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QU4LITY

DIGITAL MANUFACTURING PLATFORMS FOR CONNECTED SMART FACTORIES

D4.6 Implementation of Digital Enhancements of ZDM Equipment (Update)

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Author(s):	Christian Bolzmacher (CEA), Daniel Echebarria (UNIM), Mikel Viguera (FARR), Andrea Carcedo (INNO), Maks Tuta (KOL), Valentin Niclas (THYSS), Ifigeneia Metaxa (ATLAS), Pekka Siltanen (VTT), Xabier De Carlos (IKE), Mikel Viguera (FARR), Elena Urkia (IDEKO), R. Perez (GF) Review: Christian Knaak (FhG-ILT)

Abstract: The deliverable details the implementation of digital enhancements of ZDM for each pilot in WP4.
In particular, a short technology description, expected and achieved results as well as an implementation timeline is given for updating existing machines and equipment with digital enhancements, based on the technology platforms that are available in the consortium.

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HISTORY

Version	Date	Modification reason	Modified by
0.1	29/07/2021	First draft QU4LITY_D4.6_v0.1*	CEA
0.2	30/07/2021	Second draft QU4LITY_D4.6_v0.2	UNIM
0.3	05/10/2021	Third draft QU4LITY_D4.6_v0.3	UNIM, CEA
0.4	02/11/2021	Fourth draft QU4LITY_D4.6_v0.4	CEA
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*) file ref. in OwnCloud

1. Summary

This deliverable describes the implementation of digital enhancements of ZDM equipment into WP4's pilots. The first version details the digital enhancement type, the interfaces with the machine and process pilots as well as an implementation schedule. The second version of this deliverable due in M33 reports the results of the digitally enhanced zero-defect manufacturing process and machine pilots as described in D4.1.

The main task of this deliverable is to follow the implementation of digital upgrades as specified in T4.1, in terms of data acquisition, analytics, simulation and more. The implementation will leverage enablers developed in WP3, which will be used according to the specifications for each type of ZDM equipment. Most of the machine or process pilots will be equipped with data collection, BigData analytics and simulation capabilities (including digital twin applications). The specific enhancements to be carried out, depend on the nature and type of each machine and process pilot and are described in this document. The current and updated configuration of 6 machine pilots and 2 process pilots is given together with a succinct description of the digital enhancement type, its interfaces, expected and achieved results as well as an implementation schedule.

2. Introduction

2.1 Objectives and Approaches

Task 4.3 deals with the implementation of digital enhancements of ZDM equipment. Its purpose is to follow the implementation of digital upgrades as specified in T4.1, in terms of data acquisition, analytics, simulation and more. The implementation will leverage enablers developed in WP3, which will be used according to the specifications for each type of ZDM equipment. Most of the machine or process pilots will be equipped with data collection, BigData analytics and simulation capabilities (including digital twin applications). The specific enhancements to be carried out, depend on the nature and type of each machine and process pilot and are described in this document.

In particular, existing machines and equipment are to be enhanced with digital enablers, based on the technology platforms that are available in the consortium. As we use a data-driven approach, it means that the functionality of equipment is to be enhanced depending on the target parameters of the industrial process.

2.2 Relation to other deliverables and WPs

Based on the schema of deliverable D2.11 the following Figure 1 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.

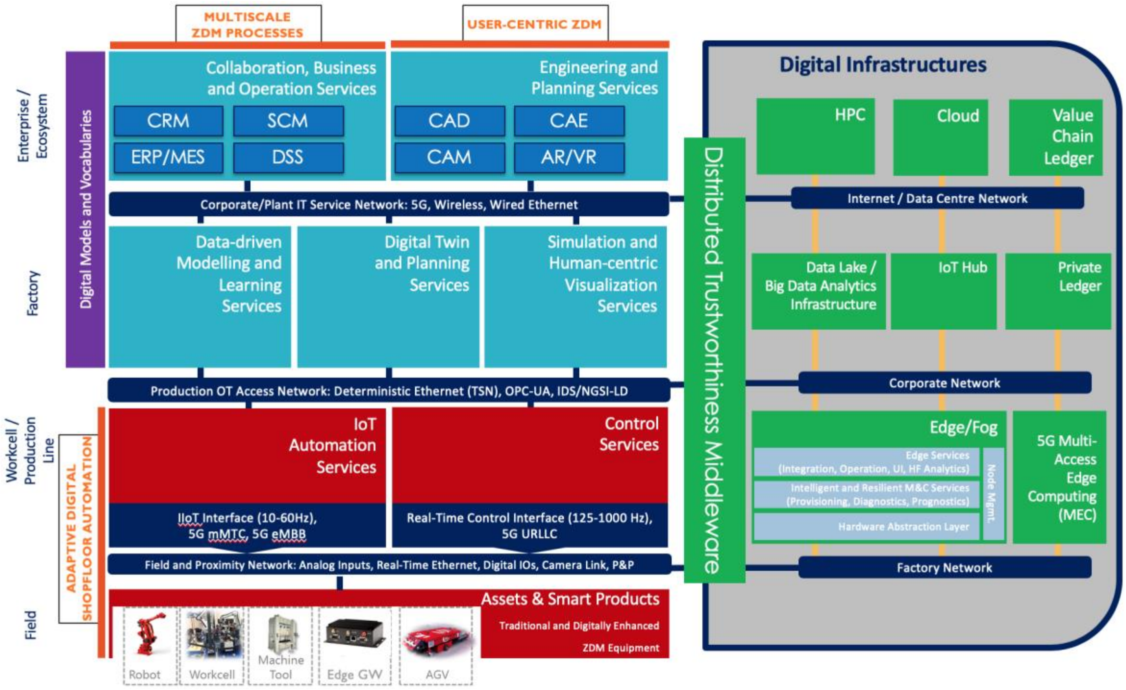


Figure 1 – QU4LITY RA mapping toward the project work-packages

In this deliverable D4.6 the focus is on the **red boxes** with the digitally enhanced equipment and shows first common possibilities for the interaction with the **blue** and **green** boxes.

3. Digital Enhancement Implementation and Timeline

3.1 Machine Pilots

- **Pilot 1: Grinding machine (DANOBAT)**

The system to be monitored is an LG machine available at the prototypes laboratory of DANOBAT used for the production of cylindrical parts. The function of the machine is to externally grind these cylindrical parts. Figure 2 and Figure 3 show the current configuration and the Qu4lity ZDM architecture of this pilot, respectively. The goal is to implement an architecture that delivers integration solutions in IoT-Edge-Cloud for condition-based maintenance and zero defect manufacturing based on vibration analysis and other continuous machine data.

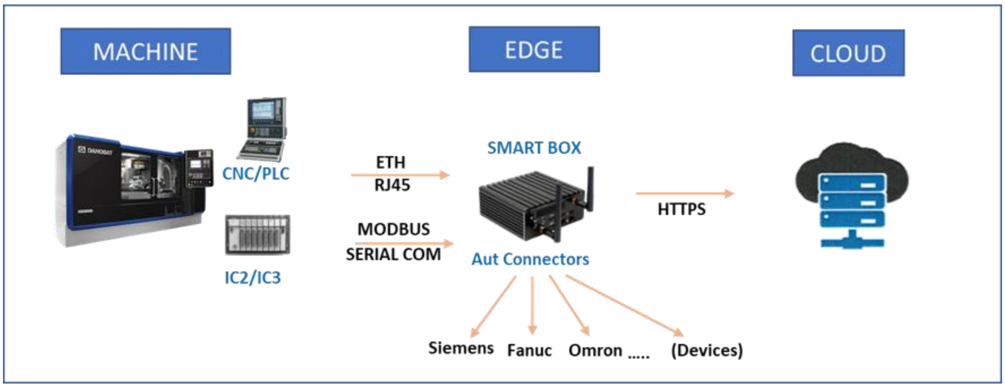


Figure 2: Danobat grinding machine pilot with connectivity.

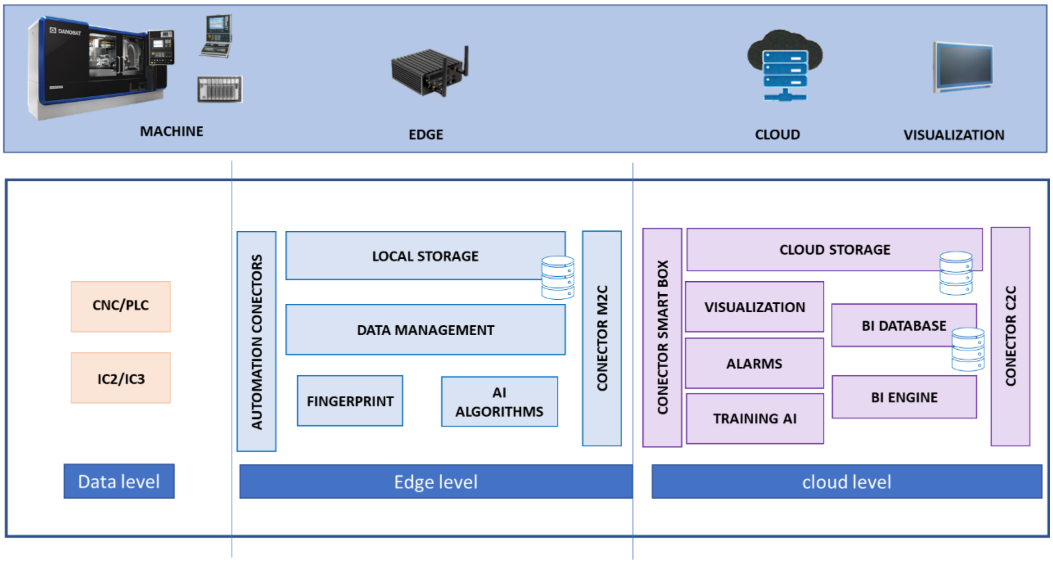


Figure 3: Architecture to be implemented on the Danobat pilot.

Digital enhancement target:

• Data acquisition • BigData analytics • Sensors
The solution must deliver high speed signal processing at Edge level and data management at fog and cloud levels in computation, storage and visualization. The research will be focalised in providing an architecture that delivers integration solutions in IoT-Edge- Cloud, in the field of CbM (Condition based maintenance) and ZDM (zero defect manufacturing), based on vibration analysis and other continuous machine data. The architecture of the Data System platform considers the development of the functional areas of connectivity, maintainability, infrastructure, integrations of application for ZDM, cybersecurity and data protection legislation.

