Integration of Non-Destructive Inspection (NDI) systems for Zero-Defect Manufacturing in the Industry 4.0 era

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***Abstract*— Industry 4.0 paradigm and its enabling technologies, such as Internet of Things (IoT), have increased the potential of industrial automation with the growing implementation of Cyber-Physical Production Systems (CPPS). They improve the production processes thanks to an optimal use of data. Based on the Reference Architecture Model Industry 4.0 (RAMI 4.0) and the Asset Administration Shells (AAS), according to standards and communication protocols, the European project OpenZDM is realizing an open platform to perform the Zero-Defect Manufacturing paradigm. The platform will be developed and demonstrated in five representative production lines combining ICT solutions and innovative Non-Destructive Inspection systems (NDI). NDI systems will be used as an Industry 4.0 enabling technology to collect and analyze data from the physical assets and convert them to value-added information, as an IoT technology. A relevant example of an NDI system is presented in this paper, based on the acquisitions of an infrared camera, to focus on the business logic unit and the OT/IT convergence and integration.**

***Keywords*—Industry 4.0, NDI, Quality Control, Zero-Defect Manufacturing, IoT integration, Asset Administration Shell, thermal measurements**

I. Introduction

Industry 4.0 refers to the intelligent networking of machines and processes for industries with the help of information and communication technology. One of the main goals implementing this paradigm, is the convergence of information technologies (IT) and operational technologies (OT), the merge of these two networks to improve production processes, increase factory flexibility and convertibility, realizing costumer-oriented solutions with optimized logistics and an optimal use of data.

Industry 4.0 paradigm underlines the added-value obtainable from the exchange of information, inside the so-called Smart Factory and between all the possible partners of the value chain. Reference [1] defines the Smart Factory as "*a manufacturing solution that provides such flexible and adaptive production processes to solve problems arising on a production facility with dynamic and rapidly changing boundary conditions in a world of increasing complexity*". Smart Factory is the combination of optimized automation, IT frameworks and an improved collaboration of different partners to form a dynamic organization. Two types of integrations are necessary: horizontal and vertical integration. According to this definition, each physical component of the industrial facility should have a counterpart, a digital representation to allow the required complete integration of the physical elements into the industrial logic. Smart Factory takes form into three main concepts: Smart Services, Smart Energy and Smart Manufacturing.

From the Smart Manufacturing point of view, in recent years the Zero-Defect Manufacturing (ZDM) paradigm has emerged, based on the quality management philosophy, concerning lean production, quality control and Six Sigma. It aims for the complete elimination of defects, through detection and correction of products and process parameters but also prediction and prevention. In the past, quality control was synonymous with human expert intervention, performing measurements and tests for random samples of the finished products at the end of the production line. With the implementation of the I4.0 paradigm, the Total Quality Management (TQM) concept takes place, as a framework to improve quality level using continuous feedback from all the parts involved in the process. Quality control should consider all the production stages, instead of the finished product, should not regard only random samples and should not rely only on humans' knowledge and experiences. In this context, measurement plays the fundamental role of providing quantitative data, which are fundamental to perform quality and process control at single process level and at factory level, as well as digital simulation.

ZDM strategies, such as defect prevention, can be achieved if the process is known in depth and the process conditions leading to defects are identified. So, data are the main character in this improvement of the manufacturing processes. Industrial activities are based on a high number of digital components producing data. Data could be collected and analyzed in huge quantities with the objective of transforming them into information, adding value to it, in terms of knowledge and economically. So, ZDM uses Internet of Things, Big Data and Artificial Intelligence to reach the new quality paradigm in the Industry 4.0 era of CPPSs.

On the flow of IoT concept, to reach a high-quality inspection for ZDM, non-contact measurement techniques are steadily gaining more and more interest. Among others, Machine Vision techniques are reliable, fast, and economic; supported by the development of new infrastructures necessary for a correct transmission of data and information, they allow automated quality inspections, faster than human operations, more accurate and repeatable, fully non-intrusive. Moreover, machine vision systems can inspect the whole parts or products involved in the process. Consider also that using machine vision techniques is particularly advantageous in industrial harsh environments where human presence could be problematic.

Non-Destructive Inspection systems could be considered a powerful tool to digitize a production process. They can measure, analyze, and develop a diagnosis that allows an improvement in quality of the industrial plants and the achievement of the Zero-Defect Manufacturing objectives. NDI and IoT together can improve the efficiency and the effectiveness of inspections and then the accuracy of the real-time monitoring of the overall process or the components.

Experimental data could be acquired during the production process taking into consideration the important issue of uncertainty. Strategy to know and possibly manage uncertainty are relevant to improve the quality of any decision taken after measured data. The quality of information derived from data, and the subsequent knowledge build-up, depends on the data, therefore their uncertainty cannot be neglected.

According to [2] also information and communication technologies (ICT) solutions should be carefully analyzed and developed to a complete and secure horizontal and vertical data integration. Near to the integration concept, also consider the importance of traceability and tracking into automated production lines to quickly identify defects and implement a correction mechanism.

II. TECHNOLOGIES ENABLING I4.0 COMPONENT INTEGRATION

New technologies, both IT and OT, and standards improve interoperability and enable secure data exchanges between different organizations at the state-of-the-art. Real added value is generated if the components map and offer their data in accordance with standards. This requires industrial communication protocols as well as standards for information modeling and framework development [3]. According to [4], standardization is an important issue to support innovative processes and harmonize the different development activities; to use standards at the beginning of an innovation project help in reducing the costs and to prevent the use of duplicate unnecessary processes or technology.

The Reference Architectural Model Industrie 4.0 can be used to define the whole organization and layout of the factory in a precise structured manner. According to the required integration layer to set up the architecture, Asset Administration Shells (AASs) can be used to close the gap between physical component and their digital counterpart. Communication protocols are analyzed to apply the most suitable standards to the transmission of information in a certain application.

A. RAMI 4.0

As Fig. 1 shows, RAMI 4.0 is a three-dimensional map showing how to approach the issue of Industry 4.0 in a structured manner. It ensures that all participants involved in Industry 4.0 discussions understand each other [5].

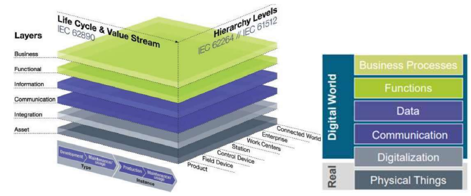

Fig. 1 RAMI 4.0 structure [5].

RAMI 4.0 combines all elements and IT components in a layer and life cycle model, it breaks down complex processes into easy-to-grasp packages, including data privacy and IT security.

To focus on the integration concept in the industry 4.0 era, great attention must be paid to the so-called axis "Layers", so to the Architecture. The first level (from the bottom) is the asset. Assets are the physical things in the real world that need to communicate with the rest of the plant and, sometimes, with other partners of the company. An asset is everything that requires a "connection" for an Industry 4.0 solution. An asset is something valuable to a company, material or not (a product, a machine, a measuring system, a human, …).

The so-called "integration" layer underlines the necessary transition from real to digital world. This "integration" layer could be represented and practically implemented through the Asset Administration Shell. The integration layer is the fundamental step to transform data into relevant and added-value information.

B. Asset Administration Shell

The Administration Shell is the standardized digital representation of the asset, corner stone of the Interoperability between the applications managing the manufacturing systems [6]. Components I4.0 are the combination of the physical assets and their logical representation. Interoperability is defined by the standards as the ability of two or more objects from the same vendor, or different vendors, to exchange information and use them for a correct cooperation [7].

The Asset Administration Shell provides a flexible framework of the information and functions that can be defined and made available to facilitate and promote the integration of industries. It proposes a standardized electronic representation of industrial assets enabling Digital Twins and interoperability between automated industrial systems and CPPSs. AAS transfer properties and capabilities of assets to

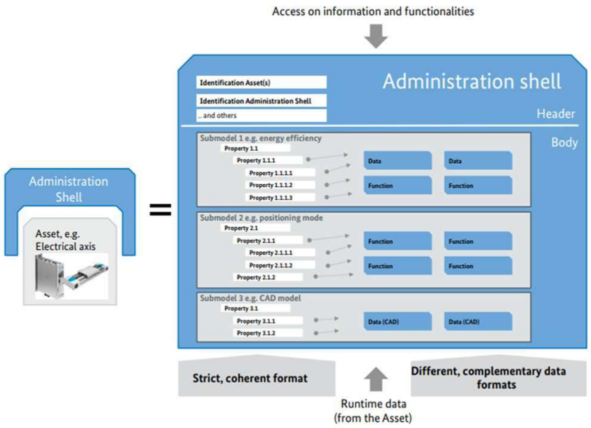

Fig. 2 Asset Administration Shell structure and components [6].

the digital world and makes them available for active and passive interaction of all kinds [8]. Capabilities refer to the functionalities or features that an asset can perform like sensing, actuation, data processing, measuring, etc. Capabilities are a main concept for a flexible and adaptable factory. They provide a way to describe and discover the functionality of an asset, helping in understanding what each asset can do, and improving flexibility and scalability of the processes.

The AAS is implemented though the metamodel, a generic standardized interface defined by IDTA in the Details of the Asset Administration Shell specification [9]. The AAS of an asset contains its digital representation, which is divided into a set of submodels, as Fig. 2 shows, to manage complex information. A submodel represents different aspects of an asset which are related in a structured quantity of properties, implementing a reflexive interface. To define the capabilities of an NDI, for example, its submodels should contain more precise information on aspects of the measurement system, like metrologic characteristics and uncertainty, connectivity, etc.

Different technical solutions are available to generate Administration Shells. In [10] some examples of implementation of AASs using different tools such as Administration Shell IO, Exlipse BaSyx and International Data Spaces (IDS) are explored.

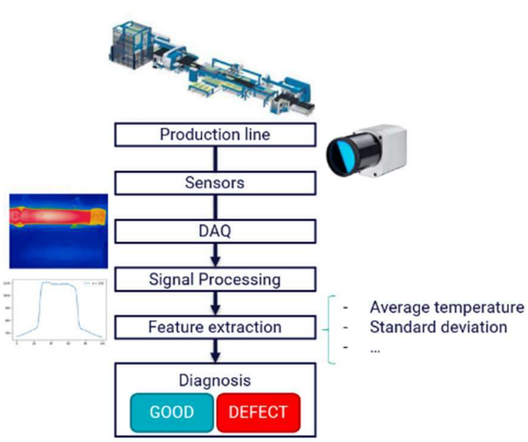

Fig. 3 NDI System inline functioning for quality control.

C. Communication protocols for IoT

Some services and protocols support or enable the required interoperability of the Zero-Defect Manufacturing process. Some of them, useful to explain the following use case and setup, are briefly described here.

- MQTT [11] is a publish-subscribe lightweight messaging protocol. It is open, simple, and designed to be easy to implement. Its characteristics make it ideal for use in many situations, particularly IoT applications.
- OPC UA [12], short for Open Platform Communications United Architecture, is a platform-independent industrial communication protocol and offers standards for data exchange in automation networks. In April 2015, the RAMI 4.0 already listed the IEC 62541 standard OPC UA as the only recommended solution for implementing the communication layer. The basic requirement for industrial communication is a network based on the Internet Protocol (IP).

Working with the Administration Shells, when they are uploaded to the server, data can be written and read from outside with REST API. REST (REpresentational State Transfer) is an architectural style for distributed systems. API is the acronym for Application Programming Interface, and it defines all the rules to follow for the communication with other software systems. A REST API is an interface utilized by two informatic systems to change information in Internet in a secure way.

III. NDI AS INDUSTRY 4.0 ENABLING TECHNOLOGY

Non-Destructive Inspections, also called Non-Destructive Testing (NDT), are the processes of inspecting, testing, or evaluating material, components or assemblies for discontinuities, defects, or differences in characteristics without destroying the serviceability of the part [13] . Modern NDTs are used in manufacturing facilities to control and increase the quality level. NDI methods allow measuring some physical quantities, processing the data, and providing a diagnosis and/or a conformity assessment without directly "disturbing" the production process. Main non-contact measurement technologies are optical sensors at various bandwidths from infrared (IR) to ultraviolet (UV), acoustic sensors, electromagnetic sensors; however, in NDIs we can also find contact sensors, which can be placed on the part to be inspected and removed automatically or manually.

NDI systems could be very useful in in-line system monitoring enabling the ZDM prerequisite 100% in-line quality control. A zero-defect strategy requires reliable information to support any decision. Reliable information requires measured data from the process and the product; quality of data is closely associated to measurement uncertainty. Traditional sensors collect data without the possibility to transmit it over a broad network. Instead, smart sensors are key elements for the digital revolution of industry, where data and information are very important: sensor paired with edge computing could enable real-time data, as Fig. 3 shows.

NDI integrated and connected can collect, transfer, and analyze data, as Industrial Internet of Things. NDI systems includes sensors and data transmission possibilities which are key components of IoT. By integrating NDI with IoT technology, the data collected from the NDI sensor can be transmitted for monitoring or for post-analysis. This can provide real-time monitoring and control of processes and components enabling real-time decision-making.

According to [14], non-destructive evaluation systems 4.0 will be element of the **Industrial Internet of Things** (IIot) that communicate with all the production machines and devices. They can become an integral part of the digital production world and the industrial data space. Smart nondestructive sensor systems are expected to become an essential part of the I4.0 world thereby giving access to the relevant data about processes and products. An NDI should be able to help the industrial context to get relevant information, value-added data. Implementing NDTs from the technology level to the data analytics level, they can supply relevant information, add value to the whole industrial facility.

In a world of increasing amount of data, **measurements** are a key factor, considering **values and uncertainties** to improve their quality and the consequent confidence level on following decision to get a proper diagnosis. With an appropriate choice of processing systems, NDIs can enable and empower the science of Metrology in the context of Industry 4.0. It is important to warrantee that measurement uncertainty satisfies the requirements for conformity assessment and diagnosis. This means a proper choice of measurement technology and a specific design of the measurement system for the actual operating conditions of the manufacturing line. The implementation of the measurement system should consider keeping uncertainty under control and the possibility to react to undesired situations. The quality of data affects the overall system performance, therefore specific Key Performance Indicators (KPI) should be developed to assess quality of measured data; any following usage of data should take these KPIs into due consideration so to enforce level of confidence of any decision taken on measured data.

Based on this NDI systems integration needs to be carefully outlined to obtain value from their real-time functioning, respecting security, and safety requirements. This integration should be on hardware-level as well as software-level to enable the above-mentioned convergence IT/OT, using new and compatible standards, paradigms, and protocols developed with the Industry 4.0 concept. NDI system integration into manufacturing processes is described in detail in the next section through the OpenZDM project use case.

A. *The European project OpenZDM*

Conforming to the Industry 4.0 paradigm and European policy priorities and research pillars, OpenZDM has the objective to realize an open platform for realizing zero defects in Cyber-Physical Manufacturing [15].

The digital platform, supporting production networks' zero-defect processing, will be built on the state-of-the-art RAMI 4.0 and AAS, using NDI methods and data-driven quality assessment techniques. OpenZDM aims to enable the use of Digital Twin services using Manufacturing Data over a secured and trusted AAS platform. The Digital Twin is one of the project's key enabling technologies for online process adaptation and waste reduction.

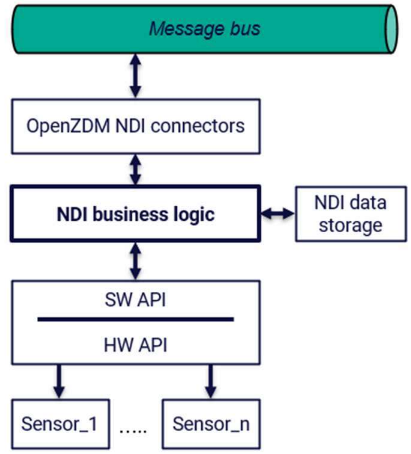

Fig. 4 NDI System integration concept.

The platform will be developed and demonstrated in five representative production lines: Vidrala, VDLWeweler, Aptiv, VolksWagen AutoEuropa, Sonae Arauco. According to the required convergence IT/OT by Industry 4.0 paradigm, the platform will combine advanced ICT solutions and innovative Non-Destructive Inspection systems.

The platform will enable the interoperability with the different digital manufacturing ecosystems, between legacy and new systems and between proprietary and open standards by the implementation of connectors and mediators. In the context of manufacturing and quality assurance, interoperability and reproducibility are related concepts. Interoperability can be seen as a key component of OpenZDM approach reproducibility, ensuring that different systems can work together.

NDIs are leading actors in the OpenZDM project. According to RAMI 4.0 and AAS concepts, each NDI should be considered as an asset, or a sum of that. In this way, its Administration Shell could become the access point for its information and value-added functions.

As Fig. 4 shows, each NDI architecture consists of the OpenZDM connector, the **NDI business logic**, and a data storage. The connector is responsible for communicating with the platform and it will allow the implementation of the Administration Shells. The NDI business logic, different for each different pilot of the project, will be the bridge between the physical asset and its digital representation, using different techniques of data processing to transform data into relevant information.

B. *NDI system integration – The use case*

According to the ZDM paradigm, different NDIs will be implemented to improve the quality of the production by adding value from data during it. Different European production lines are used to demonstrate the potential of this strategy with the objective of a significant reduction of the annual waste. As IoT technology, NDIs will allow remote monitoring for real-time decision making, instead of predictive maintenance or general controls to analyze the behavior of a process or the condition of a product. The aim is to keep track of the important production parameters, in real-time, and with the support of AI modules to identify anomalies and adjust the process parameters accordingly.

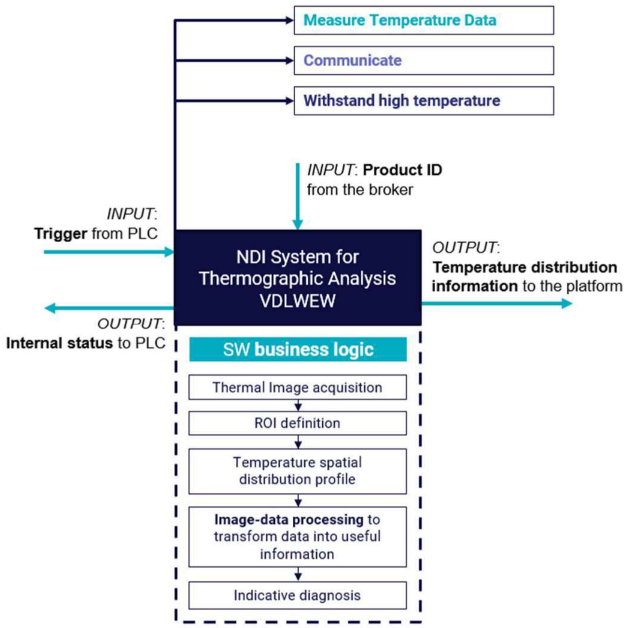

Fig. 5 NDI architecture, capabilities, and software business logic.

This will allow us to avoid possible deviation or abnormal patterns during production.

An NDI system will be designed and developed by Università Politecnica delle Marche for temperature measurements and analysis in the VDL Weweler bv, metal industry manufacturing air suspension solutions for trailers, trucks, and buses. This NDI, from the OpenZDM EU project, is leading to the attention.

From a hardware point of view, it is shown in the first part of Fig.6. It will consist of all the typical components of a machine vision system; in the use case considered, it is an infra-red camera operating in the near-infrared band, to detect temperature spatial distributions on steel bars at high temperature. The cooling jacket contains the OPTRIS thermal camera [16] allowing it a best performance inside the harsh environment. The USB Server Gigabit and the Industrial Process Interface (PIF) allow connection with the external component inside the industrial domain, such as the PC and a trigger generator. The PC allows you to control the acquisitions of the camera and to manage the trigger settings. Trigger signal is generated to get the acquisition of the product when it is stopped, to avoid noise relative to its movements. Input and output of the NDI are better described in Fig. 5.

Acquiring thermal images of the products and processing them, it is possible to obtain a diagnosis that adds value to the whole industrial production process. Images are a powerful source for measurement, they contain multiple and quantitative information that can be extracted to get a proper diagnosis. IR imaging is used for its enormous potential as a metrology tool in manufacturing. Thermography, as non-destructive technology is relevant in terms of metrology and in advanced manufacturing context, allowing, according with [17] to conduct fast assessment of surface condition, to detect possible discontinuities and to find anomalies in the distribution of thermal emissions.

The so-called business logic, that allows to reach a diagnosis from the image acquisition, is explained in Fig. 15, as a general procedure to follow from a software point of view. This machine vision software is essential to inspect the object and return an evaluation of it.

Each NDI system designed for the project will have a logical representation (the Administration Shell) to be involved into the OpenZDM platform to realize the whole Digital Twin. According to [18], future production lines must be “Plug and Produce” in nature. Plug and Produce concept improves the required flexibility of the Smart Factory paradigms. Defining systems in terms of capabilities, the AASs allow the design of a method for digitizing PnP, for developing PnP strategies. Starting from the physical setup including basic networking configuration activities, pre-integration of the components is possible extracting relevant information. This information is so digitized and organized

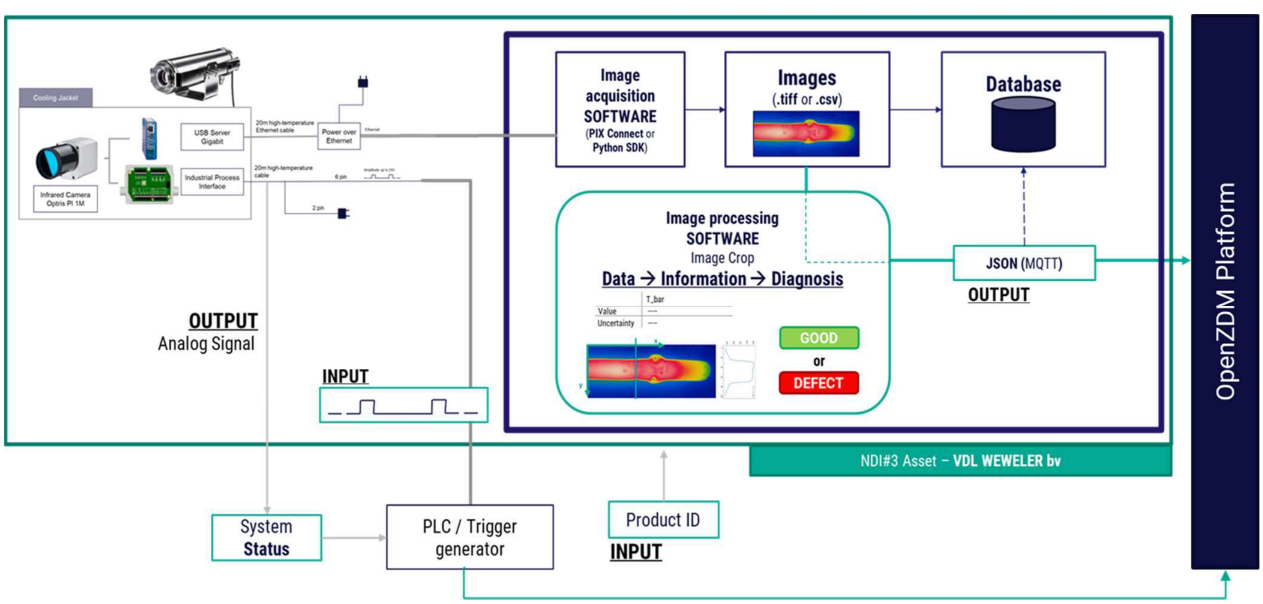

Fig. 6 NDI System integration concept to the OpenZDM Platform.

though AAS. Different Administration Shells could communicate with each other.

An explanation of the components involved in NDI Fig.6 relevant data and information of the NDI system over the entire life-cycle. In addition to persistent information relating to the temperature measurement system, Asset Administration Shell “submodels” will also contain all the real-time information useful to allow the Digital Twin definition, development, and its concrete real-time functioning. For example, using the open-source platform BaSyx to create the AAS in a standardized way, it is possible to create three different kinds of submodels: static to access data that rarely changes, dynamic for real-time information monitoring, and control component submodel to enable to asset operation modes, services and capabilities [19]. The overall PnP system correct functioning relies on the successful implementation of the communication among AASs.

Referring to the thermal camera, temperature measurements values and uncertainties will be dynamic information into its AAS, instead of the static field of view or the static range of the operating temperature. The local analysis will allow a specific image and data processing to upload real-time information in a standardized manner into the common platform and to store big data, such as images, into a local storage. The capabilities of the thermal camera will be included in the submodels, its physical properties and the real-time information. Using JSON as data model for thermal camera information, capabilities could be included as part of the submodel field. A submodel named “thermal measurement” could contain temperature values and uncertainty but also the product identifiers and a time stamp.

IV. CONCLUSION

Machine Vision techniques have a great potential for quality control in industrial application. The goal of the OpenZDM project is to realize a platform that uses NDI systems to analyze each step of some production processes to reach the ZMD paradigm requirements. The platform will implement both information and operational technologies to increase the value of the huge amount of data dominating the new industrial realities, since the Industry 4.0 paradigm definition. A zero-defect strategy requires reliable information to support any decision. Information can be built on data; quantitative data originates from measurements. In the IIoT world, quantitative data, measurement values and uncertainties, together with post-processing and diagnosis procedure, can therefore be a very powerful tool to control and improve the quality of the production. New standards, such as RAMI 4.0 and AASs, and IoT communication protocols, such as MQTT and OPC UA, can be an important part of this process of digitization and industrial quality improvement. Describing the industrial world in terms of capabilities, the Plug & Produce concept is enabled, and integration inside an industrial network of non-contact inline measurement systems is made possible in a very simply way.

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