPS is similar to the Internet of Things (IoT) and has the same type of architecture, although CPS is a stronger integration of computation, networking, and physical process. IoT is about connecting objects and machines to the Internet and eventually to each other. NIST has published the "Cyber-Physical Systems and Internet of Things" (Greer et al., 2019) in its "Cyber Physical Systems Program" to address the overlapping of these concepts. The ISO/IEC published several standards in the field of IoT, such as the ISO/IEC "Internet of Things – Reference Architecture" (ISO/IEC, 2018) to provide a standardized IoT Reference Architecture to assist the development of context specific IoT architectures. It also published the "Internet of things (IoT) – Real-time IoT framework" to address IoT system operating in real-time that is called real-time IoT (RT-IoT) systems (ISO/IEC, 2021). ISO/IEC has also published ISO/IEC TR 30166 "Internet of things (IoT) - Industrial IoT" to provide an overview of current standardization activities and the standardization landscape of

[2] https://www.zdmp.eu/

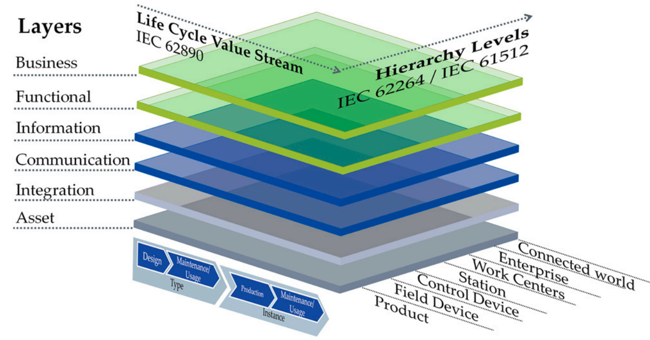

Fig. 2. The Reference Architectural Model Industrie 4.0 (RAMI 4.0). (adapted from (DIN, 2016)).

Standards Developing Organizations, consortia, and open-source communities in the IIoT domain.

RAMI 4.0 is a layer model that can be used to systematically classify and further develop Industry 4.0 technologies. It can also be helpful for defining new business models. RAMI 4.0 is based on the Smart Grid Architecture Model (SGAM) (CEN, 2012) and has been extended to include aspects for Industry 4.0.

RAMI 4.0 is a three-dimensional model whose dimensions are the vertical networking in a factory, the different life cycles of the product, and hierarchical layers (derived from SGAM) (Fig. 2). The right horizontal axis shows the hierarchical layers known from the IEC 62264 (IEC, 2013) standard for Enterprise-control system integration. It shows the individual entities in a factory grouped according to their functionality. In addition, the subdivision has been extended to include two further levels that occur in Industry 4.0 applications: the product and the networked world. This allows all elements of an Industry 4.0 environment to be mapped, from the product to the IoT. The horizontal axis on the left shows the different lifecycle phases of plants and products. The different phases are based on the IEC 62890 life cycle management for systems and components (IEC, 2020) in the field of measurement, control, and automation technology. A distinction is made between type and instance which is clearly clarified by RAMI 4.0. A type becomes an instance when development (design and prototyping) is completed, and the product is released for production. The vertical axis describes the structure of objects, which are divided into levels (layers). This form of representation comes from the world of information and communication technology (ICT), where complex systems are often represented in layers to reduce the degree of complexity.

These three axes now contain all the essential aspects of Industry 4.0, so that any objects such as a component or machine can be classified based on this architecture. In this way, Industry 4.0 concepts can be described and implemented with the help of RAMI 4.0 (Fig. 3).

2.2. Modeling of IoT systems

2.2.1. Enterprise integration

IEC 62264 (IEC, 2013) can be used as a foundation for the development of MES similarly to the VDI 5600 guideline (VDI, - Blatt 3 / Part 3, 5600, 2013; VDI, - Blatt 1 / Part 1, 5600, 2016), which provides a basis for the contents of MES and their possible applications, focuses on the automation pyramid. Other standards that target MES are the Manufacturing Enterprise Solutions Association (MESA), the NA 094 (NAMUR) and the VDMA 66412-1 (ZVEI, 2017). The IEC 62264 is also used in the RAMI 4.0 for the hierarchical levels (DIN, 2016).

The IEC 62264 standard identifies twelve functions that must be assigned in manufacturing, four of which, found in Manufacturing Operations Management (MOM), are described in detail in IEC

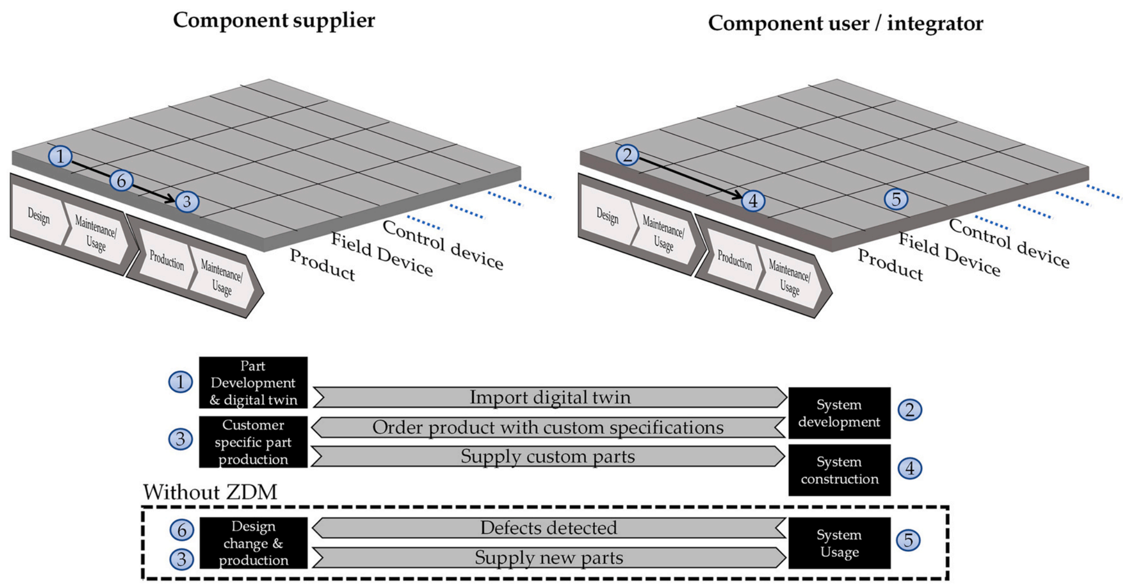

Fig. 3. Example of machine controller being supplied and integrated classified according to the RAMI 4.0.

62264–3: production operations management, inventory operations management and quality operations management and maintenance operations management. The standard defines the activities with their models, attributes, and the required data exchange within the areas. It also defines the information that must be exchanged between the activities in the areas of production, warehouse, inventory, maintenance, and quality.

The ISO 15531 MANDATE (ISO, 2017) defines a set of standards for the exchange of industrial manufacturing management data, especially with Part 44 (ISO, 2017), dealing with the modeling of data acquired by a data acquisition system at the control level and stored at the manufacturing management level. The standard is relevant to this work because it addresses quality management information and the description of a product defect.

2.2.2. OPC Unified Architecture (OPC UA)

OPC-Unified Architecture (OPC-UA) is a manufacturer- and platform-independent communication standard for industrial communication. It represents the further development of the Object Linking and Embedding (OLE) for Process Control (OPC) standard provided by the OPC Foundation and is standardized as IEC 62541 (IEC, 2020).

OPC UA introduced special servers responsible for collecting and exchanging several data from industrial control devices (Mahnke et al., 2009). Due to OPC, current and historical data, alarms, events, among others, can be made available to the software client. The server is usually targeted to a specific family of Programmable Logic Controllers (PLC) devices from a specific manufacturer or of a specific standard. Access to data in a standardized configuration shared among OPC servers is possible through OPC client modules that are integrated into applications that require access to data from control systems (SCADA, MES, and even ERP). The client can communicate with any OPC server using the standard OPC protocol to access data from PLCs of different manufacturers. The OPC UA standard has been identified as an important enabler for the realization of the Industry 4.0 factories of the future (Seilonen et al., 2016).

Based on the OPC-UA semantic information models, there are several ongoing activities to specify industry specific information models. Based on this, the so-called OPC UA Companion Specifications are defined. These Companion Specifications contain domain- or technology-specific models, the rules for mapping data and application models from the respective description domain to OPC UA. This is to ensure that vendor-independent interoperability is provided by a uniform standardized OPC UA information model of a specific target technology. This avoids that different device manufacturers use their individual information models. Nevertheless, these Companion Specifications leave enough room for proprietary extensions that may be necessary for manufacturer-specific device features. As the interest in OPC UA is growing, the number of Companion Specifications is constantly increasing. Examples of existing Companion Specifications are OPC UA for Devices (OPC Foundation, 2020), ISA-95 Common Object Model (OPC Foundation, 2013), for Weighing Technology (OPC Foundation, 2020), for MTConnect (OPC Foundation, 2019) and OPC UA for Computerized Numerical Control (CNC) Systems (OPC Foundation, 2017).

2.2.3. MTConnect

MTConnect is an open, extensible, and royalty-free communication protocol for exchanging data between manufacturing equipment and software applications based on XML (eXtensible Markup Language) that enables the various entities in a manufacturing system and associated equipment to seamlessly exchange data in a common format. The standard has become established in the U.S., particularly in North America, and is managed by the MTConnect Institute, a non-profit organization that aims to improve the use of data in the manufacturing industry (MTConnect Institute, 2021) and is the U.S counterpart of OPC UA for device communication.

MTConnect is based on XML and Hypertext Transfer Protocol (HTTP) and uses a Representational State Transfer (REST) interface for communication. Accordingly, there are many tools for implementation.

In its current version, MTConnect consists of five parts. The first part contains the terminology and determines the organization of the remaining parts (MTConnect Institute, 2021). The second part describes the metamodel for modeling devices (MTConnect Institute, 2021). Part three contains the metamodel for the data to be transmitted and thus the organization of the data flow, i.e. the communication between the network components (MTConnect Institute, 2021). In the fourth part, information about the use and modeling of assets is given (MTConnect Institute, 2021). Part 4.1 describes the modeling of cutting tools (MTConnect Institute, 2021). This description is based on ISO 13399 - Cutting tool data representation and exchange (ISO, 2006). The so-called interfaces are defined in Part 5 of the specification. These interfaces allow requests to the MTConnect Agent (MTConnect Institute, 2021).

The MTConnect architecture is relatively simple (MTConnect Institute, 2021) Basically, one needs a device that makes its data available on a network, an MTConnect agent that serves as a buffer for the device's data on the network, and a client that can retrieve the data from the agent and present it to the user.

2.2.4. AutomationML

The Automation Markup Language (AutomationML) is a neutral and XML schema-based data format for vendor-independent storage of plant engineering information. The goal of AutomationML is to link the heterogeneous landscape of engineering tools from different disciplines, e.g. mechanical engineering, electrical design, HMI development, PLC and robot controller programming, in their entirety (AutomationML consortium, 2018; Drath et al., 2008).

AutomationML can cover logic data from different tools and disciplines and supports different phases of plant design with different levels of detail. Thus, different types of logic information belonging to an industrial plant or to individual components can be stored. This variety of information can be divided into two main concepts: Sequencing and Behavior.

The AutomationML Data Format was developed by AutomationML as a solution for data exchange covering all information within the scope of production systems engineering (Schmidt and Lüder, 2015). It is an open, vendor-neutral, XML-based, and free data exchange format that enables cross-domain and cross-company engineering transfer.

AutomationML stores technical information according to the object-oriented paradigm and allows physical and logical plant components to be modeled as data objects encapsulating various aspects. Objects can form a hierarchy, i.e., an object can consist of sub-objects and itself be part of a larger composition or aggregation. In addition, each object can contain information about the object's geometry, kinematics, and logic properties (sequence, behavior, control, and information) as well as other properties.

Automation ML follows a modular structure by integrating and extending or adapting various existing XML-based data formats under one umbrella, the so-called top-level format.

2.3. Product Information Models

The international standards defining tolerances (syntax and semantics of dimensional and geometrical tolerances) are developed by ISO TC 213 "Dimensional and Geometrical Product Specifications (GPS) and Verification". The standards also include verification standards dealing with dimensional and coordinate metrology (Feeney et al., 2015). Three-dimensional models are replacing two-dimensional drawings as the main model for technical product data in the manufacturing industry (Srinivasan, 2008). This has created the need for standardized specifications of dimensions and tolerances on 3D models which has been solved by ISO TC 10 "Technical Product Documentation" in standard ISO 16792, which presents dimensions, tolerances, surface finish and other similar information as Product Manufacturing Information (PMI) on a 3D model.

The most comprehensive and complete standardization project for the unambiguous representation of product information is STEP. STEP is a collection of ISO standards, known as ISO 10303 (Feeney et al., 2015; Kramer and Xu, 2009) which enables information to be exchanged independently of any particular computer application by using a common, computer-interpretable format.

2.3.1. Digital metrology

Dimensional measurement systems consist of several components, each with different functions, such as design, process planning, process execution, measurement, and feedback and analysis of results (Sousa et al., 2022). Several commercial software systems exist for each of these components. Modern quality management systems can import and export data through various data formats and sources, such as Quality Information Format (QIF), text, ASCII and CSV, XML, serial devices (RS232), USB and virtual COM ports, AQDEF, I++ DME Interface (for CMM), and DMIS. However, the information exchange between these software systems is usually

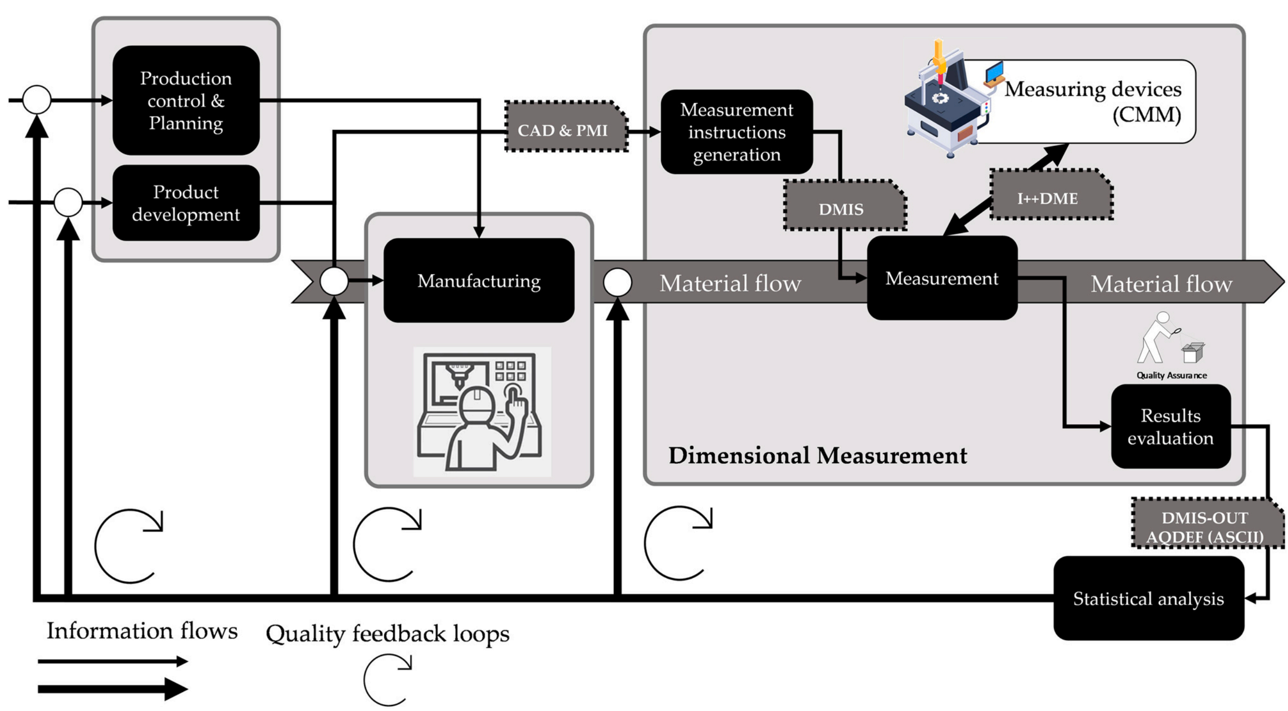

Fig. 4. Generic metrology workflow with quality control loops.
(adapted from (Imkamp and Tutsch, 2019)).

Table 1
Formats for the exchange of metrology data.

Format Name (short)	Format Name	Modeling Language	Domain	Type of Standard
QIF	Quality Information Framework	XML	Product Definition Measurement Planning Measurement Results Measurement Statistics	de jure (ANSI/DMSC QIF 3.0 and ISO 23952)
STEP AP 219	Dimensional Inspection Information Exchange	EXPRESS	Measurement Planning Measurement Execution Measurement Results	de jure ISO 10303-219
AQDEF or QML	Advanced Quality Data Exchange Format Quality Markup Language	ASCII (and XML for QML - Quality Markup Language)	Measurement Results Measurement Statistics	de facto (ISO 116462-5 working draft)
DML	Dimensional Markup language	XML	Measurement Results	de jure (DMIS)
QMD	Quality Measurement Data	XML	Measurement Results	de facto
eQuiPP	Exchange of Quality Measurement Process Plan	XML	Measurement Planning	de facto (abandoned and proceeded to QIF)
I++DME	Inspection Plus, Plus Dimensional Measuring Equipment	No Language (TCP/IP)	CMMs (Execution)	de facto
DMIS	Dimensional Metrology Interface Standard	No Language	CMMs (Execution And Planning)	de jure (ANSI DMIS 5.3 and ISO 22093)

proprietary. This large number of proprietary interfaces can be very costly for users, suppliers, vendors, and customers. Therefore, achieving interoperability within dimensional measurement systems is a pressing issue for standards developers, industry organizations and suppliers. Fig. 4 provides a generic workflow for industrial metrology with quality feedback loops and Table 1 provides an overview of the major data formats for metrological information.

The Automotive Quality Data Exchange Format (AQDEF) data format was developed by the software manufacturer Q-DAS together with a working group of major automotive manufacturers (Q-DAS, 2017). It is represented in ASCII format and is also available on XML technology in the form of the QML (Quality Markup Language) format, making it compliant with the World Wide Web standard.

ISO 10303-219 (STEP AP 219) (ISO, 2007) is a part of the STEP framework that covers the representation of measurement characteristics harmonized with Dimensional Metrology Interface Standard (DMIS), where the scope is focused on the representation of the required data for reporting measurement results. It is the first and unique standard that attempts to establish semantic associations between tolerances, measurement characteristics, dimensional measurement results and their circumstance (Zhao et al., 2011). However, the data model does not include a representation of measurement operations and strategies that specify how to measure a particular part (Majstorovic et al., 2014; Brecher et al., 2006).

The Dimensional Markup Language (DML) is part of DMIS for CMM measurement results (Automotive Industry Action Group, 2008).

The Quality Measurement Data (QMD) is a unidirectional (export of measurements) XML schema for quality measurements, including dimensionless measurements and gauge measurements and targets quality measurements with measurement devices other than CMMs (Zhao et al., 2011).

DMIS and I++DME are specifications for the interface between measurement process execution and measurement device control. I++DME has been developed by several European automotive manufacturers and measuring instrument manufacturers for the exchange of information between measuring instruments. There are many software implementations of I++DME worldwide, but neither coordinate measuring machine (CMM) software nor CMM systems offer I++DME in their published product offerings. Several vendors offer I++DME simulators that enable rapid and accurate development of I++DME implementations within the software used to execute measurement processes (Zhao et al., 2012).

QIF (ISO 23952) is a modular XML standard for metrology developed by the Dimensional Metrology Standards Consortium (DMSC) that allows closing the loop between quality and design by transporting product definitions through the measurement cycle and relating the results to the original characteristics (ANSI/DMSC, 2018; ISO, 2020). QIF (ISO 23952) is typically used either by a system that generates or consumes QIF files. These QIF documents may contain information on one part (e.g., plans, results, etc.), on several parts, or on all parts, depending on the purpose of the data exchange.

This analysis of formats for the exchange of metrology data shows that QIF provides the means to translate metrology data into knowledge, by addressing a broader scope of metrology activities (i.e., product definition, management planning, measurement results and measurement statistics), by adding specific meaning to data (i.e., semantics) and using a machine-readable data format. Other formats only partially comply with these characteristics.

3. Methodology

The research work presented here, expresses an information model for the RAMI 4.0 endorsed standard for the *Instance* Communication and Information Layers OPC UA with the objective of leveraging Quality Assurance information in a IoT distributed environment. The followed approach established standards for enterprise control integration IEC 62264 and in a smaller extent ISO 15531 (MANDATE) to ensure interoperability of the collected information with upper layers of an enterprise control system (e.g., an ERP system). For achieving this objective, a base standard domain specific information model was selected and described using OPC UA modeling rules to achieve a common interface for seamless device integration. An experimental scenario, supported by project ZDMP, requiring the integration of measuring devices in a steel manufacturing company is used to validate the proposed approach.

3.1. Requirements for the designed framework

Measuring devices lack a standard interface with adjacent systems, although the current trend of Industry 4.0 requires them to be more integrated to ensure automated quality control loops. This drives the necessity for bidirectional communication with other systems such as CAQ, LIMS, MES, and ERP. The framework will be used to execute quality activities in a manufacturing company, as well as to enable services and data access to external clients (users, applications, or other services). The objective of the framework is to improve interoperability of the measuring devices, by improving communication with the said devices and control systems like an ERP or a MES. This way, the communication with other information systems of the company (or external) are also improved (e.g., production and maintenance). The framework will provide updated data and information to management through a standardized interface. In summary, the framework will provide interoperable, accurate and reliable information.

The fundamental design considerations for the framework were considered, especially the basic functionalities as listed hereafter:

- it must be traced back to fundamental standardization in the domain such as ISO/ANSI standards for dimensioning and tolerancing, and the International vocabulary of metrology (VIM);
- making available both historical and real-time measurement information;
- guaranteeing the usage of standards and open protocols to enhance interoperability;
- supporting activities for QA approaches such as ZDM and
- support the usage of an IoT infrastructure to promote the interconnection of the digital and physical worlds.

3.2. Fundamental concepts

QA is a set of activities within a manufacturing company, part of QOM responsibility for measuring and reporting on quality, *inspections*, by integrating devices (e.g., productive devices and measuring devices), personnel, processes, and systems, to deliver *products* according to the client's requirements. Starting from a *bill of characteristics* (BoC), which contains a list of *characteristics*, derived from the product model (e.g., a STEP AP 242 file) containing *product and manufacturing information (PMI)*, that must be considered for inspection and reporting, can be transformed into a *measurement plan* which defines the required information to support high- and low-level measurement planning. For measurement planning, a detailed description of the available measurement devices, tools and auxiliar equipment (such as sensors) is necessary for the inspection tasks to be performed. These *measurement devices* require enough description to support decisions with respect to their applicability and capability. This information includes location, achievable accuracy, measurement speed, mass capacity, available working volume, calibration history and traceability. For consistency in measurement planning, automation and minimizing uncertainty, a *measurement plan* can be created, with a definition of *a measurement procedure* for measurement programming implementation that conforms to the best company, sectorial and standard practices. After the high- and low-level programming the measurement execution takes place either by releasing instructions to human operators using manual *devices* such as calipers and go/no-go gauges, or by generating a detailed *device* specific inspection program according to DMIS, or other measurement programming language, to provide equipment level commands to coordinate measuring machines (CMM) controllers or roundness instruments, for example. The result is a single or multiple *measurement results* that can be collected, reported, and analyzed for single part inspection or statistical analysis and fed back to other processes such as product design, or quality engineering or sent directly to an internal or final customer. These statistics comprise quality measurements of variable and attribute characteristics including not only of the observed values, but also a summary of statistical (e.g., averages, standard deviation, minimum and maximum). A link to the original quality *characteristics* (nominal and tolerance) is required, along with additional information such as time of measurement, time of manufacture, operator, manufacturing resource (e.g., a machine), used tools and measured items, etc. This information can support further detailed analysis (e.g., for defect prevention) and trigger the application of *corrective actions*, *preventive actions,* or *predictive actions*. Although these actions are not explicitly referred in the framework, the result of data exchange using the proposed framework is the support of said actions. Table 2 provides the description and reference of the main concepts within the framework.

Table 2
List of quality operations related concepts used in the framework.

Concept	Description	Source
actual component	a physical instance of a component[a]	ISO 23952:2020, 3.4.5
bill of characteristics (BoC)	a list of all the characteristics applied to a product.	ISO 23952:2020, 3.4.21
characteristic	a control placed on an element of a feature such as its size, location or form, which may be a specification limit, a nominal with tolerance, a feature control frame, or some other numerical or nonnumerical control	ISO 23952:2020, 3.4.29
corrective action	action to eliminate the cause of a nonconformity and to prevent recurrence	ISO 9000:2015, 3.12.2
inspection	examination of a product design, product, process or installation and determination of its conformity with specific requirements or, on the basis of professional judgment, with general requirements	ISO/IEC 17000:2004, 4.38
measurement instrument	device used for making measurements, alone or in conjunction with one or more supplementary devices[b]	OIML V2–200:2012, 3.1
measurement plan	a complete plan that contains information on what and how to measure	ISO 23952:2020, 3.4.87
measurement procedure	detailed description of a measurement according to one or more measurement principles and to a given measurement method, based on a theoretical model and including any calculation to obtain a measurement result	ISO/IEC Guide 99:2007 2.6 mod.
measurement result	set of quantity values being attributed to a measure and together with any other available relevant information	ISO/IEC Guide 99:2007, 2.9
predictive action	action to monitor the condition of an asset and predict the need for preventive action or corrective action	ISO 55000:2014, 3.3.5
preventive action	action to eliminate the cause of a potential nonconformity or other potential undesirable situation	ISO 9000:2015, 3.12.1
product	result of a process	ISO 9000:2000, 3.4.2
product and manufacturing information (PMI)	collection of information created on a 3D/2D CAD model to completely document the product with respect to design, manufacturing, inspection, etc.	ISO 14306:2017, 3.1.15
quality assurance	planned and systematic actions necessary to provide adequate confidence by ensuring that a product or service will satisfy given requirements for quality	IEC 60788, ed. 2.0 (2004–02), 3.265
traceability[c]	information about the circumstances of a quality measurement process or a manufacturing process	ISO 23952:2020, 3.4.134

[a] By analogy to a car, the design of a wheel is a *part*; the design of the wheel placed at the front right of the design of a car is a *component*; the front right wheel of a physical car is an *actual component*. (source ISO 2, 2395:2020)
[b] A measuring instrument that can be used alone is a measuring system (source OIML V2-200:2012, 3.1)
[c] The definition provided by ISO 23952:2000 differs from the one provided in VIM 6.10 which only considers the result of a measurement.

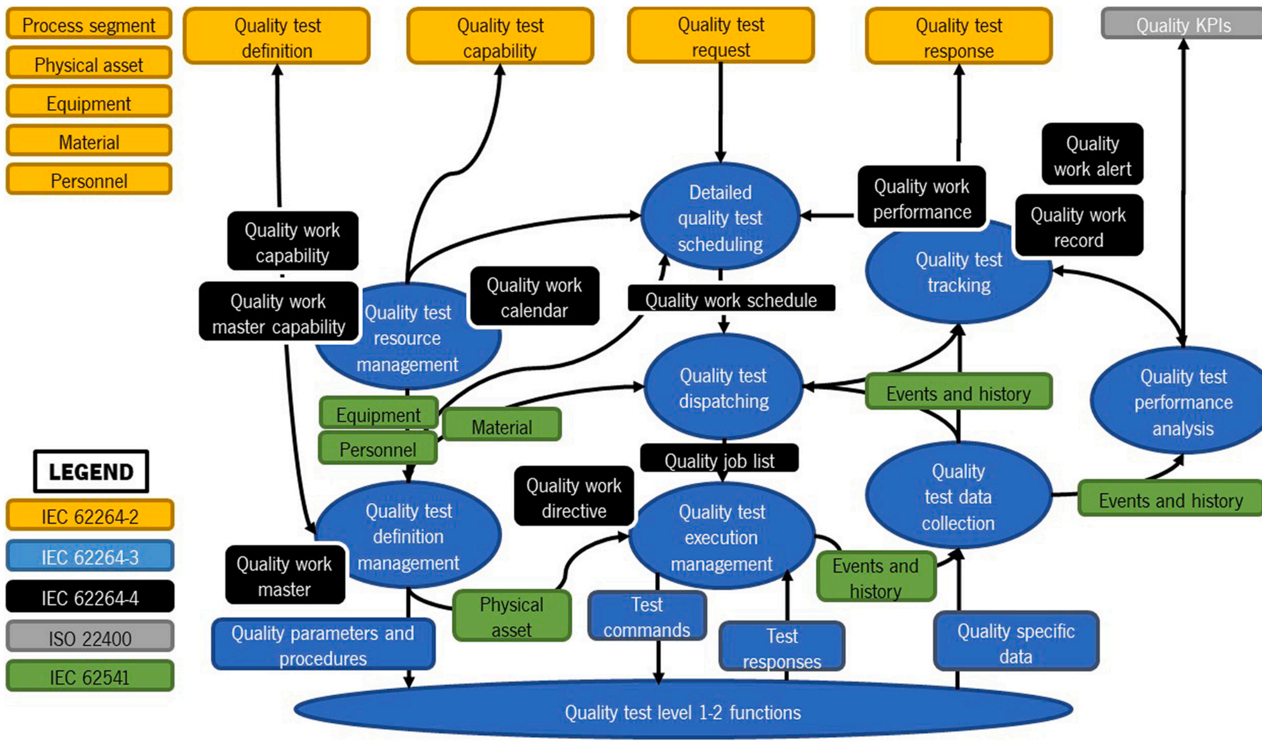

Fig. 5. Information exchange models for quality manufacturing operations management. (adapted from (IEC, 2016)).

4. Framework for device integration

A set of models for model attributes are defined in standard IEC 62264-4 to represent the information exchanged between activities defined for MOM in IEC 62264-3. IEC 62264-4 defines models of information which can be exchanged between Level 3 activities (represented as blue ellipses in Fig. 5) within an operational category or across operational categories. IEC 62264-2 defines models of information that may be exchanged between Level 4 activities and Level 3 activities and are represented as orange rounded rectangles. Quality KPIs defined in ISO 22400 are exchanged from Level 3 activities (Quality test performance analysis) and are represented in gray rounded rectangles. Other information (represented in green rounded rectangles) shown in Fig. 5 is defined in standard IEC 62541. The OPC UA for ISA 95 Common Object Model defines the information flow between MES and ERP systems which adds IEC 62264 object model representations of equipment, personnel, material, and physical assets. Fig. 5 shows the types of integration information exchanged using the information models from standards IEC 62264, IEC 62541, and ISO 22400.

The use of standard IEC 62264 guarantees that a fair degree of interoperability is achieved in the system, since the activities, information models and information flows are defined in the standard and can be used to decrease the labor required in integration efforts between Level 4 systems and Level 1–2 systems.

ISO 22400 defines manufacturing operations management key performance indicators (KPIs) defined in IEC 62264 (ISO, 2014). These KPIs reside in Level 4 since they are related to business planning and logistics. The IoT system can make use of this standard to describe and exchange KPIs relevant for the Quality and Production categories. Table 3 shows example KPIs defined in ISO 22400 for product and process quality assurance.

As stated in Section 2.2.2, several OPC UA companion specifications were already designed and published, such as a companion specification for machine tools, for machine vision and for weighing devices (a type of measuring device). These companion specifications provide the ability to exchange standard data between systems, for monitoring, digital twinning, data analytics, among others. But mostly, they bring devices closer to a plug-and-play integration.

Considering the possibility of a generic information model for measuring devices being provided in future, still no standard method is known to report measuring results. The most comprehensive formats for reporting metrology data are the AQDEF and QIF formats. These can work together with already established consensual communication protocol such as OPC UA and MTConnect to provide a common interface for measuring devices. This common

Table 3
Example KPIs.

KPI	Required Information
OEE	Availability; Effectiveness; Quality ratio
Scrap Ratio	scrap quantity (SQ); produced quantity (PQ)
Rework Ratio	rework quantity (RQ); produced quantity (PQ)
Process Capability index (Cp)	Specification limits (USL, LSL); Standard deviation (σ)
Machine Capability index	Specification limits (USL, LSL); Standard deviation (σ)
Quality Ratio	good quantity (GQ); produced quantity (PQ)
First pass yield	good parts (GP); inspected parts (IP)

Table 4
Overlapping activities in QIF and IEC 62264-4 Quality Operations Management.

QOM Activity	QIF Activity	Corresponding QIF part
Quality test resource management	Define measurement resources	QIF Resources
Quality test definition management	Define measurement process	QIF Plans
Quality test execution management	Execute measurement process	QIF Results
Quality test performance analysis	Analyze & Report Quality Data	QIF Statistics
Quality test definition management	Define measurement rules	QIF Rules
Quality test definition management	Define measurement requirements	QIF Plans

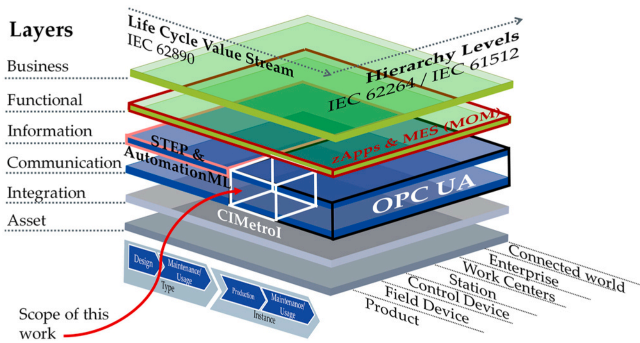

Fig. 6. OPC UA as the supporting standard for communication and information modeling for Industry 4.0 according to the RAMI 4.0
(adapted from (DIN, 2016)).

interface will not only provide the means to describe the device itself, but also to describe the measuring operation currently being performed and the results of those measuring operations, thus providing a device and dimensional component digital twin. With respect IEC 62264, there are six activities in QOM that significantly overlap with the QIF generic workflow (ANSI/DMSC, 2018) that are presented in Table 4 with the corresponding QIF part.

4.1. A standardized interface for IoT measuring devices

Besides the DIN, *Plattform Industrie* 4.0, VDMA and ZVEI recommendations for the usage of OPC UA (and AutomationML / ISO 10303 - STEP for Type definition) as the communication standard for Instances according to the Life Cycle Value Stream (IEC 62890) (Fig. 6) (VDMA, 2017; DIN / DKE, 2018; Plattform Industrie 4.0 4.0 4.0, 2018; ZVEI, 2017) - OPC UA also offers great advantages when compared with MTConnect for modeling. As clarified in Liu et al. (2018), OPC UA does not bind to a specific domain, as opposed to MTConnect that is specific for machine tools. The information modeling approach is also generic and flexible, for the reason pointed out before. It is also bi-directional, as opposed to MTConnect that is read only, and is suitable for monitoring and control, while MTConnect is only suitable for monitoring. A more extensive comparison between the two communication protocols is provided in Liu et al. (2018).

For those reasons, the standardized interface proposed by the CIMetroI is based on an OPC UA information model.

As stated in Chapter 2.2.1, the information modeling approach of OPC UA is generic and flexible. Information modeling for OPC UA is usually performed by domain specialists, that are familiar with the structure of the object and the available data. To design a domain specific information model, a typical workflow, as the one used for the creation of OPC UA companion specifications can be used: thought a UML-derived approach by defining a Role Diagram, a Use-Case Diagram, and an Activity Diagram. This article defines as approach for OPC UA information modeling based on the following guidelines:

- OPC UA Objects are used to model QIF elements;
- QIF attributes are modeled in OPC UA using Variables;
- QIF children elements are modeled in OPC UA using *HasComponent* or *HasProperty* relations to upper elements.

A standardized interface for IoT measuring device integration was designed, based on the QIF standard. A QIF document can contain very large sets of information. If it were integrally translated into an OPC UA information model it would result in a too complex structure. In the standardized information model, the MeasurementResourcesType, ProductType, FeatureType, ResultsType, Manufacturing Process TraceabilityType, CharacteristicType of BaseObjectType are defined as a complex ObjectType and focuses on the necessary QIF part to:

- Describe a *component*, belonging to a *product*, composed of *features*;
- Describe the *characteristics* that are being measured;
- Describe the *measurement resources* that are used for the *measurement*;
- Describe the *manufacturing process* responsible for defining the *characteristic* being measured;
- Describe the *measurement results*.

An overview of the OPC UA information model is provided in Fig. 7.

The Measurement Resources Type defines the *fixtures* though the Fixture Type object, the *measurement rooms* through the Measurement Rooms Type, *measurement devices* through the Measurement Devices Type, the *detachable sensors* through the Deatachable Sensors Type, and *tools* thought the ToolsType object for a complete description of the measurement resource used for the measurement.

The ProductType describes the parts and assemblies object of measurement. It can also provide a link to external CAD files (e.g., a STEP ISO 10303 file).

The FeatureType defines elements of the part, the feature information such as a circle, a line, a point, or a plane, using four aspects: definition, nominal, item, and measurement though the FeatureDefinitionType, the FeatureNominalType, and the FeatureItemType.

The CharacteristicType defines characteristics information such as circularity, cylindricity and flatness, using the same structure as FeatureType: definition, nominal, item, and measurement though respectively the CharacteristicDefinitionsType, the CharacteristicNominalsType, and the CharacteristicItemType.

The ResultsType defines the *measurement results* though the MeasurementResultsType objects, defines the component being measured though the ActualComponentType objects, and information regarding the inspection's traceability though the InspectiontraceabilityType object. The FeatureMeasurementsType objects and the CharacteristicMeasurementsType objects, as parts of the ResultsType, define the actual results of the measurement and the corresponding status (Pass/Fail).

The ManufacturingProcessTraceabilityType defines manufacturing process specific traceability information through the OperatorIndentifierType object, the MachineIdentifierType object, the ShiftType object and the ProcessParametersType object. The usage of ManufacturingProcessTraceabilityType allows the usage of

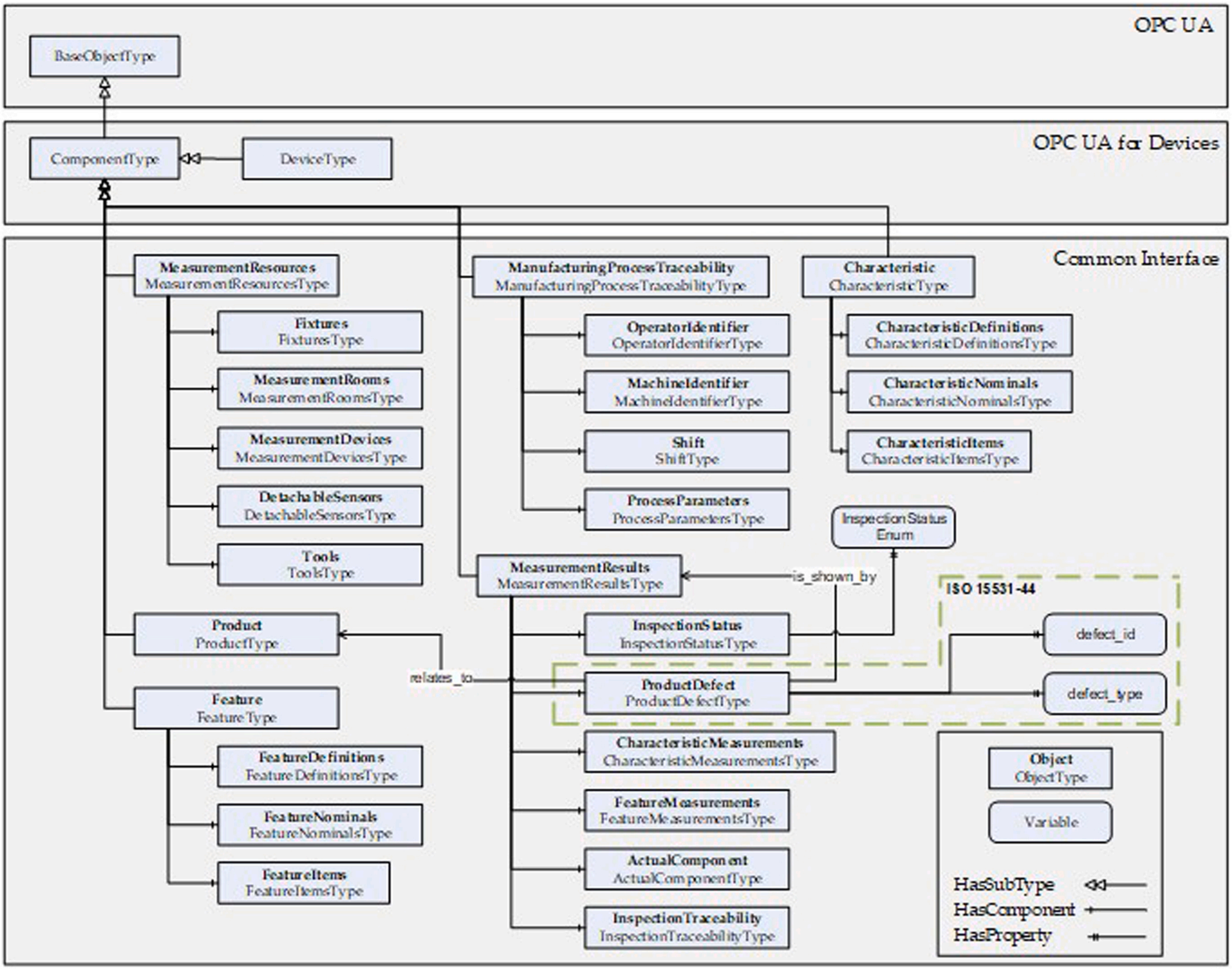

Fig. 7. Standardized interface for metrology device integration based on OPC UA.

measurement results to monitor and improve the manufacturing process.

The connection between the four different descriptions of a feature and characteristic is achieved though the described chain in Fig. 8. Each measurement (feature of characteristic) references an item, that references a nominal, that references the definition. A connection between a feature and a characteristic can be achieved if the FeatureItemIds element is used -. For the PMI stage, this

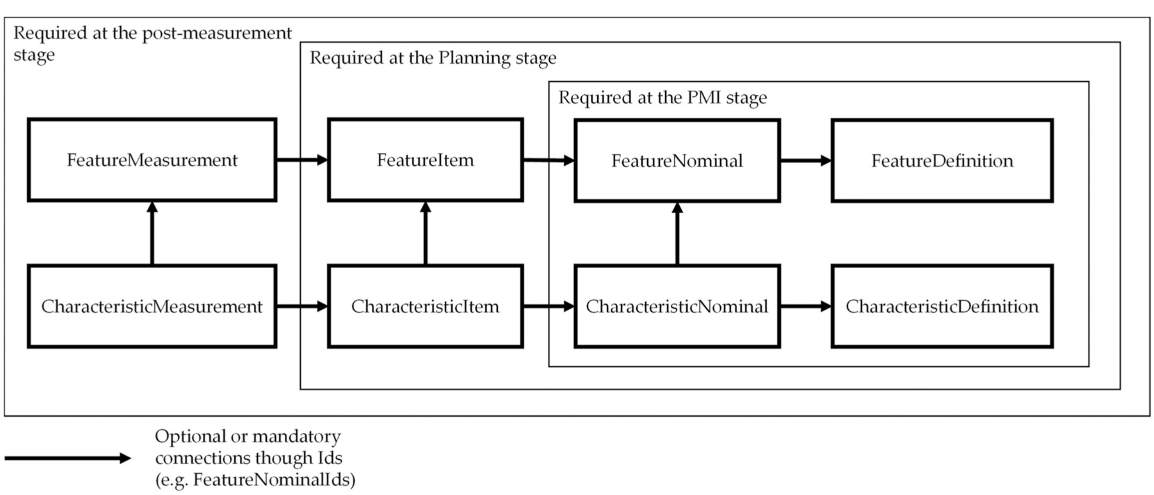

Fig. 8. Connections at the post-measurement, planning and PMI stages.

Table 5
Sample candidate concepts for defect type.

Concept	Reference
visual defect	ISO 18669-2:2020
critical defect	ISO 9154:2016
major defect	ISO 9154:2016
minor defect	ISO 9154:2016
surface defect	ISO 3290-1:2014
invisible defect	ISO 25178-73:
effective defect	ISO 25178-73:2019
cosmetic defect	ISO 25178-73:2019

connection between features and characteristics is achieved through a FeatureNominalIds element. Both Features and Characteristics are used to support the creation of a BoC in a measurement plan.

In addition to QIF entities, and additional ProductDefectType is defined, with variables *defect_id* and *defect_type* provided by standard ISO 15531-44 and references *relates_to* and *is_shown_by*. These variables allow to identify a detected defect by providing an *id* and a classification (type). A preliminary list for defect type according to ISO scope of standards is shown in Table 5 and can be used to provide the appropriate description of the defect type.

4.2. Reference architecture for metrology device integration

At the core of the developed **C**ommon **I**nterface for **Met**rology device **I**ntegration (CIMetroI) framework, there is a generic IoT architecture. The IoT architecture is based on the ISO/IEC 30141 Reference architecture for IoT (ISO/IEC, 2018) and has the four basic domains: Devices (physical entities), Sensing & Controlling, Core and Users. To the CIMetroI, the IoT system provides seamless data exchange capabilities by providing a standardized interface for measuring devices. The Devices domain consists of the physical entities of the IoT system, which can be the measuring devices, such as a CMM, a caliper, micrometer, a roundness tester, etc. using proprietary and heterogeneous data formats. The Sensing & Controlling domain comprises IoT devices, i.e., the actuators and sensors. The sensors monitor and receive data from the Devices domain, while the actuators use information provided either directly by the user or the Core domain to act on the Devices domain. Other physical entities such as IoT gateways and storage can coexist in this domain. The Core domain provides the mechanisms to analyze, simulate, manage, and operate the Devices based on information provided by the User and Sensing & Controlling domains. This domain comprises domain specific applications such as Quality Assurance, Quality Control and Predictive Quality systems. A Digital Twin of the measured components can also be managed in the Core domain. The Users domain is the main interface with the users of the IoT system, either by interfacing with an MES, an ERP, the Cloud, external user or IoT platform applications (Sousa et al., 2020). An overview of the IoT architecture for CIMetroI is provided in Fig. 9.

Some degree of data transformation is required when implementing CIMetroI. The data acquired from the devices can have a non-OPC UA interface, thus requiring to be mapped or transformed (logically, mathematically) to the standardized semantics through a transformation engine, from the non-OPC UA interface to the standardized semantics of CIMetroI.

5. Validation

5.1. Experimental Scenario

The Experimental Scenario is taking place in the scope of project ZDMP more specifically in a use case within the steel tube manufacturing domain. The actors in the Construction Use Case are a machine tool for the steel tube sector; a steel tubes manufacturer; a stone cutting machines manufacturer and a stone slabs and tiles producer. Managing the raw material at production sites is conducted by a consulting company with a field of activity that includes all stages of infrastructure construction. The steel tubes producer provides steel tubes and the stone slabs and tiles producer delivers stone tiles to the construction sites managed by this company. ZDMP will aid the construction industries when it comes to production

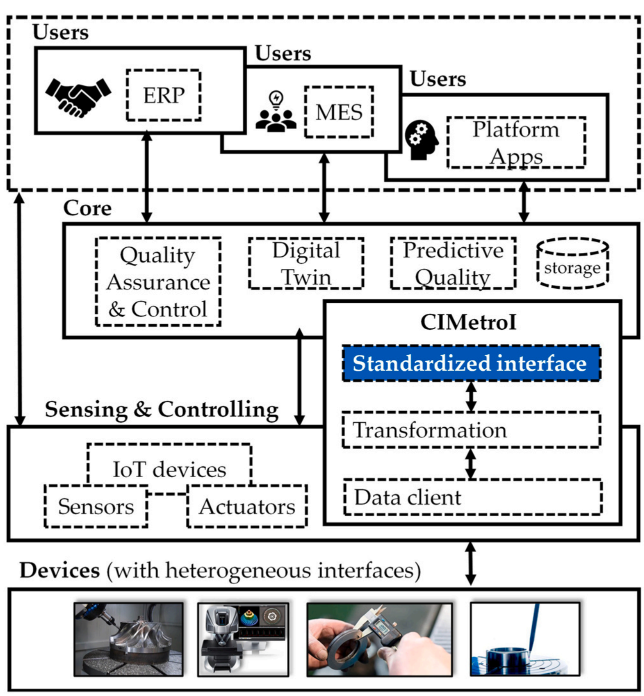

Fig. 9. Overview of the architecture for the CIMetroI.

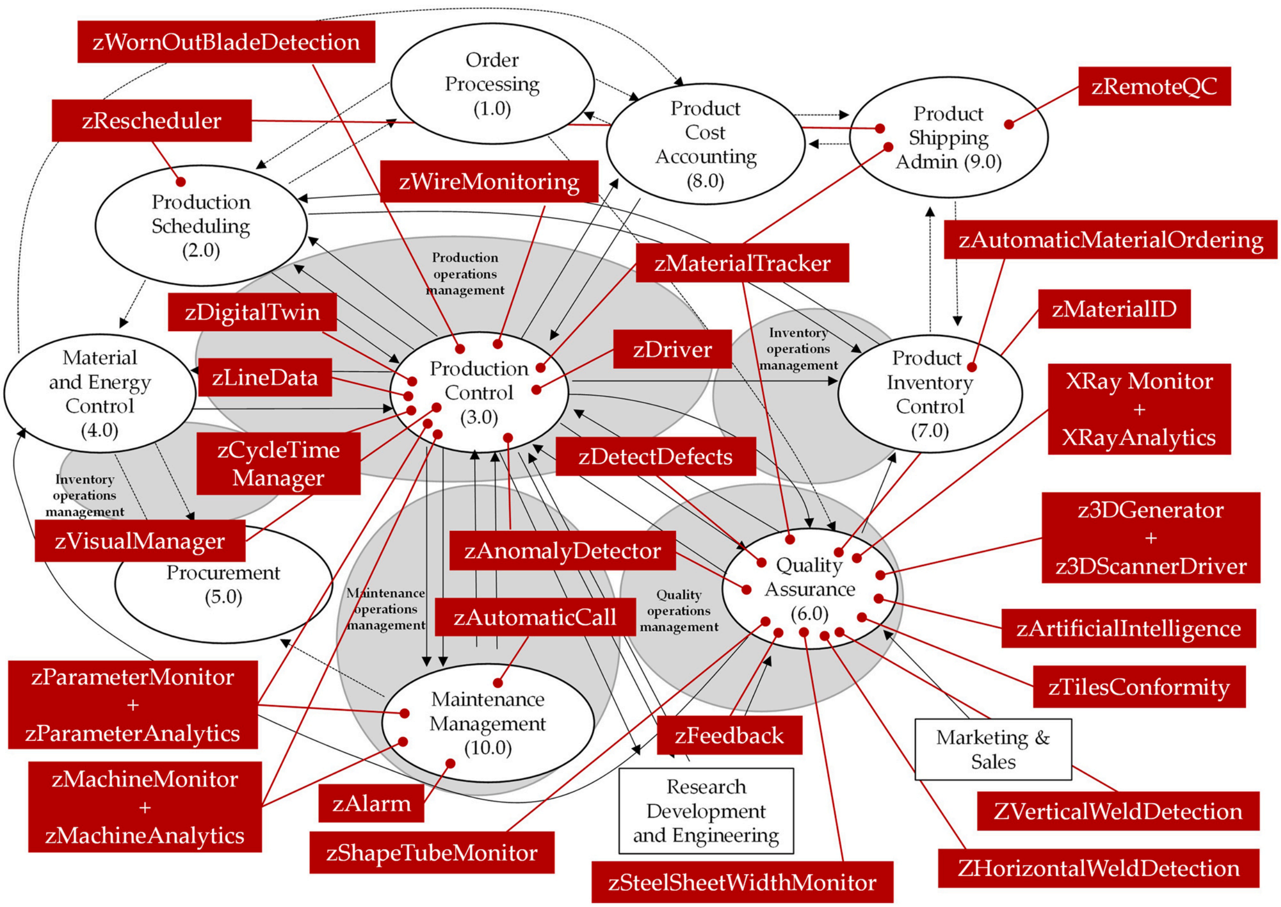

Fig. 10. zApps application domain within the IEC 62264 Manufacturing operations management model.
(adapted from (IEC, 2013)).

monitoring, equipment wear detection, quality traceability and quality control on the construction site level (Sousa et al., 2020). ZDMP offers a platform with a set of core components (zComponents) that can be used to build custom Process and Product Quality apps (zApps) which can be purchased or made available on a marketplace for other users to purchase and use. The several zApps developed within the scope of ZDMP can be mapped to the IEC 62265 Manufacturing operations management model (Fig. 10). The zApps are mainly within the scope of, or mainly interact with Production Control (Production Operations Management) and Quality Assurance (Quality Operations Management) functions according to IEC 62264. Other zApps either are within the scope or mainly interact with Maintenance Management, Product Scheduling and Product Shipping Administration functions.

The ZDMP high level architecture can be mapped to the four tier architecture pattern based on IIRA's three-tier architectural pattern (Fraile et al., 2019). Fig. 11 shows the generic steel tube manufacturing use case architecture based on the four-tier pattern. The CIMetrol is used to provide a partial description of the QOM objects, Level 1/2 entities i.e., shopfloor devices. to support zero-defects and MES objects (Fig. 5). The Information model provided by CIMetrol is used by the Data Acquisition zComponent to register and describe each device, but is mainly used by the Service and Message Bus zComponent to Read, Write or Monitor variables of the CIMetrol address space using a Server/Client or Publish/Subscribe based architecture (Mahnke et al., 2009; OPC Foundation, 2018).

The preliminary results from the conducted experiments are promising. The CIMetrol OPC UA information model provides a standard interface to all the applied measuring devices in the use case. The information model can be shared though NodeSet files (XML) which has a graph-based data structure containing the content of the information model. The NodeSets can also be imported/exported by OPC UA servers to be used by OPC UA clients expanding its usage to multiple use cases, industrial domains, measuring devices and products.

5.2. Discussion

Besides the set of Objects and Variables described in the standardized interface for metrology device integration (Fig. 7), an additional OPC UA Node can be included in the CIMetrol: a Method Node. Methods define callable Functions that are assigned to an Object or ObjectType. These can be used, for example, to describe standard functions of a measuring system, such as retrieving the results after a final inspection is performed. By adding this type of Node, not only the complete description the measuring resource, the product, the characteristics and so on is being allowed, but also common functions of the system can be described, so a generic Client can visualize and execute such available Methods on different system elements if the Information Model is commonly shared.

In fact, this research can open the debate for an OPC UA Companion Specification for industrial metrology, similarly to the ones presented in Section 2.2.2. Although a Companion Specification for vision systems and weighing scales already exists, a more complete and more generic model for measuring devices can help manufacturing companies in the creation of digital replicas of their measuring devices through a standardized Information Model.

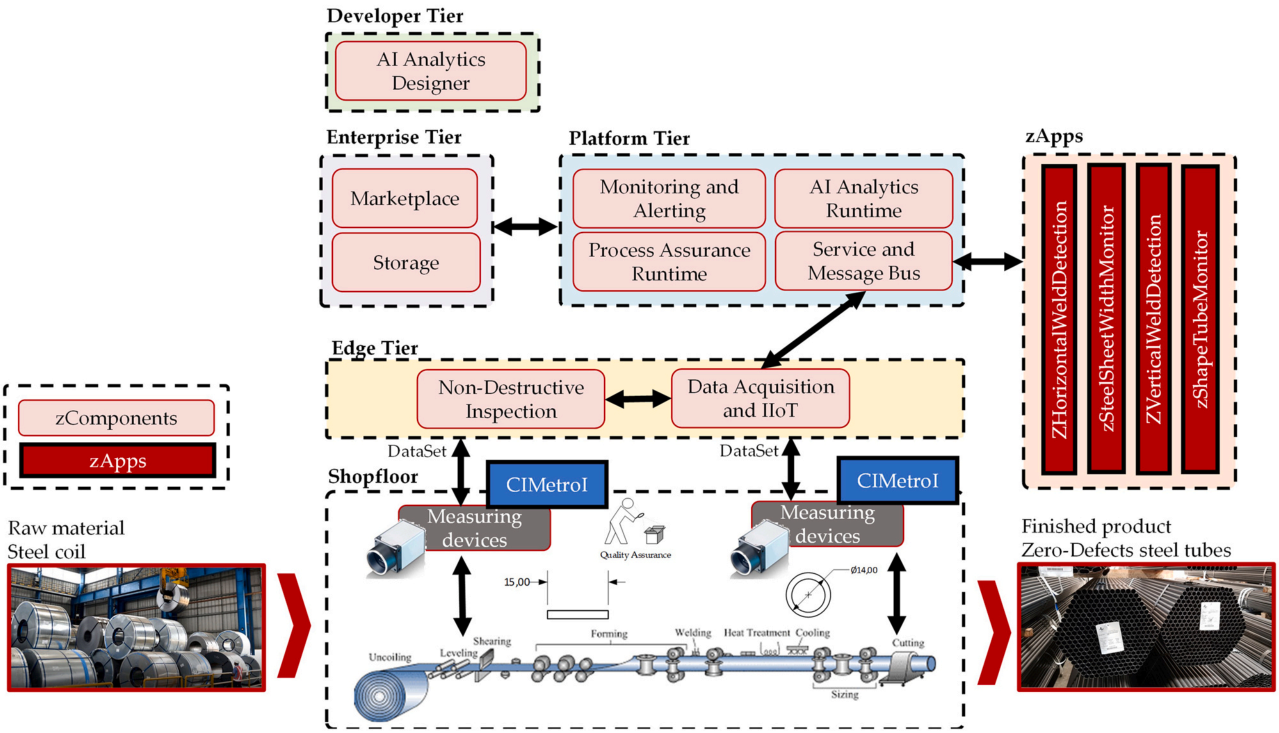

Fig. 11. Steel tube manufacturing use case architecture w/ CIMetrol.

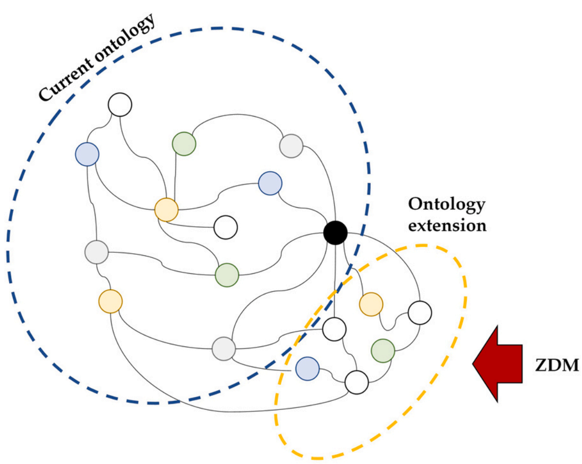

Fig. 12. Ontology extension for zero-defect manufacturing.

Although the gathered vocabulary is based on the ontology provided by ISO 23952 and ISO 15531-44, further extension on the CIMetrol information model can be achieved by an extension of the current used ontology (Fig. 12). An ontology for ZDM is being prepared based an ongoing CEN Workshop Agreement (CWA) to formalize ZDM terminology. The objective is to integrate the ontology in CIMetrol to extend the domain from Quality Assurance to Zero-Defect Manufacturing. (Fig. 12).

Additionally, the introduction of the Manufacturing Process Traceability information can help in providing the causality link between the measurement result and the applied manufacturing resources such as tools, parameters, machines and so on. This can assist in defect prevention and prediction tools and methods such as the control plan and FMEA (AIAG, 2019). The addition of FMEA to QIF workflow was already subject to study (Huang and Hedberg, 2019).

Limitations: the presented approach focuses on quality assurance of dimensional and geometrical features and characteristics. Operational features (e.g., rotation speed) don't have yet a formalization in QIF standard. For machine operation features, a companion specification such as UMATI (VDMA, 2020), MTConnect (MTConnect Institute, 2021) and the complementary MTConnect for OPC UA companion specification (OPC Foundation, 2019) can be used to address this limitation.

6. Conclusions

Industrial metrology is increasing its awareness in its central role in Industry 4.0 for reliable continuous data collection on quality characteristics of an item, either a product or a process in the scope of Quality Assurance. This puts considerable pressure in the vertical integration of measuring devices and interoperability considerations.

This work helps to close an existing gap in metrology device integration. In it, the role of standardization is emphasized in the task of vertical integration, by putting together a standard based IoT architecture, where measuring devices can have their data collected though a generic OPC UA interface to cooperate in IEC 62264 Quality Operations Management activities. This generic information model can help other system integrators in integrating measuring devices in an IoT architecture. For measuring devices with specific functions and interfaces with the manufacturing system, a companion specification such as OPC 40100–1 for Machine Vision or OPC 40200 for Weighing Technology can be used simultaneously since OPC UA supports multiple information models, although the proposed interface, based on QIF standard offers expandability and specific description of measuring devices such as a CMM, an autocollimator or a microscope.

In summary, this article provides a framework based in IEC 62264 for Quality Operations Management to describe the activities of Quality Assurance and delivers a generic interface using OPC UA to receive and send information to the QOM activities, enabling integration with upper systems such as an ERP and the creation of quality oriented KPIs.

Future work includes the extension of the information model using a ZDM ontology with additional vocabulary and domain specific information.

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CRediT authorship contribution statement

João Sousa: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Funding acquisition, **João Pedro Mendonça:** Conceptualization, Software, Validation, Formal analysis, Resources, Writing – review & editing, Visualization, Project administration, Funding acquisition, **José Machado:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing – review & editing, Visualization, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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