Digital enabler type:

The new architecture will be a hybrid edge+ cloud system. The cloud infrastructure enables big data collection and real time information, shared between Danobat and customers. The analytics knowledge will be developed in the cloud. The algorithms developed and tested in the cloud will then be installed on the Edge system. Real time analysis of these applied algorithms will trigger alarms to the machine that can also be sent to the cloud. These warnings can activate actions on the machine, send information to the operator who can take decisions or can recommend maintenance actions with DANOBAT to avoid failures. The system works in a closed loop so that the application of this knowledge on the machine can also generate new use cases that the domain expert can use and analyse to generate new smart functionalities.
IDEKO - The Data System platform allows the capture, encryption, transmission, storage and processing of data in a safe Big Data environment, applying a set of tools to the new deployment: control of alarms, the life-cycle of parts, spares, maintenance measures, real-time operational control, analysis of historical data, reports, and so on. All software components will be on the Danobat Data System. **ATLANTIS** - The deployed *Decision Support System (DSS)* is an Artificial Intelligence subsystem which manages zero-defect processes, by: ▪ Filtering out false alarms originated from predictive analytics (i.e. from Condition Monitoring and sensorial / inspection data assessed vs tolerance bands, being processed through the defect prediction and detection layers); ▪ Incorporating semantic rules and a rule-based engine to cope with detected / predicted defects identified from corroborating sources (e.g. different sources of defect detection); ▪ Deciding the mitigation actions to cope with defects and triggering the activation of the appropriate ZDM Strategy(ies);

ATLANTIS - The deployed *Remaining Useful Life (RUL) estimation system*:

- Utilize run-to-failure data to develop and evaluate a Remaining Useful Life (RUL) estimation system.
- Provides data visualization via an integrated Grafana dashboard. The dashboards offer an overview both of incoming data and the estimated RUL value.
- Informs the user with email notifications.

SINEF - A "Best practices for ZDM" manual will be integrated, which offers a stepwise guideline for ZDM.

Supplementary vibration sensors will be installed by **Ideko** and **Danobat** on the machine for predictive maintenance tasks.

Interfaces:

Current interfaces: IEC61131

Future interfaces: IEC61131, Edge/Fog node

Expected results:

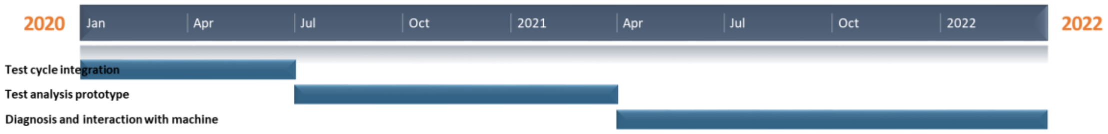
- Interoperable, useful and friendly ZDM-oriented digital platform to build more reliable grinding machines.
- AQ approach in the grinding machines will decrease scrap and reworks.
- Prediction of how the deterioration rate of equipment to plan maintenance actions before it affects the quality of the produced products.
- Increase of Remaining Useful Life (RUL) of the components and grinding wheels will increase.
- Increase of Mean Time Between Failures (MTBF)
- Reduction of Mean Time to Repair (MTTR).

Achieved results at M33:

The pilot is deployed in the machine in the digital innovation plant of Danobat. Test Cycles executed periodically, sent to the cloud for analysis, the tools in the cloud are developed. Atlantis detection of anomalous behaviour and estimation of RUL is being tested. Some improvements of the digital solution where detected and are already developed. Working now on the connection of data in real time with Atlantis digital enabler. Experts are analyzing results, defining the services and autonomous quality functions. Already on the final phase of the development and implementation where validation and KPIs measurement are taking place.

- Developed a RUL estimation technique based on the LSTM algorithm, which uses run-to-failure historical data.
- Developed an oversampling technique in order to increase the size of the provided run-to-failure data with artificial data close to the real ones.
- Developed an automatic Product Cycle detection tool based on a motif discovery technique to be used for the training of the LSTM and its online evaluation.
- Applied the RUL estimation technique to the newly generated data and evaluated the model.

Implementation timeline for pilot 1:



- **Pilot 2: Hot stamping press machine (FAGOR)**

The FAGOR pilot uses a hot stamping press machine (HHDD3-1200-3200-2500). Hot forming or press hardening is a process of metal forming, which allows forming high strength parts through quenching of boron steels heated above 950ºC. Figure 4 and Figure 5 show the current configuration and the Qu4lity ZDM architecture of this pilot. The goal of the enhancement is to get a process prediction based on data analytics of variables as well as new data analytics tools for predictive maintenance and to avoid defects (ZDM).

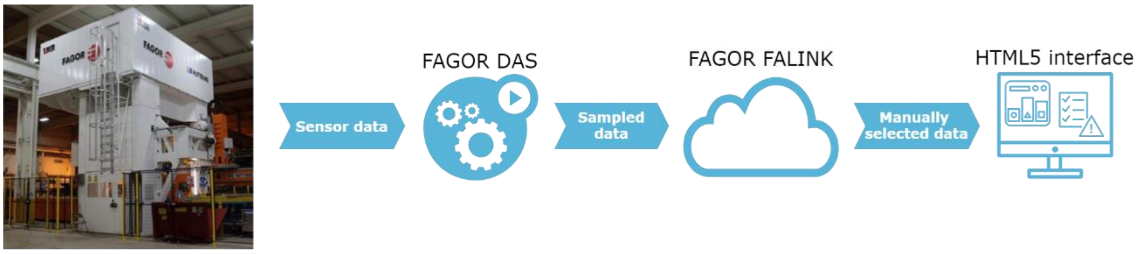


Figure 4: Fagor hot stamping press machine pilot with connectivity.

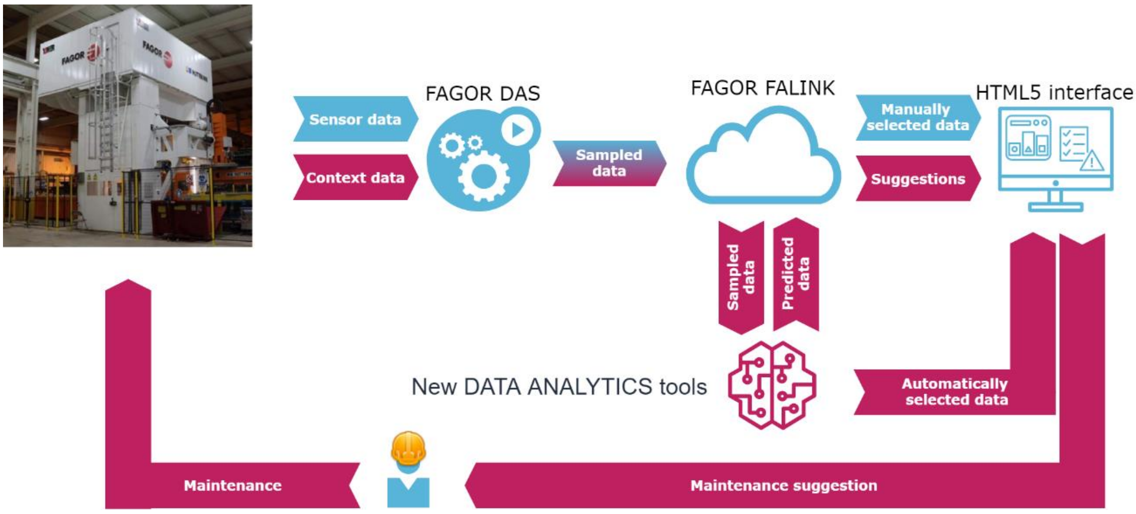


Figure 5: Architecture to be implemented on the Fagor pilot.

Digital enhancement target:

• Data acquisition • Big Data analytics
Cognitive manufacturing proposes the utilization of data across systems to derive actionable insight through the entire value chain. We envision the usage of data analysis not only at the press machine but to have a holistic view of the production.

In order to offer this innovation, the development of this project includes the following partial objectives: • Define the optimal way to identify the critical parameters that affect the operation of the press machine and measure them. Type of sensor, position, frequency of data collection... (reliability) • Define the optimal way to identify the critical parameters for manufactured parts and measure them. Type of sensor, position, frequency of data collection... (scalability) • Design and definition of a hardware / software control that collects and manages identified data (interoperability, security, trust). Definition of the Key Parameter Indicators. Design a system to acquire the Key Parameter Indicators of the process. Implementation of FAGOR ARRASATE's standard data acquisition. Adding the necessary sensors to the production line for the implementation of the data acquisition system. As well as obtaining data from the process PLCs and sensors. Acquire the necessary data for the realisation of the analysis for the ZDM solution. This analysis will find the correlations between product and machine parameters. A ZDM solution will be developed for the subsequent implementation, finding which parameters influence the quality of the product by producing more scrap. The implementation of the Zero Defect Manufacturing Solution will grant that the process parameters are optimal for the best quality outcome, preventing the scrap or at least reducing it. The solution will grant that the production line reduces its amount of scrap

Digital enabler type:

• To know in more depth the manufacturing process and which variables are more relevant to the machine (big data and analytics). • Detect defective parts and the reasons why they manufactured in this way and fix the error (hardware degradation or software reconfiguration) (big data and analytics). • Improve and optimize the manufacturing process (big data and analytics) integrating the data from machine with the rest of the value chain.
IKERLAN - IKCLOUD infrastructure allows the reception, processing and visualization of large amounts of information that is provided by the manufacturing entities:

- Reverse proxy / Load balancer
- Data router / transformer
- Distributed streaming platform
- Process scheduler
- Data processing engine

Integration requirements: Data Router, reverse proxy, API, ...

IKERLAN - IKSEC gathers all the modern competences in the cybersecurity domain and eases the application in an industrial domain.

VTT - OpenVA offers:

- data management,
- data analytics,
- visualization,
- user interface

FHG-ISST - The Industrial Data Space provides a reference architecture for supporting data exchanges in an industrial context. The reference architecture highlights technical and organizational security as well as the integrity and authenticity of data transactions in order to enable the sovereign data exchange among organizations.

Integration requirements: Realization of connector technologies according to the IDSA reference architecture.

Interfaces:

Current interfaces: Industrial PLC and SIMOTION (IEC61131)

Future interfaces: IEC61131, edge/fog node

Expected results:

Reduction in defective parts:

- Monitoring the transformation made by the press including to monitor e.g. temperature, vibrations, pressure etc. and tracing with the final product/part geometry to enable the possibility of selecting which variables affect directly the final quality of the product. This approach is one step further compared with traditional quality processes.

Production optimization:

- Aggressive machine configurations (ultrafast movement of dies, increment in the pressure made by dies) can lead to an improvement on the production at expenses of low-quality pieces and reduction in the machine lifetime.
- Conservative machine configurations (slow movement of dies) can lead to an improvement of the quality of the pieces at the expenses of a slower production. Searching for a balance between the quality and performance will lead to a sustainable production.

The implementation of this process control, would allow customers to:

- To know in more depth the manufacturing process and which variables are more relevant to the machine (big data and analytics).
- Detect defective parts and the reasons why they manufactured in this way and fix the error (hardware degradation or software reconfiguration) (big data and analytics).
- Improve and optimize the manufacturing process (big data and analytics) integrating the data from machine with the rest of the value chain.

Achieved results at M33:

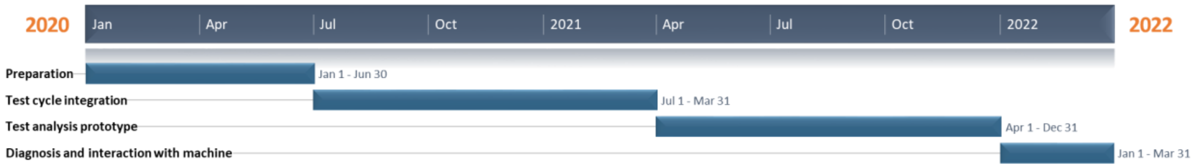
IkCloud has been successfully deployed on a European Cloud provider, implementing autonomous data acquisition and transformation. These steps are orchestrated in a daily basis updating the train dataset used by the models. In addition, cloud deployment of the candidate models is running, making new endpoints ready to be used by FALINK user interface. This way, pilot's user interface can interact with IkCloud, obtaining real time inferences.

FA-Link has been extended to support keycloak for authentication. And this way, IKSEC component for context-based authentication has been integrated within Fa-Link platform.

VTT implemented a data analysis system for managing and analyzing large data sets produced the feeder machine. Data is stored in a millisecond level and it is aggregated to easily visualize key performance indicators that can be used to understand machine status and see if there are some problems to be expected. The key performance indicators are based on creating prediction models how the machine data should behave and comparing these predictions to that actual data that is measured.

The predicted results are analyzed together with the VT data scientists and FAGOR machine experts to validate the results.

Implementation timeline for pilot 2:



- **Pilot 3: Milling machine tool (GF)**

The pilot will focus on a part of an automated cell and will be cantered in GF HPM milling series and FORM die sinking machines, which act in combination in applications in the mould and die production but also aerospace and automotive segments. Other main components of the cells are the Workshop manager software, communicating with machines and FANUC robots for execution program implementation and monitoring. Figure 6 and Figure 7 show the current configuration and the Qu4lity ZDM architecture of this pilot. The goal of the enhancement is to set up a first digital system for detecting, diagnosing, and fully compensating deviations on accuracy, productivity and sustainability of a robotized machining cell. It is based on the aggregation of information from milling and EDM machinery health, process performance and geometrical part characterization, using a common data space for making possible a realistic information integration from different types of hardware & software coexisting at different end-users factories, and targeting fully automated, zero defect manufacturing across the full chain.

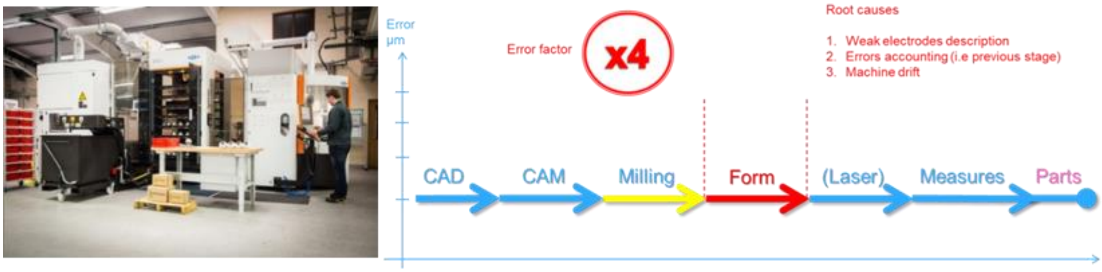


Figure 6: GF milling machine pilot current status.

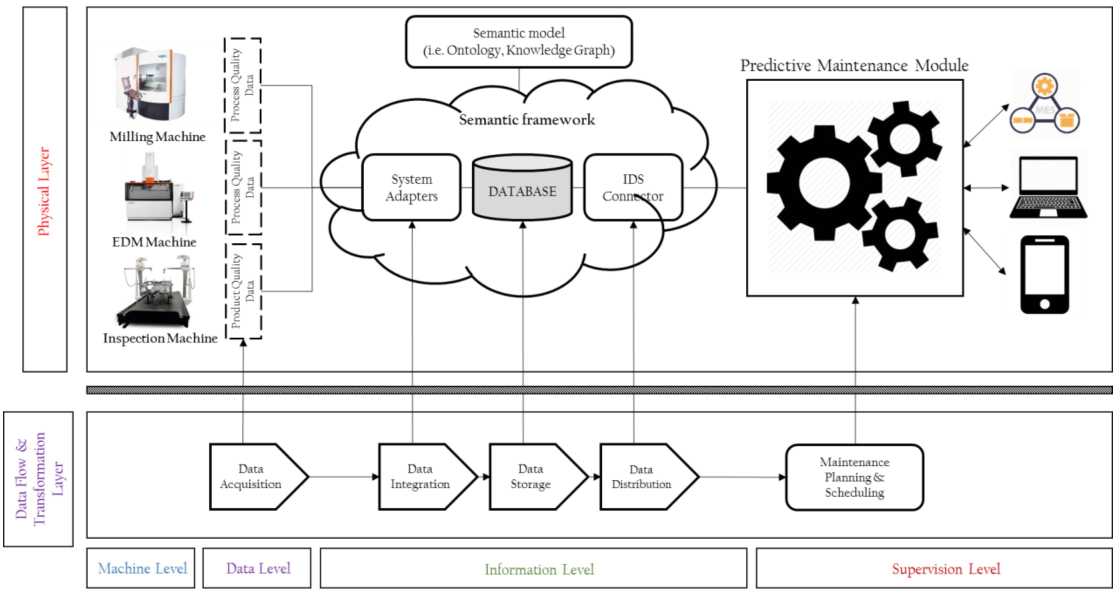


Figure 7: GF milling machine pilot future implementation.

Digital enhancement target:

• Data Collection & Data Analysis • Simulation Capabilities
• All GF devices will be equipped with rConnect interfaces which standardize data by using the OPC UA framework. • CMM systems from Zeiss and Hexagon can be integrated in the cell by using their standard communication interfaces. Inspection software from Innovalia will be used for generating and managing information from these measurement machines. • The Workshop Manager is able to interface with ERP and MES systems as well as CAD CAM modules. Current interfaces are implemented for SAP, Siemens NX and Autodesk. • A digital twin planning system will be implemented for delivering machining codes with simulation tools taking into account given process parameters and machine configuration, in an initial optimized set-up. • Data from machine sensors, monitoring process, components and environment will be collected during machining and aggregated in a common, standardized data space to be associated with data from dimensional measurements. • A cognitive zero defect framework will be developed by EPFL which will correlate product dimensional and surface quality measurements with machine component data predicting aging of machinery and process parameters drift, so to update the process simulation model and return the optimum parameters for generating the NC codes based on KPI indicators on dimensional accuracy, surface quality, productivity and sustainability.

Digital enabler type:

Measuring system integrated in the GF Mikron MILL P 800 U Integrate the cognitive system solution provided by EPFL for taking adaptation decisions during the manufacturing process.
MGEP - Analytical and numerical models to predict roughness and cutting forces in order to avoid potential defects (roughness, dimensional and geometrical tolerances…) **EPFL** - A cognitive zero-defect framework which will correlate product dimensional and surface quality measurements with machine component data predicting aging of machinery and process parameters, so to update the process simulation model and return the optimum parameters for generating the NC codes based on KPI on dimensional accuracy, surface quality, productivity and sustainability. **Unimetrik** - Integration of dimensional measurement system on machine and aggregation in common data space. Integration of the Inspection software on both CMM systems and on-machine, and interface between this software and the Central

Data Space for both delivering and receiving information into a local data processing space.

Interfaces:

The enhancement of ZDM is based on Fog node.

Expected results:

- An automated cell achieving 5um accuracy and Cpk levels higher than 1.66 for mould and die applications.
- A Machining analytical model able to consider the tool deformation surface roughness depending on the working conditions (chip load, feed rate).
- A cognitive system where the adaptation decisions taken during the manufacturing process, whether machine maintenance or process parameters, will be considered to improve the model in next manufacturing parts, e.g., if cutting forces are higher or lower to the predicted ones, material parameters will be corrected, or if an aging component produces more vibrations, check whether they remain within acceptable limits.
- An integrated continuous inspection system of the manufactured workpieces providing Cpk trend in several parameters: roughness, dimensional tolerances, geometrical tolerances
- Common data space integrating inspection data with information coming from the Machine CNC (process and components) and workspace (room temperature) so to adapt (i) the working conditions (ii) the tool trajectory (iii) the cutting tool (iv) the maintenance planning

Achieved results at M33:

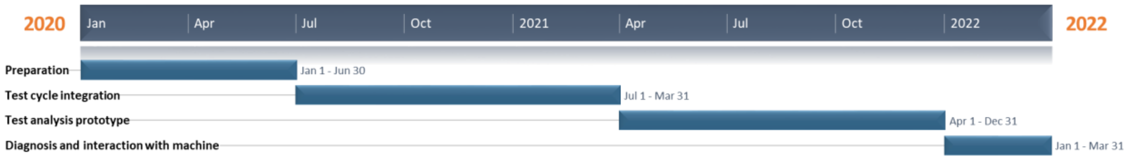
Automated code generation for automated cells with Milling and EDM technologies :

- Integration of Milling simulation and Machine learning models for time estimation of mixed processes
- CNC code generation with predictive performance and high precision adaptive module for automated cells

Coupled predictive maintenance – process monitoring twin for zero-defect manufacturing

- Large data collection campaign at Mondragon University and GF Factory for Milling devices
- Machine learning algorithms development ongoing for predictive part quality and machine maintenance

Implementation timeline for pilot 3:



- **Pilot 4: Hot stamping furnace (GHI)**

Hot stamping is a current process for the manufacture of structural parts in the automotive sector. Hot stamping is a process by which a sheet is subjected to a load between two dies, while the entrance temperature of the sheet is bigger than the austenitization temperature of about 900-950°C. This process takes advantage of the high ductility of the piece due to its high initial temperature and then proceeds to a rapid cooling to achieve the martensitic hardening of the piece. In the QU4LITY project the furnace (Rolling Beam Furnace "L Type") is of interest. Figure 8 and Figure 9 are showing the current and the future implementation of the hot stamping furnace, respectively.

The furnace itself will become the main CPPS component but the use case will also consider the data coming from transfers and the stamping press for the smart monitoring and the cognitive control loops.

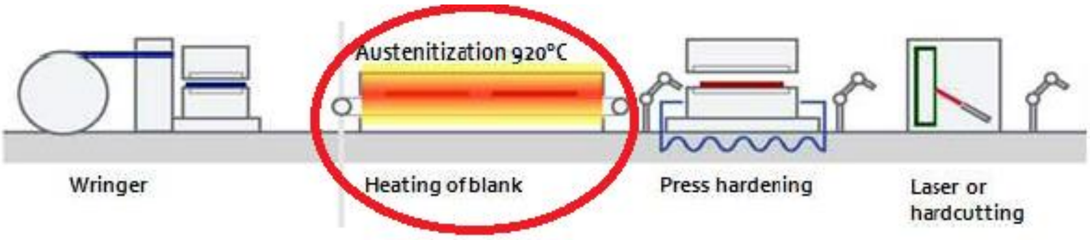


Figure 8: Furnace in a production line.

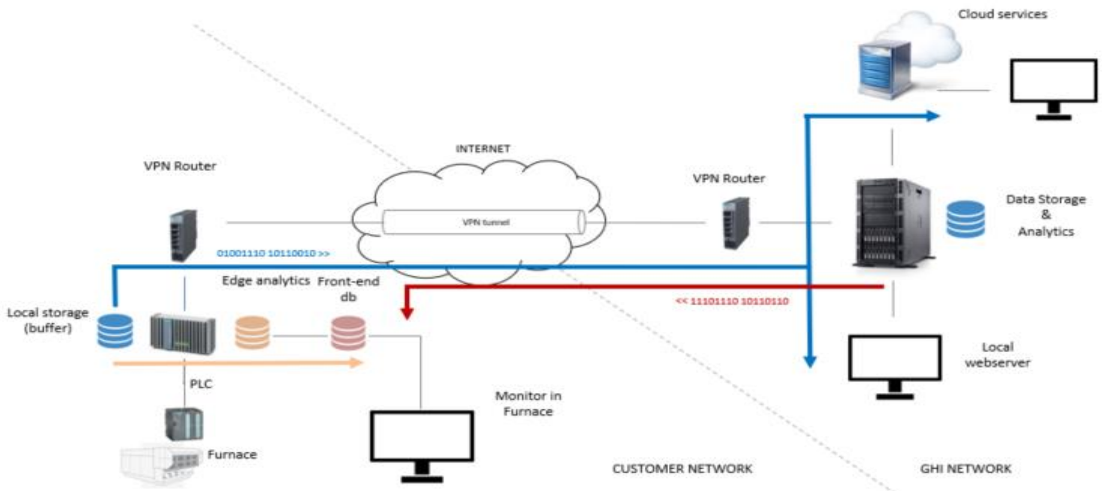


Figure 9: Architecture of the future Hot Stamping Furnace scenario.

Digital enhancement target:

- Smart connected furnace with ability for real-time connected and smart closed loop monitoring & control.
- Data acquisition
- Big Data Analytics

To solve the problem related to crack formation on the manufacturing process, GHI aims at developing ZDM solutions based on implemented improvements (sensor and data analysis) in the furnace. This will provide a more accurate control and will allow a greater vigilance of premature rupture of radiant tubes that can cause H2O infiltration into the furnace atmosphere, which on contact with the parts can cause cracks. The target is a Smart Furnace 4.0 in the context of a hot stamping line. The furnace itself will become the main CPPS component but the use case will also consider the data coming from transfers and the stamping press for the smart monitoring and the cognitive control loops.

Digital enabler type:

The following components will be implemented to create a smart furnace: • A common data space, for furnace and hot stamping installation related information secured, standardized and referenced. • A high-speed edge-powered furnace control platform allowing connected control in real-time of furnace parameters and stamping process. • A cognitive digital twin data and deep streaming analytics framework for real-time analysis of large data in motion streams and smart learning engines for correlation of part defects, press parameters and optimum furnace parameter selection (heating parameters, heating curve, energy consumption). • A big data simulation based framework, able to correlate large heating control data, furnace heating curve profiles with part heating profiles and temporal temperature variations in the hot stamping process. • Semantic data models for the furnace operation information for automated integration of the austenitization process information into learning algorithms and furnace edge control platforms.
GHI - ZDM platform (Data gathering and Data Analysis modules) development and integration **INNOVALIA** - Will define the ZDM framework. Providing support to GHI to integrate the pilot solution on the Qu4lity ZDM platform. **SQS** - Will provide support to GHI related with the digital enhancement solution interoperability and standardization.

Interfaces:

Current interface: Industrial PLC (IEC 61131). It has several digital and analog input/output cards through which process parameters (temperatures, flow rates, etc.) readings are performed and activated on the furnace control actuator elements.

Future interface: Smart connected furnace with ability for real-time connected and smart closed loop monitoring & control.

Expected results:

First phase: reduce defective parts manufacturing.

- The system will demonstrate ZDM hot stamping of safety critical parts in automotive.

Second phase: Production optimization.

- Using a holistic approach given by the ZDM control platform, will provide a balance between the different elements' interaction, leading to a sustainable production.

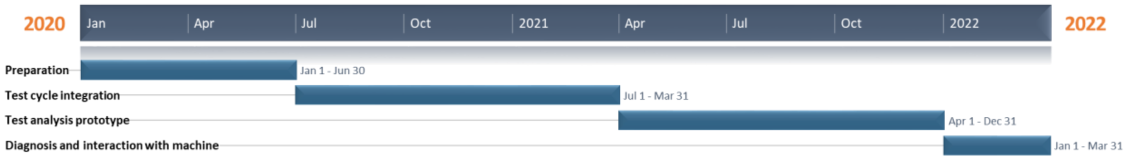
Finally: Obtain a modular solution.

Extensible, scalable, customizable and replicable system that could be transferable to other process industries.

Achieved results at M33:

- An adaptation of the current GHI data ingestion platform has been carried out, analyzing the number of influencing variables, whose control is necessary, to determine the needs of the HW solution. Applying an adaptation of the existing architecture or framework for data capture and storage.
- Work has been done on the analysis and development of advanced calculation algorithms, using tools such as R Studio, which support Big Data and Data-Mining processes to contribute to the descriptive analysis of the operability of the furnace. In addition, in this activity the correlations between the kiln variables have been defined, giving rise to the KPIs that will feed the model later and fully characterize the operation of the furnace.
- The data analysis solution has been based on the integration of advanced algorithms, so that these process variables can be tracked in real time through the visualization tools that have been retrofitted for the furnace. A furnace control HMI interface has been customized for different user profiles that allows them to view the action suggestions provided by the descriptive model.

Implementation timeline for pilot 4:



- **Pilot 5: Additive manufacturing (PRIMA)**

The pilot will focus on an Additive Manufacturing (AM) machine. In laser-based additive manufacturing, production time has a great influence to the economic efficiency of the production process. To increase the productivity but also reliability of such processes, a zero-defect AM strategy is targeted.

Nowadays additive manufacturing is still very dependent from the operator (see Figure 10) on the machine and takes continuous tuning, also during the process, because this has a very high dependency on geometry and building strategies defined by the engineers. Figure 11 and Figure 12 show the Qu4lity ZDM architecture of this pilot.

The goal is to implement new sensors into the machine and combine multimodal process data and machine data to deduce complex relationships between product quality and its influencing factors. This information will then be transferred to the fleet manager as well as in an augmented form to the operator.

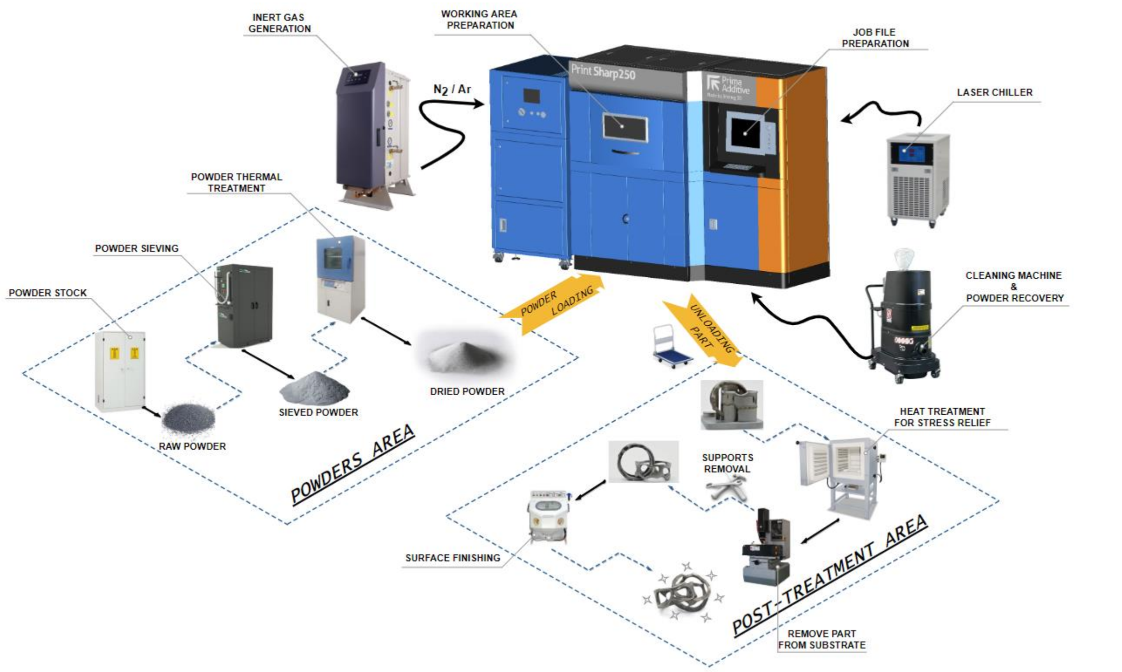


Figure 10: Laser based additive manufacturing system.

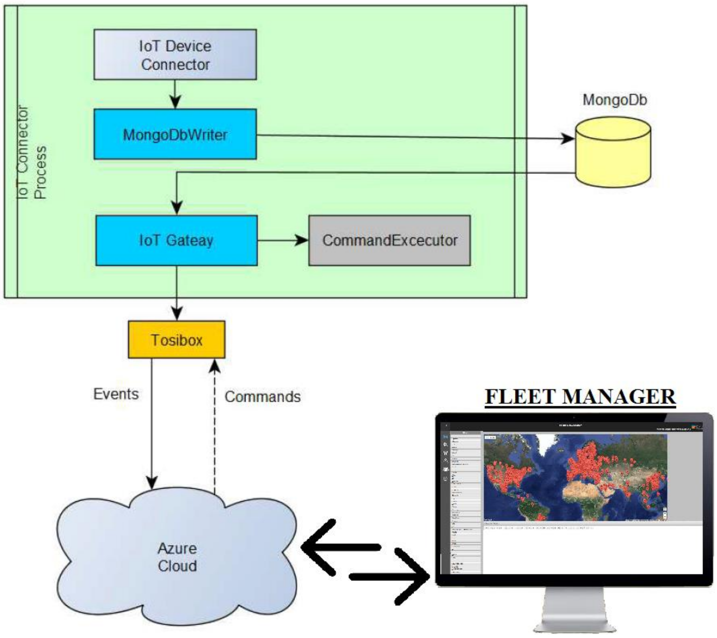


Figure 11: Future pilot implementation with connection to fleet manager.

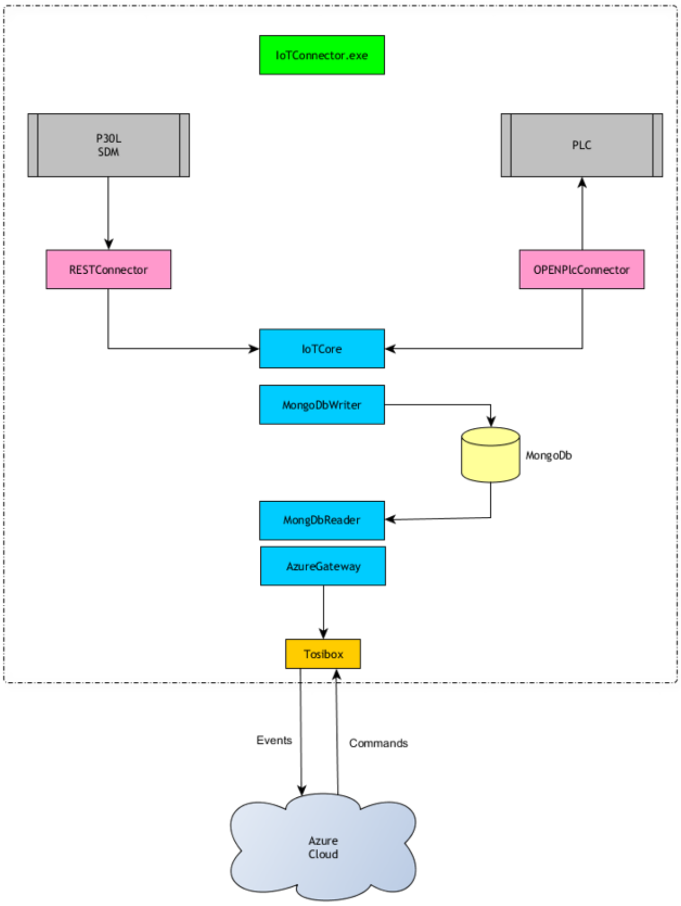


Figure 12: On machine future pilot implementation.

Digital enhancement target:

In this pilot the following main technologies will be adopted:

- Augmented reality
- Sensors system for process monitoring
- Digital twin
- Data analytics
- Decision support system

The zero-defect approach in additive manufacturing addresses the following problems:

- The time-consuming build processes need to stop if a critical defect is detected during the process. Thus, in-process monitoring is suggested for fast and reliable real-time defect detection which leads to:
  - Less powder, energy and machine time consumption;
  - Less quality assurance procedures (in defect case);
- Bad process conditions can be readjusted through adaptive process control
- Laser – based AM is currently used in high-tech industrial applications where 100% quality inspection is applied to achieve zero defect components
  - Potentially saves NDT procedures by replacing them with in-line quality assurance
- The high connectivity to the factory environments enables fast adaption to process changes and high-performance analytics through HPC for faster production decision and reliable process models.

The target is to connect to the PRIMA FleetManagement all additive machines, by developing necessary functions at machine CNC/PLC level to collect relevant data from machines and to permit to have a remote assistance to the customer by using an IoT connection.

The technical specification are related to different aspects:

- Machine Data to collect.
- PLC-Data connection structure.
- IoT connection structure.

Digital enabler type:

To allow an autonomous quality assurance system, which decides whether to cancel or continue the production process, different sources of information are required. Besides collecting machine data to observe the quality and maintenance states of the production line, in line process information is crucial to achieve constant product quality and ZDM. Real-time process and machine signals need to be analysed in by machine-learning algorithms to find structures and pattern related to the required key quality indicators (critical defects per track, distortion, keeping of dimensions). The system will be also connected to a higher-level factory data interface which allows to exchange process information and reassign the production strategy based on additional factory conditions. Figure 13 depicts schematically the different ZDM levels.

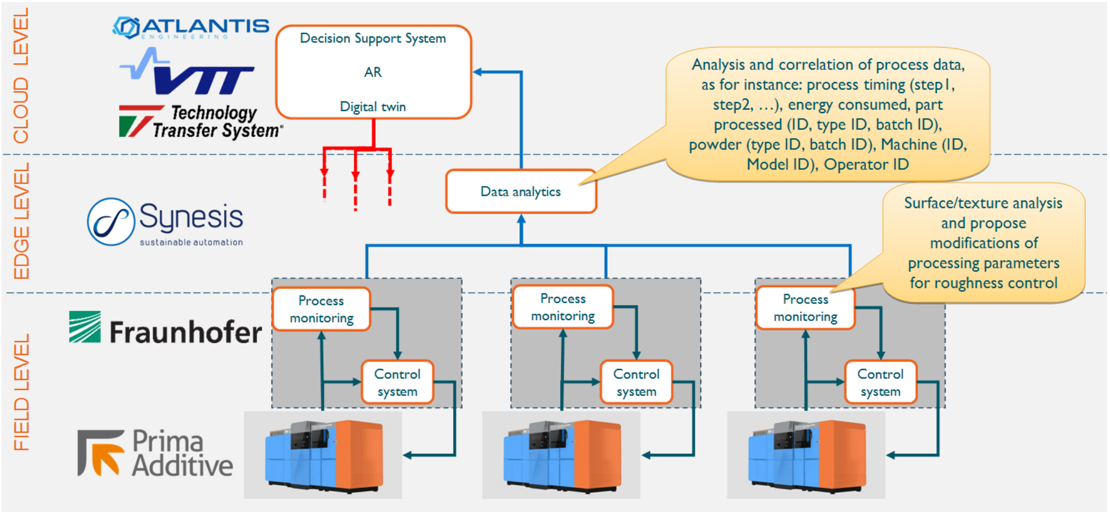


Figure 13: Future work flow for ZDM and leading partner.

The role of partners involved in this pilot will be as follows:

- **Fraunhofer ILT** will take care of the sensors integration and online image processing for surface quality estimation during the build process on the edge as well as the control of the machine at field level while **Fraunhofer IGD** provides interactive visualization of the sensors data that allows the user to annotate specific feature or highlight in a 3D view of the built part's sensory data.

- The data relating to the machine and status of process will be collected and analysed in first instance by **Synesis** at the edge level, in order to extract useful information from first rough data, such as energy consumption, status of the optics, filter, powder bed.

- **VTT** will develop a module that allows further analysis of the AM use case as well as training, work assistance, maintenance using augmented realty technologies. **TTS** provides tools and know how to establish a digital twin that allows to simulate and optimize the expected process duration based on several parameters.

- Data will be sent to cloud level in order to be used by some service providers such as **Atlantis**, for the app relating to decision support,

- The DSS combines the incoming data from various sources and creates a decision rule based on all incoming data. The gathered data are combined to create a complex event for the DSS.

Interfaces:

The current implementation is based on IEC-61499.

The future implementation is based on IEC-61499, OPC-UA, VDMA, and edge node.

Expected results:

- Modular adaptable signal processing system that can operate to RAMI standards on the edge for data-driven online quality assessment.
- Connectivity to MES and control systems
- Interaction with data space and simulation tools through the platform.
- High level decision support and overview of the AM equipment.
- Processing of complex events to reach the most suitable suggestion for the decision makers
- Mathematical combination based on logic, Boolean states and operations to create the decision tree
- User defined rules based on the shop floor procedures

Possible results: Raise early warning signals based on cognitive quality diagnosis, including anomaly detection and equipment condition reporting, control laser - based AM processes on the basis of data-driven process models, increase OEE by recommending process adjustments to the operator, reduce reject rate by application of data-driven process model that has been derived by AI algorithms and enable mode.

In-situ detection and mitigation of critical defects such as “balling” and “surface distortion” during the build process.

AR for human error reduction: thanks to new and advanced AR applications, it will be possible to mitigate human errors and increase the quality of the process because of a better machine setup.

All the above results are gathered in the DSS where they are processed as complex events and the system creates the most suitable suggestions for the user.

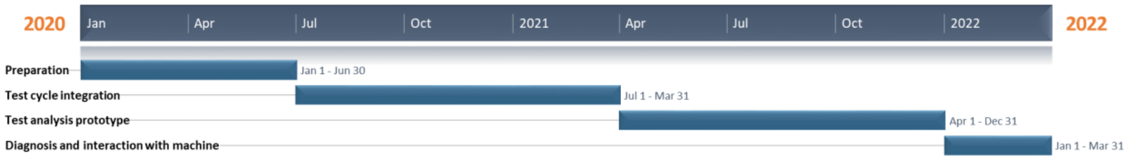
Achieved results at M33:

- Creation of the first version of the DSS application.

- Implementation of the complex event processing logic in the system. A combination of data, Boolean or mathematical expressions create the more complex rules, which describe the procedures on the shop floor.
- Testing the logic behind the decision tree creation.
- Definition of the DSS entities used in the system.
- Creation of the database schema based on the system's ontology.
- Initial integration with the rest of the QU4LITY components: API definition, calls and endpoints, suitable protocols etc.

Security implementation on the system: Authentication and Authorization mechanism.

Implementation timeline for pilot 5:



- **Experimental case 1: M3MH Software for machine tool quality control operations (UNIM)**

Currently, the mechanical manufacturing industry demands increasing quality and productivity requirements while exerting economic pressure to reduce overall costs, all in order to be able to adapt to fluctuations in demand and to make in front of increasingly smaller and customized production lots. Consequently, the machining processes are experiencing a continuous evolution towards greater degrees of automation, monitoring and self-regulation.

In order to meet the aforementioned requirements, metrological systems, both hardware and software, are currently in the process of adapting to productive environments of various kinds. One of the currently active development lines is the integration of metrological systems in the machine tool itself through the incorporation of acquisition systems in the machining equipment. And this is where the M3MH software fits.

M3MH Software allows to feedback the information captured in real time to dynamically update the manufacturing process of mechanical components, improving in this way its direct control as well as the dimensional accuracy of the obtained products.

The kind of enhancements that Unimetrik is going to work on for the service expansion that M3MH Software can provide, that will be mainly focused on the instructions conversion between DMIS code and the CNC communication protocol. Not every machining center operates with the same kind of controller in the same communication protocol, and therefore, Unimetrik has decided to work on it to expand the range of CNC controllers on which to operate.

Also, some extensions of these instructions conversion is going to be developed to allow the M3MH software tool to interact with a wider extension of machines that operate with more degrees of freedom (4,5-axes). These enhancements will improve the software flexibility and accuracy, so it will enlarge its competence.

Digital enhancement target:

In this pilot the following main technologies will be adopted: • Data acquisition • Sensor system for process monitoring • CNC communication enhancement
The main objective of this pilot is to develop new controller's communication. The actual M3MH software is able to communicate with 3 different kind of CNC controllers protocol. The goal is to extend this communication and turn the M3MH software into a global machine tool communicator. The parallel objective is to supply M3MH software with the capability to properly interact with different kind of machines that operate with different degrees of freedom (with 4 or 5 axes machine

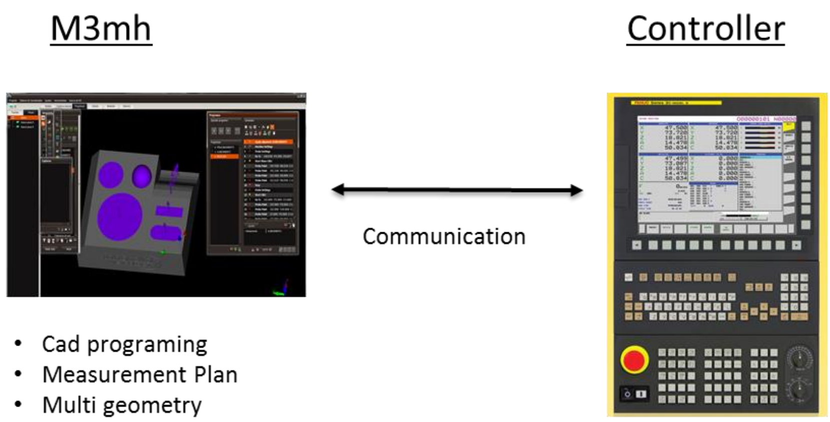
tools. Nowadays, M3MH software is only properly adapted to communicate with 3-axes machine tools. This enhancement will improve the variety of complex objects (helix) that can be measured with M3MH without stopping the process to change the object position (Faster measuring with same or better results).

Digital enabler type:

As it has been explained on the previous chapter, the most critical issue to solve is the communication between M3MH (the metrological software) and the Machine tool CNC.

To do this, in order to be able to introduce inspection routines in plans or programs that can be executed in machine tools, 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. For example, conversion instructions have been implemented with the "G" code, characteristic of some numerical machining controls.

In this way, the latest advances made and which are also in which the work continues, is in the development of a series of connectors that generate that conversion of instructions for different communication protocols with which each CNC operates. Thanks to advances in data collection and connectors, the current system makes use of the following workflows, represented in the figure below:



M3mh:

- Cad programing
- Measurement Plan
- Multi geometry
- Part Setup
- Alignments
- Tool Offset
- Machine Compensation
- Reporting

Controller:

- G-code program
- Probing points generation

Figure 14: Current configuration of the milling machine.

Below can be shown a diagram of the connectivity requirements for the M3MH solution:

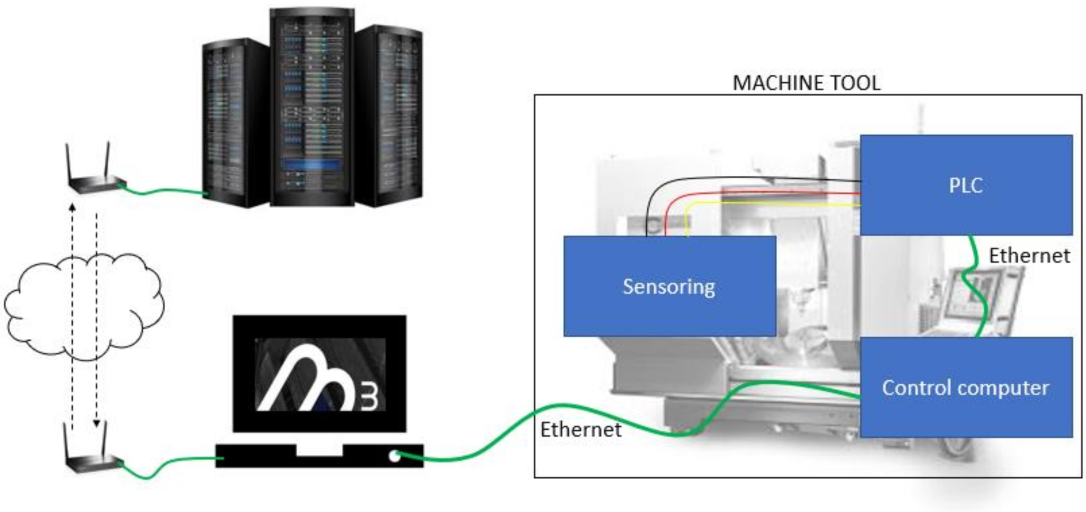


Figure 15: Future configuration of the milling machine.

The M3 software is run from a PC that it is connected via ethernet with the CNC. It is necessary to assign to the Ethernet port of the M3 computer an IPv4 address that is in the internal network of the CNC.

Next step for the configuration between the M3MH software and the machine tool is to define the workspace volume. This has to be setup from the software.

Interfaces:

For the interfacing and transforming the inputs and output optical and digital signals into visuals, the control and interpretation is made at Edge Node (as shown by Figure 16), via the Data Assembler and RobotLink.

The RobotLink translates the orders from the control plan or measurement orders in order to materialize the movement of the machine axes, thus, converting commands into signals so as to move the machine.

The Data Assembler, in turn, transforms the signals captured by the machine sensors into useful information for the point cloud processing and analysis, in the form of x,y,z positions and a vector normal to the surface at each point.

Particularly, the RobotLink is the individual component that needs to be adapted and configured for different machine control languages and degrees of freedom of the machine axes.

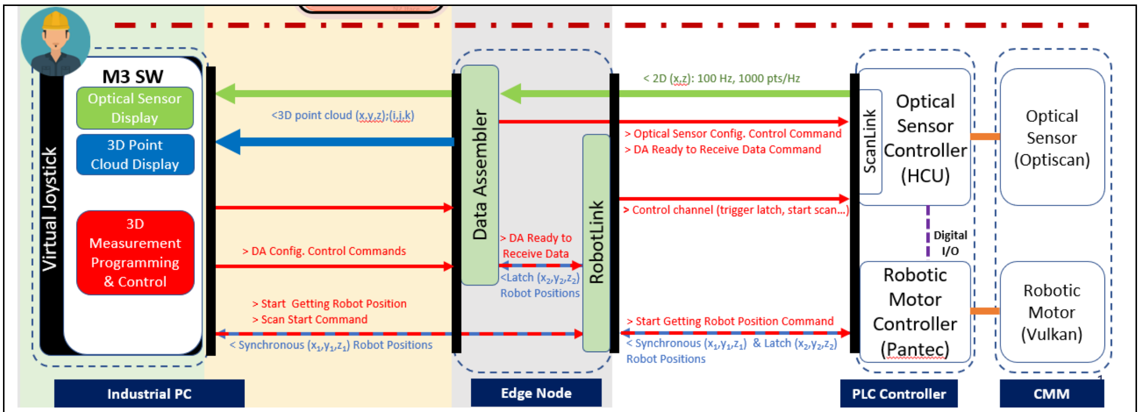


Figure 16: Architecture of the M3MH solution

Expected results:

The enhancements have to be done in an order, there can be defined 3 phases:

1. Enhance communication: Conversion instructions

During this period, Unimetrik will work on the development of conversion instructions to allow M3MH Software interact with different CNC communication protocols.

2. 5 Enhance on degrees of freedom: Axes Control

The second phase will be in charge of developing new conversion instructions to improve M3MH software operation with machine tools with more than 3-axis.

3. Validation

In the final phase the new enhancement will be tested in different machine tools, here can be fixed some parts of the software to improve its work.

Achieved results at M33:

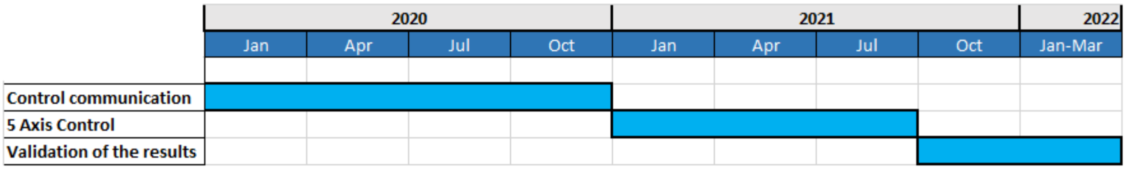
- Deployment of the full solution (M3MH) at the AIC Experimental Facility has been achieved, in a 3-axes machine tool (WEMAS VZ 1250) with TNC 620 Heidenhain control, like the one shown on Figure 17.

Figure 17: WEMAS VZ 1250 machine tool with TNC 620 Heidenhain control deployed at the AIC Experimental Facility and equipped with M3MH.

- The software has been validated as a solution in order to enable in-line, in-machine measurement operations, by equipping the machine with a set of touching probes which are accordingly mounted in the machining head and enable this operation. Specifically, thanks to this deployment, the following functionalities offered by the solution have been tested and verified:
    - Intercommunication capacity between the M3MH software and the machine CNC. This enables, among others, the unique opportunity to control the manufacturing process in real-time.
    - Sharing the same coordinate reference system for the CNC machining and the dimensional quality inspection with the M3MH software.
    - At the time of defining the measurement strategy, the possibility to simulate the whole measurement process with the help of M3MH, something particularly useful for the generation of dimensional inspection paths and measurement plans offline, instead of utilizing the CAM programme to do it.
    - Possibility to measure the part in the middle of a machining cycle, in order to minimize losses in the case of high-added value parts (e.g., turbine vanes made of titanium alloy) which require a series of manufacturing operations of several hours. This is especially useful in critical parts for the geometrical structure, as it is the case of already drilled holes.
    - Reliability and Traceability of the data, thanks to the efforts made in the interoperability of the solution with Standards such as QIF (ISO 23952:2020), through unique persistent identifiers (QPId).
    - Ability to generate customized quality inspection reports, using for that purpose capacity and productivity indicators widely utilized in Statistical Process Control, such as Cp, Cpk, Pp, Ppk, etc.

- In terms of maintenance and machine traceability of the very same M3MH system, there is, as well, the option of verifying the state of the machine (estimate the scale and perpendicularity errors on the axes) in 10 minutes, and act accordingly, if, for instance, it is discovered that the whole system needs to be recalibrated.

Implementation timeline for pilot 6:



The intercommunication between the CNC and the M3MH component was finished in late 2020, and the whole demonstrator at the AIC Experimental Facility was set-up. From that point on, work continues on the adaption of the system for 5-axes control.

3.2 Process Pilots

- **Pilot 7: Injection moulding process (KOLEKTOR)**

Because the Pilot is based in real-world production, which needs to adapt to market demands and conditions for the company to stay afloat, the initial plan of Pilot deployment has been changed. It still deals with the prediction and detection of defects on objects that are produced with injection moulding, but on a different production line and with somewhat different parts. For example, the moulding tool is now automatized and separated from the Pilot and cannot be inspected anymore. However, it provides the partners with more moulding parameters and process data and is more interconnected into the Information infrastructure of the production plant. As such, it will provide more information for the process of predicting possible defects and positions of defects.

The goal is to detect, possibly predict, and remove the cause of the process failure as soon as possible, ideally in real-time based on the collected data and by applying advanced analytics and artificial intelligence methods to better understand the moulding process. Therefore, the goal is to improve on the feedback capabilities of an already existing moulding production line, through collecting moulding process parameters, monitoring environmental parameters, visually inspecting the moulding tool and visually inspecting the moulded parts. Production line consisting of assembly line, robot assisted manipulation for visual quality control and moulding machines.

Figure 18: Current configuration of the KOLEKTOR pilot.

Digital enhancement target:

• Data acquisition • BigData analytics
The goal of the pilot is to improve on the feedback capabilities of an already existing moulding production line, through collecting moulding process parameters, monitoring environmental parameters, and visually inspecting the moulded parts.

While the first two modifications include installing sensors on existing moulding tools, which constitutes a minor change, the latter include the introduction of a robotic system, complete with a visual inspection system, i.e., the camera. Even though the expected robot to be installed is certified, and the current version of the moulding line has undergone risk assessment and safety certification, every instantiation of the complete production line requires certification. A general certification is not applicable due to many possibilities of the robot motions and tasks.

Digital enabler type:

To be able to monitor the process and process parameters, we will connect the injection moulding machine to the Sinapro.IIoT MES system and the Kolektor ZDM platform, where the gathered data will be stored. We will monitor all key parameters for controlling the injection moulding process, such as various time control parameters, pressure parameters, the measured temperature of the injection moulding tool and of the molten material. The machine and the production process will be additionally equipped with vison IoT sensors to capture visual information of the process, product and the machine. Based on the collected data and by applying advanced analytics and artificial intelligence methods we will better understand the moulding process and will be able to detect anomalies and failures as soon as possible. For example, we will look for correlations between the visually detected defects and the parameters of machinery involved in the production process. By collecting enough data, it will become possible to modify the production process parameters to remove defects of injection moulding. Because of the geometry of the moulded part, it is not possible to inspect the whole object at once. Therefore, we are planning to use a robot to perform complex movements required for inspection. We will study if it is possible to automate the removal of root cause of the produced scrap parts.
KOL – Integration of a visual quality inspection control system. Before and after the injection moulding process QA inspection is performed to detect anomalies during the production process. **JSI** – Integration of a robot system. The robot is a 6-DOF industrial robot, which will be used to move a camera, used for acquiring images for visual quality inspection of the products and the machine, to the correct spot, where it will be able take the images. **CEA** - Collecting acoustic data to termine the wear or the integrity of the cutting knife of a lathe and to apply signal-processing algorithms to identify markers that could be correlated to plastic flow conditions.

FHG-ISST - Industrial Data Space integration. The Industrial Data Space is one of several initiatives of the Industrial Data Spaces Association and provides a reference architecture for supporting data exchanges in an industrial context. The reference architecture highlights technical and organizational security as well as the integrity and authenticity of data transactions in order to enable the sovereign data exchange among organizations.

Interfaces:

The current interface is an Industrial Siemens PLC.

The future interface will be based on Edge and Fog node (OPC-UA, MQTT).

Expected results:

- Better understanding of moulding process, real-time detection and possibly prediction of failures based on advanced analytics and AI, implementation of feedback loop for troubleshooting
- Monitoring of machine parameters such as temperature, pressure, flow speed.
- Visual inspection of the moulded parts.
- Automated adaptation of process parameters to reduce scrap rate.

Our goal is to install the developed real-time injection moulding process monitoring and control, including autonomous parameter correction, in the Kolektor's production lines. By automatically correcting the parameters of the moulding machines, Kolektor will optimize the existing production process, leading to the reduction of the failure and scrape rate. This way we expect to reduce the number of parts with defects by 20%, which will result in an increased profitability of production lines that involve injection moulding.

Achieved results at M33:

KOL

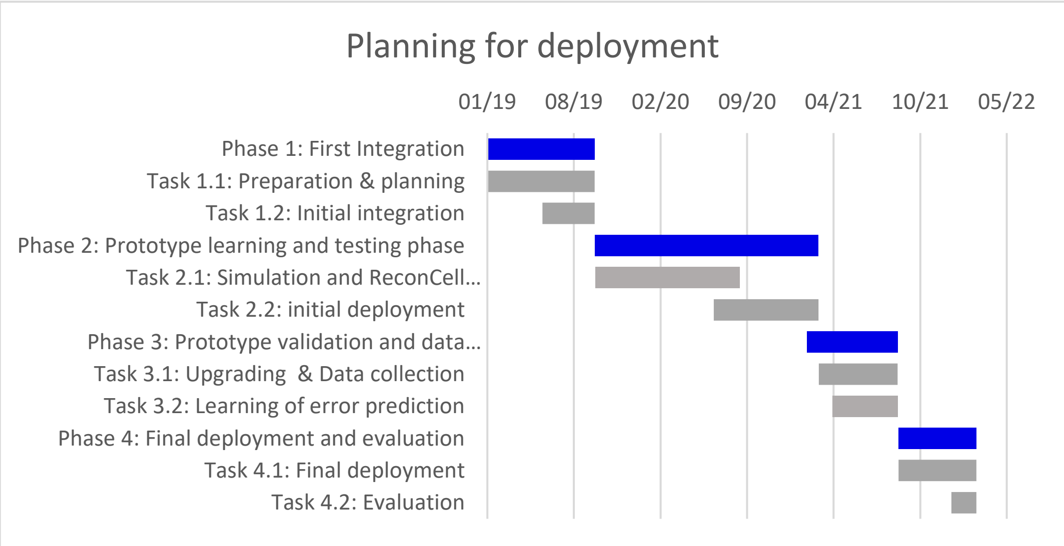
- Smart IoT device testing with the latest software upgrades of the Kolektor Visual Platform.
- Kolektor Visual Platform was extended with the device management and system resource monitoring functionality.
- Data acquisition after hardware upgrades of the production data on the pilot line.
- Upgraded the initial machine vision visual inspection AI models.
- Upgraded data acquisition from machines on pilot.

JSI - Due to limited access, JSI part was done in parallel on JSI Technological Experimental Facility (TEF),

- Integration of a robot system for adaptive visual quality control.
- Preparation of HPC infrastructure for training of neural networks for prediction of defects based on process parameters and images of parts
- Implementation of adaptive, robot supported visual quality control from a number of predefined viewing directions

CEA – In-lab tests on a lathe did not give satisfactory results for integrity and wear monitoring of the cutting knife. Deployment of such a measurement means has thus been stopped on the KOLEKTOR pilot.

Implementation timeline for pilot 7:



- **Pilot 8: Steering column assembly (THYSSEN)**

This pilot describes an electric steering columns production line. The steering column of a car (see Figure 19) consists of multiple individual parts including electric motors that are assembled to one unit. Currently, an end of the line acoustic quality test is carried out. The Qu4lity ZDM concept proposes to include an intermediate acoustic test for the monitoring of a critical assembly step with control functions for the operator as well as an AI-based supervision of the whole assembly line for predictive maintenance and general monitoring. Figure 20 and Figure 21 show the current and future configuration of the steering column assembly line.

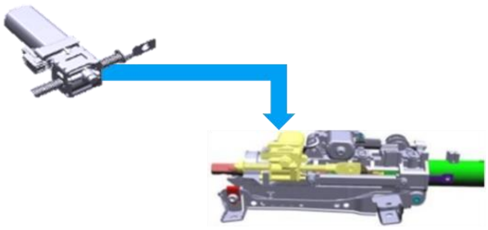


Figure 19: Steering column of a car.

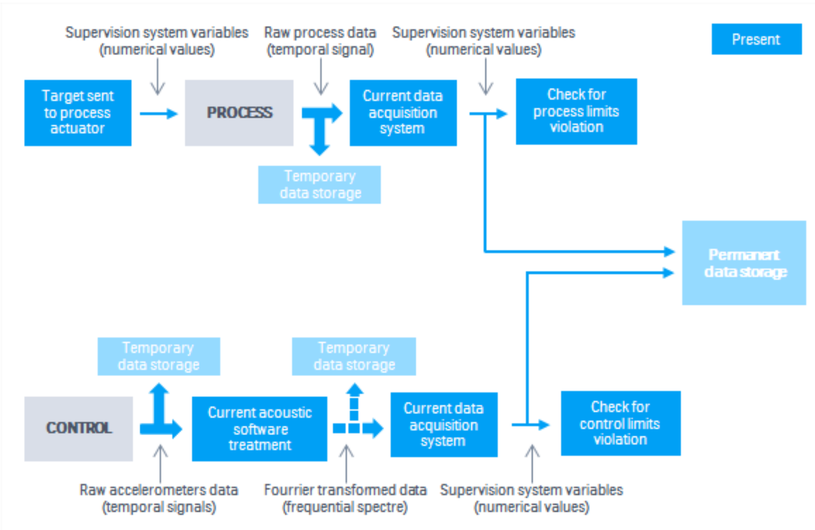


Figure 20: Current configuration of the steering column assembly line.

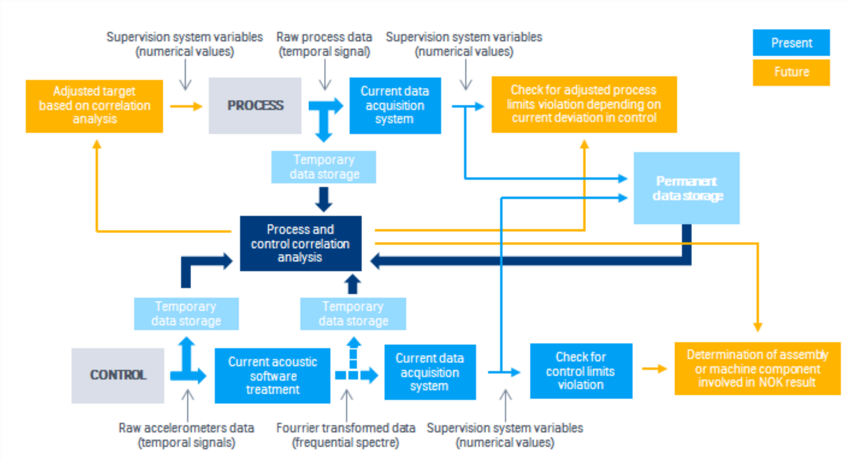


Figure 21: Future configuration of the steering column assembly line.

Digital enhancement target:

• Data acquisition • Big Data analytics
The enhancement target of this pilot is to reduce NOK parts with a correlation between process and control by the introduction of supplementary sensors on a specific assembly step. The prediction of the result of this assembly step should allow adjusting all process values to respect our Quality requirements in term of acoustic control and process operation by identifying component(s) responsible for acoustic limit excess. Furthermore, Big Data analytics will be introduced to detect potential machine interaction on measurements and avoid fall-out in the control step (OK considered NOK). AI-based analytics could also be used for predictive maintenance and to determine actuators and sensors remaining useful life. Finally, the system needs to stay flexible for future new product integrations and provide an user-friendly teaching method for AI and allows a quick correlation with process data.

Digital enabler type:

A Big Data acquisition system is added, it will retrieve raw data from process and control operation to analyze the different correlations between them by means of Big Data analytics. The goal is to be able to realize the correlation between process data and control result, and apply predictive maintenance cycles with reduced assembly line downtimes. The second enabler will be a supplementary acoustic measurement on a critical assembly step with the goal to directly operate on the part if any deviation is detected.
CEA – Acoustic monitoring. The purpose of this component is to retrieve process data from a specific process step (acoustic analysis of assembled parts with accelerometers and microphones) and to apply signal-processing algorithms to identify markers that could be correlated to specific defects.

AIT – Monitoring of whole production line. Correlation and rules establishment between process inputs and control outputs as well as predictive maintenance to detect upstream sensor and actuator deviations.

THYSSEN – Implementation of a new manufacturing execution system with Cloud capabilities.

Interfaces:

Current interfaces are based on Zpoint / TwinCat 2 and IEC 61131 / IEC 61499.

Future interfaces will be based only on MOM / IEC 61131 / IEC 61499.

Expected results:

- Solution must be implemented as a step-in current production line.
- Identification and detection of root cause probabilities for each component of the assembly, machine can interfere with the measure, deviations have to be detected as clamping or tightening forces.
- Assembly process can also influence the acoustic signature of the part, upstream deviations can be detected and corrected by the measure
- OEE : 80% *(currently 60%)*
- PPM : 5 000 *(currently 15000)*

Achieved results at M33:

For the moment, no direct improvement to production KPIs has been realized with a direct relation to the project yet, but both development of CEA and INTRASOFT solutions have reached a suitable state :

Non-intrusive sensors Testing :

- Acquisition system validated
  - *Signals stability has been improved*
  - *Multiple contact assets measurement privileged to the benefit of aerial (microphone) due to environment noise*
- Collection of multiple sample to enlarge use-cases

Analysis of sample data :

- Correlation rules to maximize OK/NOK ratio :
  - *New use-case dataset taken into account*

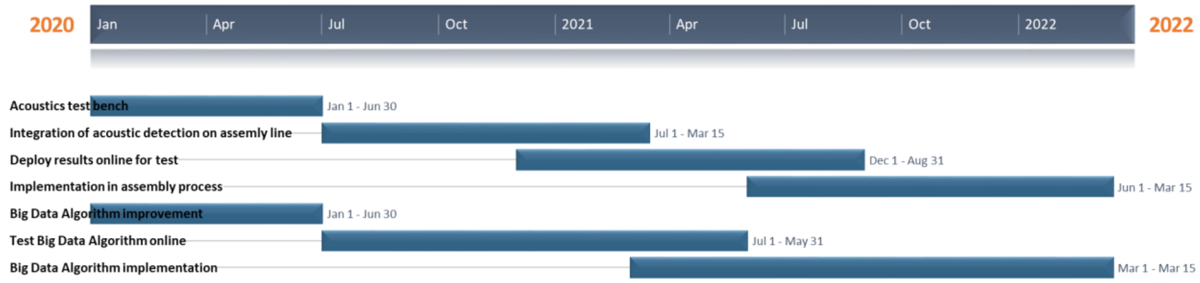
- *Correlation without precise traceability in study*

Non-intrusive PLC interface :

- Universality for any (TKP) PLC :

Single exchange table interface for any production line used (→ validated)

Implementation timeline for pilot 8:



4. Machine Enhancement Integration within the QU4LITY Framework

As advanced in D4.4 in relation to Communication and Control of Enhanced Equipment, at the Conclusions section, the Table 1 is a compendium, for each one of the 5 Machine Pilots from WP7 and 2 Machine Experimental Cases from WP6, of the Technological Enablers, the Enhanced Machine Capabilities and the New or Improved Services (Machine as part of a Process) developed, respectively, as part of QU4LITY WP3, WP4 and WP5.

This is done here, in order to have a summary of what digital infrastructure did we implement, which machine capabilities have been enhanced and how they are mapped within a process with the higher company-level IT layers and services, for clarification and wrap-up purposes of the efforts carried out in WP4 within QU4LITY.

The Overall AQ Level maturity gap overcome between the "As-Is" and the "To-Be" at each Use Case will be reported, for all Pilots and Experimental Cases, as part of D4.10 regarding Interworking and Interoperability of Enhanced Equipment.

The categories, in each of the cases, are:

Enabler types (from WP3)	Enhanced Machine Capabilities (from WP4)	Human-in-the-Loop Services list (from WP5)
IoT Smart Sensors	Smart Machine Sensing	Production Planning
Fog/Edge Computing	Augmented Decisions Support	Product Planning
Cloud and Data Spaces	Computer Vision	Maintenance Planning and Scheduling
Analytics Platforms	Edge-Powered Distributed Control	Production Supervision and Management
Artificial Intelligence	Smart Process Adaptation	Support to Humans in the Operative phase
Cybersecurity		Functional Test and Calibration
Industrial 5G		

Table 1: Summary of the Enablers, the Machine Enhancements and Factory- and Enterprise-level Services deployed in the 7 Machine use cases.

Use case	Technology / Enabler Type(s) deployed (from WP3)	Enhanced Machine Capabilities (from WP4)	New Service types or improved ones provided to Humans (from WP5)
DANOBAT	Fog/Edge Computing Cloud and Data Spaces Analytics Platforms Cybersecurity	Smart Machine Sensing Augmented Decisions Support Edge-Powered Distributed Control	Maintenance Planning and Scheduling Production Supervision and Management Support to Humans in the Operative phase
FAGOR	Fog/Edge Computing Cloud and Data Spaces Analytics Platforms Cybersecurity	Smart Machine Sensing Augmented Decisions Support Computer Vision Edge-Powered Distributed Control	Maintenance Planning and Scheduling Production Supervision and Management Support to Humans in the Operative phase
GHI	IoT Smart Sensors Fog/Edge Computing Cloud and Data Spaces Analytics Platforms	Smart Machine Sensing Augmented Decisions Support Computer Vision	Production Planning Maintenance Planning and Scheduling Production Supervision and Management Support to Humans in the Operative phase Functional Test and Calibration
GF	IoT Smart Sensors Analytics Platforms Artificial Intelligence	Smart Machine Sensing Augmented Decisions Support Computer Vision Edge-Powered Distributed Control Smart Process Adaptation	Product Planning Maintenance Planning and Scheduling Production Supervision and Management Support to Humans in the Operative phase Functional Test and Calibration
PRIMA	Cloud and Data Spaces Analytics Platforms Artificial Intelligence	Smart Machine Sensing Augmented Decisions Support Computer Vision Smart Process Adaptation	Production Planning Product Planning Maintenance Planning and Scheduling Production Supervision and Management Support to Humans in the Operative phase

ASTI	IoT Smart Sensors Fog/Edge Computing	Smart Machine Sensing Edge-Powered Distributed Control Smart Process Adaptation	Production Supervision and Management
UNIM	IoT Smart Sensors Fog/Edge Computing Analytics Platforms	Smart Machine Sensing Augmented Decisions Support Computer Vision Edge-Powered Distributed Control	Maintenance Planning and Scheduling Production Supervision and Management Support to Humans in the Operative phase Functional Test and Calibration

Conclusion

One issue for the QU4LITY Project is to discuss if the future expected results can give the QU4LITY Platform a lead to new business models and market opportunities. Interoperability between machines and platforms are essential aspects to improve the usage of digital enhancement in the different use cases.

Most of the machine or process pilots are equipped with data collection, BigData analytics and simulation capabilities (including digital twin applications) within the Qu4lity project. The specific enhancements to be carried out, depend on the nature and type of each machine and process pilot and are described in this document. The current and future configuration of 5 machine pilots, 2 process pilots and an experimental case is given together with a succinct description of the digital enhancement type, its interfaces, expected and achieved results as well as an implementation schedule. The full information about the ASTI experimental case was already provided in D4.4 regarding Communication and Control Infrastructure.

It can be seen that the current configurations of the pilots do not yet take sufficiently advantage of the data already available on the machine or process line. This is due to missing data collection capabilities and associated data analytics means. In some pilots, specific data relevant to improve overall quality is missing. It is intended to provide special sensors to gather this missing information. All this will allow artificial intelligence data analytics approaches to identify quality issues already during manufacturing or assembly well ahead the final quality check.

The main task of this deliverable was to follow the implementation of digital upgrades as specified in T4.1, in terms of data acquisition, analytics, simulation and more. The implementation is leveraging enablers developed in WP3, which are used according to the specifications for each type of ZDM equipment. Most of the machine or process pilots are equipped with data collection, BigData analytics and simulation capabilities (including digital twin applications). The specific enhancements that have been carried out, depend on the nature and type of each machine and process pilot and are described in this document. The former and updated configuration of 5 machine pilots, 2 process pilots , and an experimental case (Unimetrik) is given together with a succinct description of the digital enhancement type, its interfaces, expected and achieved results as well as an implementation schedule.

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List of Abbreviations

AI	Artificial Intelligence
AM	Additive Manufacturing
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CbM	Condition based maintenance
CMM	Coordinate Measuring Machine
CnC	Computer numerical Control
DAS	Direct Attached Storage
DSS	Decision Support System
EDM	Electrical Discharge Machining
ETH	Ethernet
HTTPS	HyperText Transfer Protocol Secure
IoT	Internet of Things
KPI	Key Performance Indicators
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
OEE	Overall Equipment Effectiveness
OPC UA	Open Platform Communications Unified Architecture
PPM	Parts Per Million
PLC	Programmable Logic Controller
RUL	Remaining Useful Life
ZDM	Zero Defect Manufacturing

Partners:

