Ref. Ares(2021)1344783 - 18/02/2021

DIGITAL MANUFACTURING PLATFORMS FOR CONNECTED SMART FACTORIES

D4.4 Distributed Communication and Control Infrastructure

(Final version)

Deliverable Id :	**D4.4**
Deliverable Name :	Distributed Communication and Control Infrastructure
Status :	**FINAL**
Dissemination Level :	**PU**
Due date of deliverable :	**30/09/2020**
Actual submission date :	**18/02/2021**
Work Package :	**WP4**
Organization name of lead contractor for this deliverable :	**UNIMETRIK**
Author(s) :	Aitor San Vicente Sebastián, Daniel Echebarria (UNIM), Pablo Salvo, Irune Mato, Oscar Lazaro (INNO)
Partner(s) contributing :	**NXT, GF, THYS, KOL, DAN, FAGOR, PRIMA, ASTI, FHG, CEA, SINTEF, INNO, GHI**

Abstract: The deliverable details enhancements in the distributed communication and controls system with digital capabilities as a means of increasing their reliability and ease of use in large plants. In particular, existing machines and equipment will be enhanced with digital automation functions, based on the technology platforms that are available in the consortium.

www.QU4LITY-project.eu

Contents

HISTORY

Table 1 – Document versions.

Version	Date	Modification reason	Modified by
0.1	1/10/2020	First draft QU4LITY_D4.4_Draft1*	UNIM
0.2	19/11/2020	Completion of Sections 2 and 3	UNIM
0.3	09/12/2020	Integration of Section 5 inputs from various end users	GHI, ASTI, NXT, PRIMA, CEA
0.4	10/02/2021	Finalisation of Section 4 and Conclusions	UNIM
0.5	16/02/2021	Changes due to the Peer Review	UNIM, MON
v1.0	17/02/2021	Deliverable ready for submission onto the Portal	UNIM

(*) file ref. in OwnCloud

1. Summary

This Deliverable provides an update for the description of the Distributed Communication and Control Infrastructure of ZDM Equipment. It is the final version of the deliverable and, as Demonstrator, is composed of both this document, in the form of factsheet, and the demonstrator videos which will be shared with the Reviewers from the European Commission and shown at the M18 and M39 Review Meetings.

The main task of the work is to leverage distributed Communication and Control functionalities in ZDM Equipment for Autonomous Quality Operations. As said, a snapshot of the current status is presented in this version of this document, which defines and describes Communication and Control technologies for every particular ZDM machine/equipment, out of the 7 use cases considered (5 Machine Pilots and 2 demonstrators deployed at Experimental Facilities).

This document starts with a brief description of this task objectives and approaches, after which the relation of this deliverable with other work packages is also shown.

The Machine Enhancement categories, understood as increased capabilities for ZDM equipment, has been presented in Section 3 – QU4LITY ZDM Digital Enhancements.

In the Section 4 – Autonomous Machines, the work being done within WP4 is contextualised in the form of defining a proposition for categorising ZDM equipment and systems regarding their capabilities in what comes to Autonomous Quality control. This has been performed in two iterations: the first was already presented at the M18 RM, while the second one is taking into account both the degree of Automation (OT level, mainly), and the Intelligence of the Control (regarding the AI capabilities at IT level).

These categories not only will constitute a common KPI for all use cases within the QU4LITY Project, to highlight the “As-Is” and the “To-Be” in terms of Autonomous Equipment, but they will be useful to endorse the Marketplace as a solution one-stop-shop in which the factories / manufacturing companies will be able to search solutions by the level of autonomy they would like to target for their shop floor layouts or AI platforms.

Section 5 – Update of the Distributed Communication & Control framework described in the first version of D4.2 is the place where the changes from the previous version of this deliverable regarding the Pilot-by-Pilot, case-by-case, study is made about the distributed C&C infrastructure and the platforms linked to it.

2. Introduction

In this Task T4.2, the enhancements of the Distributed Communication and Control systems with digital capabilities, as a means of increasing their reliability and ease of use in large plants, are to be done.

In particular, existing machines and equipment are to be enhanced with digital automation functions, based on the technology platforms that are available in the consortium. On top of these capabilities, automation functions and tools will be developed in order to facilitate rapid actuation and correction of defects (or their root causes), once those defects are detected. Such automation functions are to be provided at the field device level, the production control and the production scheduling levels, depending on the types of each machine or equipment.

As data-driven approach is used, this means that the functionality of equipment is to be enhanced depending on the target parameters of the industrial process.

2.1 Objectives and Approach

Observing bibliography[1], the easiest thing to start with is probably to pick a PDCA-style (left-hand side columns of Figure 1) simple diagram, as the proposed one in Figure 2.

[1] J.Beer, A.D.Fisk, W.A.Rogers. *Toward a Framework for Levels of Robot Autonomy in Human-Robot Interaction*. Journal of Human-Robot Interaction 3(2):74. June 2014

Table 4. Proposed Taxonomy of Levels of Robot Autonomy for HRI

Beer et al., Levels of Autonomy

87

LORA	Sense	Plan	Act	Description	Examples from Literature
Manual	H	H	H	The human performs all aspects of the task including sensing the environment, generating plans/options/goals, and implementing processes.	"Manual Control" Endsley & Kaber, 1999
Tele-operation	H/R	H	H/R	The robot assists the human with action implementation. However, sensing and planning is allocated to the human. For example, a human may teleoperate a robot, but the human may choose to prompt the robot to assist with some aspects of a task (e.g., gripping objects).	"Action Support" Endsley & Kaber, 1999; Kaber et al., 2000; "Manual Teleoperation" Milgram, 1995; "Tele Mode" Baker & Yanco, 2004; Bruemmer et al., 2005; Desai & Yanco, 2005
Assisted Tele-operation	H/R	H	H/R	The human assists with all aspects of the task. However, the robot senses the environment and chooses to intervene with task. For example, if the user navigates the robot too close to an obstacle, the robot will automatically steer to avoid collision.	"Assisted Teleoperation" Takayama et al., 2011; "Safe Mode" Baker & Yanco, 2004; Bruemmer et al., 2005; Desai & Yanco, 2005
Batch Processing	H/R	H	R	Both the human and robot monitor and sense the environment. The human, however, determines the goals and plans of the task. The robot then implements the task.	"Batch Processing" Endsley & Kaber, 1999; Kaber et al., 2000
Decision Support	H/R	H/R	R	Both the human and robot sense the environment and generate a task plan. However, the human chooses the task plan and commands the robot to implement actions.	"Decision Support" Endlsey & Kaber, 1999; Kaber et al., 2000
Shared Control With Human Initiative	H/R	H/R	R	The robot autonomously senses the environment, develops plans and goals, and implements actions. However, the human monitors the robot's progress and may intervene and influence the robot with new goals and plans if the robot is having difficulty.	"Shared Mode" Baker & Yanco, 2004; Bruemmer et al., 2005; Desai & Yanco, 2005; "Mixed Initiative" Sellner et al., 2006; "Control Sharing" Tarn et al., 1995
Shared Control With Robot Initiative	H/R	H/R	R	The robot performs all aspects of the task (sense, plan, act). If the robot encounters difficulty, it can prompt the human for assistance in setting new goals and plans.	"System-Initiative" Sellner et al., 2006; "Fixed-Subtask Mixed-Initiative" Hearst, 1999
Executive Control	R	H/R	R	The human may give an abstract high-level goal (e.g., navigate in environment to a specified location). The robot autonomously senses environment, sets the plan, and implements action.	"Seamless Autonomy" Few et al., 2008; "Autonomous mode" Baker & Yanco, 2004; Bruemmer et al., 2005; Desai & Yanco, 2005
Supervisory Control	H/R	R	R	The robot performs all aspects of task, but the human continuously monitors the robot, environment, and task. The human has override capability and may set a new goal and plan. In this case, the autonomy would shift to executive control, shared control, or decision support.	"Supervisory Control" Endsley & Kaber, 1999; Kaber et al., 2000
Full Autonomy	R	R	R	The robot performs all aspects of a task autonomously without human intervention with sensing, planning, or implementing action.	"Full Automation" Endsley & Kaber, 1999

*Note: H = Human, R = Robot. Manual represents a situation where no robot is involved in performing the task; this level is included for a complete taxonomy continuum.

Figure 1 – Levels of Robot Autonomy in Human-Robot Interaction [Ref.1].

Figure 2 – Conceptual scheme of the QU4LITY WP4 developments regarding the Machine Enhancements.

There is a slight difference between both approaches, especially in the "Act" stage, in which the concept of Flexibility is introduced as part of the Automation (as will be further highlighted later in Section 4.3.1 – Degree of Automation dimension), so, a definition of the three of them follows below:

- *Sense*: in order to interact with the workplace and environment in which it is located, a machine must, in the first place, have all the relevant hardware installed, as well as to provide that information to the human actor in the form of HMIs or somehow acknowledging abnormal behaviour. This CPSization phase, namely, the modernisation of equipment and the installation of all relevant devices for the deployment of the Cyber-Physical Systems, is the most basic one, and, without it, further work is not possible. In order to achieve this, all the relevant components relative to the Data Collection and Data Visualisation must be in place.

- *Think (Analyse and Learn)*: the concept of Automatic Awareness for a machine is important, in the sense of the machine to be able to understand what is happening around it, making possible the correlation of operational and part quality data (Digital Traceability) – this is the Think-Analyse part, from which the AI dimension can start to be developed.
  The other part is Think-Learn part, in which the machine will be able to improve the instructions programmed by humans, to automatically detect defects and to be able to correct routines *a posteriori*, profiting from the experience acquired from the past: for instance, being able to detect that
- *Act & Adapt*: the rationale behind this stage is that machines should have the capacity to change over on the fly; and moreover, to reconfigure with different production modules on the same base machine platform. They should readily be adaptable to constant size and format changes. But they shall also be adaptable to radical and unforeseen requirements through corresponding equipment changes, such as replacing a robotic carton erector module with a pouch forming module.
  Adaptive machinery requires the systems to rely on relatively advanced levels of AI, or Intelligence of the Control platform which governs them, which will be the force behind the vast majority of the decisions, not only in the planning but also in their execution.
  This kind of equipment will eventually compare favourably in all aspects of productivity measurement –OEE, RoI, TCO– as lot sizes shrink and throughput (lead-time and volume) requirements remain critical.

2.2 Relation to other deliverables and WPs

Based on the schema of D2.11, the following Figure 3 shows the dependencies and relations to the other work packages:

The colour schema used in the picture uses the following notation:

- *"WP2 – Autonomous Quality in ZDM: Vision and Specifications"* is represented using **Purple** boxes, representing defined data models and common vocabularies;
- *"WP3 – Interoperable & Trusted Digital Infrastructures for ZDM"* is represented using **Green** boxes, representing all the digital enablers and infrastructures developed or enhanced within the project;
- *"WP4 – ZDM Equipment Digital Enhancement for Autonomous Quality Operations"* is represented using **Red** boxes, representing all the digitally enhanced ZDM equipment;

- *"WP5 – Open Autonomous Quality Services Engineering and Processes"* is represented using **Blue** boxes, representing the HMI technologies and Digital Platforms integrated.

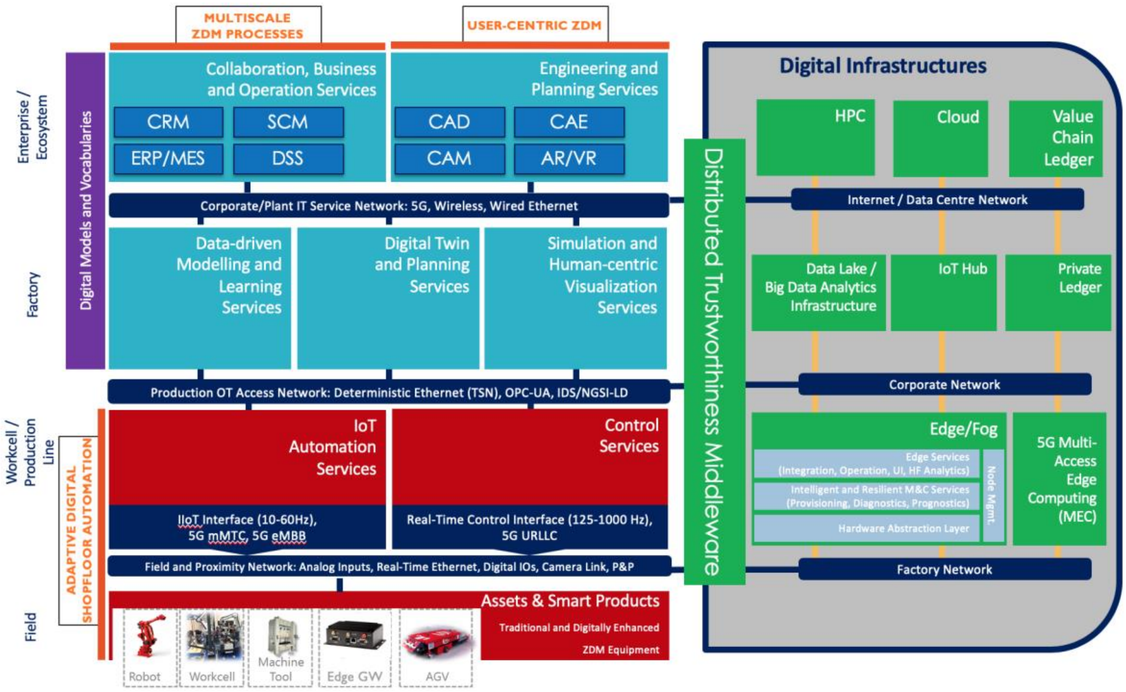

Figure 3 – QU4LITY RA mapping toward the project Work Packages.

In this deliverable D4.2 the focus is on the **red boxes** with the distributed Communication and Control infrastructure, and shows the possibilities for the interaction with the **blue** and **green** boxes.

In general, the QU4LITY Project is structured in a way in which the technologies and models are developed within WP3, then they are customised to machines and processes as part of WP4 and WP5, respectively, and then they are tested and validated in WP6 (Experimental Facilities) and WP7 (Industrial Pilots). For example, the Edge Computing technology infrastructure is developed, as an enabler, at T3.4, later on this is adapted for QU4LITY Machines at T4.2 and deployed in the form of Edge boxes at T4.3, and then this technology is validated in T4.4 from the Technical point of view, and at WP6 and WP7 from its Business side.

The methodology used in Section 4 – Autonomous Machines also ambitions to be useful for WP8 and the QU4LITY Marketplace, at the time of categorizing the assets coming out from the Project.

3. QU4LITY ZDM Digital Enhancements

3.1 General Approach

In this Section, the categories of Machine Digital Enhancements are described. In deliverable D4.3, the previous version of this document, the types of infrastructures and solutions to be implemented by each one of the Machine Pilots (DANOBAT, FAGOR, PRIMA, GHI and GF) were thoroughly detailed, along with the UNIMETRIK case to be deployed at the AIC Experimental Facility. From section 3.3 to section 8 of that document, descriptions were provided from the point of view of:

- *Particularities of the proposed Machine Solutions*: brief, higher-level description of the use case. Apart from it, specification of any relevant information on IT architecture or internal policy that should be identified as a technical restriction/requirement when designing/deploying the "To-Be" QU4LITY solution.
- *Connectivity and Configuration of Machine Solutions*: explanations of the requirements the use cases need, regarding connectivity, network topology, PLC connectivity, number of devices, protocols to be used, latencies needed, real time platforms, etc.
- *Functional Nodal Collaboration*: detail about the nodal collaboration of each pilot (in case of having fog/edge capabilities) and its network connection.
    - *Networking*: description of the computational nodes configurations capable to provide infrastructure for computing in the network. Also, information about latency, bandwidth…
    - *Computing*: type of cloud computing that is used in each pilot.
    - *Storage*: how all data is saved (locally, at clouds…)
- *Control and Monitoring*: how the control and monitoring of the developed infrastructure system are carried out, in terms of HMIs, for instance.
- *Standardisation needs*: description of the standardisation particularities of the Communication and Control infrastructure.
- *Security concerns*: particularities regarding the security on the Communication and Control infrastructure.

In this document, D4.4, all the activities to be done inside the WP are contextualised, in both this Section and Section 4 – Autonomous Machines; which will be followed by the in-detail case-by-case description to be provided in the subsequent WP4 deliverables in order, to list the Enhanced Machine Capabilities within each use case, and the Autonomy level achieved by the QU4LITY solution deployed and validated.

Additionally, it is worth noting that the definition of some cases of application of the QU4LITY technologies have undergone changes from the previous version of this document, due at M12, something for which details will be provided in Section 5 – Update of the Distributed Communication & Control framework described in the first version of D4.2

Now, to sum up all the above specified, and at M26 of the Project, enough information is available to:

- Make a complete categorisation of ZDM Digital Enhancements, something which will be documented in WP4 deliverables, starting from D4.4, in which the theoretical, high-level contextualisation framework will be introduced; and continuing through the rest of the deliverables until M30, when every pilot will specify which specific capabilities they will have their machines enhanced with, and what are the new functionalities and services provided by the QU4LITY solutions.
  This will be extended within Section 3.2 – WP4 Enhancements for AQ Machines of the present document.

- Propose, as well, and, having the beforementioned as an input, a categorisation of Autonomous Quality levels for all kinds of Machines, inferring these from the Lessons Learnt within QU4LITY Project.
  This will be dealt with in Section 4 – Autonomous Machines of this document.

3.2 WP4 Enhancements for AQ Machines with Increased Capabilities

The following categorisation portrayed in Figure 4 has indeed been agreed between all WP4 stakeholders, and presented at the M18 Review Meeting on the last October 2nd, in what comes to Enhancement of Machine Capabilities. And, as already indicated in the deliverable D8.5 – ZDM Equipment Platforms Marketplace, is not so much focused on the **"How** we can enhance the machines for AQ**?"**, but rather on the **"What** kind of capabilities are developed or improved by implementing the QU4LITY-born digital tools**?"**.

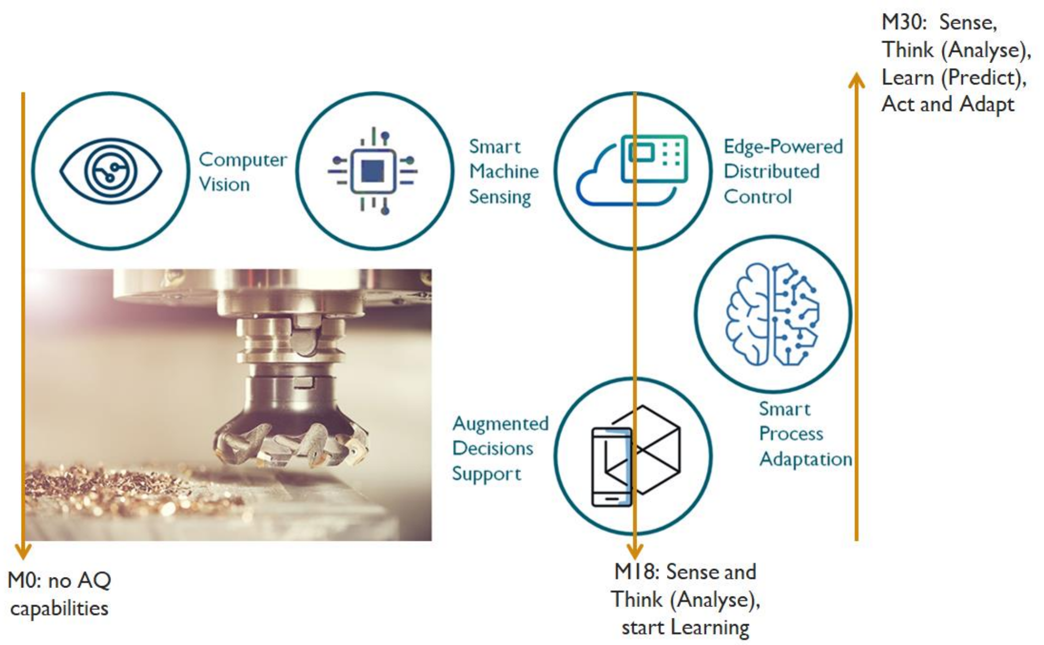

Figure 4 – Timeline of the WP4 developments, from a general perspective.

As observed, it is aligned with Figure 2, as will be later indicated. These categories, as featuring in Figure 4, are the following ones:

- Computer Vision
- Smart Machine Sensing
- Edge-Powered Distributed Control
- Augmented Decisions Support
- Smart Process Adaption

Their definition is provided in the following lines:

- **Smart Machine Sensing**, the capability for the machines to be aware of what is happening around, an enhanced capability which is closely linked to the process digital twin. Tools offering the Data Acquisition and Data Monitoring functionalities could well be inscribed into this category.
- **Computer vision**, mostly related to the product digital twins. The development of digital 3D replicas of the manufactured parts is one of the main first steps to evolve towards, and improve Control Intelligence in the path to AQ. NDT techniques such as acoustic defect detection, or 3D scanning, would fall into this category, according to this.
- **Edge-Powered Distributed Control**, the ability to make faster, decentralised, or near-to-the-Field, decisions on machine operations. As this kind of components are installed very close to the Field layer, according to the QU4LITY Reference Architecture portrayed in Figure 3, the time required for response is much slower than in the case they are collected in the Cloud (Data-at-rest) and need to be processed along with the data from many other equipment and processes. Savvy Edge, implemented by DANOBAT, for example, is one of such solutions.
- **Augmented Decissions Support**, which will help humans to make decisions, profiting from the newly acquired knowledge by the Big Data Analytics or from Machine Learning. This would be the case of Decision Support Systems, for instance, or of Augmented Reality tools which would help operators in training-on-the-job.
- **Smart Process Adaptation**, this is, the ability of learning from the product and operational data. The technogical developments in WP3 and WP4 are being adapted to machines, and this will result, in some cases, in the process being able to adapt, always under human supervision, accordingly to the knowledge acquired from the past experience. Not all Pilots will arrive to this level of AQ, described in the first iteration as "Autonomy Level 4" (as per Figure 5, introduced in D2.4 – Autonomous Quality Vision for ZDM and Quality Management Excellence -final version-). One of the Pilots which intends to arrive to this point is GF, adding the capability for their machine tools to adapt the process conditions to optimise product quality.

The first two (**Smart Machine Sensing** and **Computer Vision**) are closely linked to the Awareness the Machines must have regarding their environment, thus, constitute the core of the "Sense" stage portrayed in Figure 2.

Edge-Powered Distributed Control and **Augmented Decissions Support** are somewhere in between the "Sense" and "Think – Analyse" stages (this is part of the work done at the first iteration, until M18, as already indicated in Figure 4 and shown at the Mid-term Review Meeting) of the typical PDCA-style scheme. In this second iteration, the development and fine-tuning of tools boosting such two capabilities has continued, but more in the way of how link the "Think – Learn" with the final "Act" stage.

Smart Process Adaptation is the last capability to be enhanced at the QU4LITY Project machines, and, with that, the machines will be doted the capability of reconfiguring their processes, this is, the "Act" stage, albeit always under human supervision. This will only be achievable in the last stage of this second iteration, when the "know-how" about processes and products machines is mature enough and when machines are able to learn from past experience.

3.3 Services offered by the WP4 Solutions

These QU4LITY-born components and platforms which have been, or are to be, deployed at end users' premises, apart from enhancing machine capabilities, as commented in previous Section 3.2 – WP4 Enhancements for AQ Machines with Increased Capabilities, will also offer a variety of new Services for them, or improve the efficiency of the services that were already offered before the Project.

Of course, this is not strictly related to this Task 4.2, not even only with WP4, but it is important to highlight the work that is being conducted in collaboration among WP3, WP4 and WP5 (as already indicated in Figure 3, these services find location in the higher, left-hand side blocks of the QU4LITY Architecture, at Factory and Enterprise level) with the end users, both industrial Pilots and those who are deploying their solutions at pre-industrial Experimental Facilities.

These services, with whom QU4LITY WP5 is dealing directly, in the case of process improvement, can be categorised the following way, as preliminary described in deliverable D5.1 – Framework for User-Centric ZDM Processes, v1, and fine-tuned for their application within WP4:

- **Production Planning**: support provision for planning and simulation tools like ERP, MES or CAM. Functional requirements of the product to be produced must be considered, and also resource skills and availability. Additionally, quality requirements and manufacturing in time, must take manufacturing machine wear and machining cost into account. The user must interact with the tool by defining machining process configuration as well as production scheduling and evaluate different options and uncertainties. Optimisation methodology will support in decision-making.
- **Product Planning**: complementing Planning and Simulation tools like CAD, CAE, CAM, in order to support the user in product design and design for manufacturing. Functional requirements of the product must be considered, and also available machining resource skills. Additionally, quality requirements like machining accuracy or strength must be considered in this design and engineering phase. The user must interact with the tool by defining product geometry, material, component assembly, etc., as well as electric,

magnetic, thermal and mechanical design assessment. Optimisation methodology will support in decisions taken.

