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Autonomous Quality Control Concepts and Digital Equipment Extension for Zero Defect Manufacturing (ZDM)

Position paper

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Authors

-Odd Myklebust (SINTEF)

-Marta Alvarez (INNOVALIA)

-Ragnhild Eleftheriadis (SINTEF)

-Endre Sølvsberg (SINTEF)

-Xiaochen Zheng (EPFL-Swiss Federal Institute of Technology Lausanne)

-Foivos Psarommatis (EPFL-Swiss Federal Institute of Technology Lausanne)

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Executive Summary

This document gives an overall insight of the Autonomous Quality (AQ) Control concepts and the Digital Equipment Extension. These tools were used as a basis in QU4LITY (HORIZON 2020 programme), in order to build a unique and highly tailored Zero-Defect Manufacturing (ZDM) strategies and competitive advantages.

After a short introduction, in this document you can find a detailed description of the Autonomous Quality Control concept. Secondly, the document specifies how can the ZDM equipment entailed to help the companies in the digital transformation.

1 INTRODUCTION

The state of the art (SoTA) for Zero Defect Manufacturing (ZDM) shows the relation between the quality, the management excellence and the digital solutions and components with the Digital Ecosystems. The main thoughts and vision behind ZDM are how quality management, people, products, and processes, in close synergy, can adapt to the digital concept of Industry 4.0 and Cyber Physical Systems.

The validation of the AQ in QU4LITY has been done through 14 different lighthouse demonstrators where each of the demonstrators has described both Autonomous Quality Control Concepts and possible digital enhancement scenarios. These scenarios have been elaborated and tested in different project and at different facilities. It has been product improvement of machinery and enhancement of processes by use of ZDM strategies, methods, and techniques. Some of the scenarios have been part-engineering processes on the shop floor, like testing of algorithms in a cloud or improving the laser grip of a process in a production chain. And other enhancement consisted on the development of new software system, vision system or new machine interface systems.

2 THEMATIC 1: AUTONOMOUS QUALITY CONTROL CONCEPT

The word "Quality" is defined as a measure of excellence or a state of being free from defects, deficiencies and significant variations. This definition can be declined according to the object of interest. In QU4LITY the objective is to demonstrate, in a realistic, measurable, and replicable way an open, certifiable and highly standardised, SME-friendly and transformative shared data-driven ZDM product and service model for Industry 4.0, leveraging five competitive advantages to foster new digital business models: increase operational efficiency, reduce scrap, prescriptive quality management for defect propagation avoidance, increase energy efficiency, improved smart product customer experience.

The vision of ZDM has a clear content of performance standard, and the level of not accepting non-conformances in a smart manufacturing organisation. Using a mix of different quality methods seems to be successful from a research viewpoint. However, ZDM has been highlighted as an emerging paradigm which goes beyond traditional Six Sigma and Lean approaches where the use of detection and correction was the way to ZDM[1].

ZDM starts with investigation and analysis of quality of a process or a product in case of failures or abnormalities. When the processes or product is investigated, right strategies for further investigations and analysis of quality and health condition of the machine, or product line is done, before it goes further in the loop. It means, that you reduce the scrap by taking actions before the abnormalities or failures can affect the end quality of a process, and it will develop failure free products. Over the years ZDM has gained a lot of ground and attention from both, research community and industrial domain, which led to initiatives for the standardization of ZDM. Below is the formal definition of ZDM as an outcome of a standardization working group, by CEN/CENELEC:

> *ZDM is a holistic approach for ensuring both process and product quality by reducing defects through corrective, preventive, and predictive techniques, using mainly data-driven technologies and guaranteeing that no defective products leave the production site and reach the customer, aiming at higher manufacturing sustainability*[2].

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[1] Psarommatis, F., Prouvost, S., May, G., & Kiritsis, D. (2020). Product quality improvement policies in industry 4.0: characteristics, enabling factors, barriers, and evolution toward zero defect manufacturing. Frontiers in Computer Science, 2, 26. https://doi.org/10.3389/fcomp.2020.00026

[2] Psarommatis, F., Sousa, J., Mendonça, J. P., & Kiritsis, D. (2021). Zero-defect manufacturing the approach for higher manufacturing sustainability in the era of industry 4.0: a position paper. International Journal of Production Research, 1-19. https://doi.org/10.1080/00207543.2021.1987551

With the introduction of IoT, new possibilities such as the elimination of defects through the failure prevention or use of data to predict when a defect have arisen. This has led the quality of products and processes to be more sustainable due to a larger possibility to re-use and re-manufacture products.

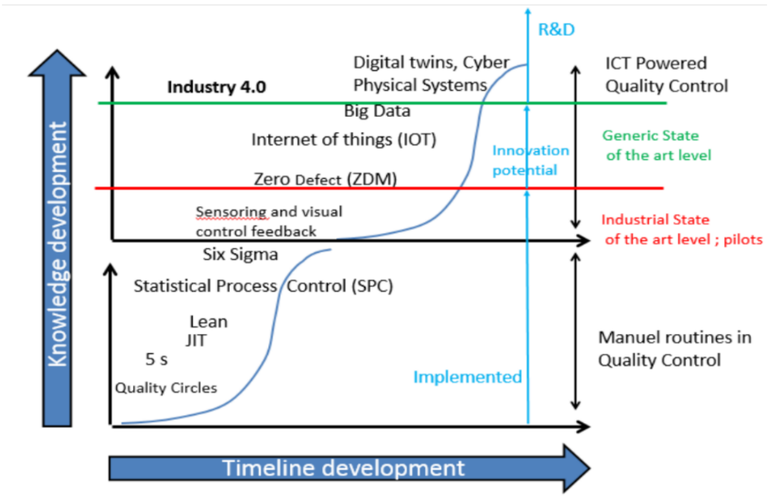

Figure 1. Overview of the SoTA for ZDM in the Quality deployment (ref: Eleftheriadis2016[3])

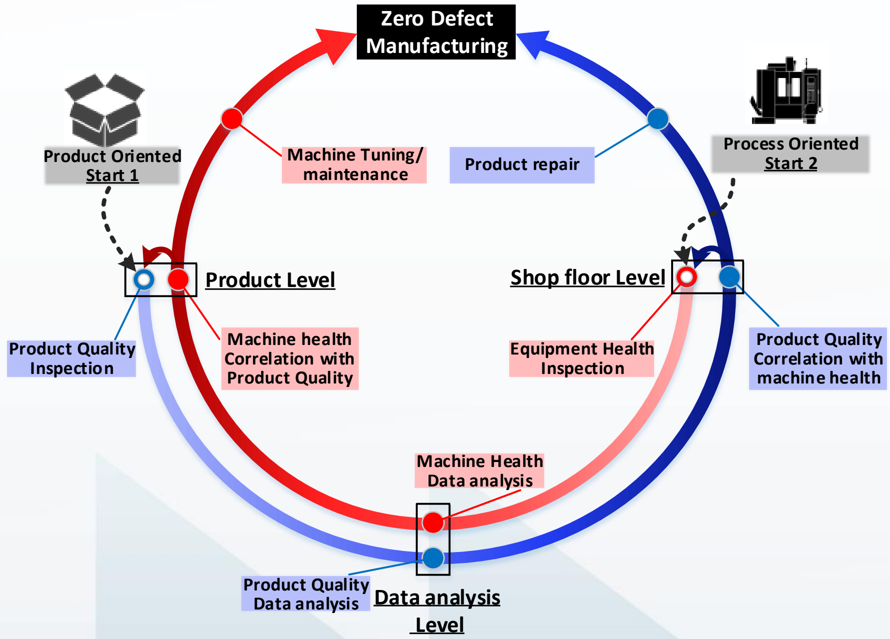

Figure 2. ZDM product and process approaches (ref: Psarommatis 2020 [4])

[3] References: Eleftheriadis, R., Myklebust, O, A guideline of quality steps towards ZDM in Industry, 2016 IEOM Conference http://ieomsociety.org/ieomdetroit/pdfs/164.pdf

[4] References: Psarommatis, F., May, G., Dreyfus, P.-A., Kiritsis, D.: Zero defect manufacturing: state-of the-art review, shortcomings and future directions in research. Int. J. Prod. Res. 7543, 1–17 (2020). https://doi.org/10.1080/00207543.2019.1605228

In the ZDM era, the importance of clear goals, digitalization of the factory and parameter measurement is key to promote the innovation perspective in the organisation. Another important factor is the cooperation between companies and organisation to adapt the new components and concepts of Industry 4.0. Those organisations which have a strategy and a clear cut on measurable goals, have an advantage to proceed their digital journey. Key performance indicators (KPI) in companies are therefore important target for measuring customers expectation to product or processes, which can further be important for reaching a clear vision of how a ZDM platform for technological use can be created.

KPI to ZDM

Product quality is a critical aspect of the manufacturing process and is directly affecting the final product cost. Quality may also affect the relations between customers and the manufacturer and by extent, the number of orders and the loyalty of customers. Quality control process could increase the cost of the product significantly. Therefore, manufacturers set up specific KPIs to monitor the performance of various systems or activities. KPI's in an organisation can be structured in two different layers: as business or operational goals. The first no one helps to monitor the benefits and competitiveness to the company that can bring the new solution. The ZDM methodology also highlights the importance of economical KPI's, this due to better understand the improvement of process goals. To reach the full potential of ZDM, measurement both before and after the enhancement or improvement must be set up. To understand this, it is necessary to have a look at economic indicators like; cost reduction compared to the Return of Investment (RoI). Normally, effectiveness and performance in manufacturing processes and eventually, automation and reduction of personnel are KPIs[5]. But actually, this can be quantified as cost of re-work, cost of scrap or re-use of material for other purposes or even environmental cost like CO2. This way of using KPI's can therefore gain the perspective of using economic goals as much as operational measuring goals for deployment of ZDM in a company [6].

Operational or other strategic KPI's are i.e., how the workforce and manufacturing assets will be handled in the future. An evolution in the flexibility and modularity of factory processes will be linked to the ability for collaboration and cognitive processes, supervised and assisted by knowledge humans. The need for high qualified personnel that handles the technological shift where service models and digital twins operate, and where the ownership of assets (either as product or as information systems or data sources) are some of the

[5] Eleftheriadis, R., Myklebust, O. The importance of KPI's that can contribute to Autonomous Quality (AQ) Control, Electrical Engineering https://doi.org/10.1007/978-981-15-2341-0_46

[6] Psarommatis, F., Danishvar, M., Mousavi, A., & Kiritsis, D. (2022). Cost-Based Decision Support System: A Dynamic Cost Estimation of Key Performance Indicators in Manufacturing. IEEE Transactions on Engineering Management https://doi.org/10.1109/TEM.2021.3133619

basic questions. We also foreseen, that some services or products can have a total change in how their business model are created and how they will be offered or sold in the new green deal community.

Most of the AQ relies in the technology shift for Industry 4.0, how communication along the value chain will exceed, and how advance connections to factory will improve quality management in a digitalized system for avoiding defective product and processes and achieving the best quality performances. If you go behind those data, they may be multiple manufacturing sites, assembly lines and machine solutions, all providing data contributing to product quality. Since the measurement data contains a large amount of process and product information, this data creates complexity for excellent quality control.

QU4LITY Model for Autonomous ZDM

The measurement and control of the product quality characteristics and their impact along with the interaction of product realization, make the final quality performance-related processes and elements constitute an organic network, which is called quality chain. In quality chain, product quality implementation process breaks the boundaries of individual enterprise and extends into enterprise group completely; being characterised by wide integration, wide synergies, agility, and openness. That is, product quality constitution flows from the material supplier to the end user.

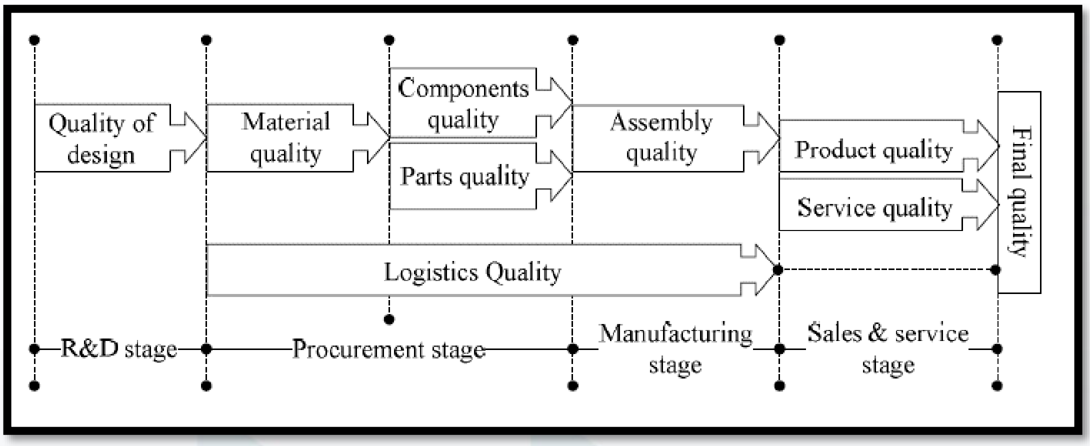

Figure 3. Autonomous quality chain components

Thus, quality control in smart connected factories go well beyond the optimisation of individual multi-stage manufacturing strategies and take an innovative collaborative collective approach, where intelligence and quality control processes address in a harmonised and orchestrated manner all phases of the product lifecycle, i.e., quality of design, raw material quality, component quality, part quality, logistic quality, assembly quality, product quality, service quality. The integrated contributions of all those quality dimensions build ultimately the final product quality. Collaborative quality control is a set of organized activities which participated by members, in order to achieve their desired product quality features.

There is a risk that implementation of autonomous ZDM control loops will derive in highly customized solutions that lack a general approach and therefore suffer from lack of portability and do not exhibit economies of scales. Therefore, it is important that the QU4LITY framework allows such universal approach, while at the same time enables the required level of customization that will leverage industrial competitive advantages. In fact, industrial manufacturing environments are always different, always specific, and always incorporate something new, since this is the actual essence of the factory capability, which differentiate one factory from its competitors. This uniqueness, while a clear manufacturing competitive advantage, represents a critical barrier for straight-forward, mass, and cost-effective deployment of AI services and solutions at a scale. AI deployments are currently strictly tailored to highly individualised implementations.

The first sketches of a new ZDM framework were made in 2011 (IFaCOM & 4ZDM projects) just before the release of Industry 4.0 reference model RAMI. The main concern here was "where comes process variation from and how to deal with it", and all the provided models from this period are based on the ISA 95 standardisation model. Today the development of RAMI architecture is partly standardized in several IEC/ISO and TC standards, but not fully integrated with ZDM actions.
The ISA model had a lot of well-known limitations to enable implementation of control loops, and there is a risk that implementation of AQ ZDM control loops will derive. A risk is that lack a general approach will suffer from lack of portability and do not exhibit economies of scales as provided. So, an important achievement for the QU4LITY framework is therefore a universal approach which enables customisation that give competitive advantages for the companies.

The QU4LITY ZDM model relies on 3 main objects:
(1) Integrated planning, design, production, and service quality flows, that establish the internal and collective quality strategies across the product lifecycle.

(2) Holistic quality control flows, which establish the individual and collective control mechanisms to ensure the effective operation of the designed quality control strategies.

(3) Cognitive quality improvement flow that responds to the dynamic and changing environment, that quality control systems will have to deal with, in particular the individual and collective learning and model development mechanisms, developed to optimise operations at local and global level for overall product performance.

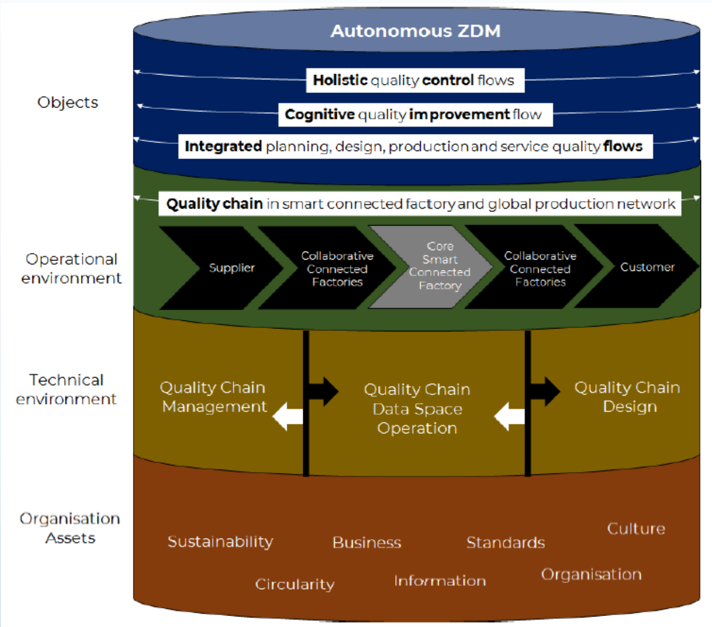

Figure 4. QU4LITY autonomous reference model (made by Innovalia)

Thus, an important achievement for QU4LITY is the development of an AQ Model with a universal approach to achieve a unified framework, where all the processes and products can be mapped. The new model enables the implementation of joint quality optimisation procedures at quality chain level and at component integrated quality system (IQS) level. The steps followed to operate the QU4LITY holistic integrated quality system (IQS) based on the component level quality model are the following:

(1) Definition of the integrated planning, design, production, and service quality information flow. Thus, QU4LITY sets the data sources support an information model that can deliver the required component-level quality control outputs.

(2) Design and deployment of the QU4LITY federated and distributed cognitive quality improvement flow under an augmented intelligence and continuous learning model. The information flow is crucial to support the development and deployment of selected AI/ML techniques in the QU4LITY infrastructure to build the cognitive dimension of the autonomous quality (AQ) operations.

(3) Set-up and configuration of the QU4LITY self-adaptive plug & control manufacturing equipment. Such self-adaptation is supported both by the embedded intelligence (in-machine & edge-powered AI) but also by coordination functions that enable equipment to coordinate multi-stage quality control strategies through feedforward and feedback control and decision support loops.

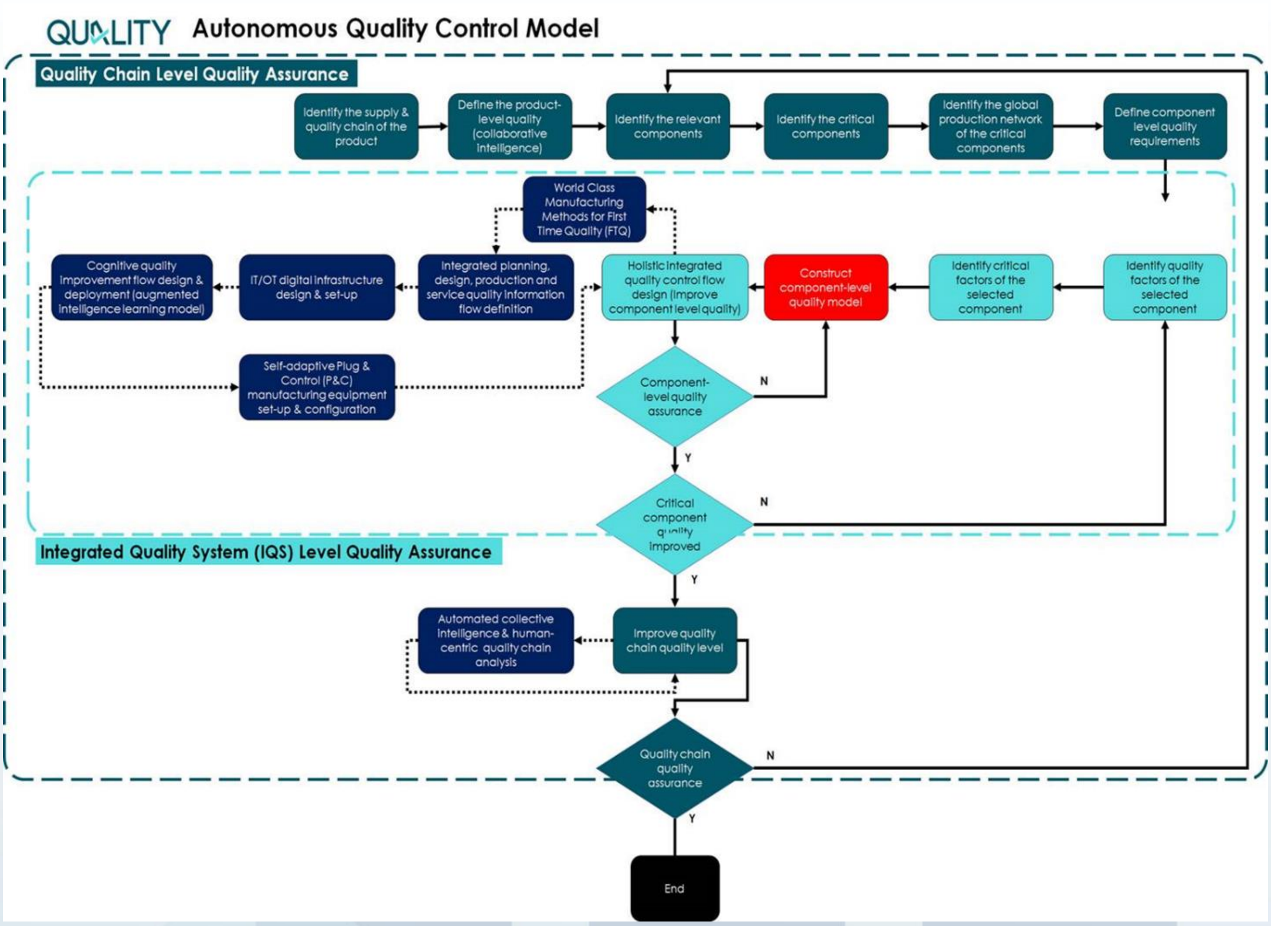

Figure 5. Autonomous Quality Control Model

The word "Autonomous" in manufacturing can be defined as "the ability of a system to gain information about the environment in which it operates, learn, and take decisions, in order to adapt itself to specific situation without the need of human intervention or working in a collaborative way with humans to argument or to complete their activities". Further we can see that Autonomous Quality is a part of a paradigm shift for the ZDM, by implementation of machine learning, deep learning, or AI and structured KPI's. This also fits very well with the integration of digital equipment with real-time quality control systems, that has possibility to close the loop and manage the deep data analysis as integrated software system or cloud solutions. We also see that knowledge of a data model-based system engineering and semantic models created to fit system architecture, make the best simulation and verification models. However, the pathway to transform all digital equipment and to realize an autonomous factory is still a way to go. The need for a more hybrid architectures that can be adapted by different companies based on their own cloud and edge structure and a reference model that can improve and reduce decision processes that predict what can happen. The QU4LITY autonomous quality model considers the design and implementation of the IT and OT integrated digital infrastructure leveraging the reliable and high-performance networking, storage, computing & processing required by autonomous ZDM operation. Such IT/OT deployment should adhere to the QU4LITY reference architecture (RA).

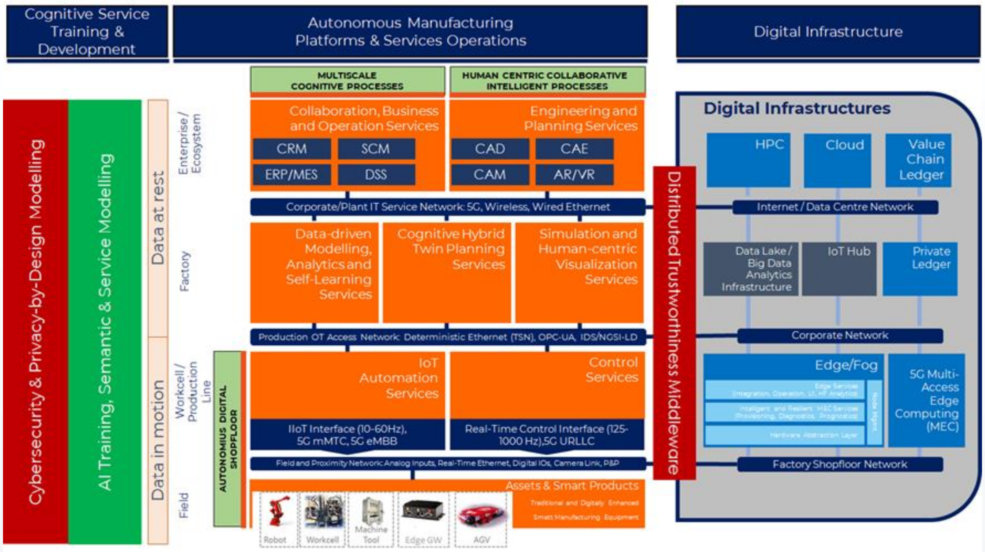

Figure 6. This reference model was made by Innovalia in the first face of QU4LITY se fig. 4 – as input to WP2

3 Thematic 2: Digital Equipment Extension

Digital Equipment Extension focuses on the specification of the various types of Zero-Defect Manufacturing (ZDM) equipment that can be digitally enhanced. ZDM equipment entailed in the QU4LITY pilots and experimentation activities are described in a generic way due to confidentiality.

The equipment specifications address enhancements to several processes and machines also driven by the requirements and needs of the real-life pilots. Adaptive hot stamping machines, self-learning autonomous systems, high precision machining, quality-controlled Additive Manufacturing, augmented reality and mixed reality platforms, human centred manufacturing systems, predictive maintenance and autonomous field service engineering are only some examples of the enhancements that were carried out in QU4LITY.

Connected smart assets make possible the development of quality management several steps further. This is achieved by enabling continuous monitoring of real-word data, identifying and addressing design problems, test failures with diagnostic tools, and making predictive maintenance in assets and inventory of factories. All this can be done by using smart, connected technologies that unite digital and physical assets. However, in the quality area it is still necessary to incorporate instrumentation, data collection capability and pre-designed software. Predictive maintenance is not a new concept, but the massive investments in technology typically needed to handle the massive volumes of data required for making this autonomously is often limited in deployment to only the largest organizations. In this new production development (NPD) of connected machine systems, new products and production lines with self-learning systems that can provide new services to customers, we will see a shift in how they work, sell, and develop new products.

The QU4LITY project has initialized the following digital enhancements:

- **Adaptive hot stamping machines**. Today this is a technology that allows ultra-high strength steel to be formed into complex shapes by heating the metal at a furnace or formed in hot condition. A total adaptivity of quality and maintenance monitoring are a goal for two of the machine tool builders in the project.

- **Self-learning autonomous systems**. Self-learning algorithms develop successful solutions for highly complex tasks without any human guidance or prior expert knowledge. In the manufacturing domain this will be a huge step towards AI. Challenging situations can become very simple. The machine needs to know which objectives are to be achieved, in order to autonomously find out how to do it.

- **High precision machining.** The machine will work on equipped CNC and connection boxes that are able to extract machining data (milling, drilling…) from the processes. This is existing digital platforms, that will be the base for data acquisition, standardisation, and interface with common Data Space. In the future, the machine builder will be able to recover information from such Data Space to a centralised cloud for analytics and application development.

- **Augmented reality and mixed reality platforms**. AR refer to "augmenting natural feedback to the operator with simulated cues". In a more restricted way, it is a form of virtual reality where the participant's head-mounted display is transparent, allowing a clear view of the real world, where rich information is added. Simulation of factories, digital twins and mixed reality platforms are growing fast and give a future vision of excellent learning tool for management, operation, quality, and maintenance.

- **Human centred manufacturing systems.** The change in manufacturing will require new skills and expertise in application engineering, user interface development, system integration and data scientists capable to build and run automated analytics for human-machine collaboration.

- **Predictive maintenance and autonomous field service engineering**. We can apply AI to robotic, automatic programming, tasks, and processes for enabling predictive control functions. In the future, the field of machine learning and AI is a promising area for argument advanced quality, safety and maintenance features and services (i.e., new business models, blockchain and distributed ledger).

- **Quality controlled additive Manufacturing, to self-reconfigurable flexible cells.** In order to reach the goals of high-quality standards in metal-based additive manufacturing, additive manufacturing machines can be equipped with a high-speed sensor system that allows the retrieval of information from the powder bed surface and the process zone, during and after the build process. The information could be processed on an edge device, where relevant information about the part quality is extracted, using machine-learning techniques. As a result, the system will recommend further actions and supports the decisions to be made by the operator in case of detected surface faults and anomalies and can also adapt to new process situations easily. Additionally, process simulation and real time digital twin will be designed for the powder bed fusion process.

The main goal of digital enhancement of equipment and machinery with digital capabilities is to improve their flexibility, intelligence, and autonomy. Based on the improvements, the enhancement will deliver machines and devices, that will be able to anticipate and reduce defects, while at the same time improving quality management and OEE. All equipment and machinery can in theory be digital enhanced or equipped. Machines with already existing data driven controls and defined interfaces will be more applicable for digital enhancement, but event older and manually machines can get digital extension and act in a more advanced digital environment. However, if the digital enhancement is not a defined service from the machine or equipment vendor, and the industrial plant is doing digital enhancement on their own, they need to have good knowledge about their data systems and the manufacturing benefits of the enhancement.

4 THEMATIC 3: DIGITAL MODELS TOWARDS AQ

One of the main challenges of AQ is the management of the heterogenous data and information of manufacturing systems. AQ relies on Industry 4.0 technology and devices, autonomously communicating with each other along value chains. The integration of process and parts monitoring and control along the value chain can enhance traceability and earlier detection enabling quality improvements and defect reductions. This multi-source data is becoming an indispensable resource for production managements and quality improvement. At the same time, the modelling technology of multi-station manufacturing system is being improved continuously. Together with the different data sources available, the manufacturing process modelling techniques provide great potential for root cause identification of manufacturing process failures. To better manage the complex industrial data, several data management tasks must be addressed, such as data acquisition and sensing, data processing and analysis, as well as decision support etc. It requires to create digital models to empower the data management of AQ paradigm.

The digital models play an important role in the QU4LITY Reference Architecture to enhance interoperability between different components. The information is generated by using, monitoring, controlling, and analysing connected entities and sub-systems, remaining within a "domain" or being exchanged between "domains". Both, raw and processed information is used by the different ZDM services and applications, to fulfil intended tasks for a given activity in the system. In this context, two levels of data interoperability are considered:

- syntactic interoperability is to exchange information in a common data format with a common protocol to structure the data.
- semantics interoperability is to interpret the meaning of the symbols in the messages correctly.

These interoperability components provide a flexible method of composing services, so that the system behaviour can be adapted at run-time to enable advanced ZDM processes.

Focusing on both product-oriented and process-oriented QU4LITY pilots, a digital model named RMPFQ (Resource, Material, Process, Functions/Features, Quality) is designed to organize relevant factors that impact quality.

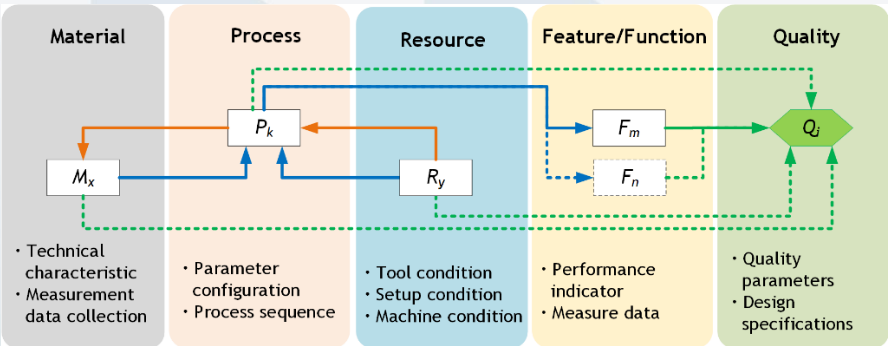

Figure 7 RMPFQ-model elements and their interrelationships

The definitions of the proposed RMPFQ-model elements are as follows:

- Manufacturing Resource, according to ISO 15531, represents the devices, tools, and means, at the disposal of the enterprise to produce goods and services, but except raw material and final product components.
- Material represents everything that is needed to produce a certain product or product component, which may include raw materials, pre-products, consumables, operating supplies, product components and assemblies.
- Manufacturing Processes are defined as processing and transforming materials into the final goods by using machines, tools, and human labour. This process is defined within the plant engineering.
- Product Functions / Features represent the distinguished characteristics of a product item, which may include functionalities like specific tasks, actions, or processes, that the product is able to perform; and/or other features like performance.
- Product Quality (Q) is defined as, according to DIN EN ISO 9000, the degree of conformance of final product functions and features to designed requirements.

As shown in Figure 7, there are several types of interrelations among the elements of the RMPFQ-model. First, a given workpiece (M) is machined by machining resources (R), e.g., a given setup (fixturing and associated tooling) and a cutting tool (R), through a planned machining process (P), composing the RPM interactions (marked with orange lines). Second, the machining process (P) uses input material (M) and resources (R) to produce one or more features (F), composing the RPMF interactions (marked with blue lines). Moreover, all the RMPF-elements may also have straightforward impact on the quality (Q) of the machined workpiece (marked with green lines). There also exist relations among different resources, i.e., machine, setup, and cutting tool, which is not reflected in the proposed model and is beyond the scope of this study.

Semantic technologies have been used as key enabling components in many intelligent systems to achieve semantic interoperability for heterogeneous data and information. Semantic models enable to capture system information in an intuitive way and to provide a concise and unified description of such information. They describe the information in standardized ontology languages, making it possible to specify direct interrelationships among various systems and models. As an advanced semantic technology, knowledge graph enables to describe model information in the form of entities and relationships, which makes it possible of creating new knowledge using a reasoner. This makes semantic modelling and knowledge graph modelling promising solutions for integrating heterogeneous DT models involved in a complex system across different domains and lifecycle phases. By combining semantic technologies with the current digital twin concept, the Cognitive Digital Twin (CDT) concept is proposed as the next evolution of digital twin.

CDT is a digital representation of a physical system that is augmented with certain cognitive capabilities and support to execute autonomous activities; comprises a set of semantically interlinked digital models, related to different lifecycle phases of the physical system, including its subsystems and components; and evolves continuously with the physical system across the entire lifecycle. A reference architecture for CDT is designed based on the RAMI4.0 reference architecture and existing CDT architectures. As shown in Figure 8, the three dimensions of the proposed reference architecture include full lifecycle phases, system hierarchy levels and six functional layers. The elements of each dimension are explained below:

- Full lifecycle phases: This dimension focuses on the full lifecycle management and continuous evolving capabilities of CDT definition. During the entire lifecycle of a system, many digital models are created to support different lifecycle phases along this dimension. For example, a typical lifecycle of a manufactured product includes production design, simulation, manufacturing process planning, production, maintenance, and recycling etc. Each of these phases may have multiple related digital models. It is worth noting that a CDT does not necessarily contain digital models covering all lifecycle phases, but it is supposed to support the integration of models across different lifecycle phases.

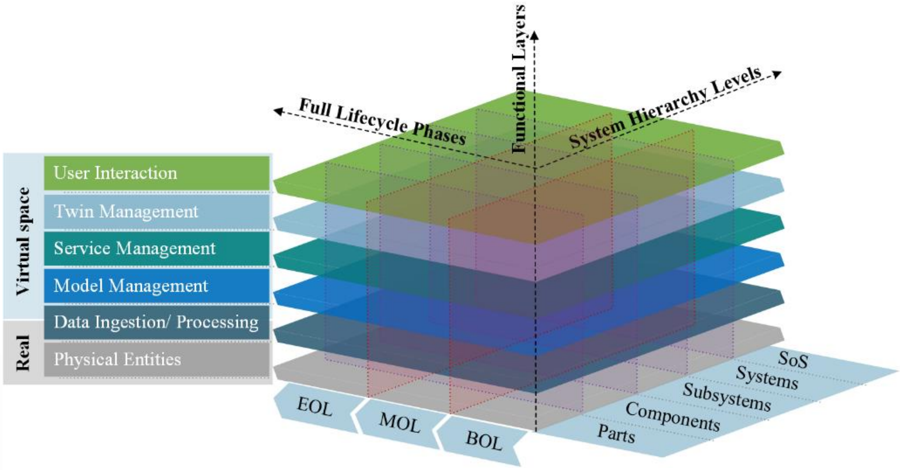

Figure 8 Cognitive Digital Twin reference architecture based on RAMI4.0

- System hierarchy levels: This dimension provides a hierarchical approach to specify the structure and boundary of a CDT. Modern industrial systems are usually highly complex system-of-systems (SoS). It is crucial to properly define the scope of a CDT. When developing CDTs, it might be difficult to create the models in a separated way simply according to the physical hierarchy of a factory as specified in RAMI4.0. Therefore, we adopted a system engineering methodology to define the structure of a complex into SoS, system, subsystem, components, and parts.
- Functional layers: This dimension specifies the different functions provided by a CDT. It is designed based on the architectural blueprint of the COGNITWIN Toolbox (CTT). The Physical Entities layer represents the system in the physical space, and the other five layers represent different functions of CDT in the digital space, including Data Ingestion and Processing, Model Management, Service Management, Twin Management, and User Interaction.

This reference architecture aims to provide a guidance for designing a general conceptual structure of a CDT. It requires many advanced technologies to develop a functional CDT and apply it to real industrial scenarios.

5 Conclusion

This position paper gives an overview of Autonomous Quality Control Concepts and Digital Equipment Extension for Zero Defect Manufacturing (ZDM).

An interaction in such as a ZDM Platform will create opportunities in new business models for cooperation in the technological ecosystem with a digital interaction, with the creation of new modelling, standards, and architecture for ZDM and the total interaction between human, machine, and company governance. A framework for ZDM will be essential to providing a full digital shopfloor with flexibility and intelligence to support Autonomous Quality.

Enhancement of ZDM Equipment is for a machine or other manufacturing device a product improvement and in this way a product development issue. For an industrial process digital enhancement will focus on the manufacturing line and be specific for the pilot factory installation.

An industrial process enhancement implementation should include complex additions to the current process lines, and emphasis on documenting and measure the changes to achieve a manufacturing set up in the direction of ZDM. This would also increase the ability to document and evaluate the progress in a continuous shop floor development for improved Autonomous Quality Control.

Autonomous Quality Control will require a holistic perspective on system analysis and on implementation. On a basic level, data quality must be sufficient to allow for relevant analysis and monitoring of the system. This is still a gap in many cases, also in the pilots in the Quality project. The use of domain expertise will aid in increasing system knowledge and help with identifying critical to quality variables for analysis and monitoring. Employing these steps and identifying relevant methodologies for analysis will increase the ability to detect anomalies and trends in the system environment. The Quality project has shown that this is not only realistic, but also that it can be automated. The main challenge is ensuring the quality of data and the traceability of the data throughout different stages of production and testing. This is still an ongoing process.

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