- **Maintenance scheduling**: planning of maintenance tasks, for which tools considering material flow and scheduling tools for resource planning are involved, such as ERP. If Predictive Maintenance is available, also a range of maintenance tasks (**Maintenance services** category) implementation will help in more flexible task integration into the ordinary production scheduling according to product order capacities.
- **Production Supervision and Management**: the key to this is for the user to control the production process quality by quality key performance indicators (KPI) to track the targeted quality. The typical example for this is a management dashboard tools as to visualise the aggregated current KPI values compared to KPI target values. In case of underperformance, the user needs to dive deeper and select the appropriate production subsystem or machine and to diagnose the problem or malfunction. Therefore, historical process data must be available, analysed in the form of SPC and visualised, as well as making trend prognosis. Analysis and prognosis functionality as background functionality is necessary, like data-based analysis models or predictive maintenance models. This category of services is located mainly at Factory level within the vertical integration of the QU4LITY Architecture.
- **Support to Humans in the Operative phase**: as the user in the field must operate at machine or product and needs feedback regarding the machines or his work, this kind of services will inform him immediately if the machining/operative process is good (pass) or not good (fail). In case of fail, repair or rework could be necessary. The difference with the previous one category (Production Supervision and Management) is mainly that this type of service is located near the Field or at Workcell level, and with the goal of seeking immediate action by the human actor, in case an alarm (visual, auditive, vibration-based…) has been triggered. Easy interpretation is necessary in case of "red light", thus, additional information to support in decision of further treatment must be included, from the acquired knowledge about the operation and product quality. Thanks to, for instance, machine learning algorithms, which will be able to identify possible root causes for a particular defect in a produced part, the human operator can be aware of the current status of the system and can intervene through appropriate actions if it considers right to do so (need to rework the part, etc.). This is always linked to improving and maintaining the most optimal operational conditions in order to maximise product quality (through the machine set-ups and parameter configuration), and differentiates itself from Maintenance services that this category is purely operational, most correlated to the defects Prediction & Prevention and Product Repair strategies, and not directly to maintenance of physical machine components.
- **Maintenance services**: service category that helps in determining if any refurbishment, repair or upgrade must be done inside the machine due to machine malfunction or product quality failure. The user must know the root cause for malfunction to know what the problem is, with very high probability,

and to react in the correct manner. These services are, logically, more linked to physical Maintenance aspect of the machine, linked to the Machine Repair and Refurbishment, and located somewhere in between both Workcell and Factory layers.

- **Functional test and calibration**: these kinds of services help in determining if a piece of equipment or a system is performing as it should once deployed in the field at the environment in which it normally works. There is a slight difference between both concepts. Functional testing is a verification that a particular device responds properly to process inputs only (if it is selective and is not containing other undesirable error sources); while Calibration is the adjusting the transmitter or equipment to known and certified values. The difference between them is the one underlying at whether simply no touching the settings in the equipment for testing, and effectively making adjustments.

4. Autonomous Machines

4.1 Autonomy and Autonomous Quality concept

As commented many times, the concept of Autonomous Quality is one of the pillars of the QU4LITY project, the other one being Zero-Defect Manufacturing. In this Section, the roadmap and evolution of a method to structure the Autonomous Quality levels will be presented. This tool should unequivocally separate one autonomy level from another, and should be applicable for all typology of Manufacturing Industries. Its ambition is to be one of the methodological assets of the QU4LITY project.

This method, or model, for categorisation of equipment according to a pre-specified definition of their degree of Autonomy, must meet a wide range of requirements that can be divided into two categories. On the one hand, there are general requirements aiming at user-friendly modeling: this categorisation must be as simple as possible for its prompt application, and at the same time must have a comprehensible description, adaptability relating to the degree of concretisation and the scope of description, reutilisation of the model, low modeling effort, as well as value-added findings based on the model. Similar approaches from previous works taken as reference have been found in bibliography[2], to make the model as universal as possible, and not only inscribed to the cases of application within QU4LITY.

On the other hand, there are specific requirements setting the subject matter and the scope of the model. Before formulating the specific requirements, the real system has to be defined and delimited: one conditioned by both people, technology and organisation. In this context, the factory is understood as a manufacturing system which is a subsystem of the system "manufacturing company". Consequently, the system boundary runs around the entire factory, so that the socio-technical system in the factory becomes the focus of investigation. Even though the focus lies on the factory, which is the entity representing the spatial implementation of production, relevant influences of the entire value-added system are also taken into account, especially at organisational level and at the time of defining how the information exchange and utilisation is, among the different pieces of equipment, workplaces and vertical levels of the said company.

Therefore, the specific requirements are as follows: first, the model should neither be industry-specific nor product-related or dependent on quantity (general validity), in order to be able to apply it to QU4LITY use cases and components, especially the digital upgrades of the Project machines. Second, according to the understanding of a socio-technical manufacturing system, the three earlier mentioned dimensions – people, technology and organization– have to be analysed on the level of the entire factory (holistic, superordinate and qualitative consideration). Third, the description of the model states is carried out with the aid of features and maturity levels (technology independence). And, fourth, the discrete stages can be compared and differentiated due to superordinate properties (discrete development steps).

[2] Bauer, D., Schumacher, S., Gust, A., Seidelmann, J., Bauernhansl, T. *Characterization of Autonomous Production by a Stage Model* (52nd CIRP Conference on Manufacturing Systems). Procedia CIRP 81 (2019) 192-197.

The deduction of features to describe an autonomous manufacturing system is primarily based on the analysis of existing concepts for manufacturing systems. In particular, the principles of distributed systems, cooperation, information technology networking, self-organisation and self-optimisation, as well as autonomous and dynamic structural units are applied at this point. Furthermore, the recent trends driving manufacturing systems towards autonomy are also reflected here. The resulting features can be divided into five categories. By these five categories, the dimensions of people, technology and organisation are taken into account, as mentioned. In total, there are twelve characteristics that can be assigned to the areas of manufacturing cell (technology), material and information flow (technology), development stages of the entities (technology), worker role (people) and factory organization (organization). The derivation of the twelve features corresponds to the determination of model variables (second step of model development). These were all considered only in the Second Iteration, not in the First one, so, they are highlighted in Figure 11.

4.2 First Iteration (One dimension)

The starting point of this definition process, in terms of autonomy levels for a factory, the following categorisation of Figure 5 was proposed in deliverable 2.4, but without any specific definition of those levels, and was presented in the M18 Review Meeting particularised for the AQ machine capabilities.

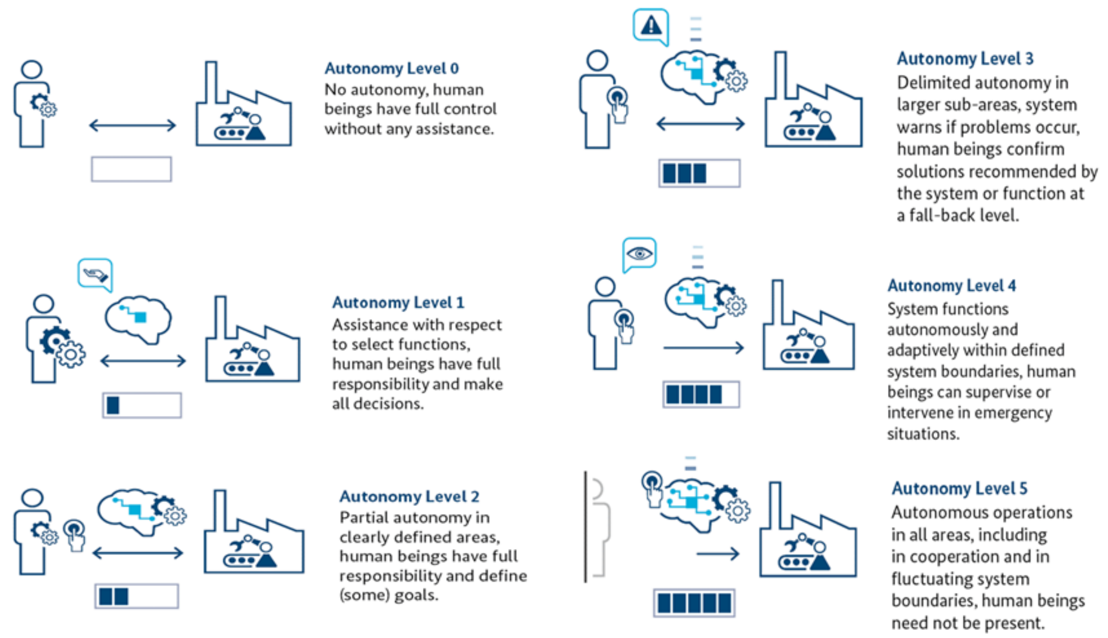

Figure 5 – Classification of Machines according to different Autonomy Levels, as categorised in QU4LITY deliverable D2.4.

The preliminar definition was as follows:

- At *Autonomy Level 0*, humans would have all the competencies in terms of controlling the operation of the machine and both the product quality.
  There are no indications of whether the machine is operating at, not yet optimal, but even safe, working conditions. Operation is run purely under human experience and controlled by human senses – thus, quite prone to unforeseen failure. Maintenance is just corrective or, at most, preventive and based on the "know-how" and experience of the human operator, but yet far from optimisation.
  Also, the part quality is measured by human operators manually, without any kind of help of automated devices, just by mechanical calipers and gauges, whose uncertainty is quite high. There is also no possibility of performing Non-Destructive Testing techniques such as X-Ray Tomography and Acoustic or Optical Scanning – the part must be destroyed in order, for example, for the quality technician to check if there were any inner macrostructural defects, such as cracks, etc., and, obviously, there is no possibility to trace back to the root cause, apart from human experience.
  Basically, the machine is treated like a "black box" in engineering purposes, with input(s) and output(s), but it is not even remotely under control.
- At *Autonomy Level 1*, the machine locates itself a step above. This is considered to be the first step to effectively control the operational process. Machine Sensors which are relevant for provisioning humans with information are installed after a study, by a multidisciplinary team, of the most probable product defects and their probable root cause in terms of operational parameters, based on expertise and background "know-how". Monitoring interfaces are also deployed, in order for humans to visualise these real-time data stream. This may be critical for failure detection, because the machine or plant operators are able to see whether there is any variable that is skyrocketing or not high enough, thus, indicating that the operation is not running properly and needs corrective action. This can be further reinforced with alerts and alarms, which could be visual, auditive or triggered by vibration. These alarms are "dumb", this is, base don operation monitoring, they acknowledge the operator that there is something which is not going well regarding the machining operation, and that there is need for immediate action. Depending on the parameter that is highlighted to be abnormal, adequate corrective actions are required, but, once more, the guidelines for these adjustments are experience-based. There is no support for a Predictive Maintenance approach.
  In what comes to the product dimension, there is no automated control at all of the part quality, as in the previous Level 0.
  This may not only be the case of industries that demand quality specifications with, for instance, broad geometrical tolerance windows; but also of manufacturers of parts that have traditionally operated with higher-value adding processes, but with a layout of relatively higher degree of automation while maintaining a low level of intelligence in the control. An example for this are some Aeronautics suppliers. Aeronautic Industry is one Sector with some of the most strict quality demand specifications, but, normally, the production

rate at these factories is low, i.e., a few dozens of parts per day: this permits the machine operators and quality technicians to perform manual inspections of each and every part. Also, the working times for the operation are high enough so that the professionals in charge have enough room to adjust the machine parameters without this impacting in the quality of more than one part, due to the machining cycle times being of many minutes in most of the cases.

- At *Autonomy Level 2*, the Process Digital Twin in the previous Level 1 continues to be present. There is definitely some degree of Process control intelligence, but this continues to be limited to monitoring and visualisation and very limited feedback to the user, maybe in the form of alerts and alarms; otherwise, the behaviour towards the process is still quite passive and interventions in the operation are merely corrective.
  In parallel, not necessarily integrated yet with the information about the Process in this level, there is also a Product Digital Twin. This means that a digital replica of the manufactured part is available and the quality inspection operation is automatic (most typically, for dimensional quality inspection, performed by an optical, X-Ray or acoustic automated cell) and substitutes the previous manual work which was more error-prone and had bigger uncertainty. Another Benefit of having the Digital Twin of the Product is that it enables Digital Traceability of the parts, which now may have a Unique Recognition Identifier – this is the previous step to, and necessary for, the correlation among the Process parameters and machine set-ups and Product quality.
- At *Autonomy Level 3*, all that was described in the previous Level 2 is maintained (Process and Product Digital Twin), but is expanded with further autonomy capabilities.
  Apart from the abovementioned, Data Analysis comes to the fore. While, at Level 0 or the lower levels, for instance, the quality inspection could be based in a statistical figure, because the value added to the part not being very high, now that there is the possibility to install a system for automated quality (more or less integrated within the manufacturing process – it might not be following an in-line inspection ZDM paradigm in which all parts undergo the same strict quality inspection, but the installation of such devices is certainly a necessary *sine-qua-non* requirement and a step towards it). Now, with the possibility to digitally record all these data, the possibility for making precise SPC analytics exists.
  Additionally to this, correlation between Process and Product data brought by Big Data Analytics platforms exists, which is, at the beginning, off-line and just qualititative. The good or bad quality is started, this way, to be associated with certain thresholds of operational parameters, beginning from the observation and study of the historical data to spot specific problems. The goal is clearly the optimisation of the process, to have a stable and repeatable machine operation while maximising product quality. This data analysis is most likely performed in a company Cloud, due to the impossibility, at this

Level, to perform the analytics in real-time near the machine. Nevertheless, the foundations for Data Interoperability are set for the next level.

This is also, as part of the Human-in-the-Loop processes, combined with associated Alarms and Recommendations to support Humans in Decision-Making. The mentioned alarms are no longer unintelligent, as the ones enabled by the plain sensors and the passive data visualisation. Now, there is the possibility to make the operator/supervisor aware of most probable root cause(s) for the identified or predicted defects, although in a semi-quantitative level and not yet in real time. Indeed, Predictive Maintenance locates itself in this autonomy level, since it is possible to start foreseeing the quality of the manufactured parts from the analysis of the actual operational conditions and events.

- At *Autonomy Level 4*, the concept of Artificial Intelligence is first present, in the form of Real-time Analytics and Machine Learning. The data analysis, that in the previous stage was performed off-line, is fully integrated and runs the closest to the actual machine operation, both physically (Edge computing) and limited by the latency.

  These Machine Learning algorithms enable the machine to get Automatic Awareness of the context the operation is running at, e.g., in the form of event predictor (a platform which takes the current process parameter data as input and offers as a result, as a more or less accurate estimation, the probability of generating a defect at that moment) are most likely available for operators in the form of portable interfaces. And, if a defect is predicted, the platform itself is able to suggest specific adjustments of concrete parameters for the operator to adjust the machine set-up, thus, permitting an Active Reconfiguration, yet human-supervised, of the machine. It also enables the effective Federation of Distributed Processes within a line, when extrapolating this same categorisation for process lines, instead than just speaking about machines, as it is done in the QU4LITY WP4. As said, Interworking and Interoperability among machines is guaranteed.

  Still in a Human-centric factory, as the target of the QU4LITY project, this is really the key for having Human-Machine Autonomous Collaborative Processes. For this to be effective and useful, huge amounts of data are to be consumed beforehand in order to train the correlating algorithms.

- At *Autonomy Level 5*, the Deep Learning algorithms will be able to cope with Automatic machine reconfiguring even without the need of human actuation or supervision, so, therefore, the figure of humans would no longer be needed. The machines and workcells will offer total Flexibility for Production and a Smart Process Adapation.

  It must be said that, although there will be advancements towards that, it is not considered a feasible, realistic scenario in the short term, at least when talking about the manufacturing industry.

It is worth noting that, although in some cases it depended on some OT-layer factors, such as the deployment of data computation capabilities for Autonomy Level 4 in order to evolve towards Real-time Analytics, it was heavily dependant on IT factors almost exclusively.

It must also be clarified that, at the time of configuring this categorisation or preliminary model, key sources of bibliography were still not taken into account, but were released later [Ref.2: Bauer et al., Ref.5: Roland Berger's "Rise of Machines…"]. This is mainly why a One-dimension model was adopted in the first place.

Along with the preliminar categorisation of Figure 5Figure 5 – Classification of Machines according to different Autonomy Levels, as categorised in QU4LITY deliverable D2.4., the ambition/scope of each of the Pilots and Experimental cases of which level they intend to arrive to (just to refresh, screenshots of the Mid-term RM are shown in both Figure 6 and Figure 7, where the Enabler types to be eventually implemented and this Autonomy target –as said, against the Figure 5 classification– could be observed).

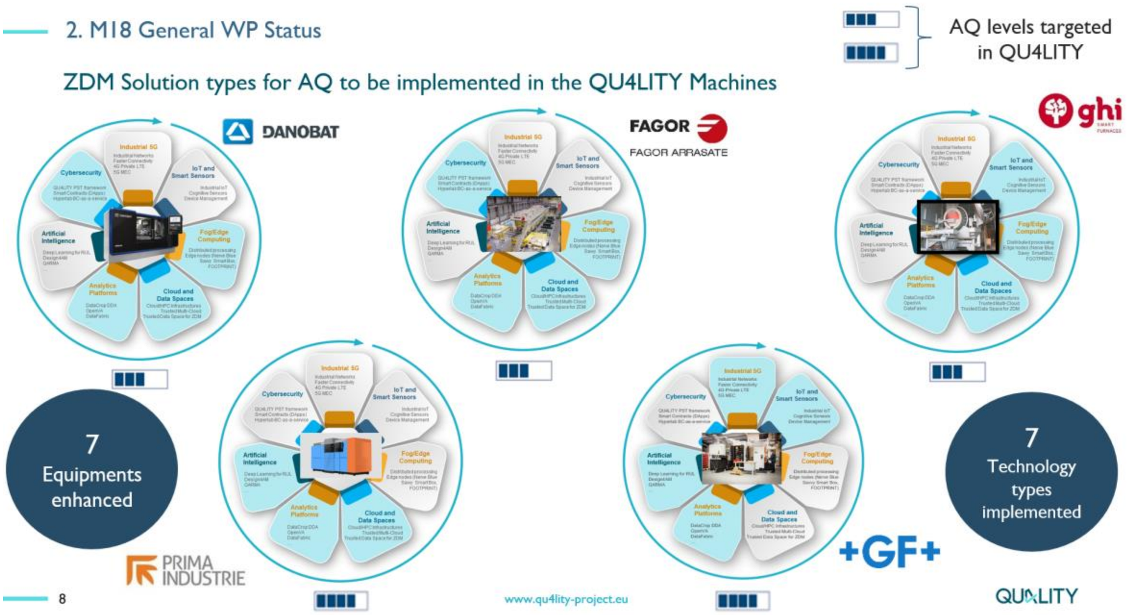

Figure 6 – Screenshot from M18 RM presentation, highlighting the Autonomy degree the Machine Pilots intend to achieve, according to the first iteration.

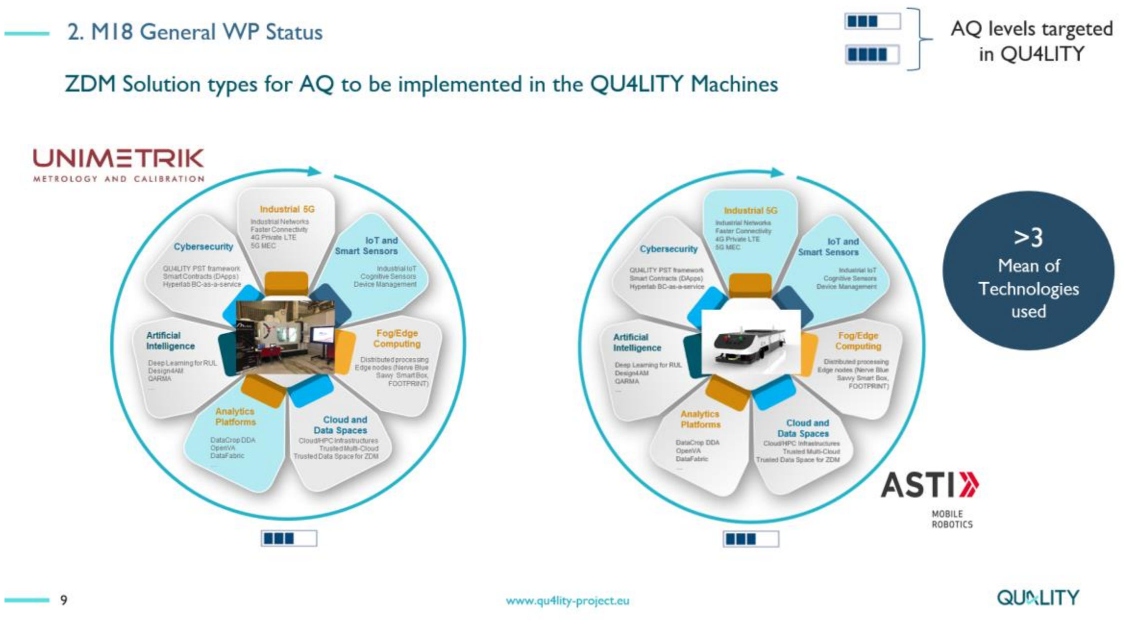

Figure 7 - Screenshot from M18 RM presentation, highlighting the Autonomy degree the UNIM and ASTI experimental cases intend to achieve (with the First Iteration).

It should be once more remarked that this (Figure 6 and Figure 7) is only a first iteration, and it was done precisely using the categorization defined as part of this First Iteration; and, therefore, the enablers used and the Autonomy level reached by each one of the use cases is something that will be assessed against the new model developed (Table 2) documented in the upcoming WP4 deliverables combined: D4.6, D4.8 and D4.10.

4.3 Second Iteration (Two-Dimensional)

It has been observed that, in general, the current situation at the Manufacturing Industry is that in which the IT and OT layers are still actually quite separated and not integrated with each other.

OT typically refers to the control and automation technologies supporting operations, which historically have been intentionally separated from IT. This separation originally generated from the different technologies involved and the different skills needed. Early IT systems were proprietary, required internal programmers and were used to calculate finance-related figures, including payrolls or commercial transactions. At the opposite end, OT consisted of turnkey, proprietary systems designed to operate only on vendor-specific equipment.

With the more pervasive use of IT technologies at the operational level, things are changing from a technical point of view. Some simple examples include the usage of Microsoft technology with continued adoption of SQL databases to collect and analyze production and process data; the rapid adoption of Ethernet-based communication protocols at the machine level; the rapid diffusion of web-based user interfaces; and the increased popularity of mobile solutions to access data and perform tasks requiring Wi-Fi networks at the shop-floor level. Nevertheless, there is still strong resistance to change at the organisational level.[3]

The following Figure 8 shows the convergence between the IT and OT (the latter understood as Industrial Automation) in the past few decades.

The field devices (such as sensors) in the bottom layer involve sending data to the logic controller, while the SCADA system executes control tasks. The Manufacturing Execution System (MES) allows users to perform complex tasks, such as production planning. The MES and the Enterprise Resource Planning (ERP) system at the top layer allow management reporting and sharing of manufacturing data, such as purchase order status with other systems (e.g. Customer Relationship Management, or CRM).[4]

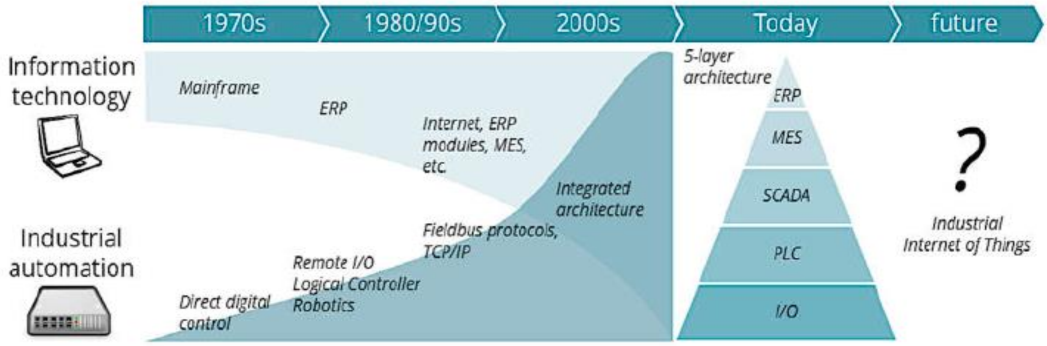

Figure 8 – Timelapse for the convergence process between the IT and Industrial Automation in the past decades [Ref.4].

Taking as reference a White paper from bibliography[5], which proposes a two-dimension matrix to provide a solution for this, a second iteration has been completed by configuring a matrix that takes into account these two big groups of variables, or dimensions, for the categorisation for Autonomous Quality Equipment:

- The **degree of Automation**, or Automation intelligence, on the one hand. This is relative to the factory/machine layout, to the physical deployment of components, and is an indicator not only of the capacity, by the machine or workcell to automatically carry with a series of operations; but, gradually, with the increase on level, will evolve in a more smart and flexible equipment, being interoperable and capable of communicate and interwork with other machines and processes and to bear with a high degree of product

[3] https://www.automationworld.com/home/blog/13315760/the-challenge-of-itot-convergence-in-manufacturing

[4] Lin, Y.-J., Wei, S.-H., Huang, C.-Y. *Intelligent Manufacturing Control Systems: The Core of Smart Factory*. 25th International Conference on Production Research Manufacturing Innovation: Cyber-Physical Manufacturing. August 9-14, 2019. Chicago, IL (USA).

[5] *Rise of the machines – How Robots and Artificial Intelligence are shaping the future of Autonomous Production*. Roland Berger, 12.2019.

customisation towards one-product batches, enabled by a fast and efficient transport and change of fixing and machining tools and resources.
The ultimate goal of increasing the level of Automation is, thus, not only to reduce the time dedicated by humans to physical tasks such as operating the machine with their own force or to transporting the materials or semi-finished product between stations, but, ultimately, and especially towards the higher levels, the main objective is to be able to configure a factory capable of producing many different types of products with minimal setup changes or extra investment, a holonic hyperconnected factory driven by auto-organised, self-configurable modular cells.

- The **Control Intelligence**, related to the level of awareness the machines have regarding their environment and the way in which they are able to improve, by themselves, the tasks that are assigned to them, and, also, especially remarkably, how the relationship between the very same machine and the human is: in *Level 0*, there is no help at all for the user, and the intelligence in place for the control activities are purely based on human intelligence (humans programme the machines and they perform the tasks); but, progressively, the machine starts getting context-aware and, with limited Artificial Intelligence (AI), wary of the working conditions, in order to support the workers and help optimising the operation in terms of quality and employed resources. Towards higher levels, the figure of humans is lesser needed, until *Level 5*, where it is not needed at all, due to the Prescriptive Maintenance approach taken by the machine itself, and the machine itself is able to run within broader Cognitive Collaboration Processes.
The objective of this axis is to increase the level of information captured by the equipment, to make it aware of what is happening around itself, and to transform these data to planning and action capabilities through an ever-learning platform, being the decision-making increasingly lying on the machine.

The categories corresponding to both dimensions are to be further fine-tuned in the following paragraphs and subsections (4.3.1 – Degree of Automation dimension and 4.3.2 – Control Intelligence dimension).

4.3.1 Degree of Automation dimension

Not only are high amounts of information available in recent research regarding the Driving Automation concept; but, also, much more specifically about the Industry, a comprehensive historical perspective, with past propositions of reference models in order to quantify the degree of Automation a Manufacturing system posseses, has been found in bibliography[6]. Some authors (as better defined in Figure 9) focused on whether it is the human actor, the computer, or the latter under supervision of the

[6] Frohm, J., Lindström, V., Winroth, M., Stahre, J. *Levels of Automation in Manufacturing*. Ergonomia – International Journal of Ergonomics and Human Factors, Vol.30, Issue 3, 2008.

former, are the relevant protagonists, regarding Information Acquisition, Information Analysis, Decision and Action Selection or Action Implementation[7,8].

Figure 9 – Diagram portraying the Levels of Automation Taxonomy (LoAT) [Ref.7].

Actually, and, as previously pointed out, the simple Sense-Plan-Act diagram from Figure 2 resembles this LoAT categorisation.

From that starting point, within the QU4LITY Project, and given also some of the experimental cases involved, the concept of Flexibility has been fusioned with the Automation dimension.

A **Flexible Manufacturing System (FMS)** is a system with the ability to respond to potential internal or external changes affecting its value delivery in a timely and cost-effective manner. Flexibility for an engineering system is the ease with which the system can respond to uncertainty in a manner to sustain or increase its value delivery.

The first Flexible Manufacturing System named "System24" was introduced in England in 1960. It was designed to produce light flat alloy components.

---

[7] Parasuraman, R., Sheridan, T.B., Wickens, C.D. and IEEE fellow. *A Model for Types and Levels of Human Interaction with Automation*. IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS—PART A: SYSTEMS AND HUMANS, VOL. 30, NO. 3, MAY 2000.

[8] Drilling Systems Automaton (DSA) Roadmap: *Systems Architecture* (https://dsaroadmap.org/wp-content/uploads/2019/06/5-of-14-Systems-Architecture-190531.pdf). 2019.

Focused Flexibility Manufacturing Systems (FFMS's) represent a competitive answer to cope with the need of customised flexibility and guarantee the optimal trade-off between productivity and flexibility. The customisation of flexibility on specific production problems leads to the minimisation of the system cost during its life cycle.

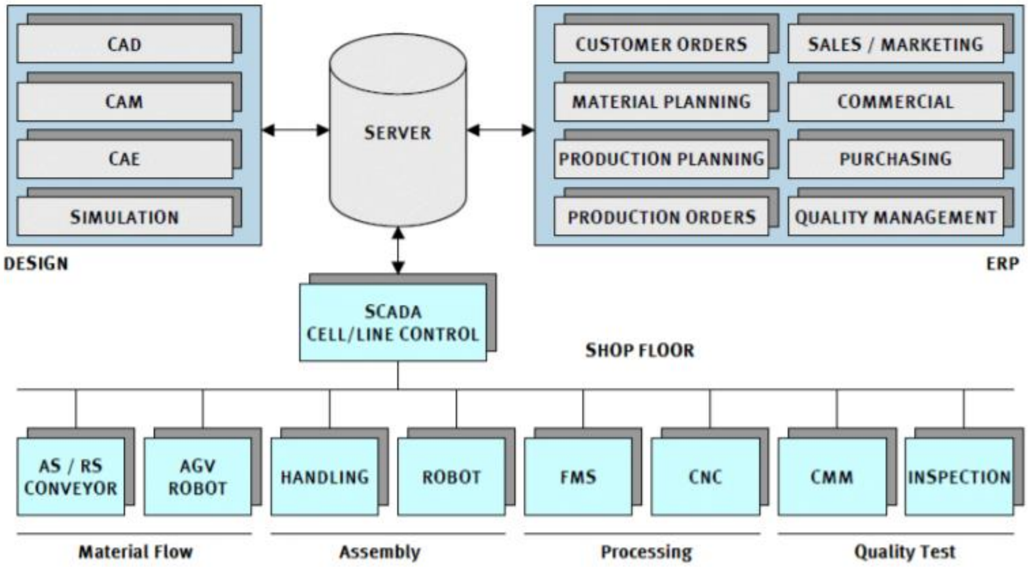

Figure 10 – Block diagram depicting the main elements of a modular Flexible Manufacturing System.[9]

The required level of system flexibility impacts the architecture of the system and explicit design of flexibility which leads to hybrid systems, i.e. automated integrated systems in which parts can be processed by both general purpose and dedicated machines.

Designing a dedicated system in which the reconfiguration option can be implemented in the future when production changes occur this leads to design a system with the minimum level of flexibility required to cope with the present production problem.

[9] Kostal, P., Velisek, K. *Flexible Manufacturing System*. International Journal of Industrial and Manufacturing Engineering (World Academy of Science, Engineering and Technology). Vol:5, No:5, 2011.

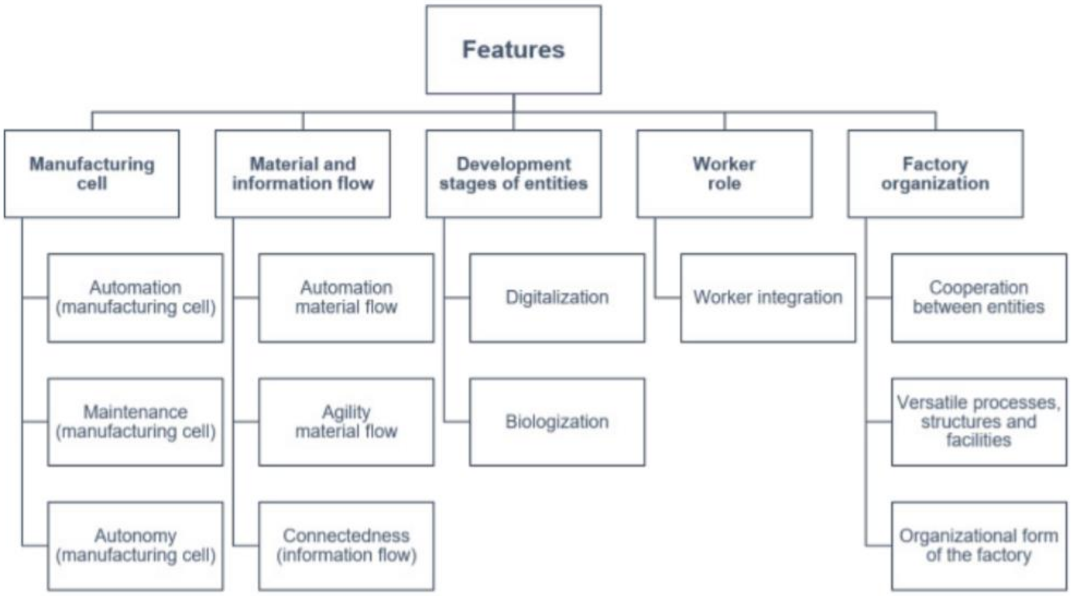

Figure 11 – Features of an Autonomous Manufacturing System [Ref.2].

The features in Figure 11 are the main ones which have been considered for the configuration of the final iteration of Autonomy level categorization in Table 2, as pointed before in the beginning of this Section (Section 4.1 – Autonomy and Autonomous Quality concept). These are relevant both for this Section 4.3.1 – Degree of Automation dimension, and for Section 4.3.2 – Control Intelligence dimension.

The main concepts, or variables, taken into consideration as part of this degree of Automation dimension are, thus:

- Automatisation of Operations
- Agility of the Material Flow
- Different degrees and types of Flexibility in Manufacturing

Taking into account the beforehand explained, within the Degree of Automation ('y' axis of the Table 2 below), the following categories have been defined. Each one of the Levels incorporates the features from the previous level and some other ones:

- Level 0: Manual Operation
  In this level, the part is machined through a manual-action machine, such as a manual lathe machine, in which the human force is still required to move at least certain elements (whether the tool or the part, most typically). **The operation and the material flow**, as said, **are not automated**.
  This is a machine in its most basic form, and predominantly corresponds to old machines from some decades ago. Regarding the human role, and, as commented at the beginning of the paragraph, **Machine operation is performed by the worker**.

- Level 1: Part processing
  The machining of the piece takes place in fixed equipment, and the manufacturing cells offers assistance for its physical execution. From this point, and until Level 5 of this Automation axis, **the machining operation is automated**, typically, in a CNC machine – this implies that human force is no longer necessary to perform the proper adding-value activities to the part, and constitutes a first step for the creation of hybrid machine-worker teams, depending on the Control Intelligence degree, which is the other axis of the matrix.
  The part is processed automatically but **Material Transport is still definitely not automated**, the flow of raw and semi-finished goods depending on human-driven forklifts.

- Level 2: Adjustable Transport among fixed machines/lines
  In this level, the most elemental Flexibility type is made possible, in the sense that the layout covers the most elemental **Material Handling Flexibility** scenarios, thus, different materials and part types can be transported and positioned properly at various machine tools in a system (through conveyor belts, etc.). The fact that **the Material Flow is partially automated** in a structured way between fixed lines and equipment is the very first step for a machine towards the Flexibility paradigm.
  It is the case of some more-or-less complex contemporary turn-key plants consisting of a group of machines **interconnected by a system of conveyor belts** to handle the raw and semi-finished material among different stations or workcells, for instance. The robots which are deployed in each station are able to pick the part from the conveyor belt and place it accordingly in the adequate place in order to start the corresponding operation (machining, quality inspection, etc.). In **a functional** (vertical) **organisational form of the factory**, which is the one associated to this level, **the processes continue to be fixed** as in the previous case, despite the physical transport among lines and equipment being partially automated.
  It may be complemented with different degrees of Artificial Intelligence, for instance, imagining a cell whose purpose is to weld different pieces of stainless steel tube in one and only big coil for applications such as Subsea Umbilicals, Risers and Flowlines, and which could be equipped with a set of sensors for the automatic aligning of the tube before the radial welding process, and a Machine Learning software as well, in order to be able to eventually achieve the automatic identification of defects in the welding seam.

- Level 3: Basic Flexibility in the handling of parts
  Here, the workcell incorporates the most elemental concepts of **Machine Flexibility**, this is, the ease due to which machine can possess and run multiple operations, and, also, **Operation Flexibility**, namely, alternative operation sequences which can be used for a processing part type. On one hand, **the Material Flow is centrally automated**. **Flexible processes,**

structures and facilities are enabled in **a segmented organisation of the factory**.
A state-of-the-art machining center, for example, is a heavier investment than the typical CNC milling or grinding machine, but offers the flexibility to carry on with different operations and even series of operations by using the same fixing tool, thus, reducing the time between successive operations and minimising the errors due to aligning the part to different CNC coordinate systems. This Automation level can even be combined also with different degrees of Control Intelligence, such as the compatibility with CAD and CAM software which is able to very precisely simulate the profile of the part to be created, leading to very accurate final dimensional quality and repeatability results in the machined parts.

- <u>Level 4</u>: <u>Aggregated Flexibility</u>
  In this step of Automation, as the comprehensive information flow of the AI platform (the other axis) brings full connectedness within factory environment, concepts such as **Routing Flexibility** (the capacity, by the system, to find alternative paths that a part can effectively follow through a system for a given process plan) are incorporated along the factory Value Chain, made possible via the digital thread – which, as mentioned, effectively means that a minimum Control Intelligence needs to be in place at the same time within the workplace. Linked to the previous one, we would have high **Volume Flexibility** (the measurement of a system's capability to be operated profitably at different volumes of existing part types, according to the Market o the individual customer's needs), as well as **Product Flexibility** (the volume of batch or set of part types that can be manufactured in a system with minor setup changes) and decent **Process Flexibility** (the volume of batch set of part types that system can produce without incurring any setup change).
  The Material Flow (tools, products) **is hybridly automated**, which means that, most probably, the transport is carried by a fleet of AGVs but under a centralised approach configuration, with a ring connection between vehicles and managed by a supervisor unit. In what comes to the factory organisation, it enables **transformable processes, structures and facilities** in **a connected factory**.

- <u>Level 5</u>: <u>Agile Material Flow in an Adaptable Layout</u>
  A fully flexible manufacturing system includes a configuration of interconnected processing workstations with computer terminals that process the end-to-end creation of a product, from loading/unloading functions to machining and assembly, to storing, to quality testing and data processing. The system can be programmed to run a batch of one set of products in a particular quantity and then automatically switch over to another set of products in another quantity. A make-to-order production process that allows customers to customise their products would also be an example of flexible manufacturing.

Connectedness within factory environment and beyond is needed at IT level, this is, the planning and production to be also fully connected and interoperable with logistics and eventual supply chain. This level would be thus characterised by a **distributed automated Material Flow**, thanks to a fleet of fully connected Automatic Guided Vehicle (AGV) configured in its decentralised approach, in which each vehicle is able to communicate itself with every other AGV in the factory in order to ensure a fluid transportation of physical tools, jigs and consumables. Also, the system is equipped with solid **Expansion Flexibility** (ability to enlarge the system and expand in order to incorporate new features and services) and **Production Flexibility** (the extra volume of batch set of part types that a system can produce without major investment in capital equipment) capabilities. Organisationally, **the factory allows the configuration of versatile processes, structures and facilities** in a **network-based competence**.

4.3.2 Control Intelligence dimension

Control Intelligence, as said, is here defined as the balance of power in decision-making between the human factor and the capabilities of the machine (AI) to acquire data from several sources, progressively be aware of its running environment and learn from its past experience.

In this dimension, something particularly relevant, remarkably to distinguish some key features in the lower-levels, is the the way in which the information flow is set-up across the different vertical layers of the factory, with software such as Enterprise Resource Planning (ERP) and Manufacturing Execution System (MES). The most widespread and comprehensive representation for this is probably the Computer Integrated Manufacturing (CIM) pyramid, completed with the inclusion of the SCADA in its adequate positioning, which is shown in Figure 12, according also to ISA-95. This pyramidal scheme implicitly relies on several hypotheses, even if these are never expressed very clearly[10].

[10] *SCADA and MES: the pyramids' secret*. Ordinal Software, 2021: https://www.ordinal.fr/en/scada-and-mes-the-pyramids-secret.htm

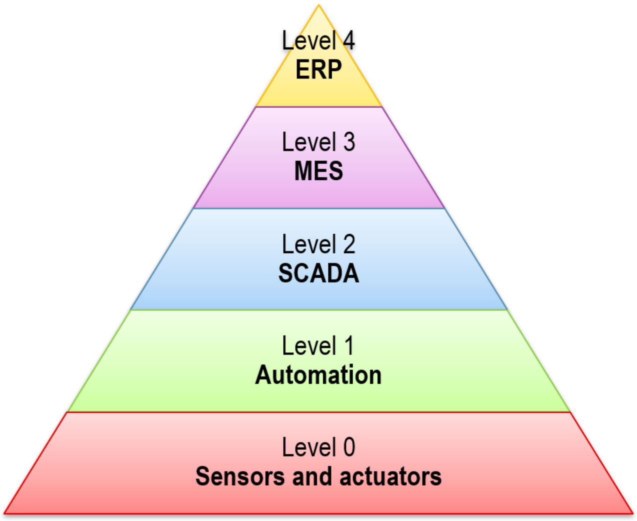

Figure 12 – Computer Integrated Manufacturing Pyramid, with the incorporation of the SCADA level [Ref. 10].

The first one of these hypotheses is the functional hierarchy, whose effect is reinforced by the representation. It implies that we go from the simplest functions (at the bottom of the pyramid) to the most complex ones (at the top of the pyramid). The second hypothesis –it is more likely the most important– is that every functional block can only adjoin with the one right above it and the one right below it. This last hypothesis is at the same time stated historically by an analogy with the traditional management structures but also by the existence of material communication types really different at each level: until not so long ago, sensors' networks, automatons' networks, and computing networks were of different types, unable to coexist on the same physical material.

Nowadays, we do not assume that the intelligence is essentially concentrated at the top of pyramid, and especially since Ethernet standard and TCP/IP protocols established themselves as basic universal layer for most networks, whether for sensors or actuators' networks, automatons or computing networks, or even the worldwide Internet connection. But, without affirming that CIM pyramid got split, at least it is possible to say that this representation is less naturally obvious than during this period.

Nevertheless, the pyramid's "secret" is to convey furtively a division which does not necessarily correspond to a functional reality, neither to a current technical constraint nor actually to the reality on the field. As said, the intelligence is not only something exclusive of the upper layers, and, also, in reality, the concept of Automation is broader than just the first step of the pyramid, so this does not pretend to be a complete separation between the OT and IT layers. It is, however, useful, in order to have some basic orientation about the integration of the different vertical levels of information ("data in motion" through the lower levels and "data at rest" towards the higher ones, according to the QU4LITY Project Architecture) inside a Manufacturing company.

At the same time, towards higher levels, different steps to be taken towards Autonomous Systems, with regard to data collection, treatment and knowledge development by the AI, are presented in the diagram which is numbered below as Figure 13.

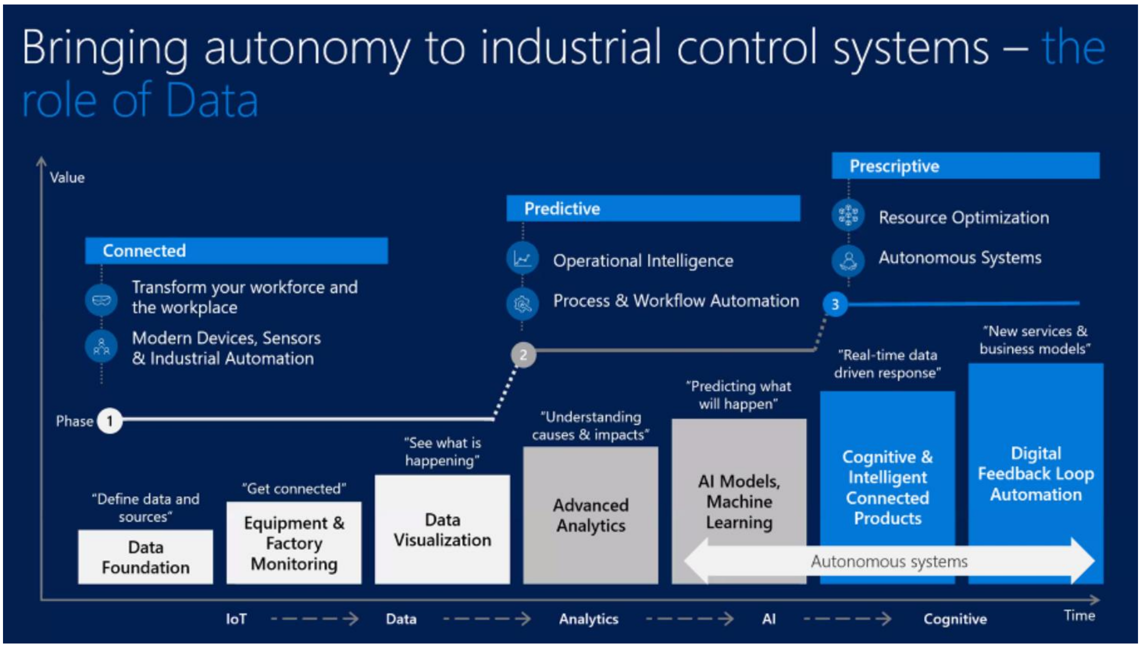

Figure 13 – Control Intelligence steps towards Autonomous Systems [Ref. Owner: Microsoft Autonomy Pathway].

The main concepts, or variables, taken into consideration as part of this Control Intelligence dimension are, thus:

- Data Acquisition and Interfacing
- Worker integration – Data Analysis and support for Decision-Making
- Awareness, by the machine, regarding its work environment
- Maintenance types (Corrective, Predictive, Prescriptive)
- Agility of the Information Flow, intra-company

When "crossing" or correlating both dimensions, both degree of Automation and Control Intelligence, in order to describe the autonomy of a single system, one of the main phenomena to be observed in the first place is that, usually, there is some kind of correlation between the partial levels of both dimensions. It does not make sense to deploy, for example, some of the most investment-heavy and technologically advanced equipment needed to configure flexible system while not even incorporating state monitoring capabilities (a simple data collection and interfacing) to that equipment – it would not even be feasible actually.

From the abovementioned, within the Control Intelligence ('x' axis of the Table 2 below), the following categorisation has been specified:

- Level 0: Control by Human Intelligence
  In this base level, the humans configure fixed values for machine set-ups: for instance, by setting the motor speed of an old, manual machine tool without CNC control. Indeed, **the machine is not necessarily digitalised** – should this be the case, it would indicate that **this machine is not able to exchange any information with other equipment or elements of the factory layout**.
  The responsibility of keeping the very same operation running and the answer to parameter deviations from set-ups, other kinds of unforeseen situations or events through intelligent reasoning is, thus, exclusively on the hands of human beings.

- Level 1: Basic Human-Programmed Control
  Here, the control of industrial operations of machines and single lines is performed only by programmed if/else-type command routines (more or less complex), what is usually called "Classic Automation" and Control Engineering. This is usually performed through a **Logic Programmable Controller (PLC)**, with no involvement at all of AI algorithms. Rules are clearly defined by humans, who maintain full control of the process at every time. **Maintenance is** still **Corrective**, **or Preventive** at most.
  A certain group of programmed rules may exist, as said, for instance, machine controls or relevant functions in order to guarantee the safe operation of the equipment and ensure no harm for humans while the operation is running, by applying an accurate and responsive correction to a control function through a Proportional-Integral-Derivative (PID) controller.

- Level 2: Assisted Operation
  In this step, multiple machines and lines which conform the Manufacturing Value Chain are centrally controlled **at SCADA level** within the factory. The **Information Flow** is thus **centralised by a controller** along the Process Value Chain inside the Workcell. Different nodes are capable of processing the machining data and start intercommunicating with other equipment in case a failure occurs which may potentially have an impact on the rest of the Value Chain, to avoid the formation of operational bottlenecks.
  The platform is able to perform support functions and, therefore, it is run as an assistance system. The AI procedures facilitate the interpretation of complex and ambiguous information via **Process Condition Monitoring**. The AI-compatible interfaces for real-time data monitoring may provide help to human users, impeding of making wrong decisions by themselves due to lack of information about the operational conditions, and providing them with limited optimisation options and rather generalistic predictions based on some recognised inputs (counting also on **Off-line Simulation**). This way, the users can have clues about plausible consequences when, later on, introducing certain programmed values to the system.
  Regarding the human factor, this level would be **somewhere between system control and optimisation by the worker and hybrid**

collaborative work between machine and worker. The operator feedbacks the system with his/her experimental "know-how", establishes the goals (acceptable quality tolerances, for instance) and, in certain circumstances, defines the intentions behind each of those actions – this is the level characterised by **Assisted Maintenance**. The responsibility of the process as a whole (which may not be the case of certain parts of the process) still lies on humans.
As commented, there is assistance in the control of the machine/line, but **the knowledge with which the control is run**, **and the boundaries of the system are defined continue to come directly from humans** and their acquired experience. An example for this is when a programmed machine PLC/CNC or Distributed Control System is able to automatically decide the need to switch to safe mode, and to immediately execute it, when detecting anomalous values of sensor readings.
The objective of the AI-powered assistance systems is mainly to reduce the complexity of the conscience needed to work within new, not-programmed or unforeseen scenarios and to guide humans in difficult situations. In relation to the scale as a whole, in this Level 2 human beings still take all the main decisions and maintain full responsibility over all processes.

- <u>Level 3</u>: <u>Shared Control with Machine Initiative</u>
At this level, the **production process** is **coordinated** at plant management level **by a central MES system**, **or** by the **corresponding ERP modules** of the company, in terms of manufacturing planning and execution. The **Information Flow** is, therefore, **centralised** by software **at Factory/Company level (full connectedness within Factory)**.
The operator defines here the limits within the AI-controlled system may operate the automatised operations. The system independently monitors (**Automatic Awareness**) its environment inside these specified limits and starts to be fully able of its own **Performance Measurement** (via SPC and over-time evolution of quality, for example), this is, to evaluate the quality of its own outcomes – through the self-monitoring of its own operations, defects and bottlenecks can be detected in real time, for example.
The idea underlying at this level is associated and linked with the Automatisation of certain tasks at OT level, within the machining operation: for instance, but no sine-qua-non, the incorporation of inline measurement technologies which are able to identify defective parts within each cycle (this would be not possible without having a digital replica, or **Digital Twin**, **of the Product**). The most complex operations, however, remain assigned to the human actor. In certain, specific areas, and within a limited time period, the system is able to **Take over the control**, as the example provided in the previous sentence for the case of quality inspection, but it is something can happen always under human supervision, who also control the results.
Current robots, which are utilised in the industry as of today, typically rely on a pre-described trajectory and use lasers or vision systems for position control, which could also be considered as a kind of "digital twin" but without

the complete environment awareness by the side of the machine, something which is not achieved until the next step (Level 3 of Control Intelligence), namely, with the performance measurement.
In any case, a **Digital Product-Process Traceability** should already be in place in this step, in order to monitor the product quality and be able to start "learning" from the process in its most basic form (Statistical Process Control, or SPC, as commented before). **Some Analytical Models may be in place**, **but** still mainly loosely, **qualitative**ly, correlating process and product parameters, and in any case, **performed off-line**.

- Level 4: Semi-Autonomous Collaborative Equipment
  At this point in the Control Intelligence staircase, the system can optimise itself through **Learning Phases**, and this data computation preferentially takes place at Fog/Edge level (at Industrial PCs and Distributed Control Systems, or DCS, deployed at machines or Workcells). This enables faster response time and problem-solving through better predictions. **Knowledge gathering** (expanding the "know-how" the humans possess, in terms of machine set-ups and production parameters to meet quality specifications of the customer) **and Decision-Making** is **in the hands of the AI platform**. Humans, at most, are accountable for a monitoring role and may intervene in emergency situations. The **Information Processing is Distributed Automated**.
  By introducing partially defined objectives by humans, if the AI recognises a pattern in the learning phase (**Machine Learning**), it can execute in a semi-autonomous way an appropriate learnt action. The system starts to function autonomous and adaptatively within the known boundaries of the system, set by humans.
  This semi-autonomy does not work only to optimise the production flux, but also to reduce inactivity times, due to the existing possibility for the problems and defects to be detected beforehand and the relevant people informed. This permits the economisation of materials, resources and part replacements.
  The role of humans is, simply, to confirm the **Predictive Maintenance** advice and recommendations regarding certain solution strategies, or to provide sporadic help to specific problems, thus, they intervene only when alerted and called for help by the system.

- Level 5: Modular Autonomous Equipment
  In this autonomy level, the highest one, a facility or a process in all its extension operates in all areas in a completely autonomous way. The system elaborates **Auto-Organised, Adaptive Solutions**, and it is able to make this in a **Fully Cooperative**, fluctuating way, with respect to both vertical and horizontal integration within the Smart Factory, but still within the system limits. Fully **Prescriptive Maintenance** is linked to this stage of Artificial Intelligence.
  A **Real-time Self-Optimisation of the production strategy** and scheduling, regarding the key specified database, is enabled within the system

limits defined by the algorithms. This is most likely placed at Factory or Company levels, at the Cloud, enabled by High-Performance Computing and 5G connectivity, which enables to process huge amounts of data and to transmit them in real time. This Information Flow and Processing is enabled by **connectedness beyond Factory/Company** (with real-time tracking in place at Logistics and Supply Chain).

The human beings are not needed at this stage, there is no need for any kind of interaction between the user and the equipment. In most industries, it is not yet considered feasible at the time of submission of this deliverable, so, it could be placed out of the scope of the QU4LITY Project.

4.3.3 Resulting diagram

The resulting diagram is the one of Table 2. As said, it is inspired on Roland Berger's Manufacturing Autonomy Levels (MAL) [Ref.5], but this model has been further tuned to fit the case particularities within QU4LITY.

The resulting diagram, by indicating the definitive Autonomy levels, understanding these as the combination between the degree of Automation and the Intelligence of the Control, is detailed in the next Table 3.

It is noticeable how some squares in both Table 2 and Table 3 have been marked in dark red – this is because they are not considered feasible in reality: for instance, just to pick the most extreme hypothetical cases, it is considered impossible to have all machines intercommunicated and the production centralized within the company ERP/MES while the operation still continues to be based on the operator using his/her own force to cut or give form to the part. At the same time, the same would apply to the opposite, a system where all material transport would be automatised by guided vehicles but without any significant support by the AI to analyse data or have a centralized information flow between machines or work stations.

The "As-Is" (before joining the QU4LITY Project) and "To-Be" (after QU4LITY) status of all the Pilots and Experimental machine cases from the QU4LITY project will be evaluated at the end of the WP4 activities against this same diagram.

This categorisation of AQ levels pretends to be, as well, a reference for the placement of the QU4LITY Assets into the Marketplace (activity corresponding to QU4LITY WP8). In this case, each one of the solutions for deployment in and enhancement of machines will be provided a range of levels they are able to operate within. However, and although the Marketplace will promote "groups of solutions" and not only individual components from the IoT Catalogue (configured as part of WP2), standalone solutions will probably not be enough to drive the relevant Pilot or use case to the desired (increased) level of Autonomy – that is why, most probably, a window will be provided for that: if it is a physical component installed at OT level, it could be complemented with one or several solutions for not only leveraging the degree of Automation of the use case at field level, but also augmenting the associated Intelligence of the Control platform, and vice versa.

Table 2 – Proposed categorisation of Autonomous Equipment (Second Iteration), the 'y' axis being the **degree of Automation** and the other 'x' axis being the **Intelligence of the Control platform**.

		degree of Control Intelligence					
		Lv.0 – Control by Human Intelligence	Lv.1 – Basic Human-Programmed Control	Lv.2 – Assisted Operation	Lv.3 – Shared Control with Machine Initiative	Lv.4 – Semi-Autonomous Collaborative Equipment	Lv.5 – Modular Autonomous Equipment
degree of AUTOMATION	Lv.0 – Manual Operation	Humans set Fixed operational values (machines without CNC) No M2M intercommunication Machine operation performed by worker Material Flow not automated	Intelligence programmed by Humans (PLC programmed rules) Machine operation performed by worker Material Flow not automated	Data monitoring and selection Off-line Simulation Assisted Maintenance Process control at SCADA level Machine operation performed by worker Material Flow not automated	Process and Product Digital Twin (Digital Traceability) Automatic Awareness of the environment by the equipment Performance Measurement First Off-line Analytical Models Plant Management by MES/ERP Machine operation performed by worker Material Flow not automated	Real-time Analytics and Learning phases Knowledge gathering, Decision-Making by the AI Information Processing Distributed Automated Predictive Maintenance Machine operation performed by worker Material Flow not automated	Auto-Organised, Adaptive Solutions Equipment is fully cooperative horizontal and vertically Connectedness beyond Factory/Company Self-Optimising of production strategies and schedules Prescriptive Maintenance Humans not needed Machine operation performed by worker Material Flow not automated
	Lv.1 – Part processing	Humans set Fixed operational values (machines without CNC) No M2M intercommunication Machine operation automated Material Flow not automated	Intelligence programmed by Humans (PLC programmed rules) Machine operation automated Material Flow not automated	Data monitoring and selection Off-line Simulation Assisted Maintenance Process control at SCADA level Machine operation automated Material Flow not automated	Process and Product Digital Twin (Digital Traceability) Automatic Awareness of the environment by the equipment Performance Measurement First Off-line Analytical Models Plant Management by MES/ERP Machine operation automated Material Flow not automated	Real-time Analytics and Learning phases Knowledge gathering, Decision-Making by the AI Information Processing Distributed Automated Predictive Maintenance Machine operation automated Material Flow not automated	Auto-Organised, Adaptive Solutions Equipment is fully cooperative horizontal and vertically Connectedness beyond Factory/Company Self-Optimising of production strategies and schedules Prescriptive Maintenance Humans not needed Machine operation automated Material Flow not automated
	Lv.2 – Adjustable Transport among fixed machines and lines	Humans set Fixed operational values (machines without CNC) No M2M intercommunication Machine operation automated Material Flow partially automated Fixed processes, Functional factory organisation	Intelligence programmed by Humans (PLC programmed rules) Machine operation automated Material Flow partially automated Fixed processes, Functional factory organisation	Data monitoring and selection Off-line Simulation Assisted Maintenance Process control at SCADA level Machine operation automated Material Flow partially automated Fixed processes, Functional factory organisation	Process and Product Digital Twin (Digital Traceability) Automatic Awareness of the environment by the equipment Performance Measurement First Off-line Analytical Models Plant Management by MES/ERP Machine operation automated Material Flow partially automated Fixed processes, Functional factory organisation	Real-time Analytics and Learning phases Knowledge gathering, Decision-Making by the AI Information Processing Distributed Automated Predictive Maintenance Machine operation automated Material Flow partially automated Fixed processes, Functional factory organisation	Auto-Organised, Adaptive Solutions Equipment is fully cooperative horizontal and vertically Connectedness beyond Factory/Company Self-Optimising of production strategies and schedules Prescriptive Maintenance Humans not needed Machine operation automated Material Flow partially automated Fixed processes, Functional factory organisation

	Lv.3 – Basic Flexibility in the handling of parts	Humans set Fixed operational values (machines without CNC) No M2M intercommunication Machine operation automated Material Flow centrally automated Flexible processes, Segmented factory organisation	Intelligence programmed by Humans (PLC programmed rules) Machine operation automated Material Flow centrally automated Flexible processes, Segmented factory organisation	Data monitoring and selection Off-line Simulation Assisted Maintenance Process control at SCADA level Machine operation automated Material Flow centrally automated Flexible processes, Segmented factory organisation	Process and Product Digital Twin (Digital Traceability) Automatic Awareness of the environment by the equipment Performance Measurement First Off-line Analytical Models Plant Management by MES/ERP Machine operation automated Material Flow centrally automated Flexible processes, Segmented factory organisation	Real-time Analytics and Learning phases Knowledge gathering, Decision-Making by the AI Information Processing Distributed Automated Predictive Maintenance Machine operation automated Material Flow centrally automated Flexible processes, Segmented factory organisation	Auto-Organised, Adaptive Solutions Equipment is fully cooperative horizontal and vertically Connectedness beyond Factory/Company Self-Optimising of production strategies and schedules Prescriptive Maintenance Humans not needed Machine operation automated Material Flow centrally automated Flexible processes, Segmented factory organisation
	Lv.4 – Aggregated Flexibility	Humans set Fixed operational values (machines without CNC) No M2M intercommunication Machine operation automated Material Flow hybridly automated Transformable processes, Connected factory organisation	Intelligence programmed by Humans (PLC programmed rules) Machine operation automated Material Flow hybridly automated Transformable processes, Connected factory organisation	Data monitoring and selection Off-line Simulation Assisted Maintenance Process control at SCADA level Machine operation automated Material Flow hybridly automated Transformable processes, Connected factory organisation	Process and Product Digital Twin (Digital Traceability) Automatic Awareness of the environment by the equipment Performance Measurement First Off-line Analytical Models Plant Management by MES/ERP Machine operation automated Material Flow hybridly automated Transformable processes, Connected factory organisation	Real-time Analytics and Learning phases Knowledge gathering, Decision-Making by the AI Information Processing Distributed Automated Predictive Maintenance Machine operation automated Material Flow hybridly automated Transformable processes, Connected factory organisation	Auto-Organised, Adaptive Solutions Equipment is fully cooperative horizontal and vertically Connectedness beyond Factory/Company Self-Optimising of production strategies and schedules Prescriptive Maintenance Humans not needed Machine operation automated Material Flow hybridly automated Transformable processes, Connected factory organisation
	Lv.5 – Agile Material and Information flows	Humans set Fixed operational values (machines without CNC) No M2M intercommunication Machine operation automated Material Flow distributed automated Versatile processes, Network-based competence organisation	Intelligence programmed by Humans (PLC programmed rules) Machine operation automated Material Flow distributed automated Versatile processes, Network-based competence organisation	Data monitoring and selection Off-line Simulation Assisted Maintenance Process control at SCADA level Machine operation automated Material Flow distributed automated Versatile processes, Network-based competence organisation	Process and Product Digital Twin (Digital Traceability) Automatic Awareness of the environment by the equipment Performance Measurement First Off-line Analytical Models Plant Management by MES/ERP Machine operation automated Material Flow distributed automated Versatile processes, Network-based competence organisation	Real-time Analytics and Learning phases Knowledge gathering, Decision-Making by the AI Information Processing Distributed Automated Predictive Maintenance Machine operation automated Material Flow distributed automated Versatile processes, Network-based competence organisation	Auto-Organised, Adaptive Solutions Equipment is fully cooperative horizontal and vertically Connectedness beyond Factory/Company Self-Optimising of production strategies and schedules Prescriptive Maintenance Humans not needed Machine operation automated Material Flow distributed automated Versatile processes, Network-based competence organisation

Table 3 – Categorisation of Autonomous Quality Equipment, by Levels from 0 to 5, taking into account logical combinations of Automation and Control Intelligence capabilities.

		degree of Control Intelligence					
		Lv.0 - Control by Human Intelligence	Lv.1 - Basic Human-Programmed Control	Lv.2 - Assisted Operation	Lv.3 - Shared Control with Machine Initiative	Lv.4 - Semi-Autonomous Collaborative Equipment	Lv.5 - Modular Autonomous Equipment
degree of AUTOMATION	Lv.0 - Manual Operation	0	0				
	Lv.1 - Part processing	0	1	1	2		
	Lv.2 - Adjustable Transport among fixed machines/lines		1	2	2	3	
	Lv.3 - Basic Flexibility in the handling of parts		2	2	3	3	4
	Lv.4 - Aggregated Flexibility			3	3	4	4
	Lv.5 - Agile Material Flow in an Adaptive Layout				4	4	5

5. Update of the Distributed Communication & Control framework described in the first version of D4.2

Herein, the modifications are detailed for the input which was provided from the section 3.3 to section 8 of the previous version (D4.3) of this deliverable. As said, some Pilots underwent through some changes in the configuration of their use case and infrastructure in which it is based, and some Experimental cases were defined since the submission of D4.3.

These changes are described below, following the same order as in the previous version, as already specified in Section 3.1 – General Approach, of this document.

Real-time cognitive hot stamping furnace 4.0

From the submission of the previous deliverable (D4.3) to the publication of the current one, changes have arisen in the final scenario for the Real-time cognitive hot stamping furnace 4.0 pilot. For that reason, in this second version, the distributed Communication and Control functionalities of ZDM equipment enhancements are going to be described again – considering this updated scenario that has been just mentioned.

Synchronisation of distributed communication of an AGV fleet

The ASTI&NXT use case was already described as part of the QU4LITY deliverable D5.5: "Tools and Techniques for Adaptive Shopfloor Automation and ZDM Processes (Version 1)".

During the implementation phase of the use case there have been some changes made, that differ from the description provided in the previously mentioned deliverable. These changes are going to be remarked and properly explained across this one and the following subsections.

Describing the use case in general terms, Automatic Guided Vehicles (AGV) are unmanned transport vehicles widely used in the industry to substitute manned industrial trucks and conveyors. They have been proved an efficient element in factory workspaces, helping to reduce logistic errors and operative costs.

Currently, the AGVs, when arriving to an intersection, stop and request the crossing priority to a traffic box by radio-frequency (RF). This traffic box writes down the request, and in case of the intersection is free (that is any AGV requested the pass before), sends a signal to allow the AGV to cross. When the AGV crosses the intersection notifies this fact to the traffic box to unlock the intersection. This way blocking situations and other incidents are avoided. This "As-Is" scenario, prior to QU4LITY, is shown in the next Figure 14. The green points represent the locations where the AGV locks and unlocks the intersection.

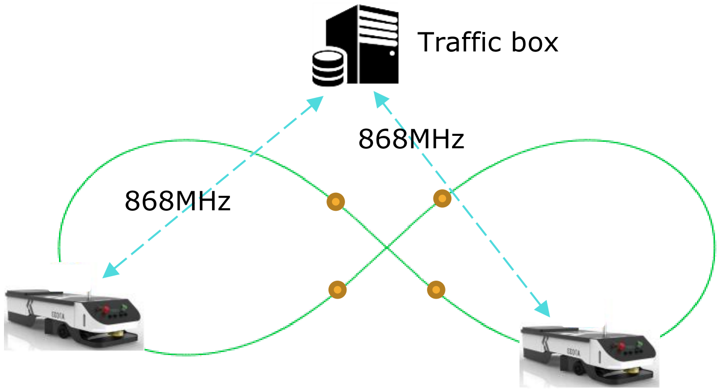

Figure 14 – Previous scenario in intersections of AGVs.

The target of this ASTI&NXT joint use case is to remove the traffic boxes and replace this functionality by the distributed control offered by IEC61499. The new scenario enabled by the protocol is shown in the next Figure 15.

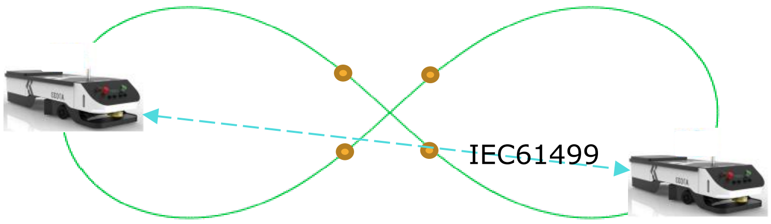

Figure 15 – "To-Be" scenario in intersections of AGVs.

A circuit consisting in a magnetic tape cross with 8 different tags placed will be prepared for the tests, as the following diagram in Figure 16 indicates.

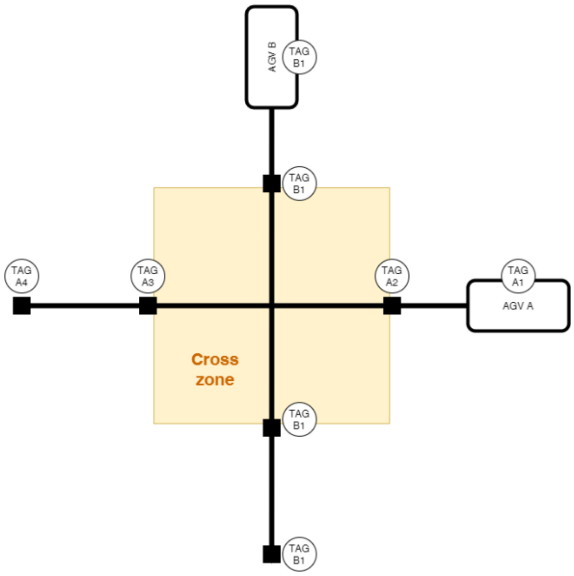

Figure 16 – Circuit and tags for the tests for the AGV C&C enhancement validation.

As shown in Figure 17 below these lines, the AGV called A, will start its movement towards the cross centre from tag A1, it will ask for permission to the traffic manager when arrived at tag A2. As the zone is free to cross, the traffic manager will allow AGV A to move towards tag A3. On the other hand, it will not allow AGV B to go inside the cross zone. By continuing the movement, it will reach tag A4, where, in order to go back to tag A1, it will need to ask the traffic manager again for permission.

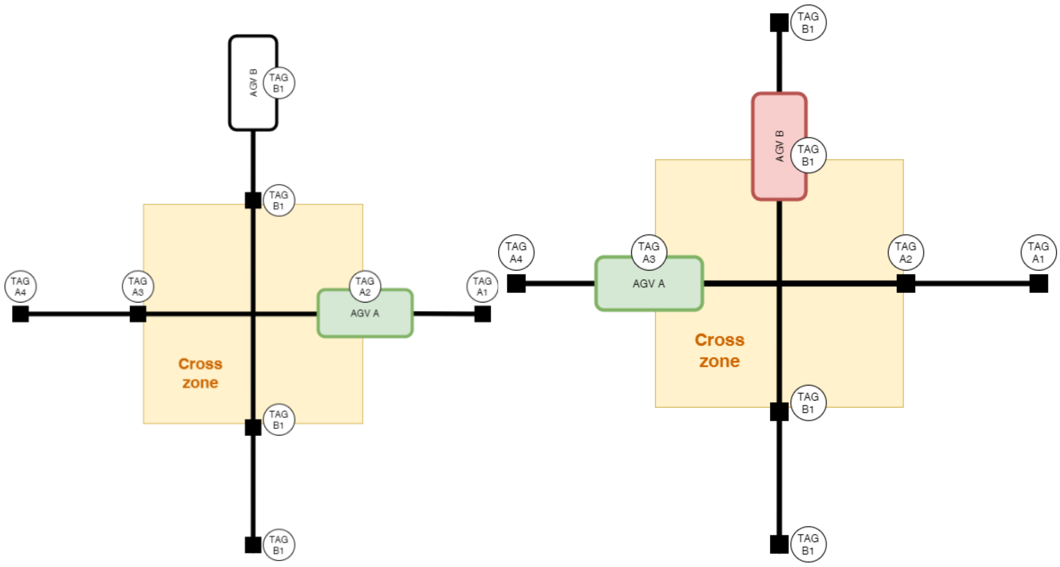

Figure 17 – AGVs use case movement and operation.

Regarding the changes mentioned before, with respect to what was introduced in D5.5, the first one made was in choosing a new HW platform on which the IEC 61499 runtime will run. Instead of the Linux-based PC planned at the beginning, a Raspberry

Pi will host the runtime. For this purpose, the IEC 61499 runtime was ported to this platform.

Another change made during the implementation phase is, that instead of the previously planned communication via Websocket now the IEC 61499 runtime will communicate with the legacy PLC on the AGV by using a TCP server, which is executed on the Raspberry Pi decentralised FB application and communicating with the phyton script of the CANBus from the legacy PLC with IEC 61131.

Recently, ARC Advisory Group has stated that General Electric's IEC 61499 Integrated Development Environment (IDE), which is used to design, deploy and manage industrial control systems, could contribute decisively in the future to achieve effective IT/OT convergence and consequently to reduce unplanned downtime, which ARC believes now costs industry about $100 billion annually.[11]

TSN and Time Synchronisation for ZDM

With the emerging of Industry 4.0 and its concepts of quality, e.g., Zero-Defect Manufacturing (ZDM) and Autonomous Quality (AQ), the future industrial networks have to satisfy the stringent requirement of time-sensitive communications. The communication systems such as shopfloor network must support reliable communications with low delay and jitter for the industrial applications and equipment. These communications allow remedying the potential problems, optimise the manufacturing, and minimise the defects on-line. For instance, critical applications such as motion control and automation process require guaranteed times for their commands. The commands must be delivered to end systems within bounded time, as will be discussed in the following subsections of this document.

5.1 Machine application cases System Architecture

AM Pilot Adaptive Control Technology

The main change at the PRIMA Additive Manufacturing Pilot consists of the incorporation of Engineering as partner in the use case. Engineering will take care of blockchain solutions for secure updates sharing, as portrayed in Figure 18.

[11] Information on a Report by ARC Advisory Group, called *The Road to Universal Automation*, analysing Schneider Electric's EcoStruxure™ Automation Expert, based on the principles of universal automation and the IEC 61499 standard: https://www.arcweb.com/industry-best-practices/road-universal-automation-0

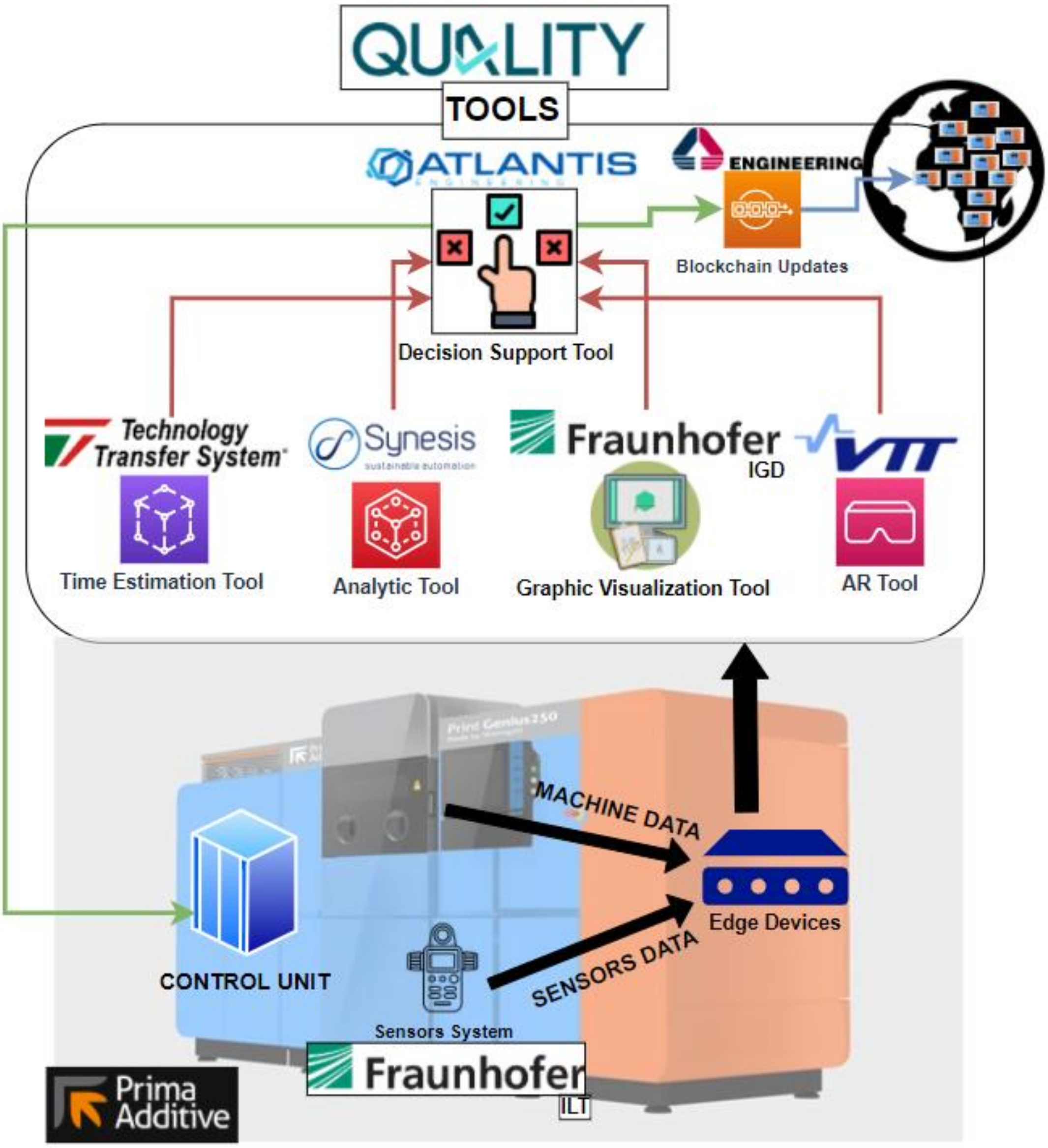

Figure 18 – PRIMA Pilot "To-Be" scenario.

The adding of the Blockchain technology is included here in this Section, but is very much more linked to Section 5.6 – Security.

Further detail about Blockchain deployment and testings as part of the PRIMA experiment will be provided in the deliverables due from the submission of the present document to the end of the QU4LITY Project, namely, D4.6, D4.8 and D4.10.

Digital Twin for Zero-Defect machines and Automated lines

The new architecture for the GF pilot is the following, presented in Figure 19. In addition to the technology provider participants that were presented in the previous version of this deliverable, we can add the participation of Unimetrik in the in-line measurement at the milling machine tool, at GF's **Connected, intelligent Automated Aerospace component Manufacturing Line Business Scenario**.

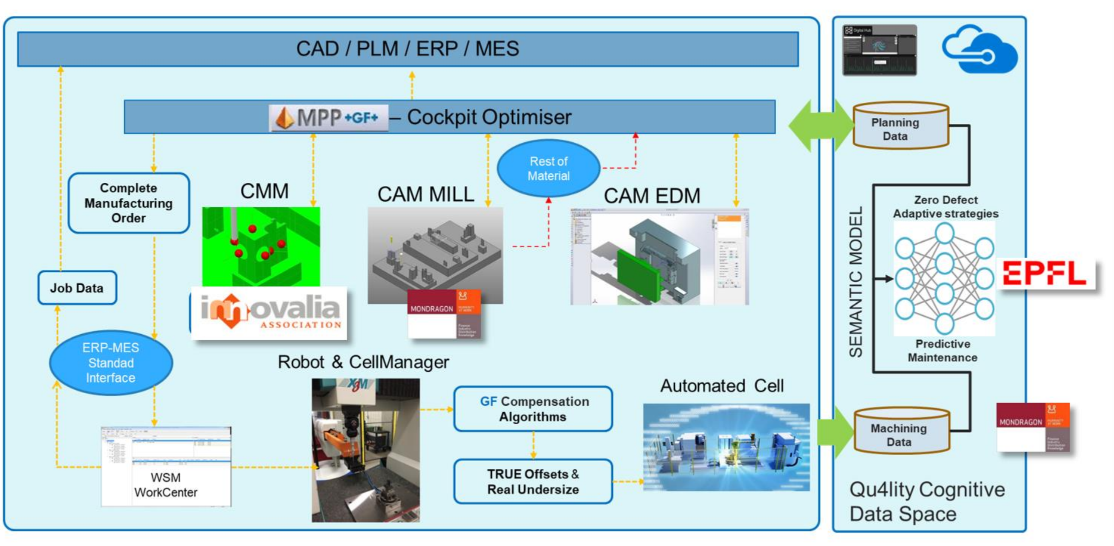

Figure 19 – Architecture of the "To-Be" +GF+ Pilot.

The functional characteristics for Unimetrik's M3MH software were extensively presented at the first version of this deliverable, as this is a solution that has also been deployed at the AIC Experimental Facility as part of WP6 activities.

To sum up what was previously described in D4.3 as **"Metrological capabilities for machine tool"**, the functionalities of the software lie mainly on the capacity, by the software component, of communicating with the CNC controller. This is done in order to be able to introduce inspection routines in plans or programs that can be executed in machine tools, via a series of conversion instructions between DMIS code (Dimensional Metrology Interface Specification), typical of coordinate measurement measuring machines, and The CNC communication protocol used by the Machining Center with which communication is established.

The benefits are a clear advance towards the ZDM and AQ paradigms: all parts of a batch are measured, without the necessity of taking off the part from the machine and transporting it to a laboratory – thus, the errors of using different fixing tools are also eliminated. In addition, in high-added value parts, thanks to the deployment of M3MH, the machine tool is able to perform a dimensional measurement in the middle of a manufacturing cycle, something enabled by a fast change of the tool and its replacement by a touching probe. This way, an irreparable defect is detected much faster (as portrayed in Figure 20) and we avoid keeping providing added value to such a part.

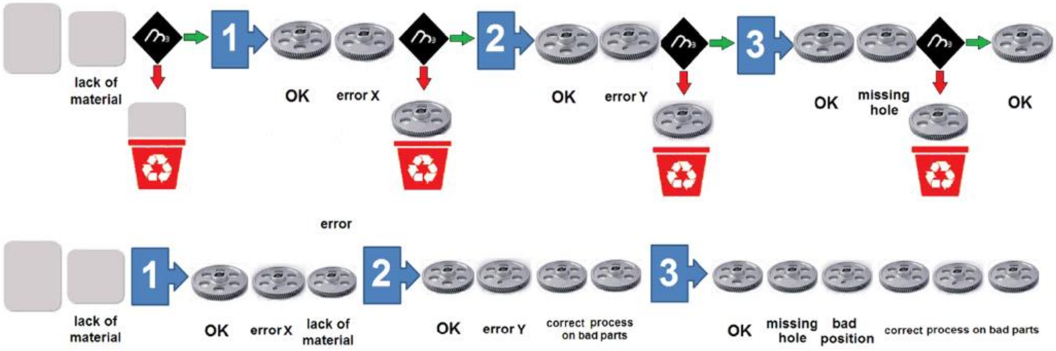

Figure 20 – M3MH Control Loop Scenario.

As with the PRIMA case, and all the rest of machine digital upgrades, and although the C&C framework was included in D4.3, the details for the final implementation and assessement of the benefits and WP-specific KPIs at GF will be documented in D4.6 and D4.8, respectively, due at the end of the activities of this Work Package.

Real-time cognitive hot stamping furnace 4.0

GHI has recently started to develop Big Data solutions for their industrial furnaces, in order to provide industrial furnaces with a high added value in terms of services that are linked to the information that can be gained through the "smart furnace", offered to the customer, where, on operation, can for example, support decision-making on production or reduce energy consumption. For this, GHI proposes a common data gathering system architecture applicable transversally for every kind of industrial furnace they design and assemble:

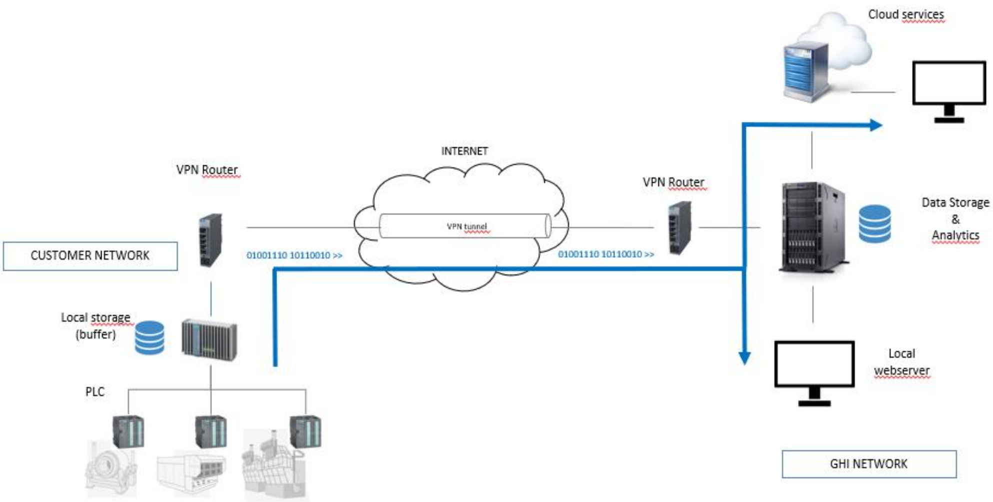

Figure 21 – GHI data gathering common Architecture.

In the scheme of Figure 21, the data gathering and data transferring Hardware architecture that GHI has built can be observed, something that the company intends to apply to all customers where this furnace smartisation solution is to be implemented, followed then by a data analysis and visualisation tool.

However, the solution implemented in this use case, is more complex, involving other production steps, expanding the furnace control loop to a further stage, integrating quality control data that allows a better improvement of the furnace operation – thus, to design a Zero-Defect Manufacturing strategy in order to reduce the manufacturing of defective parts on the hot stamping process.

That is to say, that the global scenario for the pilot also involves the presence of Innovalia and SQS, that are in charge of integrating these quality control data into the Beyond platform, making use of a secure industrial data sharing system based on the IDSA Reference Architecture. Taking this into account, the final scenario will be more likely to the diagram of Figure 22 below:

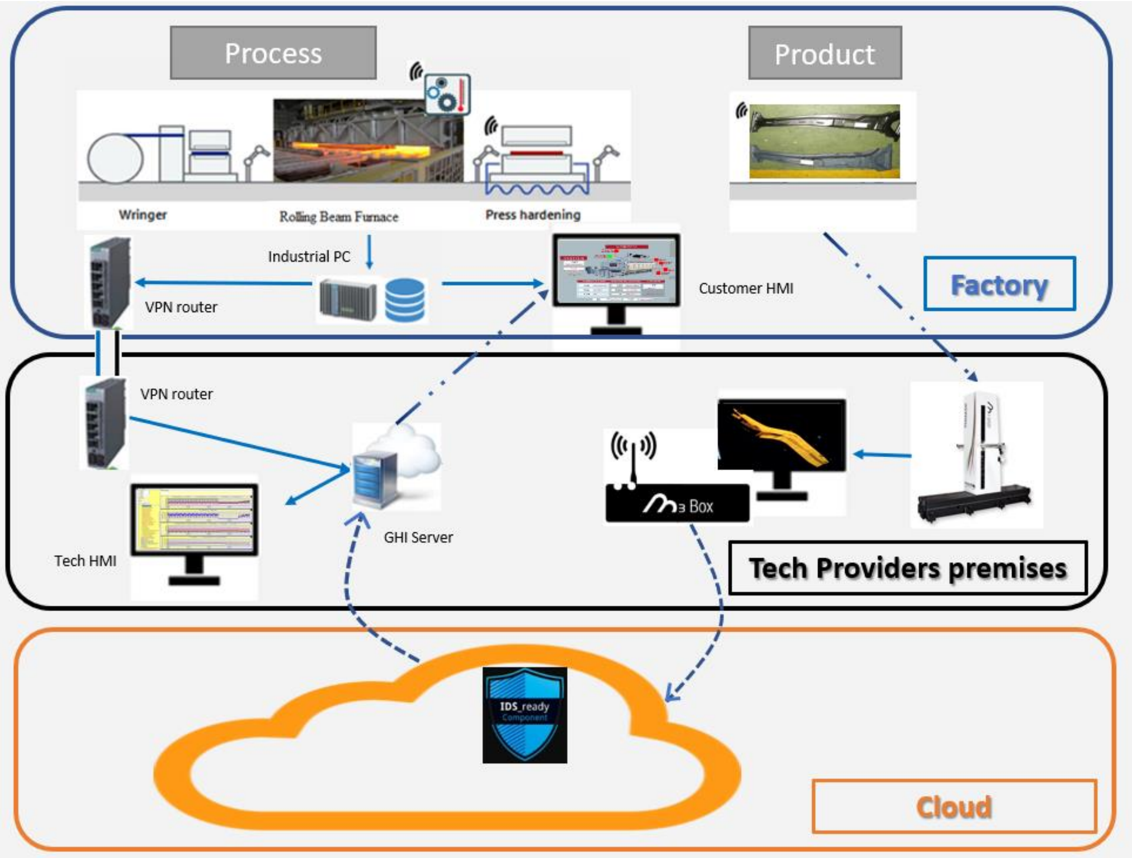

Figure 22 – Real-time cognitive hot stamping furnace 4.0 pilot architecture.

Further details regarding the multiple components that build-up this pilot will be mentioned on the following points, at least regarding to the Communication and Control infrastructure aspects of the pilot.

Synchronisation of distributed communication of an AGV fleet

The IEC61499 **Runtime Environment** (RE) is located on an appropriate device or an AGV in this use case, and responsible for the execution of the control and automation logic or a specific algorithm for data analysis and predictions to facilitate rapid actuation and correction of defects (or their root causes), once defects are detected.

The IEC61499 application and the engineering is completely hardware independent. The IEC61499 runtime itself is simple portable to different environments: from small to large hardware devices, and different operating systems, and edge nodes.

The hardware-specific parts of the IEC61499 runtime are encapsulated in the Operating System Abstraction Layer (OSAL) into the following parts:

Network and communication, Memory, Scheduling, HW I/O, Exception handling.

Different specific hardware services for IEC61499 are encapsulated in Service Interface Function Blocks (SIFBs), which are mostly accessible over IEC61499 Libraries, to have a hardware-independent IEC61499 application.

One if this SIFB's, a TCP Server, is used for the communication with the legacy PLC on the AGV and integrated in the overall decentralised application approach to interact as a Software CPSizer.

The following Figure 23 shows the architecture of the IEC614499 runtime, which was ported to the Raspberry Pi device, which is a LINUX derivate, where an OSAL-component already exists:

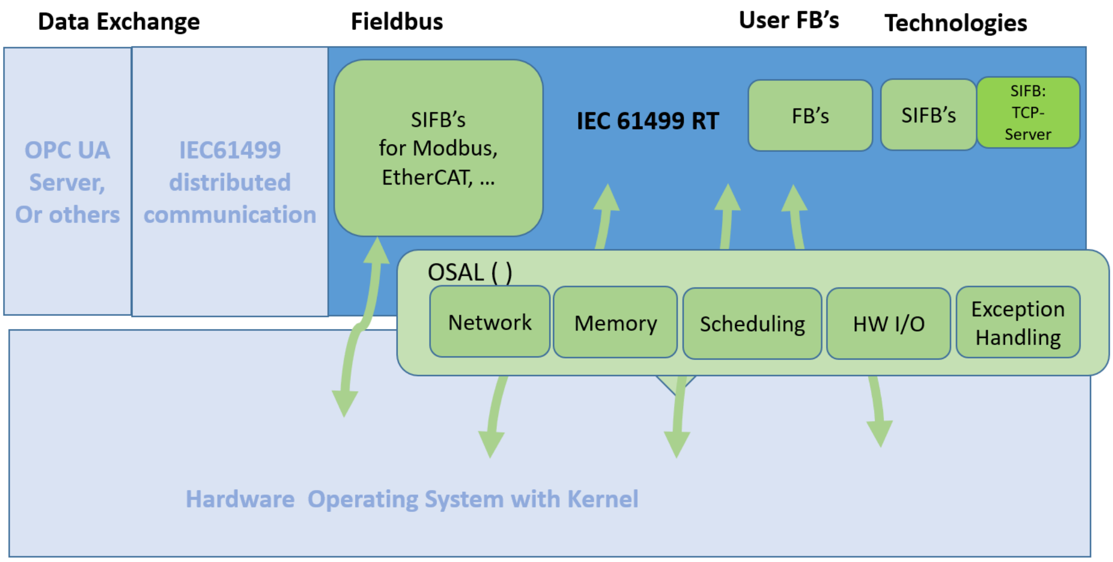

Figure 23 – IEC61499 runtime architecture.

TSN and Time Synchronisation for ZDM

As already explained in the D4.3 document, in particular at its section 3.2, IEEE Ethernet Time Sensitive Networking (TSN) is a set of standards that extend Ethernet to support real-time communications. These standards are expected to fulfill different requirements in future industrial networks. Four important sub-domains in TSN are time synchronisation (i.e., IEEE 802.1AS), guaranteed latency (e.g., IEEE 802.1Qbv), reliability (e.g., IEEE 802.1CB) and resource management (e.g., IEEE 802.1Qcc)[12,13] (Figure 24). In the mentioned figure, 802.1AS allows the talker and listener synchronize their clocks, 802.1Qbv and 802.1CM allow the TSN switches perform scheduling, and 802.1Qcc allows all the devices configure their parameters.

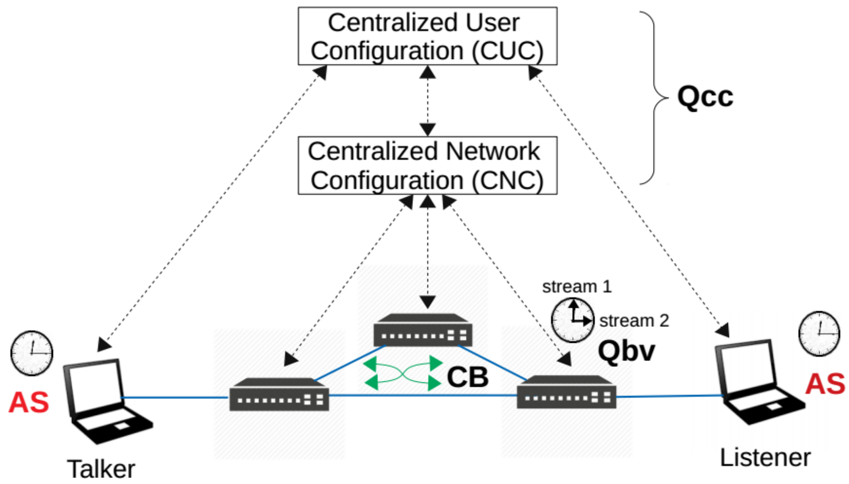

Figure 24 – Four important sub-domains of TSN.

5.2 Connectivity and Configuration

Real-time cognitive hot stamping furnace 4.0

Regarding the connectivity and configuration of the whole pilot, this will be described in two separated parts. On one side, for the data acquisition system for GHI, and, on the other side, the quality control process scenario at Innovalia's lab.

Firstly, we will start with the GHI data gathering system.

The operation parameters that will be measured on the Furnace4.0 are gathered through IoT sensors and transmitters that will be connected with PLC's analogical/digital inputs. This means that this PLC has several digital and analog

[12] M. Gutiérrez, A. Ademaj, W. Steiner, R. Dobrin and S. Punnekkat, "Self-configuration of IEEE 802.1 TSN networks," *2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Limassol, 2017, pp. 1-8, doi: 10.1109/ETFA.2017.8247597.

[13] T. Striffler, N. Michailow and M. Bahr, "Time-Sensitive Networking in 5th Generation Cellular Networks - Current State and Open Topics," *2019 IEEE 2nd 5G World Forum (5GWF)*, Dresden, Germany, 2019, pp. 547-552, doi: 10.1109/5GWF.2019.8911720.

input/output cards through which process readings (temperatures, flow rates, etc.) are carried out and the actuator control elements of the furnace (valves, relays, inverters, etc.) are operated.

The data gathering system directly attacks the value of the input variable, output variable or the intermediate variable of the PLC that most closely matches the engineering reading. That is to say, that for the analog values captured, the data gathering system itself makes a transformation of this analog value, so that it fits with the engineering one. For this purpose, an analysis of the furnace and the data gathering system is carried out, deciding the variables to be captured.

The data gathering system is optimised from the PLC so that all data can be consulted in a single, per acquisition cycle, in this case, 1 second. All variables are grouped within the same database (DB), which, in turn, is subdivided into two DBs, one for analog variables and one for digital variables.

The PLC is connected via Ethernet with the Industrial PC, where the data connection, capture and storage software is hosted. Standard libraries are used for the connection to the PLC and the frequency, start pointer and length of the data frame to be acquired are programmed, as well as the database where that frame will be stored.

The capture database is structured with a single table of four columns, containing the timestamp, analog frame, digital frame and synchronisation indicator. The selected database is Microsoft SQL.

A synchronisation of databases is also programmed, because the Industrial PC acts as a buffer and temporary repository of them against loss of connection with the server. The information is synchronised in real time with the server through the VPN connection established with the server.

The applicability scenario of the data ingestion system requires the remote connection of the data capture equipment with the GHI server hosted on GHI facilities. This connection is only possible through the Internet and communications networks of potential customers who want to integrate this solution. To generate an "internal cloud" of capture equipment with the server, a VPN tunnel concentrator solution is chosen.

The connection equipment architecture requires a VPN concentrator connected to the data server that listens. Each of the client routers establish the connection through the Internet, going to the public IP where the server is hosted.

All data collected by the remote PCs connected to the PLCs is hosted on the GHI server. Synchronisation is done through client computers, and a database is generated per integrated device. All information is collected in SQL databases.

There is a double communications interface, so that data acquisition services are carried out through one of the interfaces, while the raw data query, etc. is carried out through the other interface.

Once all this data flow is explained, the system connectivity requirements will be summarised next in the following Table 4:

Table 4 – Requirements for System Connectivity, for the case of the Real-time cognitive hot stamping furnace 4.0.

Platform	Requirements
Machine1_MainPLC	IPv4 Connectivity Connectivity required with Machine2, Platform1 OPC-UA protocol Profinet protocol for communications with Machine2
Machine2_AnalysisPLC	IPv4 Connectivity Connectivity required with Machine1, Platform1, Machine3 OPC-UA protocol Profinet protocol for communications with Machine1
Machine3_IndustrialPC	IPv4 connectivity Connectivity required with Machine2 Connectivity required with Platform1,2 OPC-UA protocol required VPN Tunnels for data transmission
Platform1_DataAdquisition	IPv4 connectivity Connectivity required with Machines1,2,3 Connectivity required with Platform2 OPC-UA protocol for data acquisition VPN Tunnels and MQTT system for data transmission
Platform2_DataStorage	IPv4 connectivity Connectivity required with Platform1,3 Backup systems, redundant system required VPN Tunnels and MQTT system for data transmission

Platform3_DataAnalysis	IPv4 connectivity Connectivity required with Platform2 Connectivity required with Platform1 R and Python required for analytics VPN Tunnels and MQTT system for data transmission

As a brief summary, it can be seen that, between all the hardware elements that compounds the data acquisition system, an IPv4 connectivity is the only requirement that will be provided through Ethernet cable, complying with OPC-UA standard and Profinet protocols. This scenario is represented on the following diagram in Figure 25:

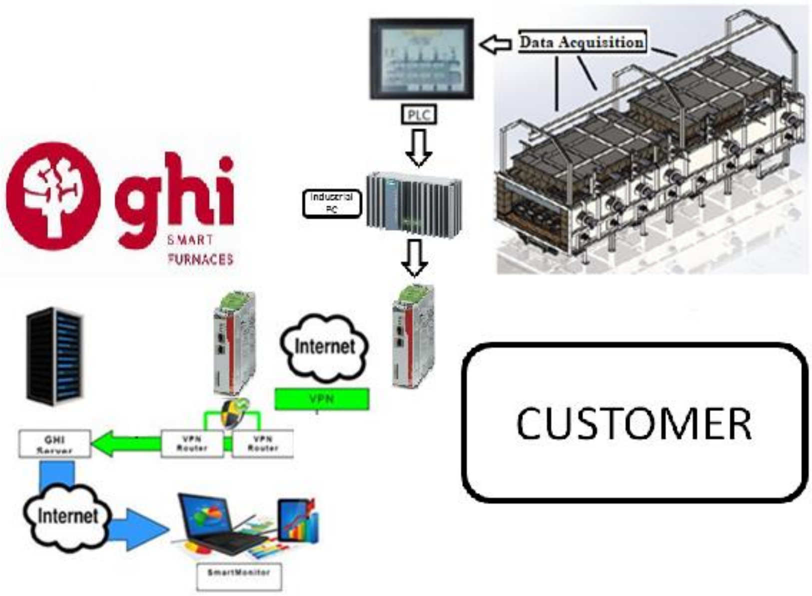

Figure 25 – Smart furnace data gathering connectivity Architecture.

On the other side, we have the quality control process scenario carried out at Innovalia's lab.

With the aim of developing applied and connected metrology solutions inline, Innovalia is developing components which allow them to improve its ability to capture and distribute metrological information that enables a better adaption and integration into the manufacturing line.

With this perspective, the quality control system starts from the proper Coordinate measuring machine (CMM), from which its controller is connected through an Ethernet cable to the Edge-powered quality control system that allows:

- The Storage and Management of the data gathered through the 3D Scanner and/or Touching probes, but also from other sensors installed for the machine condition monitoring.
- The provision of local processing capabilities in isolated domains.
- The obtention of Remote access and centralised control, being capable to control the operation of the CMM itself.
- The development of a Multi-service gateway via virtualisation, for which M3 applications have been installed, in order to be able to have this centralised control.

This Edge-powered quality control system supports Fieldbus connectivity, and also integrates a Time Sensitive Networking (TSN) switch for open, standard deterministic Ethernet communication, permitting the access to the enterprise bus and M3 cloud services. This device is then connected to the computer/laptop where M3 Software for the GD&T parts digitisation analysis is running.

The information and knowledge obtained after this GD&T analysis will then be transmitted back again to the Edge-powered quality control system where the communications among the different modules will win in flexibility and latency. It enables data to be used in three ways: at the edge, on the local enterprise server or remotely in the M3 Server located on the cloud. This gives users the flexibility to choose where and when data is stored, visualised and processed.

Moreover, this edge powered device (M3DGE) also acts (as it contains it), at the same time, as an IDS connector, through which we will carry out the trusted transmission of quality information that GHI will integrate into its BEYOND platform. This IDS connector will be FIWARE-based in the term that the data sharing will be done through the Orion Context Broker via a publisher/subscriber MQTT messaging protocol. This scenario is represented on the following diagram in Figure 26:

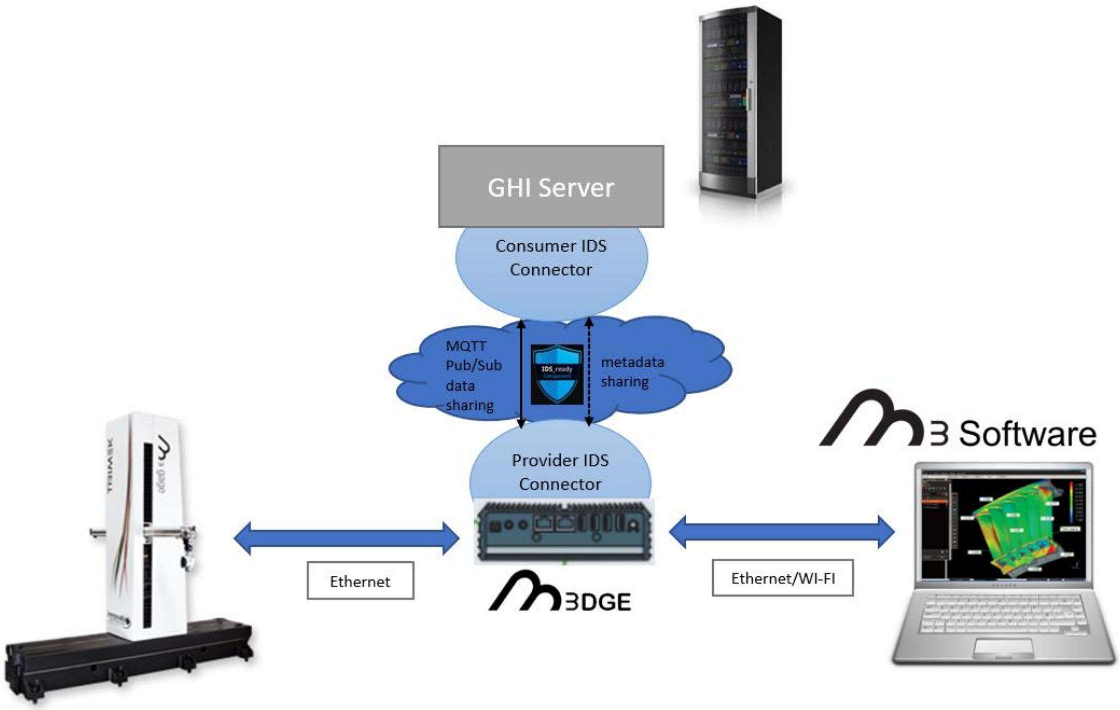

Figure 26 – Quality control system architecture for data sharing with GHI.

Synchronisation of distributed communication of an AGV fleet

For the use case described previously described at Section 5.1 – Machine application cases System Architecture, two types of an IEC 61499 application were developed by using the NxTTechIDE IEC 61499 engineering tool:

- IEC 61499 application with a centralised architecture approach, and
- IEC 61499 application with a decentralised architecture approach

During the implementation of the first use case from ASTI, the decentralised architecture approach was used.

AGV IEC 61499 centralised architecture approach

For controlling a system of AGVs, two main types of function blocks (FBs) are developed, which play a main role in the IEC 61499 application:

- A Function Block (FB), which is used for controlling of an AGV unit
- A Function Block (FB), which represents the AGV Supervisor logic

With the centralised architectural approach, all AGVs participating in an IEC 61499 network are interfacing with an AGV Supervisor. The logic of the Supervisor is deployed to an independent device, separated from the AGV units within the IEC 61499 system and is communicating via the NXT cross-communication protocol (Figure 27).

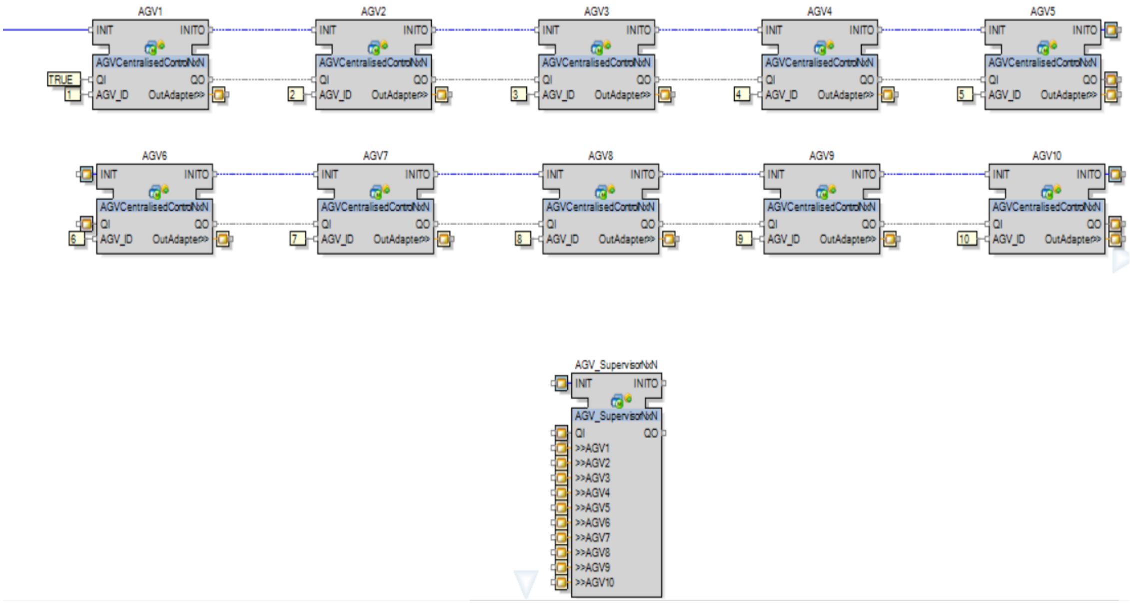

Figure 27 – AGV Centralised approach: NxN connection.

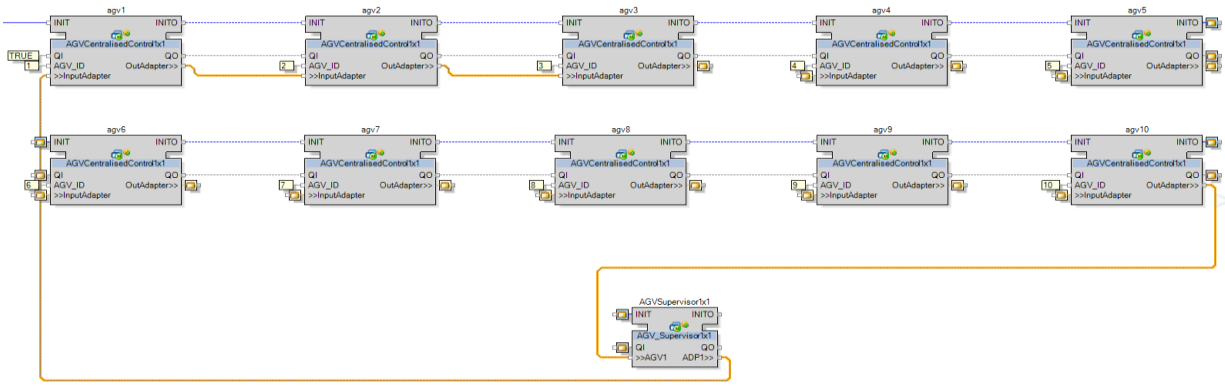

Figure 28 – AGV Centralised approach: ring connection.

Information relevant for the AGV communication (e.g. availability of some area) is stored inside of an AGV Supervisor FB, which plays a central logical and deciding role for a whole system. For instance, taking as an example a use case where an AGV wants to cross a section in a field: First the AGV needs to send a request to ask the AGV Supervisor if that section is not currently used by another AGV in the field. Then based on the response it gets from the AGV Supervisor it can perform certain actions.

Regarding the connectivity between AGVs and the AGV Supervisor, two types of connections are made:

- Each AGV is directly connected to the AGV Supervisor (Figure 27)

- Each AGV is connected to the next AGV in the system (its neighbour), up to the AGV Supervisor, which is again connected to the first AGV, forming one circular connection ring (Figure 28).

For the second approach, if one AGV wants to send a request towards the AGV Supervisor, a message will be transported through all AGVs, which are connected between those two entities. Each AGV will simply reroute the received message to the next point. In this case only one entry point is necessary, which is used to receive messages from all AGVs in the system. In contrast, in the first approach the AGV Supervisor FB needs to have an entry point for each AGV in the system.

The ring connection approach also has a weak point. In case that one or more AGVs are offline (defect mode), the connection will be broken, and the information will not be transmitted. For the first approach, where each AGV is directly connected to the AGV Supervisor, this situation would not cause any problems.

AGV IEC 61499 decentralised application approach

With a decentralised approach strategy, the logic which is implemented within the AGV Supervisor is migrated to the AGV FB unit. The result of this is that each AGV is working as an independent logic unit. Basically, each AGV unit has all system information stored in its device, providing it with a complete overview of the required information, which should be synchronised with all AGVs in the IEC 61499 network (**mark**: Information which is relevant for the system of AGVs in a field, e.g. Section occupancy, availability…). In case that one of the AGVs wants to occupy an area, it is mandatory to notify all the other AGVs in the field, about its forthcoming actions. Updating all other AGVs in the field is being done in the following steps:

- Acquire a writing permission from all AGVs in a field (After a permission is acquired, only one AGV can perform a writing operation)
- Update all AGVs in the system with the information relevant to a current action
- Release writing permission (unlock writing command for other AGVs)

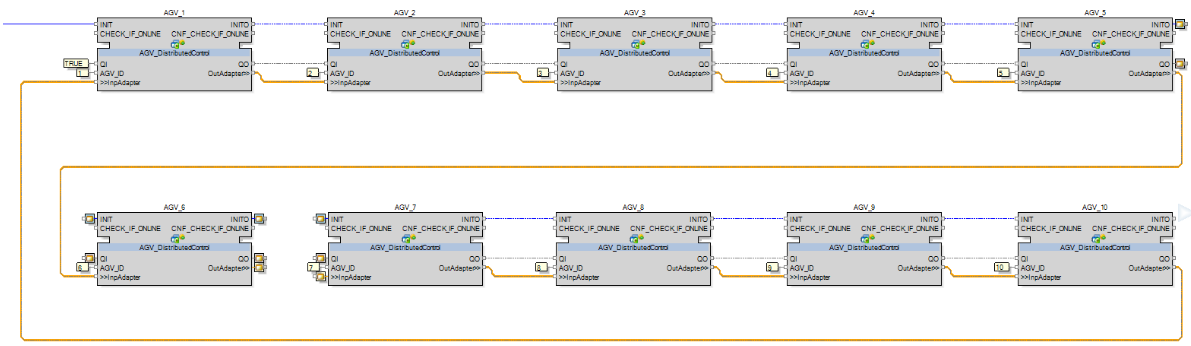

Figure 29 – Decentralised approach: Ring connection.

Figure 30 – Decentralised approach: NxN connection.

Regarding the connectivity between AGVs, two different types of connections are implemented:

- All AGVs are connected in one circular ring connection (Figure 29)
- Each AGV in the system is connected to the other AGVs (Figure 30)

As mentioned in the centralised approach, one advantage of the ring connection is the simplicity of the FB implementation, as in this case each AGV FB needs to have only one entry point (which is exposed as a generic input) to communicate with all other AGVs. In contrast, in the second approach each AGV needs to have as many entry points as the number of AGVs in the system.

One weak point of the first approach is that in this case one AGV system is offline, and the connection between the AGVs could be broken, which causes a system malfunction. This problem is fixed with the second approach, where each AGV is connected to all other AGVs in the system. This means that when one AGV is not operable, the application will automatically evade it and reroute a message to the next available AGV. For this purpose, an additional FB is added next to the AGV FB (Figure 31), which has the task to ping each AGV in the system before a message is routed to that AGV unit. In the case when one of the AGVs is not available, this FB will wait for some amount of time and after that it will check the next available AGV in the system.

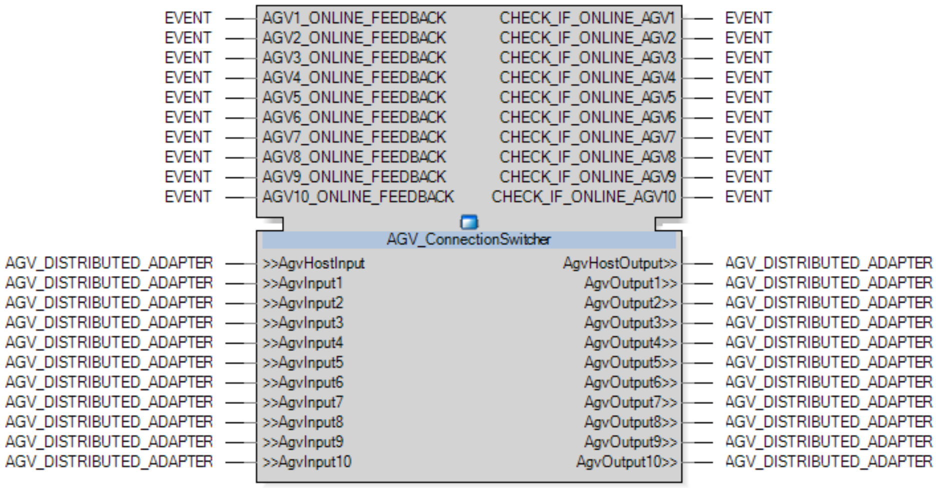

Figure 31 – AGV Distributed Architecture Connection switcher.

Figure 32 and Figure 33 present, in a nutshell, the overview of the composite AGV FB for a decentralised and centralised architecture, respectively.

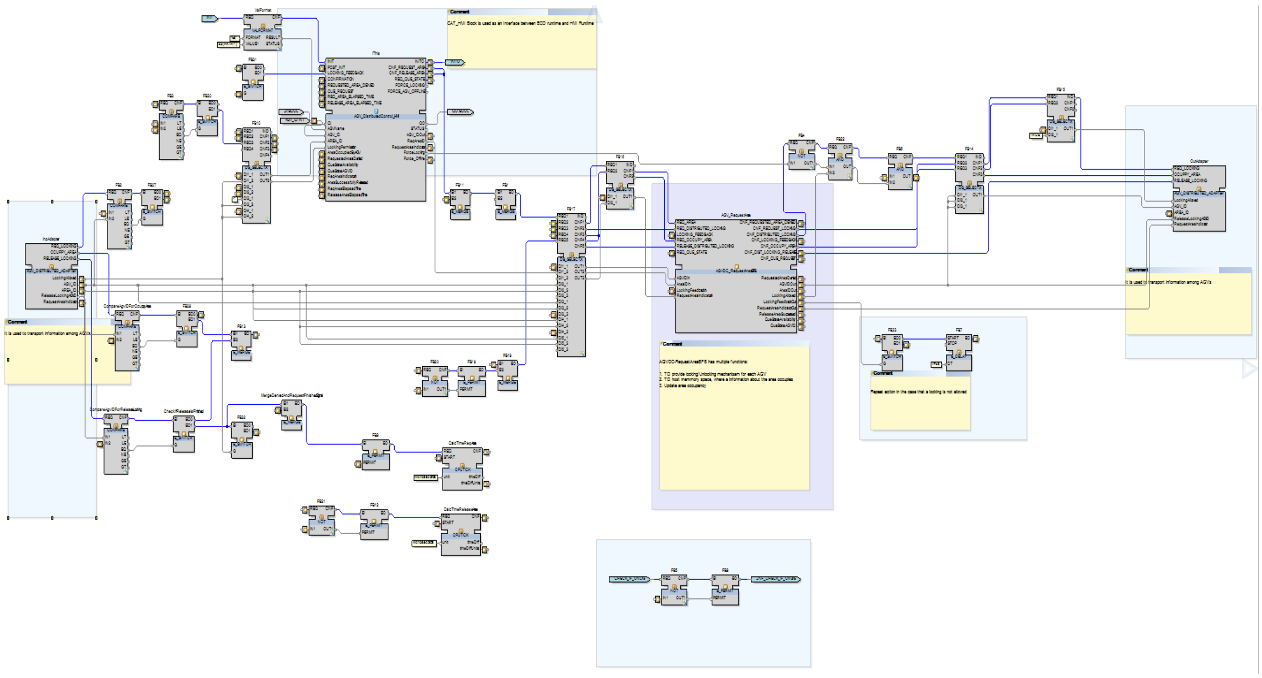

Figure 32 – AGV_Decentralised FB- Composite view.

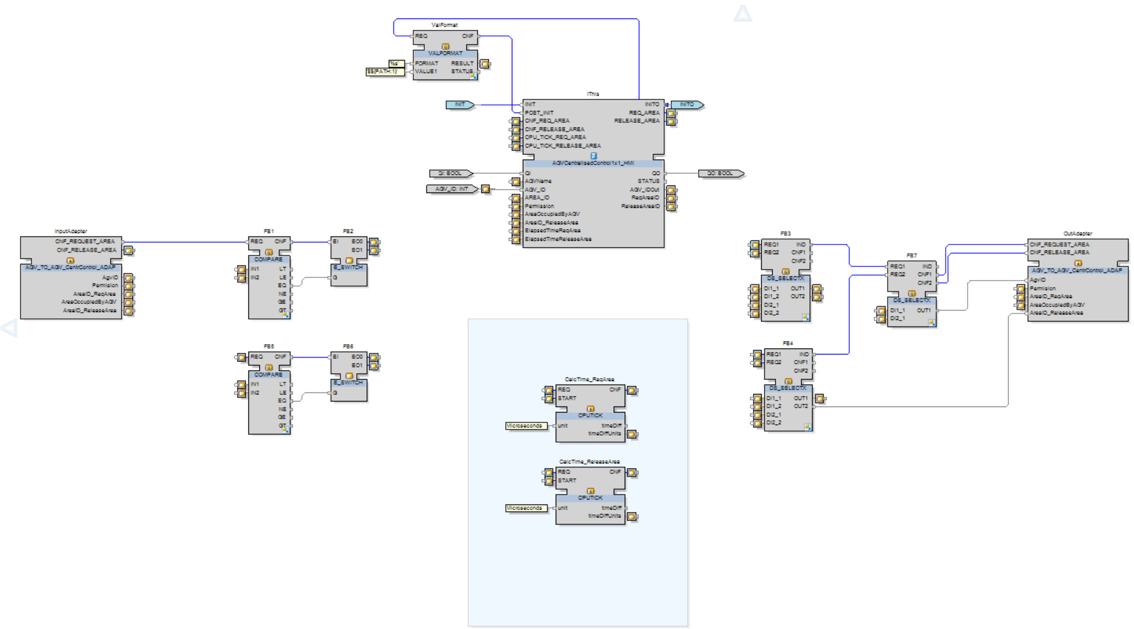

Figure 33 – AGV_Centralised FB Composite view.

TSN and Time Synchronisation for ZDM

The real-time communications among the devices such as robots and sensors involve in transmitting, routing and scheduling the data in timely manner. To this end, the devices have to first synchronize their clock/time. Figure 34 illustrates an example in which the clocks of sensors, robot, vision machine and TSN switches are synchronised to each other. As a key standard in TSN, IEEE 802.1AS (hereafter referred to as simply AS) allows network devices to synchronize their clocks with high precision. Therefore, IEEE 802.1AS is expected to have an important role in the future industrial networks, especially to support Zero-Defect Manufacturing and Autonomous Quality.

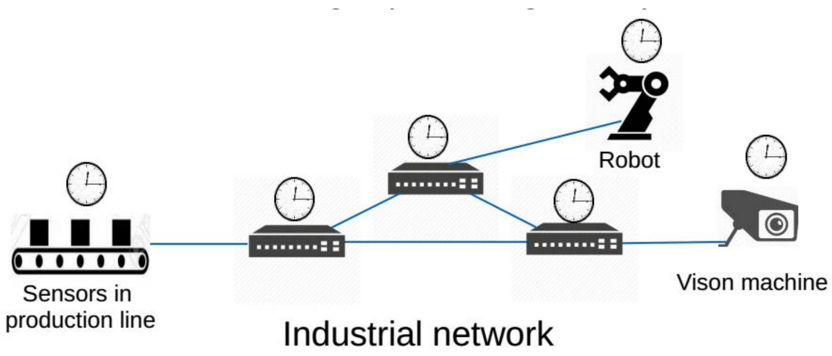

Figure 34 – Devices in industrial network.

However, managing and configuring AS are challenging works because they require to take into account various AS parameters and network information (e.g., topology, traffic pattern). Moreover, the future networks also require flexibility and reconfigurability, which have important effects such as low time-to-integrate and on-the-fly configuration. As a result, when deploying AS, we utilize Software-Defined Networking (SDN) to implement an IEEE 802.1Qcc-based management solution, improving the system's efficiency. The management solution allows to manage and configure TSN, focusing on IEEE 802.1AS.

As part of the experiment by CEA, implementation and verification of the accuracy of AS in a TSN testbed has been carried, managed by SDN paradigm[14]. The evaluation results have shown that the testbed provides highly precise synchronisation, on the scale of hundred nanoseconds. The standard IEEE 802.1AS has been deployed into NXP © SJA1105 Ethernet switches. There is also available implementation from NXP; however, this implementation allows to have full control on the switch. A testbed with two end-nodes and two switches has been set up: they connect together in a linear topology (Figure 35). The time synchronisation program on the end-nodes is implemented based on linuxptp[15]. Since linuxptp is an open software, it can be managed by one of CEA's plugin inside SDN southbound API (named NEON).

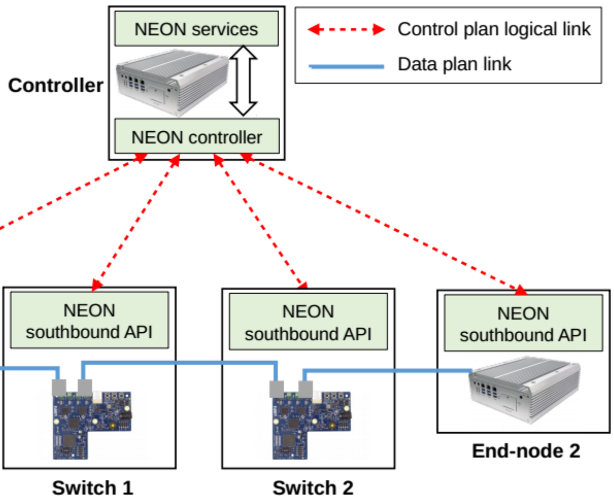

Figure 35 – TSN Experiment setup.

To evaluate the performance of synchronisation, the TS process has been executed for 140 seconds, and the change on clock time over real time (Figure 36) has been measured. After applying the parameters received from the NEON service, the nodes start to synchronise their clocks. In Figure 36, after less than 40 seconds, the clocks of GM and the end-node are synchronised to each other. Before that, the difference between two clocks was in the order of million seconds.

Inside the sub-chart above of Figure 36, although the curve appears to be completely horizontal before dropping down, the clock time of the end-node indeed increases. This is because the measurement is at the scale of million seconds. Similarly, inside the below sub-chart, although the drop-down curve appears to be completely vertical,

[14] M.- T. Thi, S. Ben Hadj Said and M. Boc, "SDN-Based Management Solution for Time Synchronization in TSN Networks," *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Vienna, Austria, 2020, pp. 361-368, doi: 10.1109/ETFA46521.2020.9211923.

[15] R. Cochran et al., "The linux ptp project."

the clock time indeed decreases over real time (as seen in the above sub-chart). After being effectively synchronised, the two clocks almost tick in the same rate.

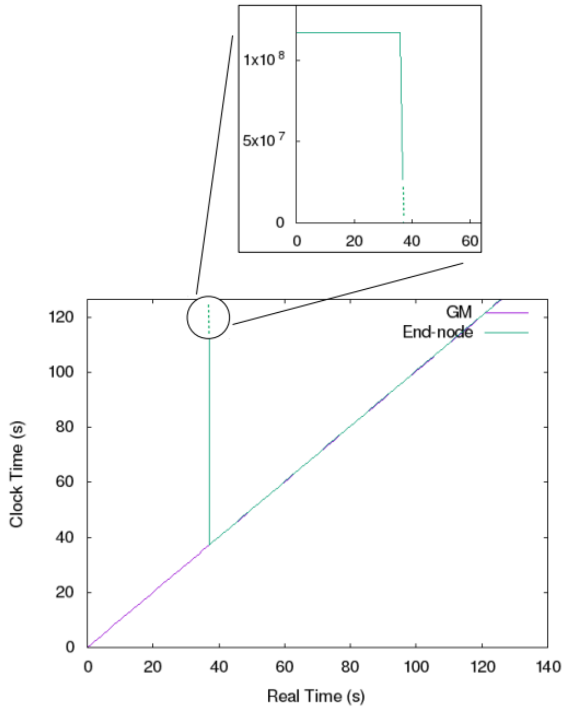

Figure 36 – Synchronizing GM clock and end-node clock.

Figure 37 shows the accuracy of synchronisation, i.e., the offset between slave node and the GM, which is on the scale of hundred nanoseconds. This is a tight accuracy for local area network, compared to other works in the literature[16], which have the offset "on the microsecond scale". Specifically, with the legacy synchronisation protocols, the accuracy is on the scale of microsecond (IEEE 1588) or millisecond (Network Time Protocol - NTP).

[16] P. Volgyesi, A. Dubey, T. Krentz, I. Madari, M. Metelko and G. Karsai, "Time Synchronization Services for Low-Cost Fog Computing Applications," *2017 International Symposium on Rapid System Prototyping (RSP)*, Seoul, 2017, pp. 57-63.

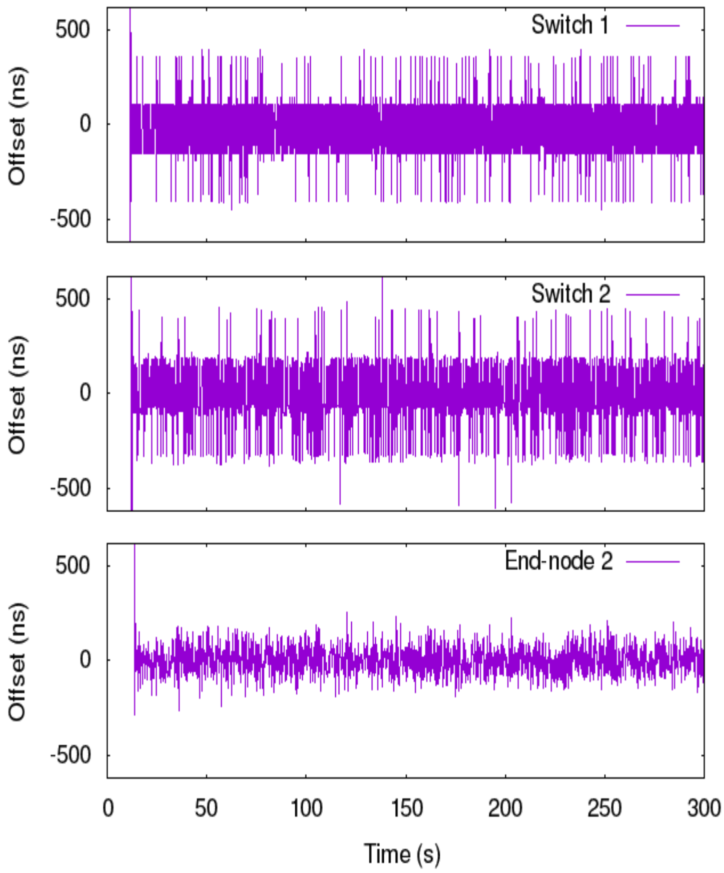

Figure 37 – Clock offset between slave nodes and GM.

5.3 Functional nodal collaboration

Real-time cognitive hot stamping furnace 4.0

Regarding the solution developed by GHI about its data acquisition system, it is based on a master-slave nodal collaboration, in which the central server houses all the data collected by the remote PCs connected to the PLCs located in each customer. Synchronisation is carried out by client computers, and one database is generated per integrated computer. Additionally, the translation table with which the captured frame composed of multiple concatenated variables can be interpreted is defined. All the information is collected in SQL databases.

The following diagram in Figure 38 reflects the actual scenario for the data gathering nodal collaboration system:

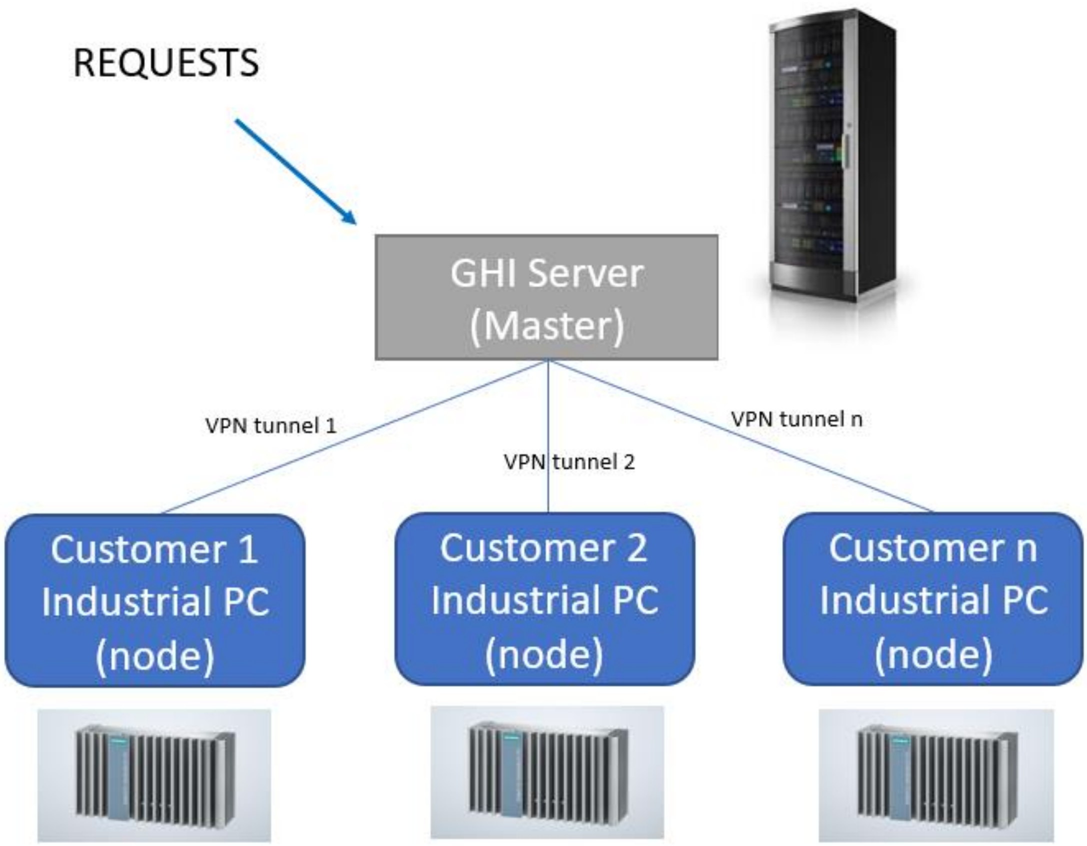

Figure 38 – GHI data gathering nodal collaboration system.

Regarding the nodal collaboration on the quality control scenario, it is also based on a master-slave configuration. The Edge-powered quality control system will act as the central (master) element – it will be in charge, on one side, for the CMM operation; but also from, first, the point-cloud gathering, and, then, from the quality control information analysed through M3 Software. Moreover, this device integrates the IDS connector through which this quality information will be shared with GHI.

Synchronisation of distributed communication of an AGV fleet

For creating the prototype application and depending on the architecture of the application following FBs have been developed to fulfil the specifications mentioned in the previous chapters:

- For the centralised architecture (Figure 39):
    - *AGV_Centralised* CAT object
    - *AGV_Supervisor CAT*
- For the decentralised architecture (Figure 40):

- *AGV_Decentralised* CAT Object

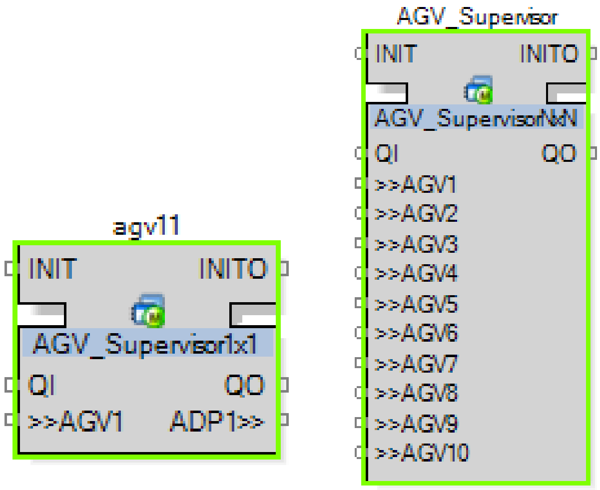

Figure 39 – AGV CAT objects: 1. AGV Centralised architecture.

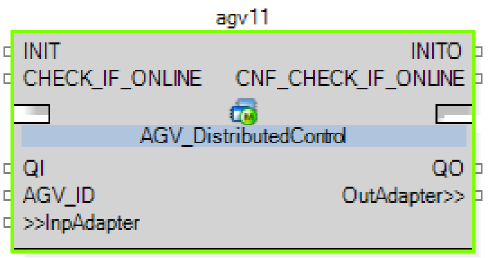

Figure 40 – AGV CAT Objects: 2. AGV Decentralised architecture.

Additionally, all above mentioned FBs are composed from more simpler FB types, which are forming functional entities such as:

- IEC 61499 Adapters (whose goal is the Data Exchange, will be detailed immediately below these lines).
- IEC 61499 Basic FB (which is used for Data Storage, as will be later included in Section 5.3.3 – Storage).
- IEC 61499 Service FB
- IEC 61499 IEC Service HMI block (which enable the Data Visualisation and Monitoring and will be later detailed at Section 5.4 – Control and Monitoring).

Above mentioned FBs are implemented as a CAT objects (Composite Automation Type), which is an extended version of a composite FB defined by IEC 61499 standard.

As commented, for the data exchange between different FBs within an IEC 61499 application, an adapter concept of the IEC 61499 standard is used (Figure 41).

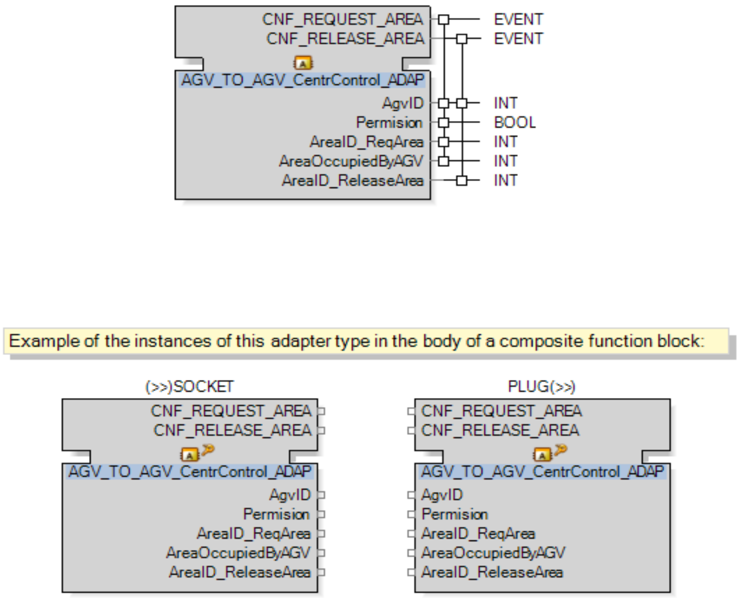

Figure 41 – IEC 61499 Adapter Concept-Centralised Architecture.

As already mentioned, within the centralised/decentralised architecture two types of connections between objects are created:

- Ring connection
- All AGVs are directly connected to the AGV Supervisor object

Based on the type of connection, an adapter has a different role regarding on how the information is transferred from a source to a destination object.

If we observe a "Ring connection" and take in consideration that an adapter is based on a socket-plug concept, then each AGV_Centralised / AGV_Decentralised FB instance consists of an input (adapter socket) which is directly connected to the output (adapter plug) of a previous AGV object instance and an output (adapter socket) which is connected to the input (adapter plug) of the next instance.

Each AGV in the system is uniquely identified by its ID number. This number is used as a parameter in each message exchanged in the system, which in the end is used to identify the source and destination of the message.

By a definition of IEC 61499 standard, an adapter is defined as bidirectional, what means that one connection can be used to send and receive information. This feature is highlighted in a use case, where all AGVs in the system are directly connected to the AGV Supervisor FB (Figure 42). In this approach, a message is directly transported to the destination, without the need to go through all devices connected to the chain.

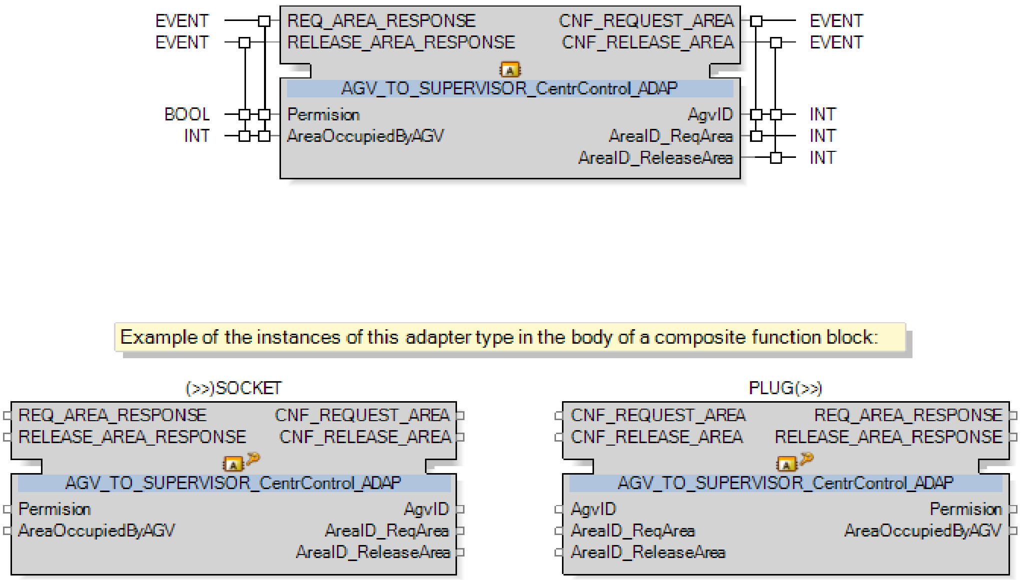

Figure 42 – Adapter concept for a bidirectional communication.

5.3.1 Fog/Edge computing

Real-time cognitive hot stamping furnace 4.0

Regarding the GHI data gathering system, the network configuration is described here.

The furnace process provides lots of measurements taken by sensors. These will be connected to the PLC by common analogical wires. From the PLC, via Ethernet, will be connected the Industrial PC and the furnace controller computer. Around the PLC a LAN architecture is to be constructed. From the Industrial PC to the VPN router, another Ethernet cable will be installed. The VPN router is connected through the Internet (WAN architecture network) with another VPN router that will connect itself with the GHI server through an Ethernet cable. The Cloud and the user computer are connected through the Internet with the VPN nodes.

The PLC bandwidth is programmed to 1 second, so, in that period of time, it will arrive one measurement from each sensor. Also, the analogical signals that have been transformed to digital signals are sent to the Industrial PC and to the furnace control computer, so the bandwidth is constant. From the Industrial PC to the GHI server, there is a different bandwidth – here, a large quantity of data is being managed, and it has to be stored first for its later data processing.

The latency of the different communications the Ethernet cables are switched to 125 µs. VPN latency communications depend on different factors, one of those is encryption (the more data is encrypted, the more latency has), and it has to be reduced as much as possible.

About the quality control scenario, it has been previously described on Section 5.2 - Connectivity and Configuration. In addition, it can be said that the connection between the Edge-powered quality control system and the CMM is, in reality, between the edge system and the two controlling elements of the CMM, as summarised in Figure 43. On one side, Scanlink, that is the interface protocol (Ethernet, TCP/IP, serial communication) for the measuring sensor (the touching probe or OptiScan, or 3D Scanner) controllers; and, on the other side, Pantec, that is the CMM controller.

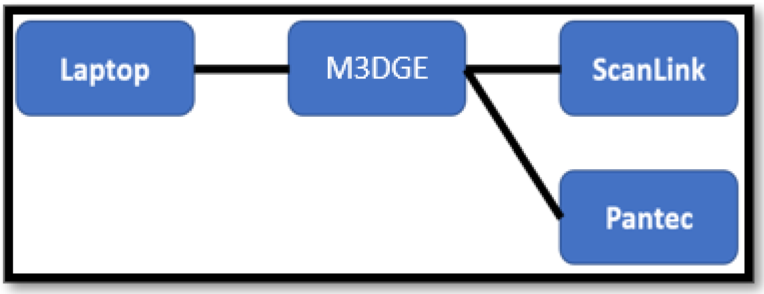

Figure 43 – Edge-powered quality control scenario connection scheme.

5.3.2 Cloud computing

Real-time cognitive hot stamping furnace 4.0

Regarding the GHI data gathering system, some details about the computing capabilities are described here.

The transformation of analogical signals to digital signals happen through the PLC, with an implanted software that transforms the units that come in (from -32000 to 32000) and circulates digital data of the transformations. The data which is stored in the Industrial PC is structured in SQL (Structure Query Language) for a better processing. In the GHI server, the data is processed with Python, Matlab and R software.

The algorithms development is based in a based code criterion that is completed with different packages, and developed internally. In this way, each service and client own its proper script of services which are subdivided in particular scripts for facing each task or to complete necessary calculations.

This task division is based on taking advantage of the knowledge and the generated code for the diversity of clients that share solutions of similar furnaces. Even though each scenario has each own particularity, this structure is flexible and lets, in this way, an adequate version control.

About the quality control scenario, a brief description regarding the computing capabilities of the Edge-powered device can be provided. This edge device, called M3DGE, has been designed for harsh industrial environments and it is based on an Intel Atom x5-E3940 4 cores CPU offering 1.8 GHz and 4GB RAM.

5.3.3 Storage

Real-time cognitive hot stamping furnace 4.0

Both local and cloud storage solutions are required on this scenario. There are multiple devices on the whole pilot that act as local storage devices, some of them momentarily, which are actually rather transmission and processing elements, and other ones that allow a prolonged storage, such as the GHI in-house server and the M3DGE device, this last one with a capacity for 256 GB SSD storage.

On the other side, there are also cloud storage systems, mainly motivated for the necessity of an industrial data space where the quality control data will be shared in a trusted manner and IDS-compliant with GHI.

Synchronisation of distributed communication of an AGV fleet

The **Basic FB** (Figure 44) is used to store all relevant information for a system. For a centralised architecture, this FB is placed within AGV_Supervisor FB and by decentralised architecture it is placed within AGV_Decentralised FB.

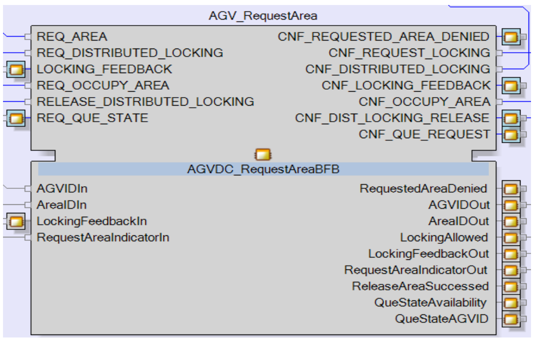

Figure 44 – Basic FB for Information Storage.

5.4 Control and Monitoring

Real-time cognitive hot stamping furnace 4.0

Along the previous sections, the control flow that both the GHI data acquisition system and the quality control system have, has already been described. Therefore, this subsection will be more focused on the tools that allow us to monitor both the operation of the furnace and the CMM.

In order to validate all the code and algorithms developed for the data analysis system, some visualisation tools are required. For visualisation of intermediate solutions (processed data but not correlated yet) the decision to work in the Shiny environment (Figure 45), within R, has been taken.

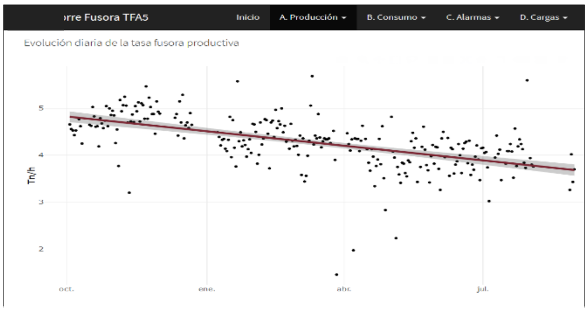

Figure 45 – Visualisation of the Shiny environment.

The evolution of the obtained data is contrasted with that of the raw data by an expert in the machine and process, which is the one who declares the validity (or not) of the results obtained, giving rise to a new iteration or to the standardisation of the generated code.

The visualisation of the raw data is carried out through tools based on Visual Basic (Figure 46), where the complete list of variables is available, selecting up to five plotting environments and a single time range. The variables are dragged and plotted.

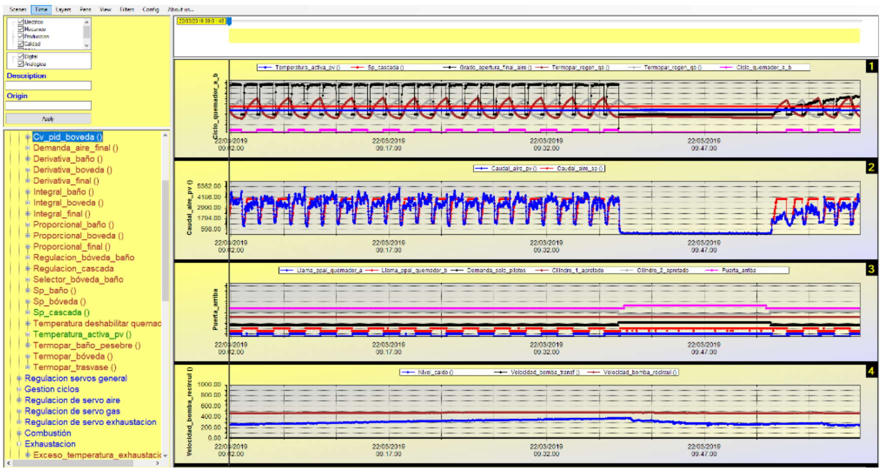

Figure 46 – Visual Basic visualisation.

During this first period, until M21 of the Project, a first data analysis started checking the evolution of some parameters and evaluating the impact of each variable in the modelling of the process. Some of the direct variables identified as critical

(Temperature at each zone, Rolling beams speed, Dew point, Dry air flow rate to the furnace and Power demanded by zone); while others as indirect variables (Number of part movement maneuvers, Time spent by the part in the furnace, Door opening time…).

For the analysis and filtering of the variables in time series, several scenarios were identified, in which the evolution of the variables should not be considered by the model. In this way, only stable cases would be used – in which no noise is produced due to an unsuitable furnace state. Several of these phases were identified and discarded in the analysis.

On the quality control scenario, the metrological framework is based on the software that allows to operate the machine and perform the measurements but also to carry out the Geometries, Dimensions & Tolerances analysis. This is M3 Software (portrayed in Figure 47), that, within an easy-to-follow visualisation tool, allows the user to not only quickly discern if the part is OK or not OK, but also whether and where the manufacturing process or even the design is failing.

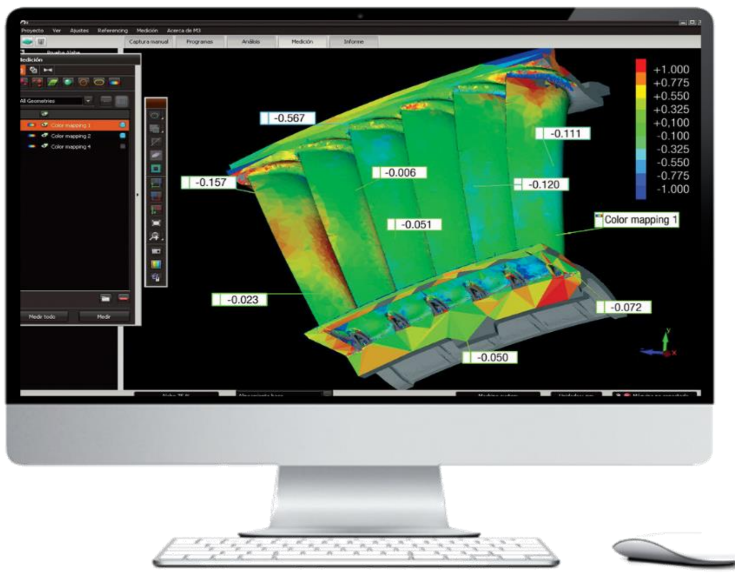

Figure 47 – M3 Software visualisation.

Synchronisation of distributed communication of an AGV fleet

Beside adapters, which are used to connect two FBs and transfer data between them, and Basic FBs, a **HMI block** (*IEC 61499 Service FB Type*) is also used as a component of the AGV FB, which enables the visualisation of the system and observation of process data (Figure 48).

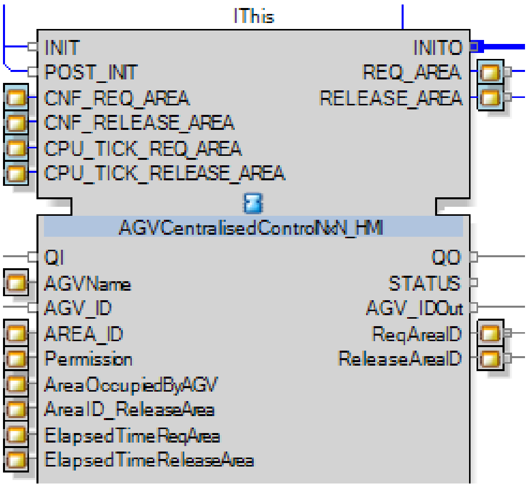

Figure 48 – CAT-HMI block.

This HMI FB serves as a connection between NXT HMI runtime and NXT ECO runtime (executable environment), exposing process variables to the HMI Interface, as in Figure 49:

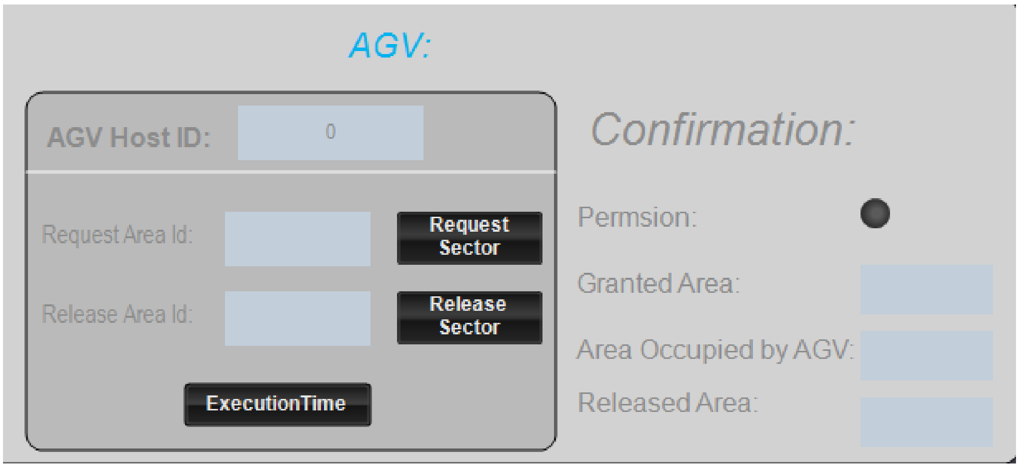

Figure 49 – AGV HMI Interface.

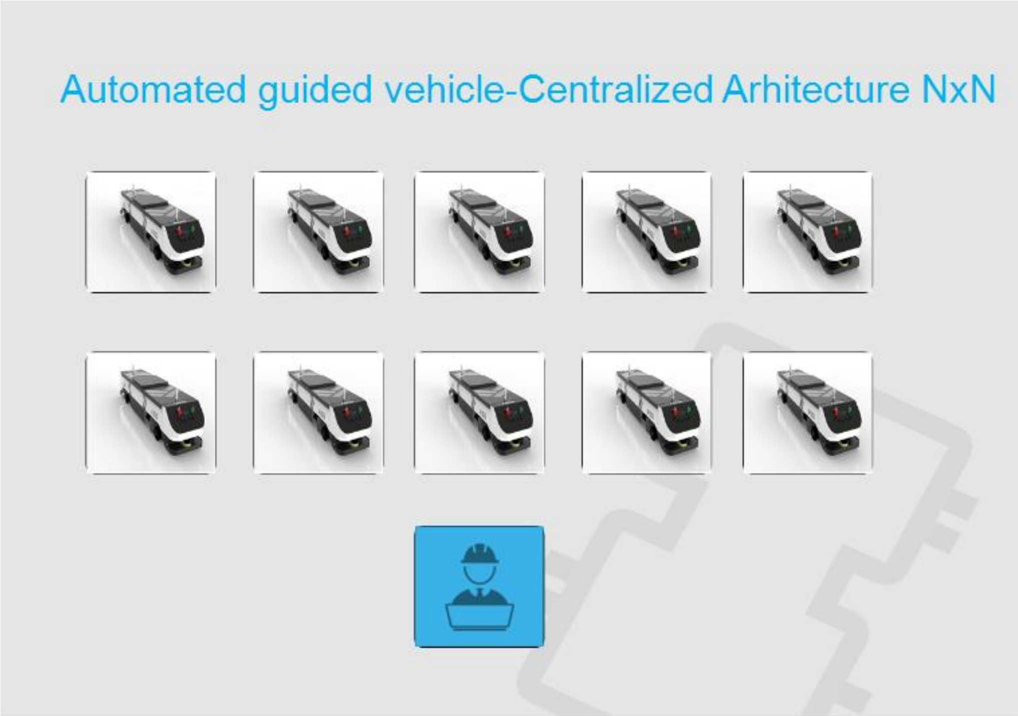

Figure 50 – NXT HMI: Overview of all AGVs in a system.

5.5 Standardisation

Real-time cognitive hot stamping furnace 4.0

To describe the standardisation scenario regarding the whole pilot, it is considered that the best way is describing all the components that form the global scenario, one by one, by identifying the connection among them and with interoperability standards involved on each. Starting from the mapping of the components on the QU4LITY Reference Architecture in Figure 51:

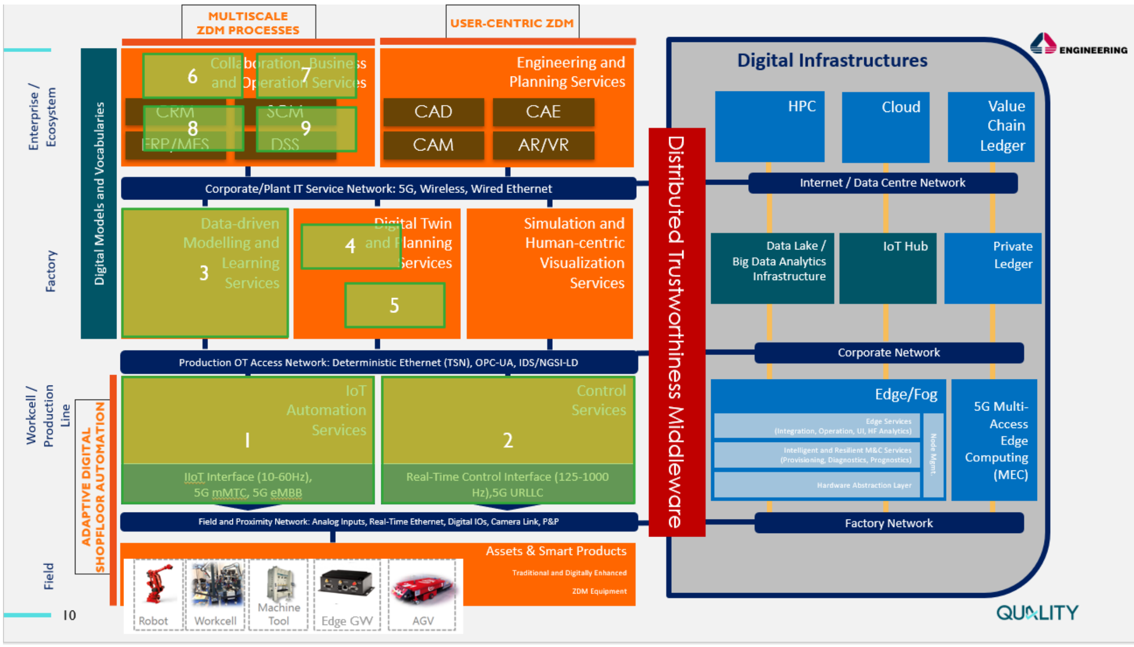

Figure 51 – Component Mapping for Pilot#8: GHI.

1. IoT Automation services: ***Furnace Data Gathering System***

   - **Brief description**: This system must be able to process all the data gathered from the IoT elements integrated on the Rolling beam furnace, incorporating a series of connectors that will manage to ingest all the relevant data.

   - **Connected to components:** 3 & 4.

   - **Interoperability-standard (for each connection)**: 3(OPC-UA (IEC 61131)); 4(OPC-UA (IEC 61131)).

   - **Data exchange format (for each connection)**: 3 (XML); 4 (XML).

2. Control Services: ***Edge-powered Quality control System***

   - **Brief description**: This component acts as an intermediary for real-time communication and control system between the Coordinate Measuring Machine and M3 Software. In addition to be capable to gather the quality data and control the machine, this component will be also in charge for the secure, trusted and contextualised data sharing to the QC data space.

   - **Connected to components:** 5.

   - **Interoperability-standard (for each connection)**: 5 (OPC-UA).

   - **Data exchange format (for each connection)**: 5 (XML).

3. Data driven Modelling and Learning Services: ***Furnace Data Analysis***

    - **Brief description**: This component consists on a data analysis platform that will allow the furnace to improve its operation through the development of algorithms that allow the optimal austenitisation temperature to be maintained homogeneously on the part.

    - **Connected to components:** component 1, 4 & 6.

    - **Interoperability-standard (for each connection)**: 1(OPC-UA (IEC 61131)); 4(OPC-UA (IEC 19941 - MQTT)); 6(OPC-UA (IEC 19941 - MQTT)).

    - **Data exchange format (for each connection)**: 1 (XML); 4 (XML); 6 (XML).

4. Digital Twin and Planning Services: ***BEYOND Monitor***

    - **Brief description**: This component consists of a service derived from the furnace data analysis platform for the Real-Time visualisation and monitoring of its operation, allowing the evaluation of KPIs with visual indicators of inefficiencies and deviations from optimal operation.

    - **Connected to components:** 1 & 3.

    - **Interoperability-standard (for each connection)**: 1(OPC-UA (IEC 61131)); 3(OPC-UA (IEC 19941 - MQTT));

    - **Data exchange format (for each connection)**: 1 (XML); 3 (XML).

5. Digital Twin and Planning Services: ***GD&T parts digitisation***

    - **Brief description**: This component consists on the metrological software that carry out the acquisition of 3D point clouds and Quality control information from the parts that will be measured – this means, the digitalisation of a physical object in order to obtain quality control information.

    - **Connected to components:** 2, 7 & 8.

    - **Interoperability-standard (for each connection)**: 2(OPC-UA); 7(QIF); 8(QIF (ISO 23952 - NGSI)).

    - **Data exchange format (for each connection)**: 2 (XML); 7 (M3 extension file); 8 (JSON).

6. Collaboration, Business and Operation Services: ***BEYOND Reporting***

- **Brief description**: This component consists of another service derived from the furnace data analysis platform that generates monthly furnace status reports.
- **Connected to components:** 3, 8 & 9.
- **Interoperability-standard (for each connection)**: 3(OPC-UA (IEC 19941 - MQTT)); 8(QIF (ISO 23952 - NGSI)); 9(OPC-UA (IEC 19941 & ISO 27070 - NGSI));
- **Data exchange format (for each connection)**: 3 (XML); 8 (JSON); 9 (JSON).

7. Collaboration, Business and Operation Services: ***Quality control Data Analysis***

- **Brief description**: This component will carry out advanced analysis of the quality data obtained from the CMM measurements with the objective of detecting deviations trends and defective parts to later find the correlation with the industrial furnace parameters.
- **Connected to components:** 5 & 8.
- **Interoperability-standard (for each connection)**: 5(QIF); 8(QIF (ISO 23952 - NGSI)).
- **Data exchange format (for each connection)**: 5 (M3 extension file); 8 (JSON).

8. Collaboration, Business and Operation Services: ***Quality control Data Space***

- **Brief description**: A cloud data space for a secure and trusted data sharing, to enable the correlation between quality control data from hot stamped parts and furnace operational data, endowing the data analysis system by knowledge to optimise the operation of the furnace for a ZDM production system.
- **Connected to components:** 5, 6, 7 & 9.
- **Interoperability-standard (for each connection)**: 5(QIF (ISO 23952 - NGSI)); 6(OPC-UA (IEC 19941 - NGSI)); 7(QIF (ISO 23952 - NGSI)); 9(QIF (ISO 23952 & ISO 27070 - NGSI));
- **Data exchange format (for each connection)**: 5(JSON); 6(JSON); 7(JSON); 9(JSON).

9. Collaboration, Business and Operation Services: ***IDSA components validation services***

- **Brief description**: A validation service for components according to the standards formulated by IDSA, which regulates the trusted and sovereign sharing of data, as a key tool to promote and enable global information and business transactions between enterprises.
- **Connected to components:** 6 & 8.
- **Interoperability-standard (for each connection)**: 6(OPC-UA (IEC 19941 & ISO 27070 - NGSI)); 8(QIF (ISO 23952 & ISO 27070 - NGSI)).
- **Data exchange format (for each connection)**: 6(JSON); 8(JSON).

5.6 Security

Real-time cognitive hot stamping furnace 4.0

In this solution architecture, there are two main points where security of Communication and Control infrastructure is performed:

- For the communication with the PLC, The PLC requires additional configuration to allow access to the generated DB. Once completed, the equipment is ready to deliver data to the Industrial PC.
- For the communication with the GHI server, VPN connections provide a solution for a specific security need: securing communications between systems. VPN connections provide protection for data that flows between the two endpoints of the connection. IPSec and OpenVPN are used to establish the tunnel, generating the private and public keys that are loaded into the devices. Once the connection is established, the data capture PC and the server are able to communicate to each other and, therefore, synchronisation between both databases is possible.

6. Conclusions and Next steps

The infrastructure and tests carried with regard to the Communication and Control framework of each experimental case (whether to be as part of the Demonstration work of WP6 or WP7) has been provided in this D4.2 deliverable, either in its first version (released on M12) and/or completed with the input within this document. All cases have been described in detail with respect to the field work performed.

In the deliverable D4.6, the complete and final list of components used in each Pilot and Experimental case will be listed. Meanwhile, the deliverable D4.8 will also detail which capabilities have been enhanced by each, according to the categorisation in Section 3.2 – WP4 Enhancements for AQ Machines with Increased Capabilities.

The categorisation of Autonomous Quality Equipment described in 4.3 – Second Iteration (Two-Dimensional), and WP4 will map, before the end of the Project, the pre- and post-QU4LITY scenarios in each one of the Industrial Pilots and Experimental cases, according also to the descriptions provided in this deliverable and the rest of the documentation from within WP4. This will act as a common KPI for all.

As also commented in one paragraph at Subsection 4.3.3 – Resulting diagram, this categorisation of AQ levels pretends to help publish and classify the assets from the Project at the QU4LITY Marketplace. Each solution will be provided the Autonomy level to which they are able to boost an individual Facility or Industrial Pilot. This would be one of the main indicators associated to a QU4LITY solution, along with the Technology Readiness Level, or TRL.

At the end of the project, the WP4 will also provide, for each use or application case (both Pilots from WP7 and Experiments deployed at WP6 pre-Industrial Facilities) will be able to fill in Table 5 accordingly.

Table 5 – Enhancements of Machines, as WP4 outcome.

Use case	**Technology / Enabler Type(s) deployed (from WP3)**	**Enhanced Machine Capabilities (from WP4)**	**New Services ready to be delivered, or improved ones (from WP5)**	**Overall AQ Level reached at the Use Case**
DANOBAT				
FAGOR				
GHI				
GF				
PRIMA				
ASTI				
UNIM				

List of Figures

List of tables

List of Abbreviations and Acronyms

Abbreviation or Acronym	Meaning
µs	microsecond
3D	Three-Dimensional
AGV	Automatic Guided Vehicle
AI	Artificial Intelligence
API	Application Programming Interface
AQ	Autonomous Quality
C&C	Communication and Control
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CAT	Composite Automation Type
CI	Control Intelligence
CIM	Computer-Integrated Manufacturing
CMM	Coordinate Measurement Machine
CNC	Computer Numeric Control
CPS	Cyber-Physical System
CPU	Central Processing Unit
CRM	Customer Relationship Management
DB	DataBase
DCS	Distributed Control System
DMIS	Dimensional Measuring Interface Standard
Dx.x	QU4LITY Deliverable x.x
e.g. / i.e.	example given / in example
ERP	Enterprise Resource Planning
FB	Functional Block, as per definition by the IEC 61499 standard
FFMS	Focused Flexibility Manufacturing System
FMS	Flexible Manufacturing System
GD&T	Geometric Dimensioning and Tolerance
GM	GrandMaster node, in a Master/slave asymmetric model of communication
HMI	Human-Machine Interface
HW	Hardware
I/O	Inputs and Outputs
IDE	Integrated Development Environment software application
IDS	International Data Spaces
IEC	International Electrotechnical Commission standards
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IP	Internet Protocol
IT	Information Technology
JSON	JavaScript Object Notation
KPI	Key Process Indicator

LAN	Local Area Network
LoAT	Levels of Automation Taxonomy, according to Parasuraman et al.
M3	Multi-Sensor Massive Measurement (commercial product of UNIMETRIK / Innovalia Metrology)
MAL	Manufacturing Autonomy Levels, by Roland Berger
MES	Manufacturing Execution System
ML	Machine Learning
MQTT	Message Queuing Transport Telemetry
Mxx	Month xx of the QU4LITY Project
NGSI	Next Generation Service Interfaces, a protocol developed by OMA to manage context information
NTP	Network Time Protocol
OEE	Overall Equipment Efficiency
OPC-UA	Object linking and embedding for Process Control – Unified Architecture
OSAL	Operative System Abstraction Layer
OT	Operational Technology
PC	Personal Computer
PDCA	Plan-Do-Check-Act
PID	Proportional, Integral and Derivative controller
PLC	Programmable Logic Controller
QIF	Quality Information Framework
RAM	Random-Access Memory
RE	Runtime Environment
Ref.x	Reference x, within this D4.4 deliverable document
RF	Radio Frequency
RM	QU4LITY Review Meeting
RoI	Return on Investment
SCADA	Supervisory Control And Data Acquisition
SDN	Software-Defined Networking
SIFB	Service Interface Function Blocks
SPC	Statistical Process Control
SQL	Structured Query Language
SSD	Solid-State Drive
SW	Software
TCO	Total Cost of Ownership
TCP	Transmission Control Protocol
TRL	Technology Readiness Level
TSN	Time-Sensitive Networking
Tx.x	QU4LITY Task x.x
VPN	Virtual Private Network
WAN	Wide Area Network
WPx	QU4LITY Work Package x
XML	Extensible Markup Language
ZDM	Zero-Defect Manufacturing

Partners: