DIGITAL REALITY IN ZERO DEFECT MANUFACTORING

D5.6 Tools and Techniques for Adaptive Shopfloor Automation and ZDM Processes (Version 2)

Deliverable Id :	**D5.6**
Deliverable Name :	**Tools and Techniques for Adaptive Shopfloor Automation and ZDM Processes (Version 2)**
Status :	**Final**
Dissemination Level :	**PU**
Due date of deliverable :	**30.09.2021**
Actual submission date :	**13.10.2021**
Work Package :	**WP5**
Organization name of lead contractor for this deliverable :	**ATB – Institut für angewandte Systemtechnik Bremen GmbH**
Author(s):	**ATB – Ana Teresa Correia, Marcel Dechert, Feryal Fulya Horozal, Sebastian Scholze**
Partner(s) contributing :	**FHG, JSI, INNOVALIA, NXT, PACE, SQS, SYN, TUDO**

Abstract: This deliverable presents the project's final activities towards enabling the development and deployment of adaptive digital shopfloor automation and ZDM processes. In particular, it presents the tools and technologies used and adapted for this purpose and highlights the main implementation features of each tool within the specific QU4LITY pilot or use case they are used. Moreover it gives an evaluation of these tools and technologies with respect to their contribution to the enhancement of adaptive digital shopfloor and ZDM processes based on the pilot requirements that address the adaptability functionalities of digital shopfloor and ZDM processes.

Co-funded by the Horizon 2020 Programme of the European Union

Contents

History

Version	Date	Modification reason	Modified by
0.1	20.05.2021	ToC created	ATB
0.2	15.06.2021	First input collected from each technology partner	ATB, FHG, INNOVALIA, JSI, NXT, PACE, SQS, SYN, TUDO
0.3	08.08.2021	ToC updated	ATB
0.4	09.09.2021	First input from each partner integrated and harmonized in the document	ATB
0.5	24.09.2021	Final input added from technology partners	ATB, FHG, JSI, NXT, PACE, SYN, TUDO
0.6	04.10.2021	Final input added from technology partners	INNOVALIA, SQS
0.7	05.10.2021	Final input from each partner integrated and harmonized in the document	ATB
0.8	06.10.2021	Document sent to the internal reviewer	ATB
0.9	12.10.2021	Internal revision received and integrated	TTS, ATB
1.0	13.10.2021	Final version submitted	ATB

1. Introduction

1.1 Scope and Purpose of the Deliverable

This document, D5.6, presents the results done within Task 5.3, Adaptive Digital Shopfloor Automation, after the submission of the first deliverable D5.5 [1] in M16 and is the second and final deliverable of this task. Task 5.3 is part of the activities that contribute to WP5, Open Autonomous Quality Services Engineering and Processes, supporting the engineering of Zero-Defect Manufacturing (ZDM) processes based on the Autonomous Quality (AQ) paradigm. As elaborated in D2.12 [2], Reference Architecture and Blueprints (Final Version), in detail, the concept of ZDM in QU4LITY is a holistic quality management approach that ensures both process and product quality by reducing product defects through corrective, preventative and predictive techniques. It leverages data-driven technologies to guarantee that no defective products leave the production site.

As specified in D2.12 [2] the domain of adaptive digital shopfloor automation includes functionalities supporting automated monitor and control of Assets and Smart Products in the physical world, contributing to the Automation and Control domain of QU4LITY. Automation and Control domain includes functionalities enabling efficient and reliable data exchange and intelligent control over the physical production processes and assets.

The main goal of Task 5.3 is to provide the means for the development and deployment of adaptive digital shopfloor and ZDM processes. Within the scope of this goal Task 5.3 focused on engineering the capability of the digital shopfloor and ZDM processes to adapt themselves to various changing conditions of the shopfloor and to reconfigure themselves following the detection of defects, equipment degradation patterns and other related criteria while the machines/production lines are in operation.

1.2 Approach

Task 5.3 contributes to adaptive digital shopfloor automation and ZDM processes by providing a comprehensive toolset of adopted and customised tools and technologies, which are used in the QU4LITY Pilots and Use Cases. This toolset covers a wide spectrum of technologies including data monitoring based context awareness technologies, ontology-based data processing technologies, reconfigurable robotics technologies, automation technologies for Industry 4.0, composable digital shopfloor technologies, augmented reality technologies, AI and machine learning technologies and data exchange enablers based on the MQTT (MQ architecture). These technologies are introduced and analysed in depth in the first deliverable D5.5 [1] of this task. Based on these technologies, the toolset for adaptive digital shopfloor automation in QU4LITY consists of the following tools and technologies:

1. Context awareness framework (used in the Continental Pilot);
2. Ontology-based data processing (used in the Airbus Pilot);

3. Adaptive visual quality inspection (used in the Kolektor Pilot);
4. NxTTech IDE and EcoRT runtime system (used in the NXT and ASTI use case);
5. AUTOWARE composable digital shopfloor verification and validation framework (used in the GHI and GF Pilot);
6. Pacelab WEAVER augmented reality for operational support (used in the Continental Pilot);
7. Improved failure classification enabler (used in the Siemens Pilot);
8. Data analytics tool for additive manufacturing (used in the Prima Pilot).

In this deliverable each of these tools is presented together with a short overview of the pilot or use case they are used in. Background technologies used in the development of each tool is briefly introduced and the major strengths of the tool are elaborated within the context of industrial innovation. Moreover, main implementation features of each tool are highlighted and each tool is evaluated with respect to their contributions to adaptive digital shopfloor automation and ZDM processes within respective the pilot or use case.

1.3 Relation to the QU4LITY Reference Architecture

Task 5.3 contributes to the work in WP5 to enable the engineering of ZDM processes based on autonomous quality. Figure 1 illustrates an overview of WP5 vision.

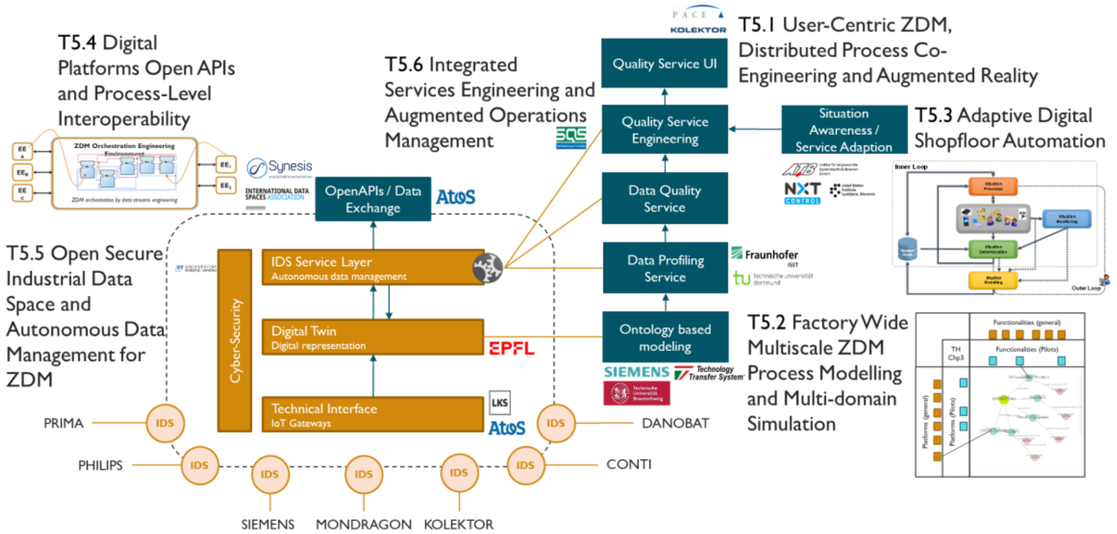


Figure 1: WP5 vision

WP5 activities comprise of tasks that leverage digital platforms functionalities through:

- Customisation and integration of user HMI technologies and platforms to ZDM processes (Task 5.1),
- customisation and integration of simulation processes and digital twins to the multiple-stage ZDM processes based on AQ (Task 5.2),
- adaptive digital shopfloor automation and ZDM processes (Task 5.3),

- enhancement of digital platforms based on OpenAPIs (Task 5.4),
- integration of digital platforms to the open secure Industrial Data Space (Task 5.5), and
- enabling an open and integrated service engineering approach base on the integration of functionalities from multiple platforms (Task 5.6).

The QU4LITY Reference Architecture (Q-RA) is the conceptual framework that acts as a base reference for the design and the implementation of QU4LITY based solutions.

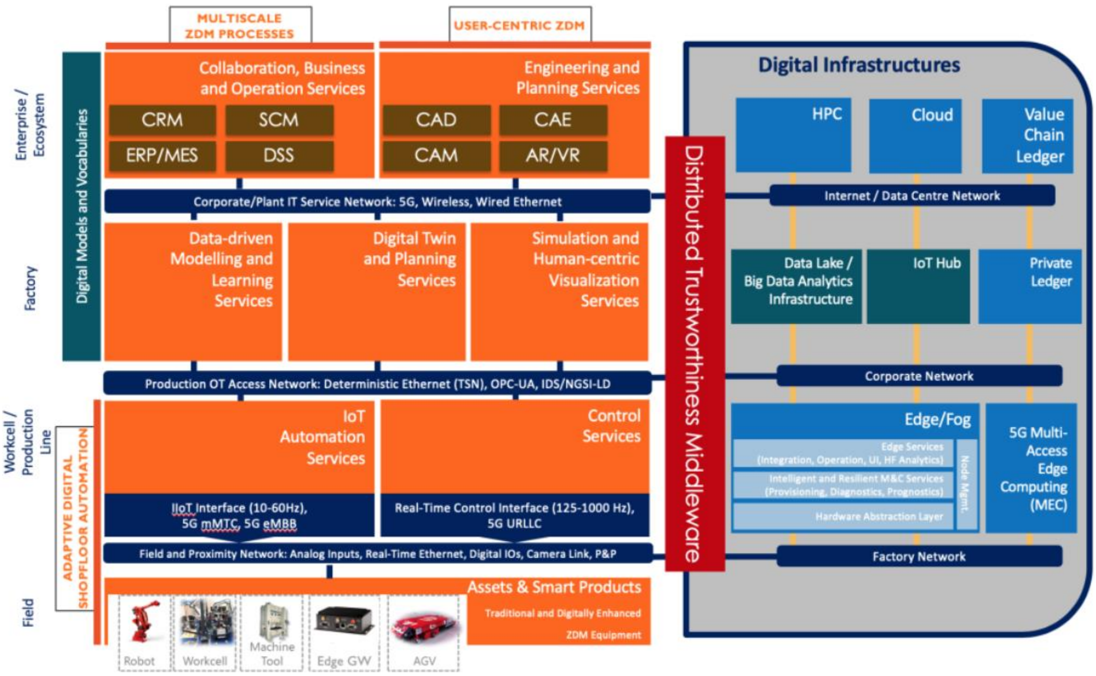


Figure 2: QU4LITY Reference Architecture

Table 1 gives an overview of the mapping of the tools and technologies from Task 5.3 to the QU4LITY Reference Architecture. The eight solutions from Task 5.3 contribute to many areas of the Digital Manufacturing Platform & Service Layer of the QU4LITY Reference Architecture including IoT automation services, data-driven modelling and learning services, simulation and human-centric visualization services, control services, field devices & products and engineering and planning services.

Table 1: Mapping of Task 5.3 Solutions to the QU4LITY Reference Architecture

Tool / Technology	Pilot / Use Case	Digital Manufacturing Platform & Service Layer	Digital Infrastructure	Services
Context Awareness Framework	Continental	IoT automation services	Data lake / big data analytics infrastructure	Context handling and data monitoring services
Ontology-based Data Processing Techniques	Airbus	Engineering and planning services, simulation and human-centric visualization services, data-driven modelling and learning services	Local access to future cloud-based solutions	Requirements management for industrial systems, verification for industrial systems design, model-based industrial system design
Adaptive Visual Quality Inspection	Kolektor	Data-driven modelling and learning services, IoT automation services, field devices & products	HPC	Data acquisition, machine vision, IIoT MES/MOM, robotic workcell
NxTTech IDE and EcoRT Runtime System	NXT & ASTI Use case	Control services, IoT automation services	Edge digital infrastructure	Real-time control services, data monitoring services, supervisory services, asynchronous services, control loop services, auto-discovery services
WEAVR Augmented Reality for Operational Support	Continental	Engineering and planning services, simulation and human-centric visualization services, control services, field devices & products	VR/AR services linked to WLAN, smart devices connected to factory network, data lake/big data analytics infrastructure, smart glasses/holoLens	AR operator guidance/maintenance assistance
AUTOWARE Composable Digital Shopfloor Verification and	GHI, GF	Simulation and human-centric visualization services		Simulation, error identification, functional validation

Tool / Technology	Pilot / Use Case	Digital Manufacturing Platform & Service Layer	Digital Infrastructure	Services
Validation Framework				
Data Analytics Tool for Additive Manufacturing	Prima	Simulation and human-centric visualization services, data-driven modelling and learning services	Edge	Visualization of KPIs on a dashboard, data aggregation and KPI evaluation
Improved Failure Classification Enabler	Siemens	Data-driven modelling and learning services	Data lake / big data analytics infrastructure	Pseudo error reduction

1.4 Deliverable Structure

The deliverable is structured as follows:

- Section 2 presents each tool and technology that is part of the toolset of Task 5.3.
- Section 3 evaluates each tool and technology from Section 2 with respect to their contribution to enabling adaptive digital shopfloor automation and ZDM processes.
- Section 4 concludes the deliverable.

2. Tools and Techniques for Adaptive Shopfloor Automation and ZDM Processes

2.1 Context Awareness Framework

2.1.1 Overview

The Context Awareness Framework is composed of several components and is a framework that processes data coming from connected data producers (systems, devices, products) via the Context Monitoring component in Figure 3. The framework can use this data and combine/use it with services provided by external service providers (External Services in Figure 3) to extract the current situation (context) of these connected data producers with the so-called Context Extractor components in Figure 3. The Context Provision component makes the context available to further use.

The overall context extraction process follows the structure of sensory systems or CPS to collect & deliver context relevant data about processes / equipment / products to reason for this context based on an ontology, which is further evolved and enhanced through similarity measures.

Figure 3 shows the conceptual architecture for the Context Awareness Architecture that is specified in this document.

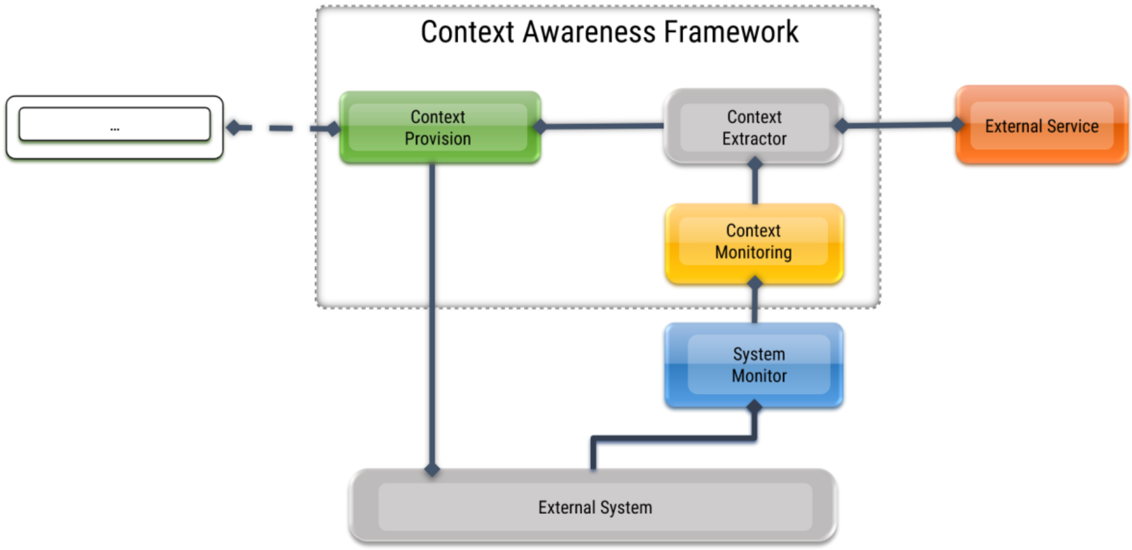


Figure 3: Conceptual Context Awareness Architecture

2.1.2 Background Technologies

To create the described solution based on the functional specifications, several technologies and tools are needed. These tools support the creation of specific services describe out of the requirements or offer the ability to sum up all parts of the system.

The components specified in this deliverable that will be implemented starting from the previously mentioned projects Self-Learning, ProSEco and SAFIRE and will be extended using the Java programming language. For developing and maintaining the context model (ontology), Protégé will be used. Protégé is a widely accepted open-source platform that offers the ability to develop and visualise complex models, including properties and relations, and allows for export of the model in different formats (e.g. rdf, owl, turtle, etc.). To monitor the information out of files and Web Services several additional Java compliant libraries will be used.

The repositories are based on a POJO[1]-based approach, which is serialized into an abstraction layer that covers many legacy database systems to work with (e.g. MySQL or H2). The specified tool rely on the abstraction layer as persistence enterprise system and does not require a mandatory database but only a compliant one as technical foundation.

2.1.3 Envisioned Industrial Innovation

The Context Monitoring / Extraction method uses monitored “raw data” provided by systems / sensors as well as knowledge available in different systems, and possibly external services analytics, to derive the product / machine / process current context. Using the context models the monitored data is evaluated and the context extracted. Based on the identified context, context models can be compared to previous ones and stored. A continuous process, coordinating with the monitoring, and followed by the reasoning process to give current contextual meaning to the provided knowledge, is built around the extraction of context.

The main industrial innovation expected is that the context identified by the Context Awareness Framework and provided to other tools in the shopfloor to automate and adapt certain processes and outputs based on the context in which the products / machines / processes are being used.

2.1.4 Pilot / Use Case Description

Continental Automotive is shipping products to its customers that have gone through numerous tests. This is done to ensure Zero Defects at the product are arriving at the customer OEM and when the car buyer is receiving his vehicle. The KPI related that is 0km PPM (Car has gone 0m, means it is evaluated the quality of the car when first time is taken into operation. PPM = parts per million defective. Expectation towards suppliers is meanwhile in the direction of 0 ppm). No part leaves Continental plants that does not have only “OK” test results. It is being tested against specifications agreed between the supplier and the customer. Test and Inspections are mainly

[1] https://en.wikipedia.org/wiki/Plain_old_Java_object

performed by Electronic Equipment: Solder Paste Inspection Systems, Automatic Optical Inspection, In-circuit Test and Functional Test. All data involved in the production and testing of the Continental products are saved in the so called Continental datalake.

Within the Continental Pilot the Context Awareness Framework was extended by an interface to enrich the Context Extraction with additional information provided by an external service, in this case a Big Data Analytics service (see the right block of Figure 4).

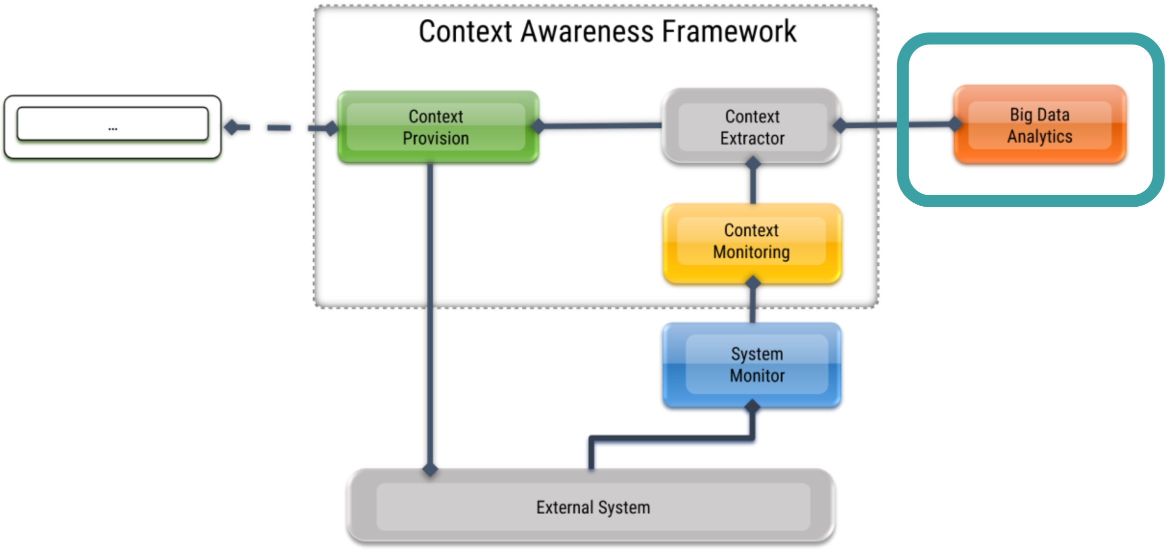


Figure 4: Context Awareness Framework applied in the Continental pilot (high level overview)

The so called "Online Data Acquisition and Industrial Data Analytics" pilot application makes use of Cloud technology and the Big Data analytics technology with the support of the Context Awareness Framework (provided by ATB). The Big Data Analytics component (provided by Sintef) applies technology to handle the huge amount of structured and unstructured data while ATB applies Technology for Analytics and Evaluation of risk sitting in individual Production sequences (within the Context Extractor component).

2.1.5 Technology Implementation

2.1.5.1 Technology Description

Based on the Context Awareness Framework, we have implemented a pipeline to retrieve relevant data, process and analyse it and finally make the information available to users within Continental.

The following are the main components of the pipeline with respective steps followed from data source to context provisioning to the end user:

1. Context Monitoring
    a. Retrieve data from Continental datalake

2. Context Extraction
    a. Pre-process and format data
    b. Run analysis algorithm of the Big Data Analytics service
    c. Store results in MongoDB
3. Context Provision
    a. Rest API

The context monitoring component can be configured to access different data sources and scheduled to run in defined time intervals. On every iteration, all steps listed above are executed. For the purpose of prototype testing, it was set up to retrieve historical data, which can be used to evaluate and improve the underlying big data analytics algorithm. The algorithm is only delivering good results if the units analysed are very similar. For this reason, and taking the advice of a domain expert from Continental into account, we considered all units produced within a 4-hour timeframe as one batch for the purpose of our analysis. This ensures that we are comparing reasonably similar units, as parts produced in such temporal proximity to each other are usually manufactured under the same conditions.

In the first step (*1.a)*) the relevant data is downloaded via SQL query, which is dynamically constructed depending on the timeframe that was configured. The raw data is stored in CSV format. In the second step (*2.a)*) the CSV file is passed to a python script developed to pre-process and format the data. The Python script based on the Pandas and Numpy libraries fulfils several important tasks:

- Firstly, the script combines the name, id, and associated test plan into a tuple, which is needed to uniquely identify each test step.
- Secondly, incomplete data is filtered out. The analysis algorithm of the Big Data Analytics service works best if all the variables are present. Therefore, units, which do not have all the expected test measurements present, should not be processed further at this point (they are stored in a separate file for later). This is done to negate the problem, that tests of the same unit can be part of different batches, since those are arbitrarily separated only based on the timestamp.
- On the next iteration, the units that were left over, will be considered again.
- Finally, the main operation begins, i.e. the relevant numerical test measurements are combined with the unit ids and converted into a 2-dimensional format. In the raw data, the test measurements are not grouped by unit. For the multi-variant analysis, this grouping is important, since it is supposed to consider multiple measurements along the production process of a unit.

In the third step (*2.b)*) the resulting formatted dataset is passed to the Big Data Analytics Service, which runs the custom multi-variant algorithm. The algorithm calculates the Mahalanobis[2] distance for each unit of the set and a critical value for the whole set. If the distance value is greater than the critical value, the unit is considered an outlier in relation to the other units in

[2] https://en.wikipedia.org/wiki/Mahalanobis_distance

the set. The results are stored in CSV format and in parallel these are written to a MongoDB. This facilitates fast access to the data and allows to run complex search and filter operations.

This data is then exposed via a RESTful API. The API was specified mainly with the Frontend in mind (in the Continental pilot implementation case), but could also be consumed by other potential apps/products. The API can also be accessed via Swagger UI, which additionally provides an OpenAPI specification. [3]

The final step in the specific implementation of the Context Awareness Framework for the Continental pilot is the presentation of the Context Provision results to the user by means of a User Interface Frontend. The Frontend is designed to enable access to the results of the statistical analysis in an easy-to-use and flexible way. It allows the user to view, search and export the relevant data.

2.1.5.2 Technology Architecture

When designing the architecture, we prioritized performance, stability, and extensibility. By our choices of technologies and data formats, we wanted to ensure that the system can be altered and extended with reasonable effort in the future. For this evolutionary prototype, it was preferable to rely on an unstructured Database (MongoDB) because of its flexibility. Compared to SQL databases, it can easily support data in many different formats without additional effort e.g., for database migrations. Similarly, the use of the CSV format allows us to do quick iterations on individual steps of the pipeline.

There are 3 main Components updated/developed in the scope of the Context Awareness Framework for the “Online Data Acquisition and Industrial Data Analytics” pilot application.

1. Context Monitoring and Extraction Java Application
2. Python Data Formatting (script)
3. User Interface Frontend

[3] https://swagger.io/tools/swagger-ui/

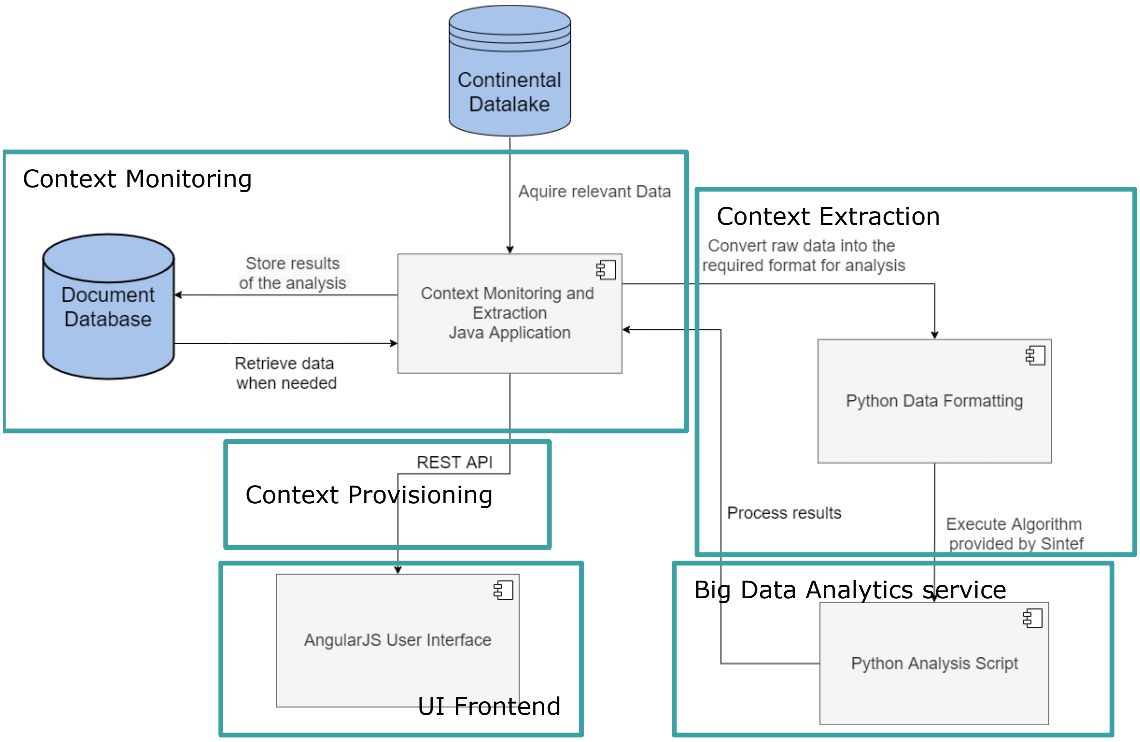


Figure 5: Detailed Pilot specific architecture

The Context Monitoring and Extraction Component is a Java Application based on the Spring Framework [4], which serves as the central component connecting all the other parts. It handles all the steps of the pipeline mentioned above. The Context Monitoring component gathers the data from the datalake. The Context Extraction interacts with the MongoDB and the Python Analysis script algorithm (Big Data Analytics service). The Context Provision Component provides the REST API. It is a pure backend service, which is not coupled to any particular frontend. This means the application can operate on its own and the API could be used by other clients as well.

The REST API is based on Spring Boot Web and Spring Data Mongo libraries. The Spring Mongo repository interfaces are used to query the database. Those methods are then used by the REST Controller, which handles incoming Requests to the different endpoints. The API can handle requests to get the analysis results in JSON and CSV format. It also offers various endpoints for filtering and aggregation. Currently, the API is read-only, meaning there are no POST or PUT endpoints that would allow manipulation of the data.

The Context Extractor component of the java application executes a python script for data pre-processing and formatting using the Apache Commons Exec library.[5] If the script succeeds, the resulting CSV file will be passed to the Python Analysis script. In case of failure, e. g. if the input could not be processed, the Context Extraction application will recognize the error, log it and terminate the pipeline. In that case, the next pipeline iteration will continue with the subsequent

[4] https://spring.io/
[5] https://commons.apache.org/proper/commons-exec

batch. When both python scripts were successfully executed, the results are parsed and a reference to the resulting CSV file is stored in the MongoDB (Document Database in Figure 5).

The User Interface Frontend is an Angular SPA (Single Page Application), which serves as the main point of access for the end-users of the prototype. The code is managed separately from the Java Application and can therefore be maintained and improved independently. The Frontend heavily relies on the REST API of the Context Provision component as a source of data, because it is using the same underlying data model. The UI is detailed in section 2.1.5.6.

2.1.5.3 Data Input

The central data source is Continental's Datalake, which is a cloud-based relational database containing data from the MES (Manufacturing Execution Systems). Most relevant for the prototype is the current and historic production process data and the corresponding testing measurements.

2.1.5.4 System Integration

The Context monitoring component interacts with the Continental datalake as a data source. The Context Extraction component interacts with the data analysis algorithm script. The integration with the Continental datalake is achieved with a JDBC connection using the appropriate Amazon Redshift database driver. Continental is currently migrating the MES datalake to RDS (Relational Database Service), which requires some adjustments to the way data is received in the future (as the migration is complete). As of now, the system is not writing back to the Continental Database for simplicity sake but it is prepared for this step and will be implemented in the future.

The algorithm was provided in the form of a Python script and put into the classpath of the Context Monitoring java application from which it can be executed using the Apache Commons Exec library. This approach allowed rapid prototyping, as no interfaces needed to be specified and developed between the Context Extraction and the data analysis algorithm script.

2.1.5.5 Deployment

For the deployment of the pilot specific implementation, it was decided that Continental providing the infrastructure to host the prototype was the best approach. This has several advantages. First of all, the datalake is only accessible from within the intranet so no extra permission and security issues need to be considered (i.e. no VPN connection is needed to connect the pipeline prototype to the database). Additionally, Continental keeps full control over access to the data, since the user base is inside Continental. This also means that there is no immediate need to add SSL encryption to the prototype. Continental set up an AWS t3.medium instance running Ubuntu, which has the necessary software installed, most importantly Docker.

The pipeline prototype consists of 3 Docker containers, which are defined and connected using docker-compose, see Figure 6. The structure of the three containers reflects the architecture described in Figure 5.

- Context Monitoring and Extraction (java application) + Python Analysis Script
- MongoDB
- Angular Frontend

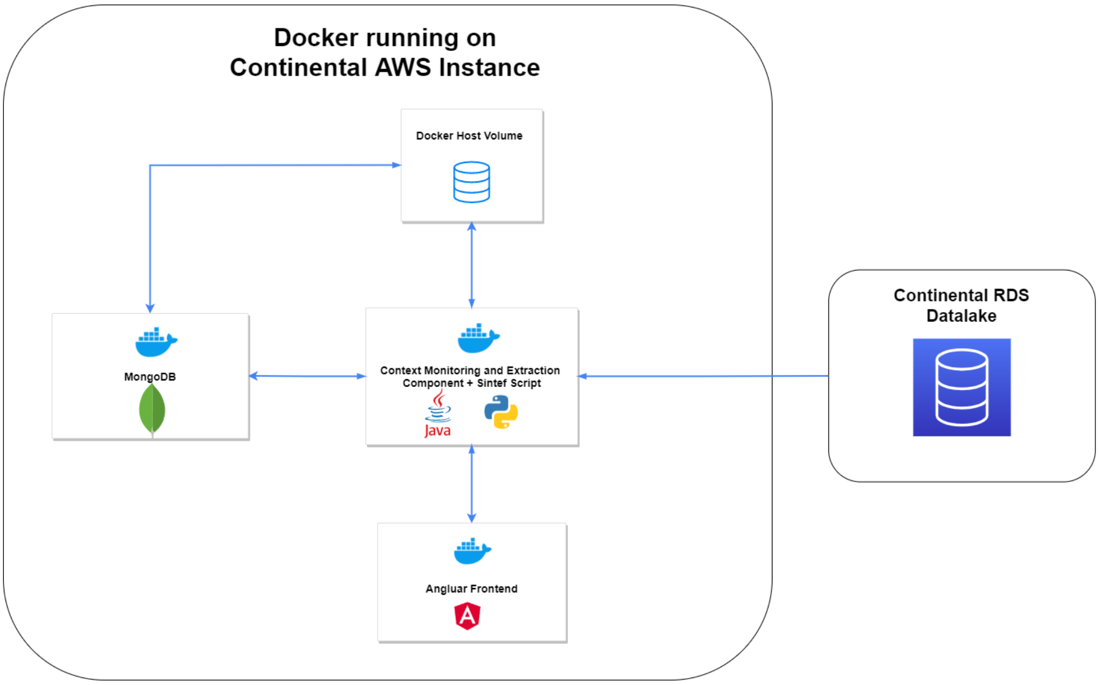


Figure 6: Docker Containers

The Java Spring application can be built and packaged as an executable .jar by the build-tool Maven6. Within a Dockerfile, the .jar file is copied into an image alongside the two python scripts. To be able to run both the Java and Python code, we created a custom image that combines Python 3.8 and Java 11.

The MongoDB container is based on the official MongoDB image provided on Dockerhub.7 Apart from creating the database and user, no further configuration is necessary.

The Angular Frontend has its own Dockerfile, which consists of two stages:

- The first step is to download the NPM dependencies and build the Angular application. An environment variable can be set to specify configurations for different environments. This way, the server address of the API the frontend should use can be configured differently e. g. for local and production environments.

[6] https://maven.apache.org/
[7] https://hub.docker.com/_/mongo

- The second step of the Dockerfile adds an Nginx web server with appropriate configuration, which exposes the SPA on the desired port. The Dockerfile is then referenced in the Docker-compose.

The containers share the same Docker network so that they can interact with each other. Currently, the data is stored in a Docker Host volume, i.e., directly on the virtual machine (VM). In the future, the data might need to be moved to an AWS Bucket, if more scalable storage space becomes required.

2.1.5.6 User Interaction

The user interface was developed in order to make the results of the Context Awareness and Data Analytics accessible to a wider audience within Continental and the Qu4lity project. To achieve this, we collaborated closely with Continental to ensure that the user flow is as intuitive and understandable as possible. The user interface allows to view the results of the analysis on 3 layers of granularity:

1. Overview of all analysed batches/sets of products (units);
2. View of one specific batch;
3. Details on a single outlier[8] unit (i.e. a unit that is identified as faulty).

On the following text, all the presented information and possible user interactions are described in detail.

Overview of All Analysed Batches: On the starting page (see Figure 7) the user is given an overview of the data that has been processed and analysed.

[8] a statistical observation that is markedly different in value from the others of the sample

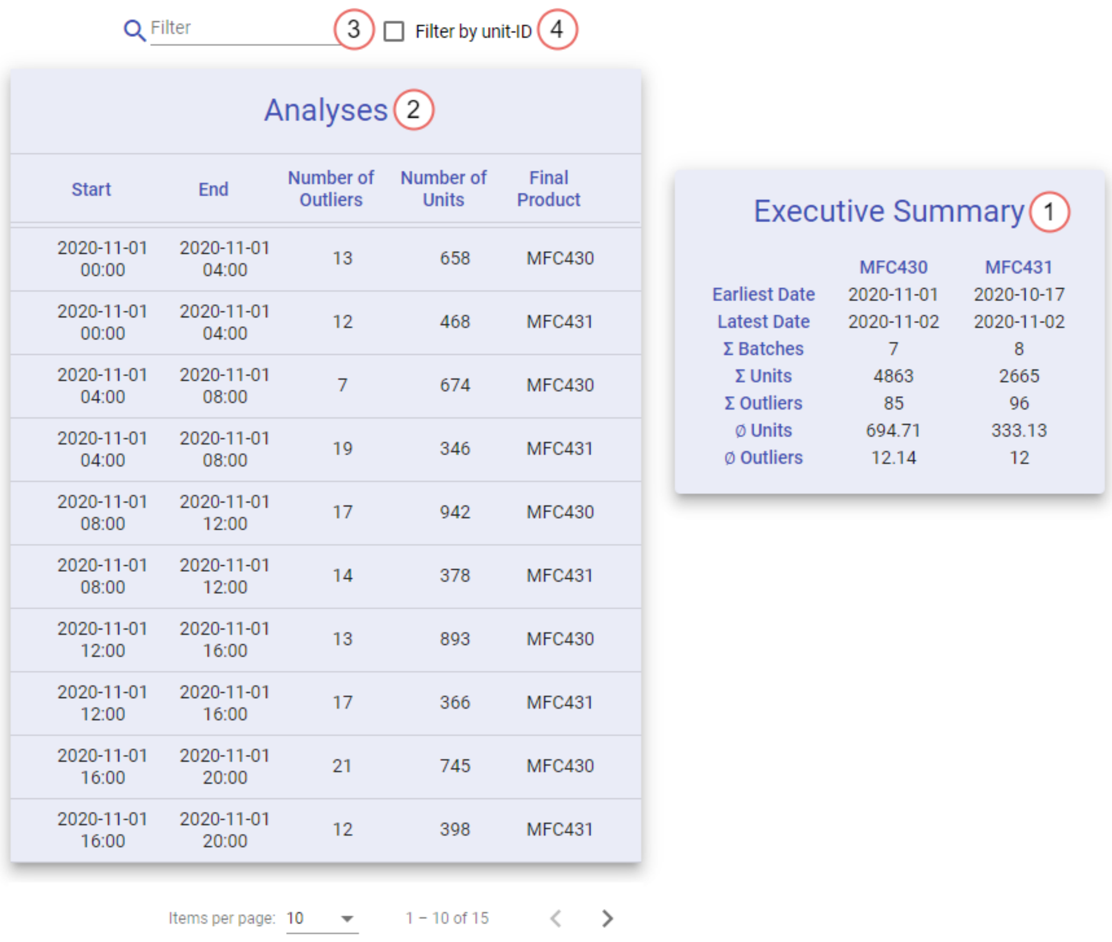


Figure 7: Overview of all analysed batches

(1) An executive summary, which gives an overview of the available data with regards to the timespan, volume and identified outliers is shown to the user.

(2) The main component on the first page is the data table, which lists the batches of units, which have been processed by the pipeline.

(3) The user can filter the list of batches by any of the columns in the table. E.g., if only batches containing data for the final Product MFC430 should be shown, the user can type that String into the filter. The filter will match any occurrences in the visible data including substrings.

(4) The Unit id filter already goes deeper, as it allows to find individual units based on their id. This can be very useful for Continental in case they are looking for a specific unit, e.g., from a list of customer returns.

When clicking on one of the batches in the table, the second page opens: **View of a Specific Batch.** This second page allows the user to take a deeper look into an analysed batch. Here, the user can learn more about the outliers that were detected by the Mahalanobis distance algorithm.

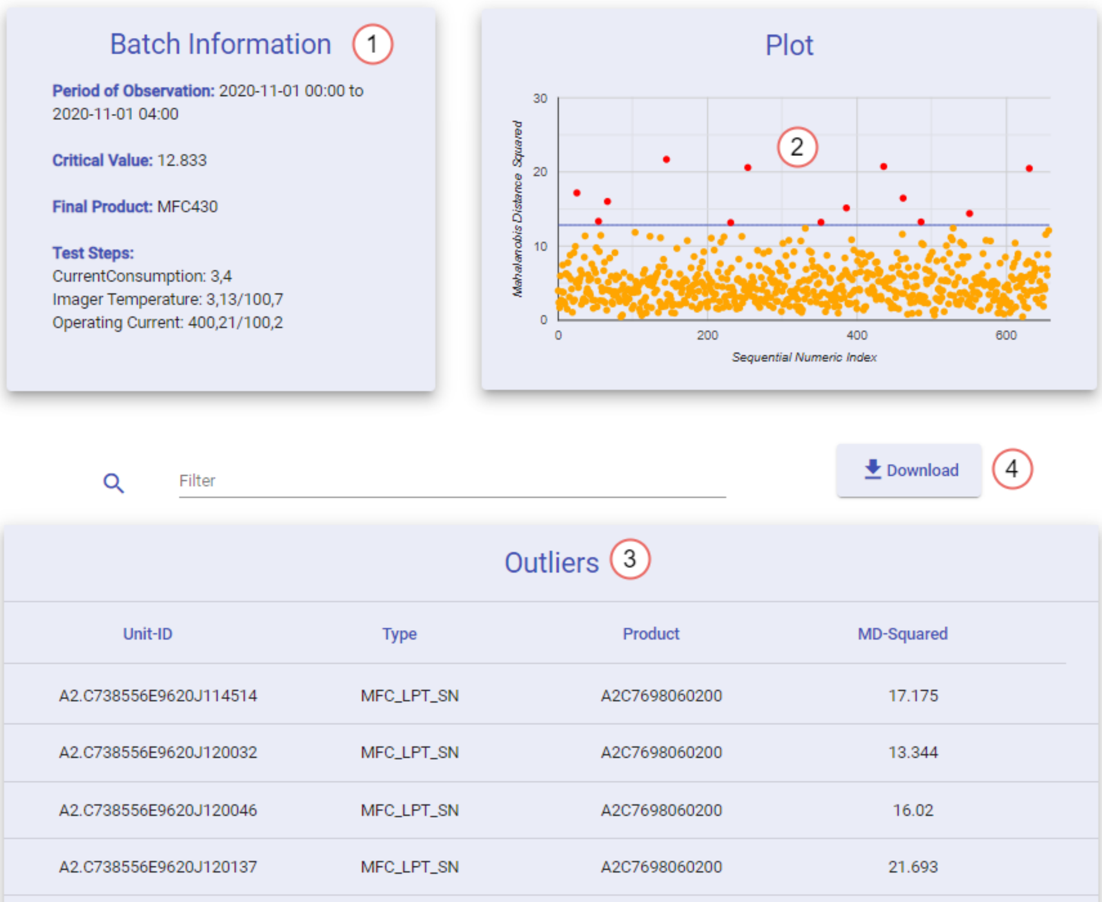


Figure 8: View of one specific batch

(1) This box lists important information about the selected batch of units, namely the covered product and time period, the test steps considered in the analysis and the critical value (i.e., the threshold which is used to identify outliers).

(2) The plot visualizes the results of the analysis for this batch. Each dot represents the Mahalanobis distance value that was calculated for one unit. The dots above the critical value line are outliers in relation to the similar units and are therefore highlighted in red.

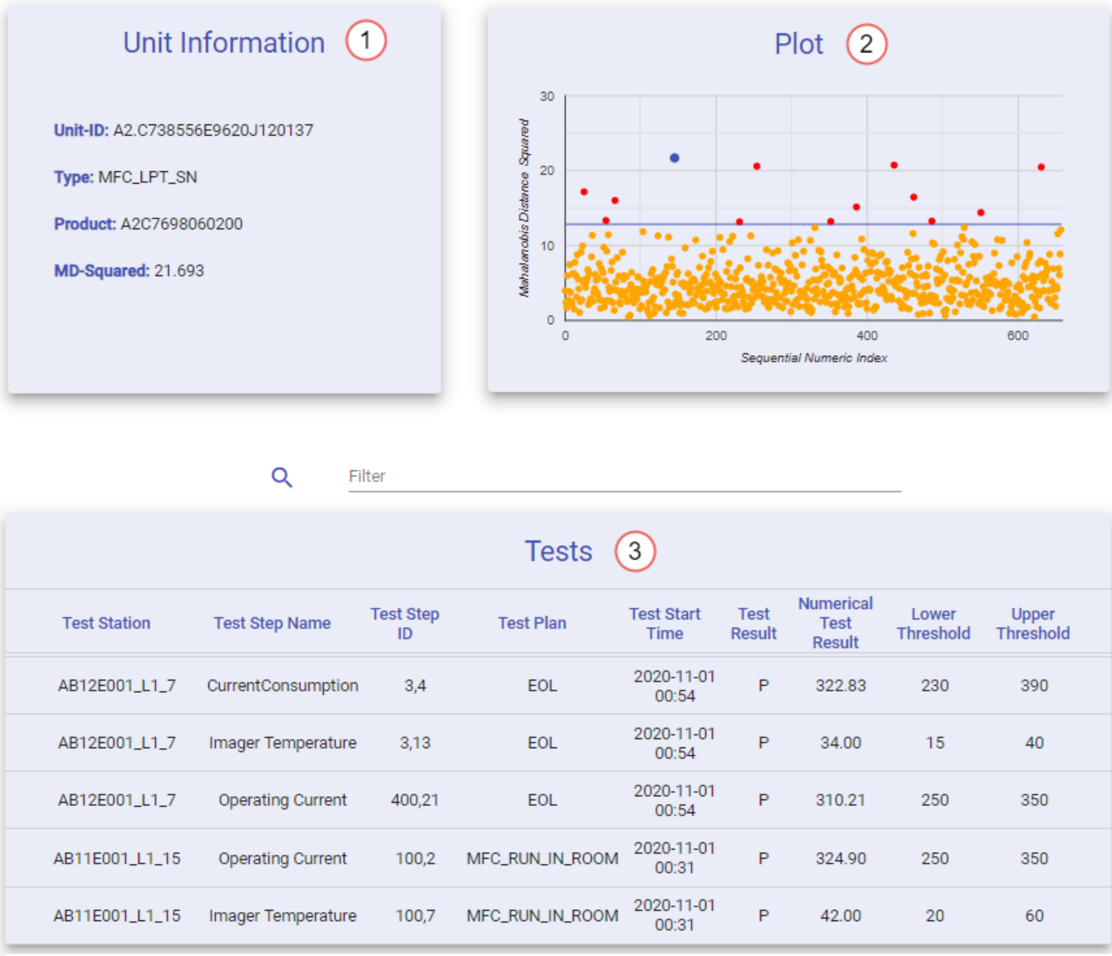
(3) The table shows some information about the outliers that were detected in this batch.

(4) There are 3 download options.

i. The analysis results for the full batch
ii. The analysis results for the outliers only
iii. A zip file containing both of the above-mentioned files and the plot in PNG format

By clicking on a unit in the table or a dot in the plot, the user is redirected to the third page, which will show more details on that specific unit:

Details on a Single Unit: The main idea of the third page (see Figure 9) is to make transparent on what basis the MD-squared value was calculated, as it allows the user to investigate the raw data that was fed into the algorithm.



Test Station	Test Step Name	Test Step ID	Test Plan	Test Start Time	Test Result	Numerical Test Result	Lower Threshold	Upper Threshold
AB12E001_L1_7	CurrentConsumption	3,4	EOL	2020-11-01 00:54	P	322.83	230	390
AB12E001_L1_7	Imager Temperature	3,13	EOL	2020-11-01 00:54	P	34.00	15	40
AB12E001_L1_7	Operating Current	400,21	EOL	2020-11-01 00:54	P	310.21	250	350
AB11E001_L1_15	Operating Current	100,2	MFC_RUN_IN_ROOM	2020-11-01 00:31	P	324.90	250	350
AB11E001_L1_15	Imager Temperature	100,7	MFC_RUN_IN_ROOM	2020-11-01 00:31	P	42.00	20	60

Figure 9: Details on a single unit

In Figure 9:

(1) The information on the selected unit that is shown in the top left-hand box corresponds to one row inside the table on the previous page.

(2) The plot is the same as on the previous page except that the selected unit is highlighted in blue. The plot also allows quick navigation to another outlier unit by clicking on any red dot.

(3) The list shows the results for each individual test and some additional information about the test, which is intended to help the user, e. g. a quality or production expert, to interpret the results.

2.2 Ontology-based Data Processing Algorithms and Techniques

2.2.1 Overview

During the early phase of an aircraft program, Industrial Architects are evaluating different industrial scenarios. One of the activities is to perform trade-off to optimize the future industrial architecture using a great variety of performances like:

- Industrial assets cost: Every decision involves trades and opportunity cost is the most desirable alternative given up as the result of a decision. The importance lies in creating opportunities and variation in the economy. Different types of financial trades are made by the company to maintain or increase the scope of charges to save and take care of the business economy which is the most important pillar of the company.
- Labour cost: Labour cost must be part of the most important parameters used by industrial architects. It is important from the fact that the direct labour cost is taken as the basis of estimating the amount of factory overheads while determining the product cost.
- Lead Time: Lead time can play a crucial role in determining the financial success of a company. In manufacturing company as AIRBUS, lead time often represents the time it takes to create a product and deliver it to a consumer. The most efficient production schedules have the least amount of lead time possible. The tool to be implemented allows to manage and run different lead times by exploring interesting areas and comparing different scenarios that do not come out of the range of targeted lead times.
- Different kind of non-quality risks within the extended enterprise: Managing quality is crucial for businesses. Quality products help to maintain customer satisfaction and loyalty and reduce the risk and cost of replacing defective products. That fits perfectly in the optics of the framework which aims primarily at a factory with zero default manufacturing.
- Production Ramp-up: To compete as a manufacturer in today’s environment, with severe competition and rapidly decreasing product life cycles, the ability to manage production ramp-up successfully has become a vital issue. One determining factor for the manufacturers to be flexible and that enable them to respond to customer demands is the ability of introducing new products in new or existing production systems successfully. Many of the factors that influence the outcome of the production ramp-up are actually possible to control by process and methods of trades off.

Examination and evaluation of alternative ways for a specific decision to make are needed to be performed in a collaborative environment enabling concurrent engineering. Finding the balance between all of these components is what will drive the trade in industrial domain.

Process, methods and tools of trade to be implemented will manage these parameters by:

- Putting constraints on the trades that stick with the expectations of the company to provide benefits;

- Providing a set of optimal to explore the design space;
- Integrated of management of trade studies;
- Iterations to zero defects manufacturing;
- Iterations to autonomous quality.

2.2.2 Background Technologies

State of the Art on Ontology: Ontology engineering is the general term for methodologies and methods for building ontologies. The results of ontology engineering provide domain knowledge representation to be reused efficiently, and prevent waste of time and money which are usually caused by non-shared knowledge. In addition, it helps Information Technology (IT) to operate with interoperability and standardization.

Semantic Modelling: Ontology represents the nature of being, becoming, existence, and so on in the way of philosophy. Ontology can be described as the machine understandable meta-model which defines different kinds of concepts and their relations based on the consensus knowledge among not only the members of the domain but also computers. An ontology serves for enabling the machine to understand the context in the way of interoperability and description of a meta-model.

An ontology represents the following ideas together:

- Semantic modelling can help defining the data and the relationships between entities.
- An information model provides the ability to abstract different kinds of data and provides an understanding of how the data elements are related.
- A semantic model is a type of information model that supports the modelling of entities and their relationships.
- The total set of entities in our semantic model comprises the taxonomy of classes we use in our model to represent the real world.

The main objective of semantic modelling techniques is to define the meaning of data within the context of its correlation, and to model the real world at the abstract level. The benefits of exploiting semantic data models for business applications are mainly as follows:

- Avoiding misunderstanding: by providing a clear, accessible, agreed set of terms, relations as a trusted source and discussions, misunderstandings can easily be resolved.
- Conduct reasoning: by being machine understandable and through the usage of logic statements (rules), ontologies enable automatic reasoning and inference which leads to automatic generation of new and implicit knowledge.
- Leverage resources: by extending and relating an application ontology to external ontological resources, via manual or automatic mapping and merging processes, the need for repetition of the entire design process for every application domain is eliminated.

- Improve interoperability: semantic models can serve as a basis for schema matching to support systems' interoperability in close environments where systems, tools and data sources have no common recognition of data type and relationships.

Ontologies provide formal models of domain knowledge exploited in different ways. Therefore, it is important that ontology plays a significant role in many knowledge-intensive applications.

Depending on corresponding languages, different knowledge representation formalisms exist. However, they consist of the following minimal set of components and share them:

- Classes represent concepts, which are taken in a broad sense. For instance, in the Product Lifecycle domain, concepts are: Lifecycle phase, Product, Activity, Resources, Even, and so on. Classes in ontology are usually organized in taxonomies through which inheritance mechanisms can be applied.
- Relations represent a type of association between concepts of the domain. They are formally defined as any subset of a product of n sets, that is: $R \subset C1 \times C2 \times ... \times Cn$. Ontologies usually contain binary relations. The first argument is known as the domain of the relation, and the second argument is the range.
- Formal axioms serve to model sentences that are always true. They are normally used to represent knowledge that cannot be formally defined by the other components. In addition, formal axioms are used to verify the consistency of the ontology itself or the consistency of the knowledge stored in a knowledge base. Formal axioms are very useful to infer new knowledge.

For instance, Energy Efficiency at Buildings domain could be that it is not possible to build a public building without a fire door (based on legal issues).

Instances are used to represent elements or individuals in an ontology.

As a Design Rationale (DR), ontology can be used as follows:

- Level 1: Used as a common vocabulary for communication among distributed agents.
- Level 2: Used as a conceptual schema of a relational database. Structural information of concepts and relations among them is used. Conceptualization in a database is nothing other than conceptual schema. Data retrieval from a database is easily done when there is an agreement on its conceptual schema.
- Level 3: Used as the backbone information for a user of a certain knowledge base. Levels higher than this plays roles of the ontology, which has something to do with "content".
- Level 4: Used for answering competence questions.
- Level 5: Standardization 5.1 Standardization of terminology (at the same level of Level 1) 5.2 Standardization of meaning of concepts 5.3 Standardization of components of target objects (domain ontology). 5.4 Standardization of components of tasks (task ontology)

- Level 6: Used for the transformation of databases considering the differences of the meaning of conceptual schema. This requires not only structural transformation but also semantic transformation.
- Level 7: Used for reusing knowledge of a knowledge base using DR information.
- Level 8: Used for reorganizing a knowledge base based on DR information.

OntoPPlan: OntoPPlaN is an ontology based on the state-of-the art including semantic modelling, as presented above in this section. Its modular structure grounds on work on ontology engineering, e.g. as described by Spath et al. [3], resulting in a proceeding for the development ("engineering") of ontologies as presented in the following figure.

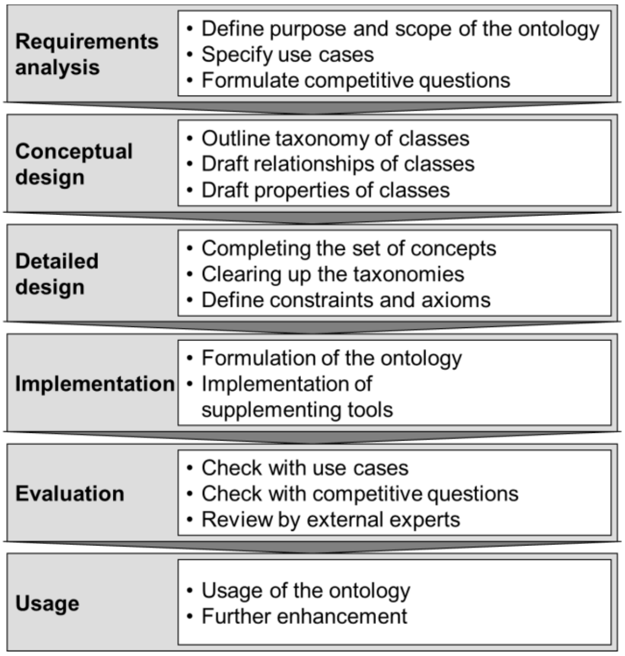


Figure 10: OntoPPlan Schema

The structuring of the overall ontology as a set of sub-ontologies, thereby follows typical approaches, e.g. by Guarino [4], resulting in a top-level, domain, task and application ontology, but introduce an additional level, the application case level. This level is intended to address an actual application case at a company, whereby the more general application level is seen as independent of a company, i.e. individual case. This highly modular approach targets a maximum level of re-use of existing ontologies (i.e. modelled concepts and relations) to prevent "re-inventing the wheel" effects (so, to reduce unnecessary efforts and build upon proven solution bricks) and to focus on new elements. Existing ontologies, e.g. from the Fraunhofer Innovationcluster Digitale Produktion [5], from the EU-funded projects amePLM [6], iProd, and Z-BRE4K especially targets general concepts, engineering processes and artefacts as well as manufacturing engineering and predictive maintenance related part-models.

Production Management 4.0: In production management, in the last decade a proven toolset of instruments was developed to eliminate waste ("muda") and to focus on the essential perspective of production: value creation. These instruments mostly focus on the value stream and put the employees in the centre of the view. On the other side, digitization tendencies in production and manufacturing as they can be subsumed by the term Industry 4.0 are mostly technology-driven. In Industry 4.0, the typical approaches are derived and may be clustered by terms of application cases, i.e. promising combinations of technologies and cases with expected positive effects on the competitiveness of a factory or manufacturing system, respectively. So, typically production management in the sense of lean management and lean production and Industry 4.0 collide as the worlds (perspective) human-centered and technology-driven collide.

	Lean		Industrie 4.0
Approach	Holistic (person + technology + organization)	↔	Technology as driver
Philosophy	Respect, problem solving, employee development	↔	Feasibility, (self-)optimization
Foundation	Stability and standardization	+	Integration, adaptive
Control principle	Flow, FiFo and Pull	+	Dynamic, situation-dependent
Information acquisition	Current location, current material ("Go and See")	+	Situation-dependent, data processing in real time
Improvement	Reactive in day-to-day business through employees	+	Self-optimization, prediction

↔ contradiction + supplementation

Figure 11: Production Management 4.0

In Production Management 4.0, these two worlds are combined by a holistic view on people (employees), organisation and processes as well as technologies [7]. By an integrated analysis, the methodology Production Management 4.0 identifies promising combinations of lean-elements with Industry 4.0-solutions to advance manufacturing systems and workplaces, for instance of cases of Smart Machine, Augmented Operator [8] etc. Despite of the methodology itself, Production Management 4.0 relies on proven building bricks from lean and Industry 4.0 serving as the essential components [9], which, especially in combination, play out their full potential. By means of QU4LITY, the Production Management 4.0 will be advanced and piloted towards Zero Defect Manufacturing, thereby increasing the impact of its application substantially.

2.2.3 Envisioned Industrial Innovation

As-Is Industrial System design (in operation): Today, the industrial or manufacturing system design is based on MBE methods, for both product industrialization (by Manufacturing Engineers) and industrial system design (by Industrial Architects), similar to the ones shown in "next section/4. Behaviour models". No SE or MBSE methods are applied operationally.

Generally, Industrial requirements are managed on tables with manual traceability during processes and resources design process. Trades are done to select different process and resources design options, analysing disconnected simulations. Decisions are made based on

Manufacturing Engineers and Industrial Architects experience during a collaborative engineering process.

To-Be Industrial System design in TRL7: In order to assure the operational performance of the industrial system in operations, as per defined program requirements, an MBSE method is being adopted to support the Industrial system design, with a current TLR7 maturity level.

To-be Manufacturing System Design:

- Tool agnostic industrial design process
- Continuity from Industrial architecture options definition to process detail definition
- Requirements traceability up to design choice
- Co-simulation between models in different modelling languages
- From partial and case-by-case behaviour models to parametric behaviour models
- Apply ontologies for reasoning and decision making

Innovation potentials:

- Implement a collaborative trade space process inside Airbus and with suppliers
- Perform a business transformation that includes new organizations and new roles to develop the models and to perform manufacturing engineering activities
- Predict behaviour, explore architectural alternatives early in the development process, and perform trade studies to assess which design choices make the most sense for manufacturing performance
- Develop a digital twin based on logistics/production planning simulation

2.2.4 Pilot / Use Case Description

New A321 Final Assembly Line: Following its strategy to keep its overall production system at the leading edge of technology and to increase industrial capacity and flexibility, Airbus has decided to create new A321 production capabilities at its site in Toulouse.

By mid-2022 the current A380 Lagardère facility in Toulouse will accommodate a digitally-enabled A321 line as a step to modernize the A320 production system in Toulouse. The new facilities will provide more flexibility for A321 production, while keeping the overall single-aisle industrial capacity in Toulouse flat.

Scope: The proposed scenario is one assembly process: the fuselage orbital junction process to be designed for one station (Station 40) of the Final Assembly Line (FAL) for the Aircraft Product A321.

The trade-off to be made is between a manual process and an automated process using a flex-track robotic mechanism, to achieve defined industrial performance requirements.

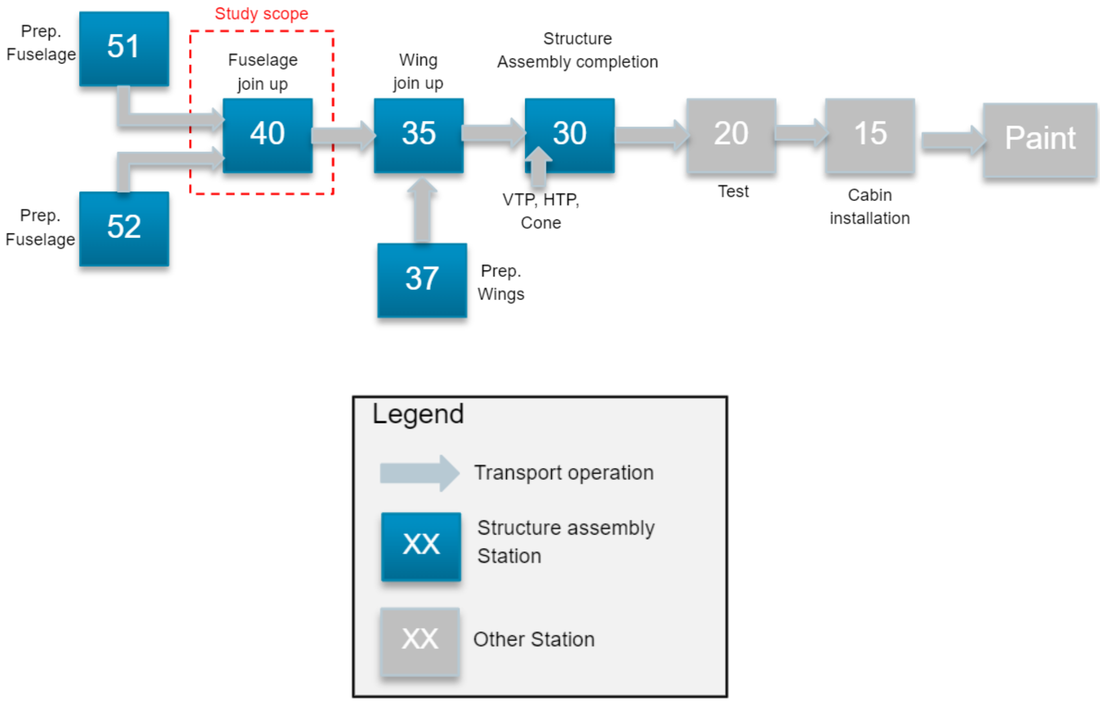


Figure 12: Building process example

Key parameters are the following ones:

- Drilling operation duration
- Number of workers
- Co-activity (operation sequence): Maintenance operations and non-quality

Performance KPIs include the following:

- LeadTime
- Rate
- OEE per Station
- Ergonomic
- BC workload // OEE of Flex Track

Manual process consists of the following:

- External drilling operations are performed by the operator (semi-automatic process)
- Internal drilling operations are performed by the operator (semi-automatic process)

Flex Track process consists of the following:

- External drilling operations are performed by the Flex Track
- Internal drilling operations are performed by an operator

During the early phase of an aircraft program, Industrial Architects are evaluating different industrial scenarios. One of the activities is to perform trade-off to optimize the future industrial architecture using different performance parameters like Labour cost, Industrial assets cost, Lead Time and different kinds of defect risks within the extended enterprise.

The current situation provides some findings:

- Manufacturing Processes are not enough agile and not enough flexible in order to answer to the complex and competitive environment and to the incessant changes needed concerning both the performance (need to improve the ramp-up) and the product (change of MSN) on the assembly lines.
- Engineering, Manufacturing & support processes are still considered in a sequential approach.

For solving part of the problems, Product Line and Co-design concepts need to be tackled. An MBSE approach where the Industrial System is seen as a System like any other (in parallel to the Aircraft) will allow to structure and to optimize the development of Industrial System and will allow to perform trade-off more efficiently.

The figure below shows a typical MBSE solution architecture. Very important aspects are standardization of the Industrial System definition and decomposition (supported by a semantic meta model) and Interoperability between different simulation parametric models (to be able to perform an analysis integration).

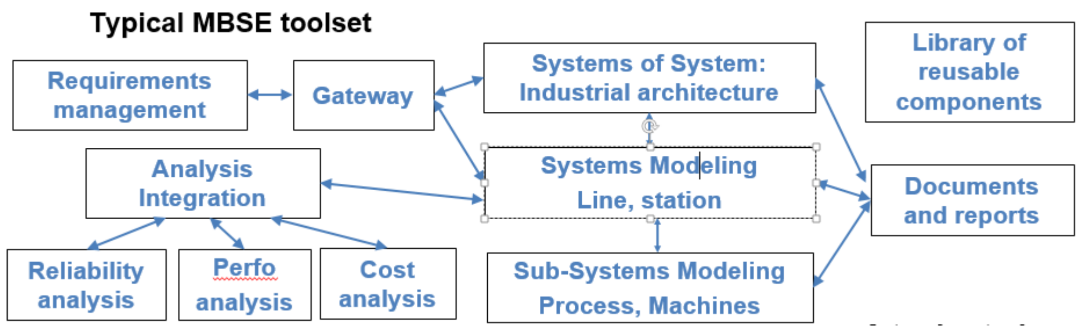


Figure 13: Typical MBSE toolset

Figure 14 shows the Trade Process example:

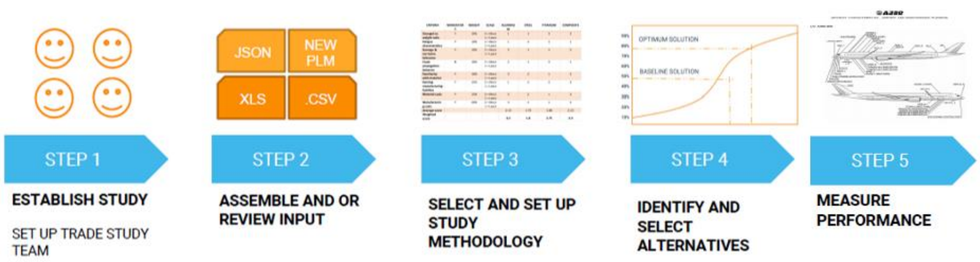


Figure 14: Trade Process example

Moreover, digital continuity that embeds digital twins' concepts complete these views.

Benefits for Implementing Trade Space Exploration: The concept of zero-defect will be practically utilized in our manufacturing environment to:

- Improve quality
- Reduce industrial assets cost.
- Reduce labour cost
- Reduce lead time
- Improve ramp-up
- Improve safety and customer expectation.

2.2.5 Technology Implementation

2.2.5.1 Technology Description

This project is fully supported by the Model Based System Engineering as system engineering methodology that focuses on creating models and solution architecture related to models:

- Model based system engineering (MBSE) models: The MBSE models allows a calculation of manufacturing-related metrics such as material use, labour, tooling, etc.
- MBSE solution architecture: MBSE solution architecture allows a standardization of the Industrial System definition and decomposition (semantic meta-model) and an interoperability between different simulation parametric models to be able to perform a parametric integration (ontology).

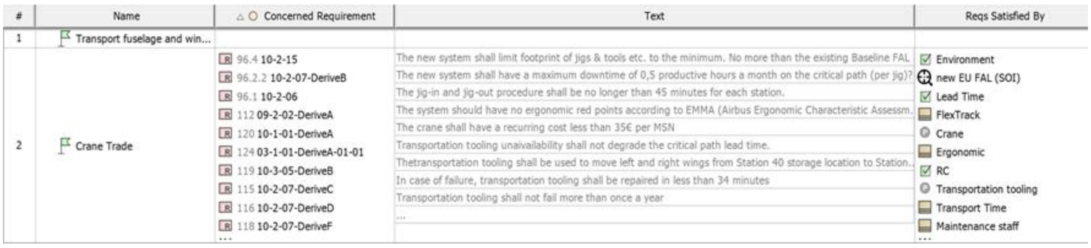
Figure 15: Industrial System design in TRL7

The idea for the prototype is to build an integrated platform of processes, methods and tools that are centred on these two approaches to support trade process: ZDM and autonomous quality.

The integrated platform to build for supporting trade space involves multiple engineering options and sites and at least one Airbus supplier. The need is to deploy the solution at a large scale and at a low cost for Airbus and its suppliers. The pilot will demonstrate the applicability of the approach to design an industrial system at a high level (Supplier network, Factories, Machines and processes) for near Zero-Defect Manufacturing. By taking the Industrial System as a whole, Autonomous Quality control loops will be integrated at the pertinent points. Also, the easy reconfiguration of the manufacturing process will be compliant with AQ concepts. AQ for ZDM will also ensure to keep the right quality level as a target.

In order to assure the operational performance of the industrial system in operations, as per defined program requirements, an MBSE method is being adopted to support the Industrial system design, with a current TLR7 maturity level.

At the beginning, the industrial requirements are imported from database in SysML to be managed and cascaded through the industrial system architecture definition. Across the resources design process, these industrial requirements are going to be traced up to the final design choice.



#	Name	Concerned Requirement	Text	Reqs Satisfied By
1	Transport fuselage and win...			
2	Crane Trade	96.4 10-2-15	The new system shall limit footprint of jigs & tools etc. to the minimum. No more than the existing Baseline FAL	Environment
		96.2.2 10-2-07-DeriveB	The new system shall have a maximum downtime of 0,5 productive hours a month on the critical path (per jig)?	new EU FAL (SOI)
		96.1 10-2-06	The jig-in and jig-out procedure shall be no longer than 45 minutes for each station.	Lead Time
		112 09-2-02-DeriveA	The system should have no ergonomic red points according to EMMA (Airbus Ergonomic Characteristic Assessm.	FlexTrack
		120 10-1-01-DeriveA	The crane shall have a recurring cost less than 35€ per MSN	Crane
		124 03-1-01-DeriveA-01-01	Transportation tooling unaivailability shall not degrade the critical path lead time.	Ergonomic
		119 10-3-05-DeriveB	Thetransportation tooling shall be used to move left and right wings from Station 40 storage location to Station..	RC
		115 10-2-07-DeriveC	In case of failure, transportation tooling shall be repaired in less than 34 minutes	Transportation tooling
		116 10-2-07-DeriveD	Transportation tooling shall not fail more than once a year	Transport Time
		118 10-2-07-DeriveF	...	Maintenance staff
		...		...

Figure 16: Requirements Management Example

At meantime, the involved Industrial System Architecture will be decomposed into its sub-systems and components, respectively, with the support of MOFLP method. Besides, based on the decomposed industrial system, trades will be defined in order to evaluate design options.

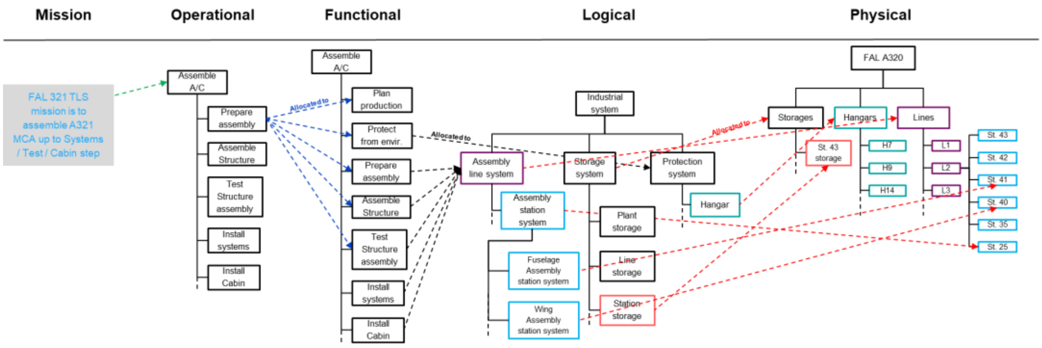


Figure 17: MOFLP Layers Example

Once the industrial architecture options and the trades to be performed are defined following the MOFLP method in SysML, different options in each trade will be simulated and compared. Within the prototype, a co-simulation between models in different modelling languages is pursued to be performed, which increases the compatibility of the simulation tool, as well as reduces the time of model transformation and adaption. Instead of partial and case-by-case behavioural models, the parametric behavioural models are to be achieved. It is also aimed to reach a digital continuity from the architecture definition to the models definition.

Also different defined process sequences (e.g. PERT, Gantt, etc.) are intended to be imported from the data source, which is connected to the SysML definition. Meanwhile, the ergonomic simulation and NC simulations for the assembly line will be executed and as input for the Trade-off process. Later, the scenarios will be optimized through a trade process.

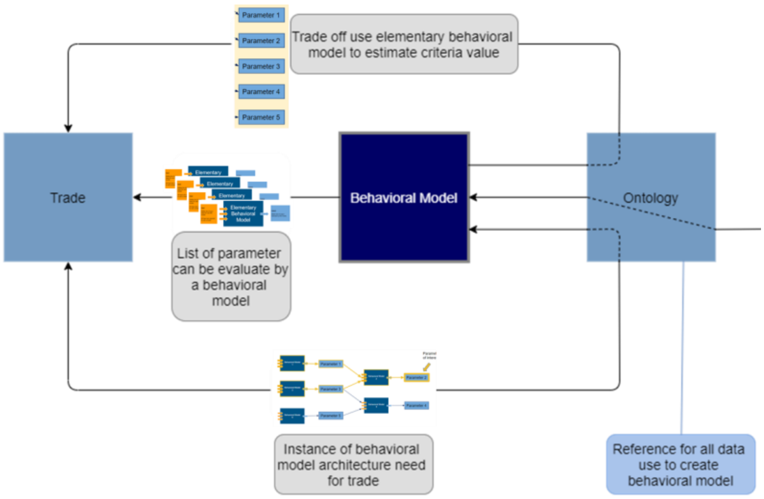


Figure 18: Schema of Scenarios Optimization

The parameter ontology will be developed for a semantic integration between Industrial Architecture parameters, behavioural model parameters and the trade-off interface. So that the continuity will be assured, from the Industrial architecture options to process detailed definition.

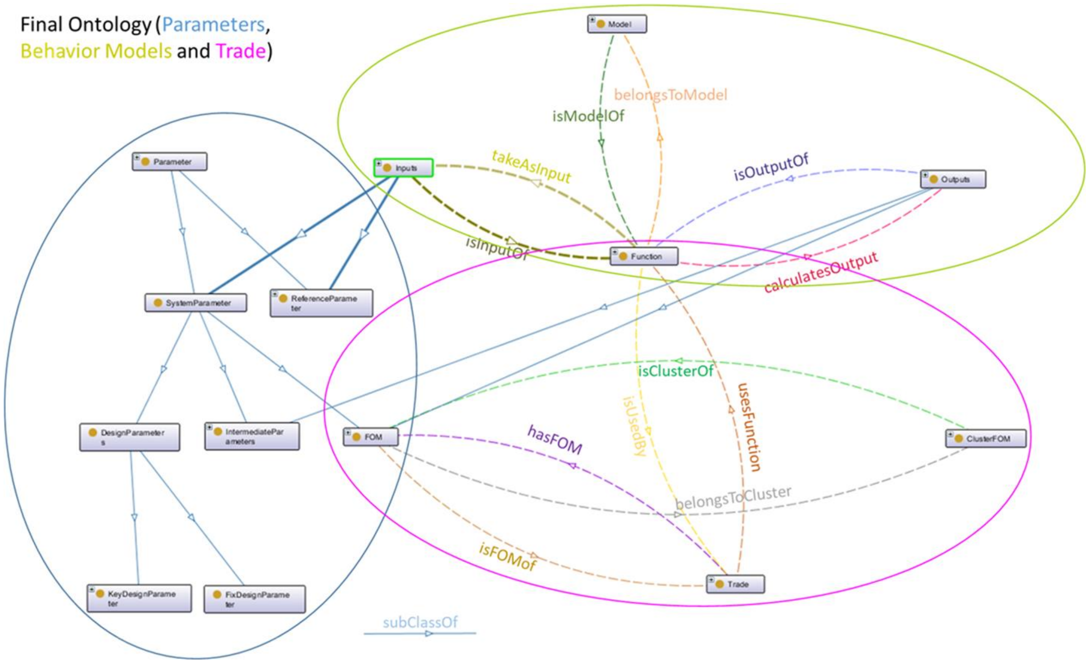


Figure 19: Semantic integration – Parameters, Models and Trades

The interface between Behaviour Models and Parameters plays the role of taking system and reference parameters as input for building behaviour model functions. The interface Function between Behaviour Models and Trade delivers function information from behaviour models as a necessary part for trade-off process. Meanwhile, the trade also contains the Figure of Merits (FOM) from industrial architecture parameters database. Besides, the interface FOM, which interacts between architecture parameters, behaviour model parameters and trade-off parameters, consists of the automatically calculated outputs from behaviour model and the industrial system parameters. With this architecture, the involved parameters through the whole process are able to interact with each other part and the continuity of data and information flow are being ensured.

2.2.5.2 Technology Architecture

Main Components: The demonstrator (hereafter as prototype) to be developed in Airbus Pilot consists of 5 different components, integrated to support a seamless design process. The components of the prototype are listed as following and illustrated in the subsequent figure:

1. Requirement Management Block
    a. Requirement specification
    b. Requirement tracking
    c. Requirement verification via system integration
2. Architecture Definition Block
    a. Industrial system Architecture definition via SysML following MBSE / MOFLP methodology

    b. Enriching architecture information in/with ontology
3. Visualization Block
    a. Co-Simulation Visualization
        i. Intuitive virtual assembly line
        ii. Virtual assembly process
    b. Trade Results Visualization
        i. Data Analysis for simulation results
        ii. Visualization of KPIs of scenarios for trade-off
4. System Integration Block
    a. Representation of domain knowledge
    b. Representation of individuals (scenarios to be traded off)
5. Verification Block
    a. Ontology-driven Discrete Event Simulation process
    b. Verification of scenarios with simulation results

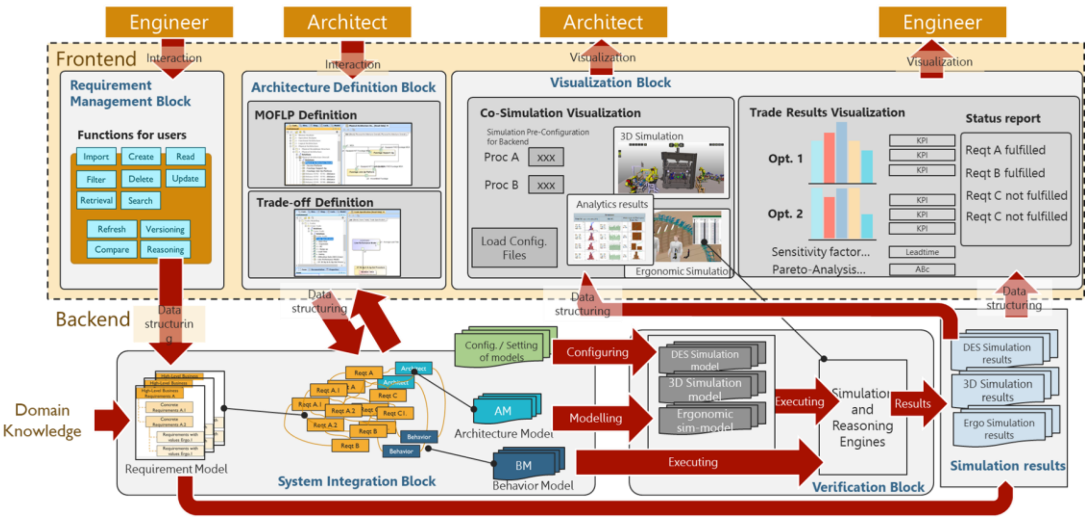


Figure 20: Prototype Functional Architecture

The prototype architecture depicts the interaction between different functional blocks. It includes the data flow, interfaces between functional blocks and main functionality within each functional block.

To differ the roles of each functional block, they are basically divided into frontend and backend concerning the user.

- In the frontend side, engineers and industrial system architects are dealing with the proposed user interface directly, for example, configuring the architecture of the industrial system or viewing results for decision support.
- In the Backend side, mainly the data pipeline is implemented. It consists of data acquisition, data processing, simulation etc. Data acquisition relates in this case to the

manual capture of domain knowledge. This will be represented in ontologies. By means of the ontologies, not only the process information themselves are managed and contained, but also an high level abstraction of business, for example, classes or types of process, requirements and so on. The aim is to ensure a broad usage of the information (knowledge) in similar contexts, which means the domain, and also to guarantee the reuse of that information, so that different individual scenarios of process, process steps and their relations be represented under the same framework.

2.2.5.3 Data Input

The prototype to be built in Airbus Pilot focuses on the scenario in the design phase of an industrial system, which differs from other Pilots which are to be implemented in a production line. Therefore the prototype doesn't perform the functionality of constantly reading stream data and processing data in real-time. Consequently, the data input, in this case, refers specifically to data and information needed to develop the prototype and to test and verify the results. As long as the prototype provides viable functions, the users can start to use it for industrial system design. In this phase, the input data for the prototype are:

1) Data input for development: requirements on designing an industrial system, architecture of an industrial system, domain knowledge, process information, criteria for trade off
2) Data input while in use: data generated by using the prototype, e.g. system architecture designing, operations on requirements, configuration for simulation etc.

The specification will be described in two parts in the following tables:

Table 2: Data input for prototype development

Data input	Description
Expert knowledge	Export knowledge is acquired via interviews with Airbus experts. The gathered knowledge is used for developing the ontology so that data and information during engineering can be managed in the ontology.
Industrial system process description	The original formats of process description are various, such as ReqIF, XLS, PDF, MMAP, PPT etc. regarding the fuselage joint assembly process. Data and information like process name, operating time, resources etc. are contained. They are processed and represented in OWL. Derived from the process description, needed information for 3D simulation, e.g., geometric information, dimensions, positions etc. are to be used.
Industrial system architecture (build concept)	The information about industrial system architecture, which are to be validated, is derived generally from the industrial system design. The original formats are various, such

Data input	Description
	as ReqIF, XLS, PDF, MMAP, SysML etc. After consolidating, the data and information of architecture of the system to be designed and validated is included in OWL.
Requirements of industrial system design	Requirements are in the formats of ReqIF, XLS, PPT etc., which are not only Top-Level Industrial Requirements, but also requirements for designing the industrial systems towards design key performance indicators etc. The information is also to be integrated in OWL, whereas the requirement management and validation of system design could be connected.
Criteria for trade-off	The data input is derived from current situation especially for developing the prototype. They will be used as criteria to determine and decide the simulated and experimented concept alternatives in trade-off.

Table 3: Data input in prototype while being used

Data input while in use	Description
Action of creating in Requirements Management	The data input for prototype will be generated by users who add new requirements into prototype.
Action of reading in Requirements Management	The data input into prototype will be generated by users who wish to read the states of requirements fulfilment, when the design is altered.
Action of updating in Requirements Management	The data input into prototype will be generated by users who update/ change the description/ specification/ dependencies etc. of existing requirements
Action of deleting in Requirements Management	The data input into prototype will be generated by users who wish to delete requirements
Modelling for 2D/3D simulation	The data input into prototype will be generated by users who create the behaviour model in simulation environment. The modelling process itself creates data which can influence other components of the prototype.
Action of updating ontology vocabulary	The data input into prototype will be generated by users who wish to add, change or delete terms in vocabulary. This will affect the hierarchy/architecture of the industrial system and further affect the requirements management, design and trade-off process
Action of updating ontology	The data input into prototype will be generated by users who changes the hierarchy/structure of the system in ontology

2.2.5.4 System Integration

General Description: For each component of the prototype to be developed, tools will be used to build up the process chain for semantic integration of industrial system design.

To automate the process chain in Industrial System Design, the system components (functional blocks) are integrated via several interfaces. Each system component is principally run/driven by the respective tool, which requires an input and delivers an output. Thus, the system integration will be described below in the view of the data pipeline throughout.

Data Pipeline: Different functional blocks e.g. requirement management block, architecture definition block, verification block etc. are integrated via proper interfaces and therefore the data pipeline represents the approach to integrate the functional blocks in system well.

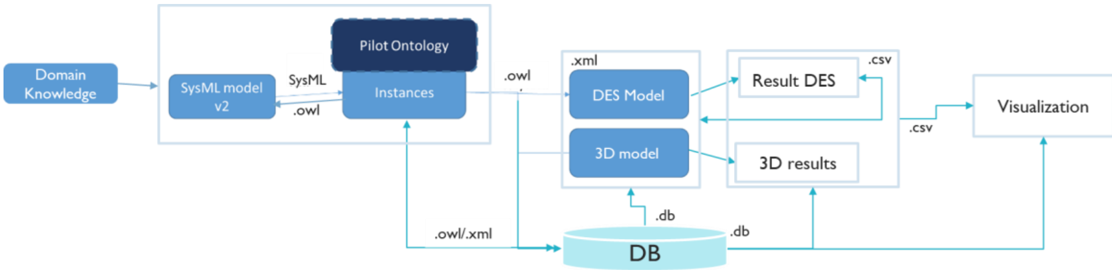


Figure 21: System Integration & Data Pipeline

Domain Knowledge: Input for requirement management block, architecture definition block and system integration block. They are in various formats e.g. description of an industrial system, engineering requirement, process information etc.

System Architecture and Pilot Ontology: These two functional blocks take input from domain knowledge and build respectively system architecture and ontology for the case in Pilot. They complement and enhance mutually, especially the complement of ontology from the system architecture block. The output of the two functional blocks are ontology files in the format of OWL for verification blocks/co-simulation, as well as input for requirement management block. For automation, it is also considered to storage in a database as common resource for other functional blocks.

Co-simulation: includes Discrete Event Simulation and 3D Simulation, which collaborates in the way of using the same formats for simulating and processing, as well as coupling one after another. The input for co-simulation is OWL-file including information needed for these two simulations. After parsing, needed information will be processed and extracted from OWL and in separate XML/CSV as input for simulation. It is considered to use sqlite3 within Python as database to synchronize the input and output of respective simulation.

Visualization: With the input of simulation results and processed information for design decision support in CSV format, the visualization block then presents them in a proper form and layout.

2.2.5.5 Deployment

According to current plan, the prototype is not to be deployed in a production environment. It serves as a Proof-of-Concept (PoC) for Pilot owner. Thus, the prototype will be first be built and deployed in the development environment stepwise regarding different MVP-level (Minimum Viable Product). The deployment plan is to be discussed and coordinated in pilot team also concerning the IS/IT resources of other WPs.

2.2.5.6 User Interaction

Following are descriptions and illustrations of User Interaction, which are in development status and going to be further developed as planned.

User Interaction Regarding Requirement Management: Engineer could perform various activities via GUI of Requirements Management Prototype. They include sorting, filtering, searching, adding, editing requirements and their properties.

An engineer could also operate & manage requirements via graphic views, e.g. adding elements, nodes and edges. An engineer could export content as .xlsx-format for further work and .owl-format for downstream atomization. An engineer could retrieve key requirement information with the help of Semantic Information Retrieval.

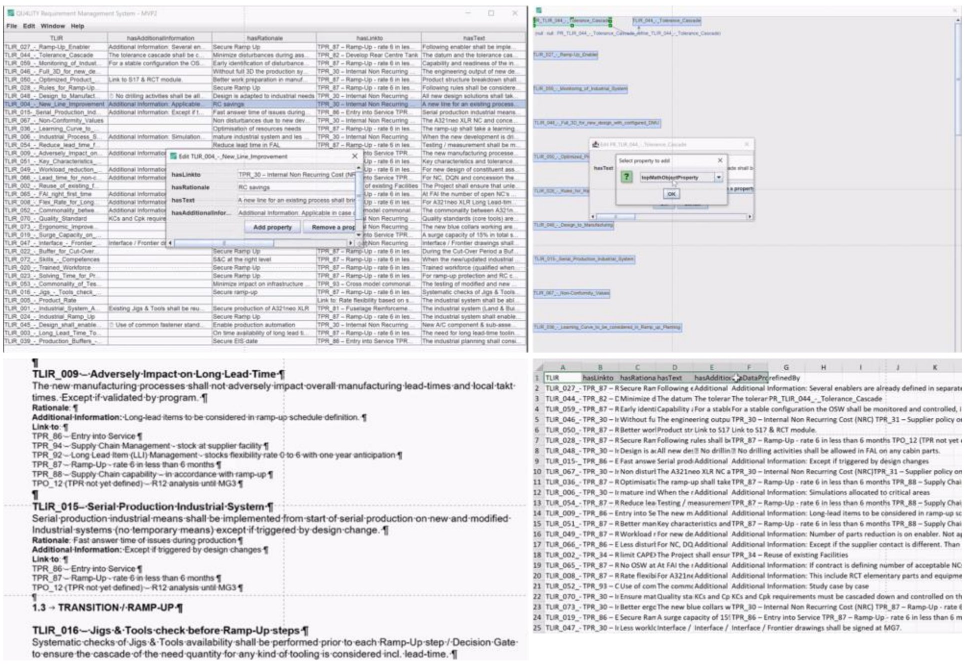


Figure 22: Example of User Interaction Requirement Management

User Interaction Regarding Modelling System Architecture: Engineer/Architect could design the industrial system architecture via the tool's GUI by adding and editing the nodes and edges from SysML. Engineer/Architect could use the SysML model for trade space exploration directly.

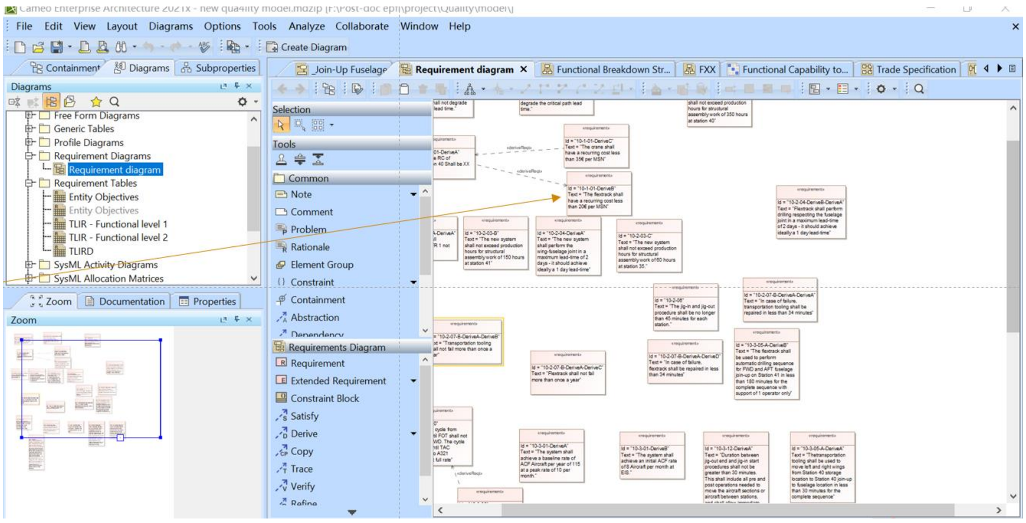


Figure 23: Example of User Interaction Modelling System Architecture

User Interaction Co-Simulation: Engineer could configure relevant parameters in GUI to receive the simulated key information for scenarios, as well as Gantt-Diagram, see and choose scenarios which are experimented and explored via Discrete Event Simulation, see 3D modelling of workstation, work process running and operations in detail, intuitively, see data analysis of simulation results for the scenario, which, for example, sensitivity analysis, Pareto analysis etc., for trade-off, and export results and reports for further usage.

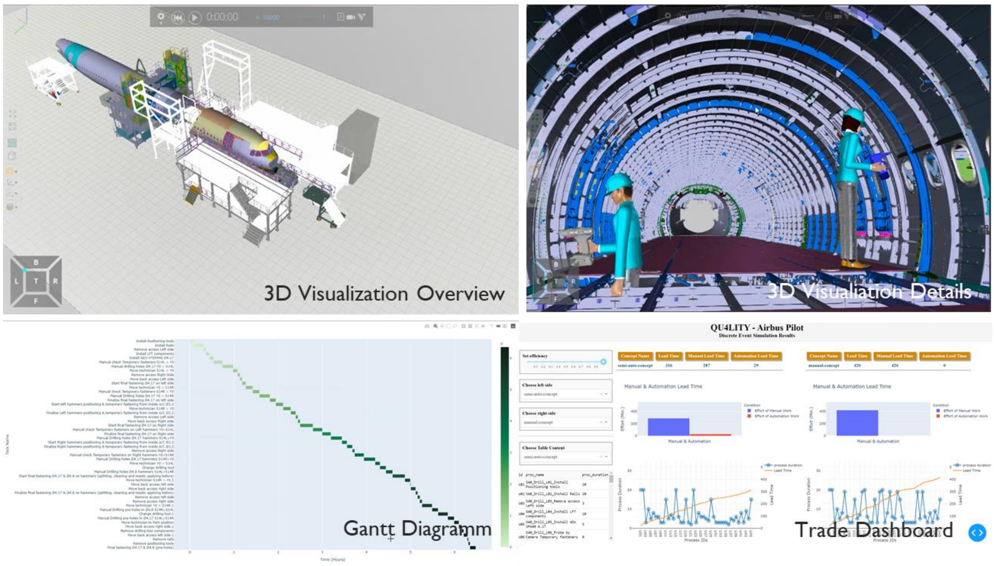


Figure 24: Example of User Interaction Co-simulation and Trade-off Support

2.3 Adaptive Visual Quality Inspection

2.3.1 Overview

Production with injection moulding, which is a manufacturing process for producing parts by injecting molten material into a mould (injection tool), is widely used. Injection moulding can be performed with different materials such as metal, glasses, elastomers, thermoplastic and thermosetting polymers. Material (heated, melted) for the part is injected into a tool cavity, where it cools and hardens to the configuration of the cavity. Injection moulding is widely used for manufacturing a variety of parts, from the smallest components to entire body panels of cars. Depending on tool design one injection cycle can produce one or many (even more than 100) products.

Parts to be injection moulded must be very carefully designed to facilitate the moulding process; the material used for the part, the desired shape and features of the part, the material of the mould, and the properties of the moulding machine must all be taken into account.

Anomalies anywhere during the moulding process may degrade the quality of moulded parts. Currently, the company Kolektor, which is the provider of the Pilot, cannot predict or detect these failures in real time. As a consequence, it may produce many false parts before even knowing this. Without real-time information about the production process, it is also impossible to correct and optimize the process.

The final visual quality inspection should accurately detect and appropriately classify the errors on the final (semi) product, at the pace of the production. Proper visual quality inspection, specifically on complex parts, requires appropriate vantage points, so that there are no occlusions of the inspected product by some of its other parts or elements of the production cell. Thus, the Adaptive Visual Quality Inspection tool will focus on the final visual quality inspection, specifically on the proper and timely camera positioning and image evaluation.

2.3.2 Background Technologies

Visual Inspection: Visual inspection is implemented within the Kolektor pilot through the use of the Kolektor Imaging Software KIS 4.0. It is an all-in-one machine vision framework. The software offers the possibility to fully customize applications to customer's needs. Generalized and modular architecture enables rapid prototyping and fast deployment. It enables cost savings and improved time to market. The KiS 4.0 framework is platform and HW agnostic, includes methods based on deep neural networks, and supports communication protocols of the factories of the future including communication with robots through ROS standard messages.

Robot Motion Planning: Robot motion planning has been applied in the pilot in the sense that the correct sequence of motions that guides the camera (on top of the robot) through a set of predefined vantage points, but the order will be determined dynamically, by an algorithm. In this sense, classical motion planners will be applied. The goal of autonomous planners is to enable robots to automatically compute their motions from descriptors of tasks and models acquired from sensors.

By the task it solves, motion planning can be divided into four categories: navigation, coverage, localization and mapping. Coverage is planning of the movement that will cover certain amount of points in space, and this is what will be applied.

Reconfigurable Elements – (Passive) Rotary Table: When the object needs to be visually inspected with an in-hand camera from the other side, this may require a large robot to achieve the proper pose. This is often impractical. An alternative is to rotate the object. Instead, we added to apply a passive rotary table to address the issue when the robot's workspace does not allow sufficient reachability for vantage points from all relevant sides. The workpiece is placed on the table that can be rotated by a robot to move the workpiece to the desired orientation. The actuation and sensing utilize the robot's actuators and sensors. In such a system, a good positioning repeatability is achieved with pistons pushing plungers into the holes of the table top to fix it. Consequently, the table can be fixed only at a finite number of discrete orientations. The pistons are retracted when the workpiece needs to be re-oriented. The proposed solution is cheaper to manufacture than standard rotary tables with active actuation and sensors.

Alternatively, an active rotary table may be used, but this introduces additional costs. The active rotary table, which has also been added, is based on a stepper motor connected to KIS 4.0 through ROS.

2.3.3 Envisioned Industrial Innovation

Today, visual inspection is based on manually pre-defined postures (relation) between the camera and the object, and either the complete object, or – in order to save time - some critical parts are checked. These are always the same and specifically in the case of injection moulding (of plastics), they do not adapt to the current state of the process (parameters) and do not predict what might go wrong based on the set of current and previous outcomes.

With prediction on what might go wrong, we can re-position the robot holding the camera, or re-orient the object to achieve an optimal vantage point of the area in-question. Thus, we can spend less time on quality inspection, but still achieve the same or even lower scrap rate. The goal of the Pilot is to reduce the number of parts with defects by 20%, which will result in increased profitability.

As part of Task 5.3, we introduced new reconfigurable elements, specifically a rotary table, which will allow passive re-orientation of the object. This will allow us to use a smaller (cheaper) robot, because it does not have to reach so far to get a vantage point, which can be reached by rotating the object. The reconfigurable elements are depicted in Figure 25.

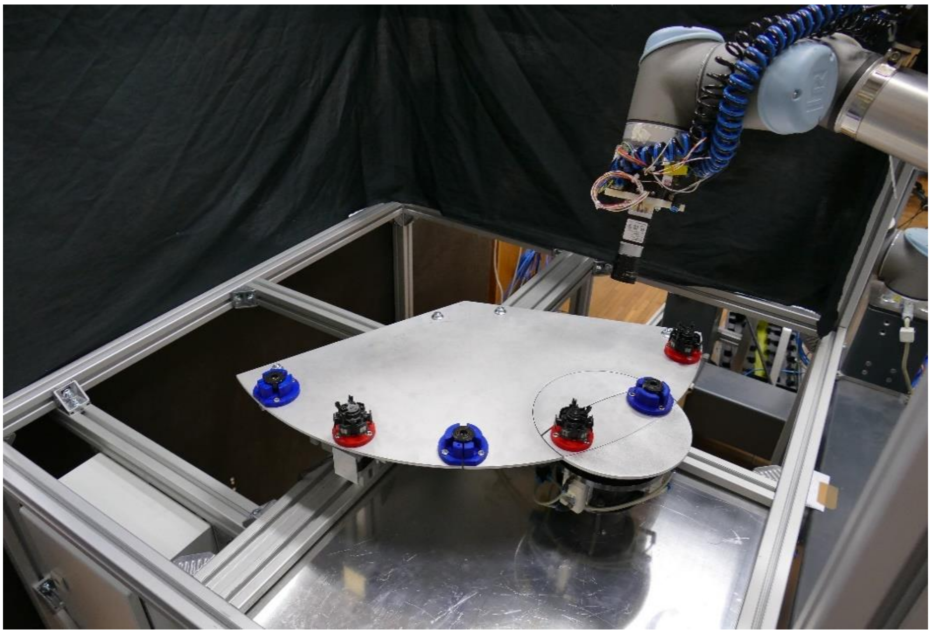


Figure 25: Physical model of the quality inspection cell at JSI, with products in the fixtures. Reconfigurable elements, i.e., the passive rotary cell and the rotary fixture, can be seen

2.3.4 Pilot / Use Case Description

Information about the injection moulding process is collected in different manners. It includes the moulding process parameters (inputs and outputs), environment parameters, images for visual inspection of products or parts of products, including images taken by a camera mounted on the robot.

The implementation of the proposed technologies in the project is within the Kolektor Pilot. The main focus is on adaptive visual quality inspection to reduce the scrap rate of the Kolektor production line. In this aspect, the main aim is to improve the visual quality by real-time fault detection and goal-directed acquisition of images for visual quality inspection by implementing a feedback loop (e.g. changing the viewpoint or area of inspection), and possibly prediction of failures based on advanced analytics and artificial intelligence (setting process parameters, etc).

The Kolektor Pilot in general expects to reduce the number of parts with defects by 20%, which will result in increased profitability of production lines that involve injection moulding. Adaptive visual quality inspection and other aspects of the pilot, such as real-time injection moulding process monitoring and control for the purpose of autonomous parameter correction will be developed for the Kolektor's production lines (see Figure 26), at first in partial mock-ups made for testing, so that the production process can continue unhindered.

Figure 26: Injection moulding line at Kolektor with marked final quality inspection cell

The final visual quality inspection implementation with a robot guiding the camera around the product (see Figure 27) is placed at the JSI Technological Experimental Facility (TEF), shown in Figure 28, and a broad view with the attached mock-up of the visual quality inspection cell in Figure 29.

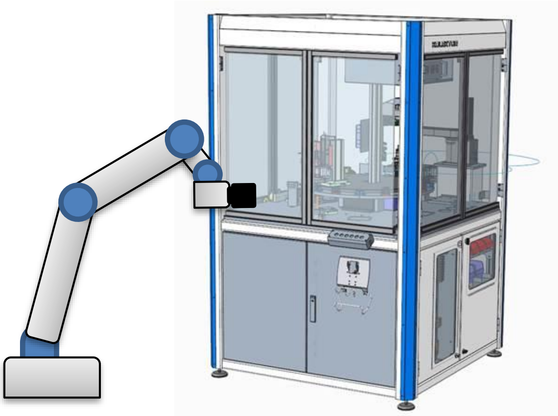


Figure 27: Quality inspection cell at the end of the moulding line. A robot was added next to the cell to guide a camera for visual quality inspection. A schematic of the robot is depicted because the implementation is at the JSI TEF

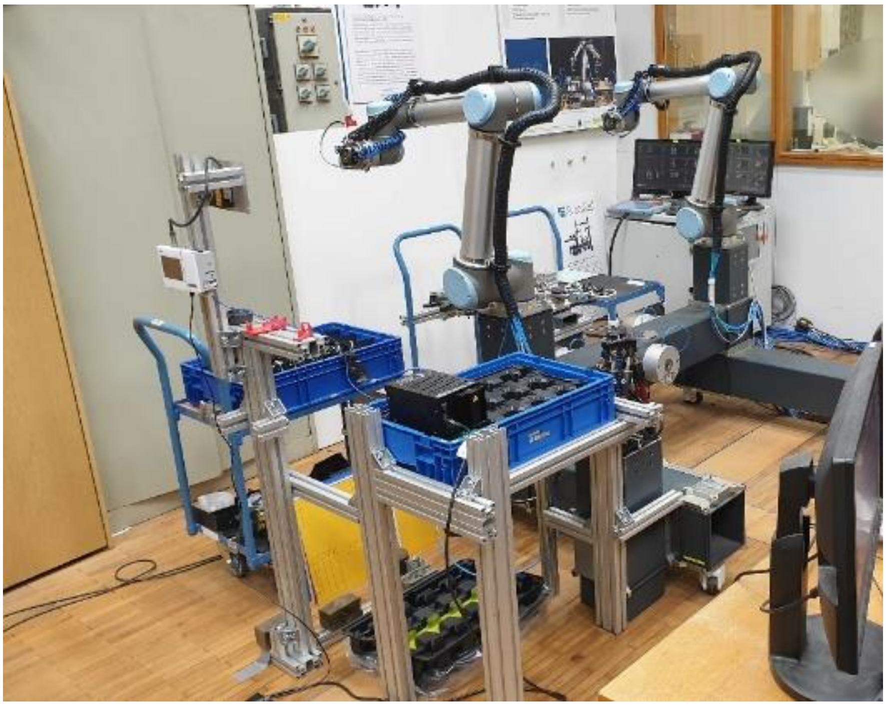


Figure 28: JSI Technological Experimental Facility called Reconcell

Figure 29: JSI TEF ReconCell with the attached real-world model of the quality inspection cell of the Kolektor moulding line

The production line of the pilot produces two semi-products, a stator and a rotor for car parts (name of product and customer withheld). Figure 30 depicts the products, with the stator on the left and the rotor on the right.

Figure 30: Moulding line products: stator (left) and rotor (right). The complexity of the stator requires inspection from various vantage points

2.3.5 Technology Implementation

2.3.5.1 Technology Description

The main aim is to improve the visual quality by real-time fault detection through goal-directed acquisition of images for visual quality inspection in a feedback loop (e.g. changing the viewpoint or area of inspection), and possibly prediction of failures based on advanced analytics and artificial intelligence (setting process parameters, etc). The implementation is set at the JSI Technological Experimental Facility (TEF) called ReconCell.

Within Task 5.3, dealing with Adaptive Digital Shopfloor Automation, we implemented adaptive visual quality inspection. The robot with an in-hand camera can adapt its position and by extension the camera viewpoint, in order to be able to see the required area of the inspected object. Appropriate positioning of the camera is crucial for proper visual inspection. However, with a relatively confined space, due to other production and inspection elements, the robot by itself cannot achieve optimal viewpoints for all the required surfaces of the object. Therefore, we will use adaptive ZDM elements of ReconCell, as described in D5.5: Tools and Techniques for Adaptive Shopfloor Automation and ZDM Processes. Specifically, we added a passive rotary table and an active rotary fixture (seat for product). This allows the robot to rotate the object either with the use of its own motors in the case of the passive table, or rotate the inspected part continuously with the active fixture. Thus, the required viewpoints with respect to the object are achievable. The combination of different viewpoints enables optimal visual inspection. In the sense of reconfigurability, it allows the system to optimally change the vantage point. The robot changes the orientation of the objects, but also its vantage points.

For example, the robot has a set of predefined vantage points. Given the prediction of the errors, it guides the camera to the vantage point that allows inspection of the area at which an error has the highest possibility of occurring. Furthermore, it changes the order of the required vantage points. Therefore, based on the prediction (which is not by itself part of this prototype), the complete motion of the camera is adapted. The objects of inspection are depicted in Figure 30. Note that this implementation is focused on the robotic aspect, i.e., on the robot motion that automatically guides the camera to the desired vantage point or through the desired vantage point sequences. The determination of the vantage point, however, is discussed separately in the Pilot and through work in the project's WP7.

The implementation took place on the JSI Technical Experimental Facility platform ReconCell, depicted in Figure 28 and Figure 29. Inside the inspection workcell (see Figure 32 and Figure 33), the passive rotary table and an active fixture were added. The robot system, along with an in-hand camera, was placed next to the physical model of the inspection cell of an injection moulding line at Kolektor, as depicted in Figure 27 and Figure 29. The inspection cell with a schematic of the external robot is depicted in some more details in Figure 27. The physical implementation of the cell is shown in Figure 29, Figure 32, Figure 33 and Figure 25. A visualization in RViz, generated from the CAD and used for the generation of motion, is shown in Figure 31.

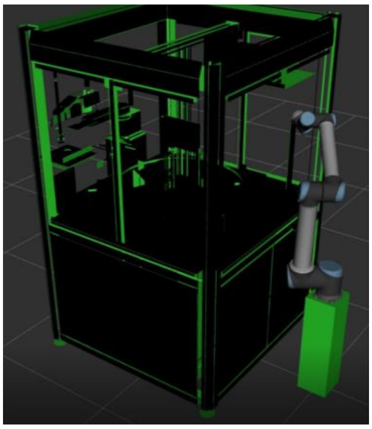


Figure 31: Visualization of the robot and the cell in RViz

2.3.5.2 Technology Architecture

The main components of the prototype are the robot, operated in Robot operating system (ROS) and the visual inspection system (camera + software), operated by the KIS – Kolektor Imaging Software 4.0. The robot, while operated in ROS, receives commands from the KiS 4.0 software. Basic interaction between the robot (UR -10 robot) and the visual system (KIS) are through standard ROS messages.

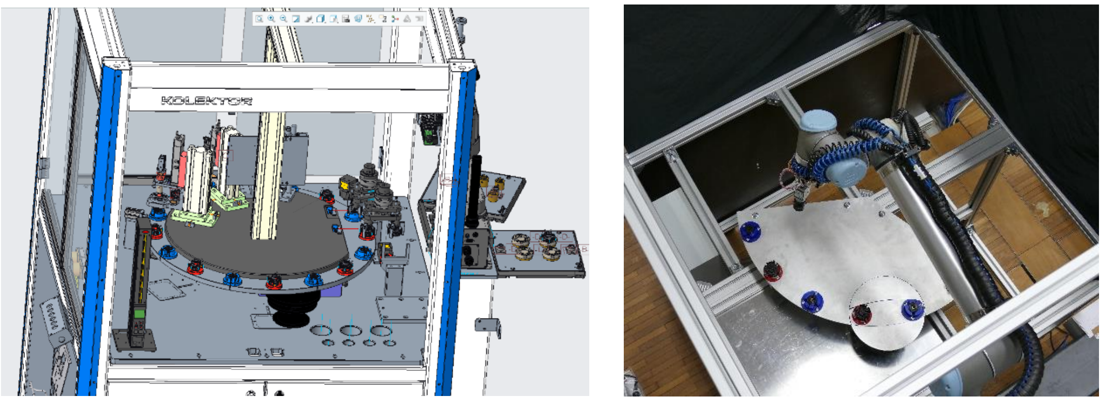


Figure 32: CAD Model of the cell at the Kolektor production line and the physical partial twin at the JSI ReconCell TEF facility (image taken from above). The passive rotary table (black in the CAD) is in the physical model covered with the same material that serves for the large plate

However, in the grand scheme of the Pilot, other components include: the moulding machine, the MES, acoustic monitoring, Industrial Data Space and Visual Components 3D simulation and visualization tools. The data flow between the KiS 4.0 and the Sinapro IIoT MES/MOM system,

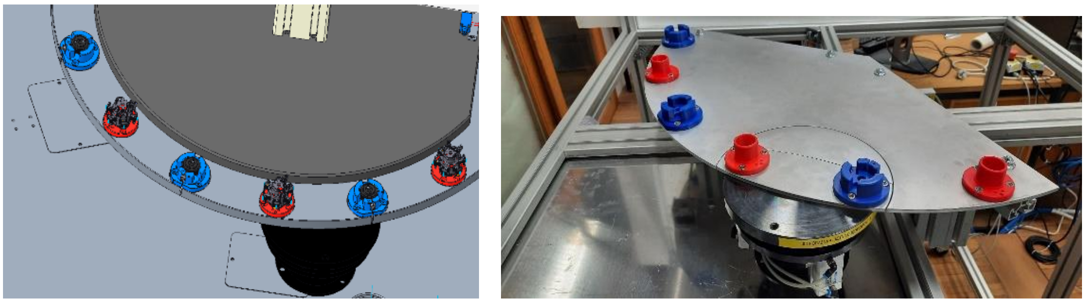


Figure 33: CAD model of product fixtures and the close-up of the partial physical twin at JSI TEF

which connects the process machines other than the robot and the camera, is via the MQTT protocol. The interoperability standard is based on Sparkplug B specifications – MQTT Topic & Payload definition.

2.3.5.3 Data Input

For its operation, the prototype needs to receive the desired vantage point over the product of inspection. This is determined based on the process parameters and ambient parameters.

This prototype implements the motion of the robot to the autonomously selected vantage points, or through a desired series of vantage points, which are selected from a list of possible vantage points. The motion is not programmed in advance, but planned online for each given sequence.

2.3.5.4 System Integration

The robot control and image acquisition are implemented within the KIS 4.0 system. Other parts of the system connect to the KIS through the Sinapro IIoT MES/MOM system, which connects the process machines other than the robot and the camera, via the MQTT protocol. The interoperability standard is based on Sparkplug B specifications – MQTT Topic & Payload definition.

2.3.5.5 Deployment

The worldwide situation with COVID-19 and its effect on the market and consequently also the Pilot provider has forced a change of plans for final deployment. Due to the limited accessibility to the Kolektor facility and due to the change in production demands by the company Kolektor, the adaptive visual quality inspection was implemented and deployed at the JSI TEF RecoCell, as a proof of concept.

As explained throughout Section 2.3, a mock-up of the final quality inspection cell was installed within the JSI TEF. We received the production line products (see Section 2.3.2) from Kolektor and placed them into the fixtures. We then generated the control signal of the Kolektor KIS 4.0 to start the visual quality inspection (our software architecture is based on ROS and KIS 4.0 triggers an action server with a standard ROS message).

As described in D3.4: HPC and Cloud Resources for ZDM, the vantage points for the inspection are determined based on the process parameters with a previously trained deep neural network. KIS 4.0 triggers the robot motion for visual quality inspection with a list of predefined camera vantage points. The robot autonomously guides the camera through the appropriate points. Its path is planned online (see Section 3.3.2). The collected images are returned to KIS 4.0 (again using ROS interface) for processing.

2.3.5.6 User Interaction

There are 2 aspects to user interaction: setting up and production. Additionally, the visual quality control process during the production can be either triggered by KIS 4.0 or by the user. In the latter case, the interaction is through a terminal interface. In the former case, the control computer needs to run the proper services (action server).

To set up the visual quality control cell, the camera vantage points have to be collected, and the correct distance between the camera and the object needs to be defined. However, because the object of inspection has several surfaces and because the camera focus depth is quite shallow, the setting of the correct distance to the object is not trivial. We, therefore, implemented a robot-supported autofocus procedure based on the image focus measure [10]. Because only a small part of the image with the correct surface for inspection needs to be in focus, we implemented a graphical interface where the operator marks an area in the image. The robot moves the camera to the correct distance from the surface in this area, so that the image is optimally sharp in that same area. Once the optimal distance has been determined, the camera location (vantage point) can be stored amongst other vantage points. As explained above, when the KIS system triggers visual quality inspection, the robot takes the camera through some of the specified vantage points as determined by the outcome of the neural network.

2.4 NxTTech IDE and EcoRT Runtime System

2.4.1 Overview

The NxTTech IDE and EcoRT are based on the IEC 61499 standard[9][10] [11]. IEC 61499 is a standard for modelling distributed control systems for use in industrial automation. Its event driven execution model allows an explicit specification of the execution order of Function Blocks (FBs). The FB of IEC 61499 is an abstraction that represents a component, which is usually implemented in the form of software but can also take the form of hardware.

The NxTTech IDE is an IEC 61499 compliant engineering tool. It is used to create an object-oriented distributed control application in the form of systems of connected FB networks. The object orientation of IEC 61499 makes engineering of new applications simple and fast.

The EcoRT is a software component which enables controllers to execute the control logic written in IEC 61499. The runtime system manages fundamental tasks such as event-based communications between IEC 61499 runtimes, real-time clock synchronization between runtimes and authentication and security.

As mentioned above, the IDE is used to develop control applications presented as networks of FBs, to distribute and map parts of the application to different hardware (HW), deploy, run, test, and debug the application. It is also used to develop libraries of predefined FBs that can be used to easily create applications by drag and drop. The IEC 61499 based EcoRT is ported to different HW components on which the IEC 61499 application should be executed.

Currently, the IDE and the EcoRT are used in an AGV (Automatic Guided Vehicle) use case where an IEC 61499 control application was developed in the IDE and is tested in the communication between AGVs when negotiating the crossing of an intersection and also when exchanging information with other HW like machines, lights or doors.

[9] https://www.iec61499.de/
[10] https://en.wikipedia.org/wiki/IEC_61499

2.4.2 Background Technologies

To develop the first prototype control application the NxTTech IDE (before named nxtStudio) and the IEC 61499 base runtime system (EcoRT) were used. These technologies were described in D5.5 [1] (chapter 2.4).

2.4.3 Envisioned Industrial Improvements

Currently, the AGVs used in our use case do not communicate directly with each other. All commands, requests and feedback are sent via a traffic box for small scale systems or via a server for large scale systems.

The IEC 61499 based control application is used to transfer all or part of the logic into the AGVs so that they can communicate with each other and do not need the coordination from a server or traffic box. It is still in discussion if the server can be completely removed or if some functions still need to be placed there.

Another improvement that we can point out is that using the NxTTech IDE a library creator can develop FBs in an object based manner and store them in a library so that an application engineer can easily create a new application or change an existing application with a simple drag and drop of FBs from this pre-defined library.

Also, the online change feature supported in the IDE and EcoRT gives a possibility to easily add new AGVs in the system without the need to stop the execution.

The IEC 61499 applications developed in the NxTTech IDE are HW independent. This means that the application is developed without taking care of the HW and can easily be distributed over several devices. The communication paths between these devices are created automatically by the IDE.

The integrated HMI runtime system provides a great interface for operators but also for monitoring, maintaining, and controlling the system.

2.4.4 Pilot / Use Case Description

Within the QU4LITY project, NXT and ASTI have identified a use case (Figure 34) in WP4 which focuses on developing a distributed control solution for a system of AGVs.

Currently, the control logic is centralized either in traffic boxes for small and medium systems or in servers for large systems.

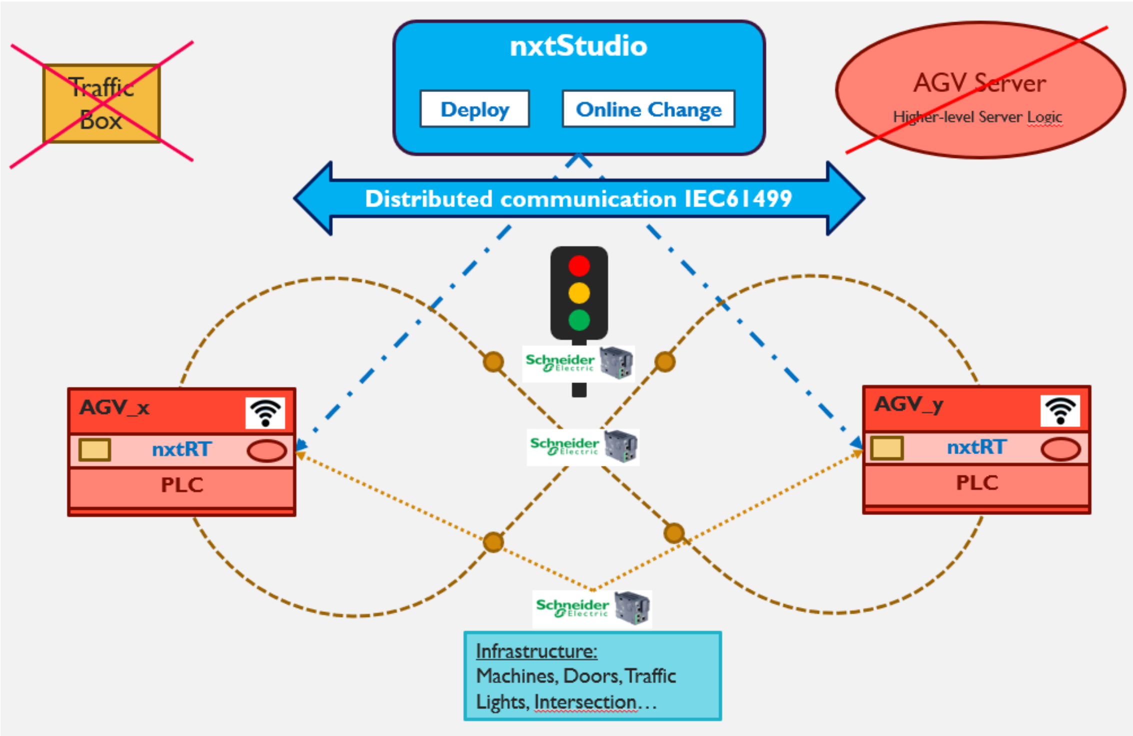


Figure 34: IEC 61499 based distributed communication between AGVs

In this use case, the main goal is to partially or totally remove the centric control logic, depending on the number of AGVs in the system and distribute it among the AGVs. The idea is that the AGVs communicate with each other to avoid collision when for example crossing an intersection. To achieve this the distributed control communication from NXT based on the IEC 61499 standard are used.

In the first step the IEC 61499 base EcoRT was ported to a Raspberry Pi which is placed on the AGV. The communication between the IEC 61499 runtime system and the IEC 61131 based programmable logic controller (PLC) is realized by using a Python script as presented in Figure 35.

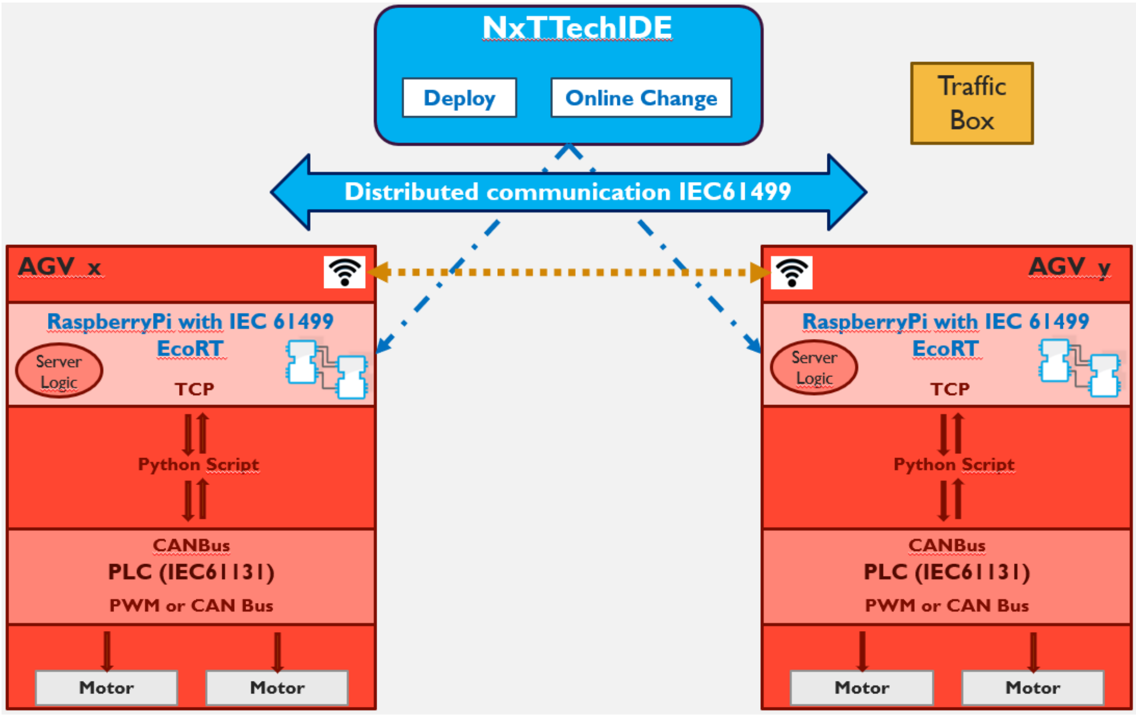


Figure 35: Communication between the IEC 61499 EcoRT and the IEC 61131 PLC

The IEC 61499 based communication between two Raspberry Pies was tested and these tests showed good results. The next step was to develop the IEC 61499 control application and to distribute it among the corresponding AGVs using the NxTTechIDE.

The second phase included testing the communication between the AGVs while they are crossing an intersection. Additionally, a machine, door or traffic light was added to the IEC 61499 network and the AGVs needed to communicate with it.

This use case was developed to test and demonstrate the developments done in WP4 and WP5. It is currently reconstructed as part of WP7, where the IEC 61499 based communication between an AGV, a Robot and other infrastructures like doors or machines will be the focus.

2.4.5 Technology Implementation

2.4.5.1 Technology Description

For the identified use case in Figure 34, two types of an IEC 61499 application are developed:

- IEC 61499 application with a centralized architecture approach.
- IEC 61499 application with a decentralized architecture approach.

IEC 61499 Centralized 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, which is used for controlling an AGV unit, and a function block, which represent the AGV supervisor logic.

With the centralized 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 36).

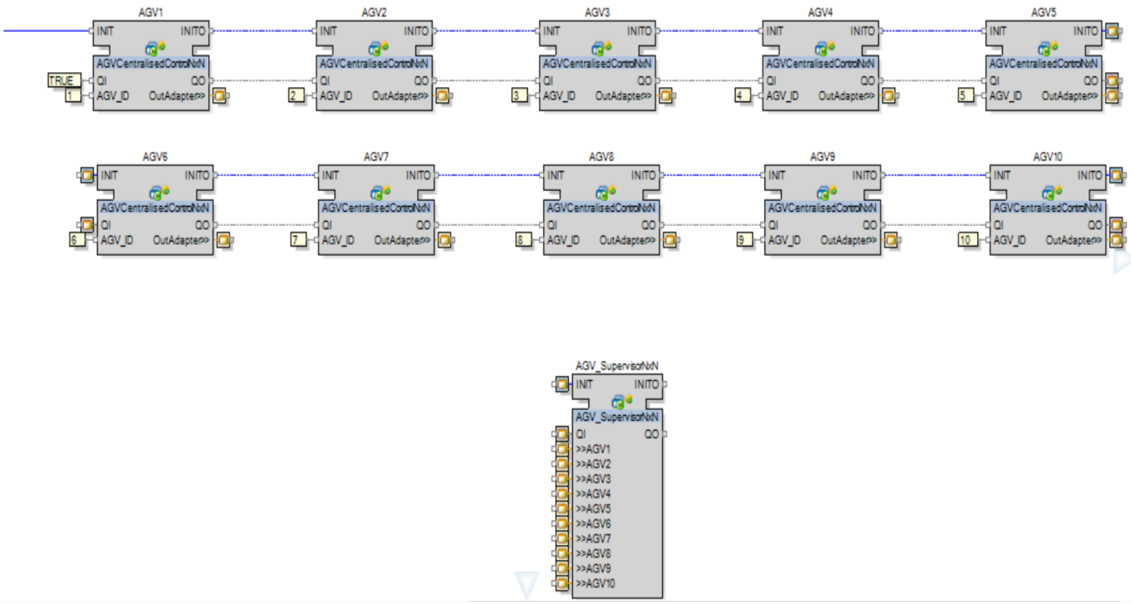


Figure 36: AGV Centralized approach – NxN connection

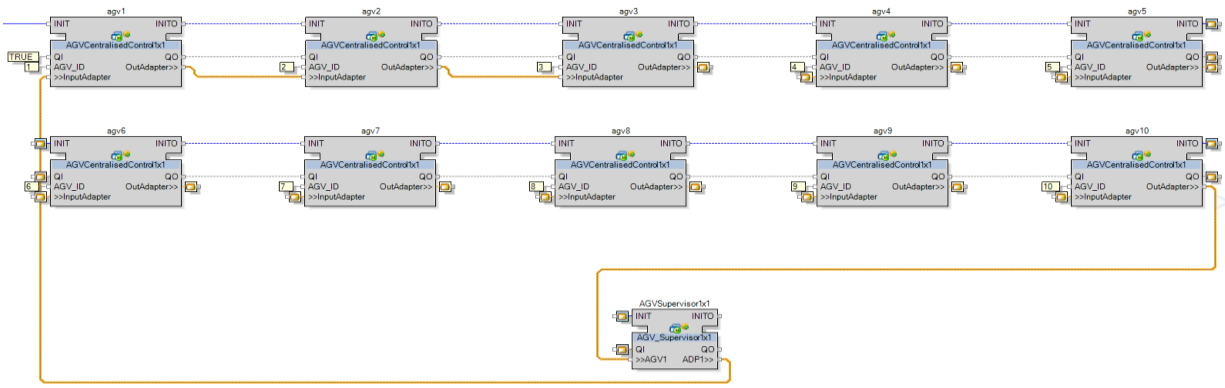


Figure 37: AGV Centralized approach -ring connection

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 realized:

- Each AGV is directly connected to the AGV supervisor (Figure 36).
- 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 37).

For the second approach, if one AGV wants to send a request to 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 Decentralized Application Approach: With a decentralized approach, 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, e.g. Section occupancy, availability, etc. which should be synchronized with all AGVs in the IEC 61499 network. 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).

2.4.5.2 Technology Architecture

For creating this technology 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 centralized architecture: AGV_Centralized CAT object and AGV_Supervisor CAT (Figure 38).
- For the decentralized architecture: AGV_Decentralized CAT Object (Figure 39).

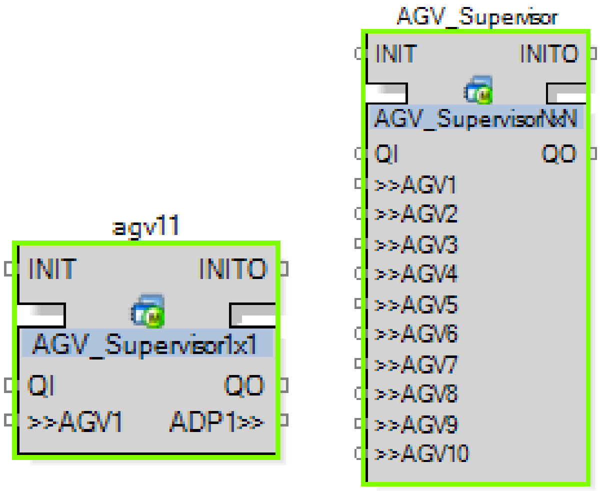


Figure 38: AGV CAT objects: 1. AGV Centralized architecture

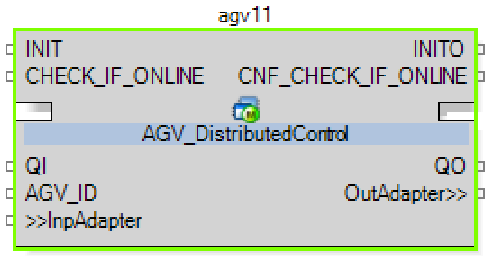


Figure 39: AGV CAT Objects: Decentralized architecture

Additionally, all above mentioned FBs are composed of more simple FB types, which are forming functional entities such as IEC 61499 Adapters, IEC 61499 Basic FB, IEC 61499 Service FB and IEC 61499 IEC Service HMI block.

Adapters: For the data exchange between different FBs within an IEC 61499 application, an adapter concept of the IEC 61499 standard is used (Figure 40).

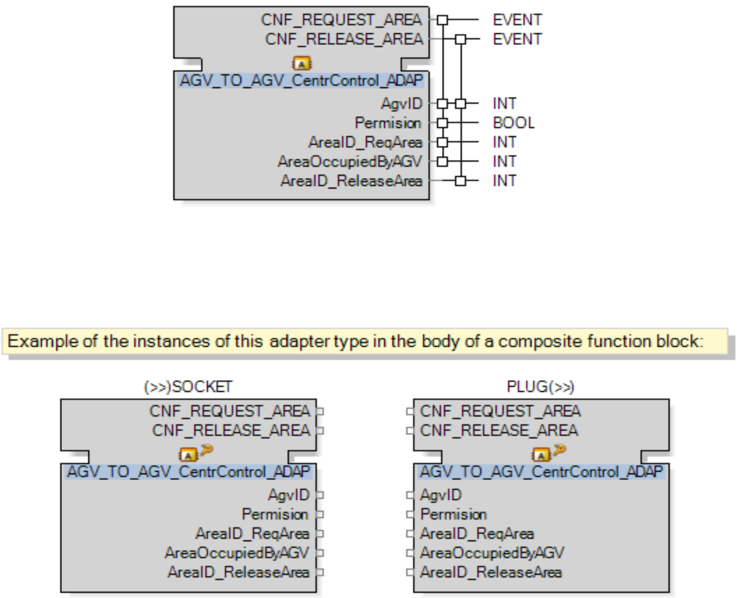


Figure 40: IEC 61499 Adapter Concept-Centralized Architecture

As already mentioned, within the centralized/decentralized 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 how the information is transferred from a source to a destination object.

If we observe a “Ring connection” and take into consideration that an adapter is based on a socket-plug concept, then each AGV_Centralized/ AGV_Decentralized 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 (Figure 37).

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 36,

Figure 41). In this approach, a message is directly transported to the destination, without the need to go through all devices connected to the chain.

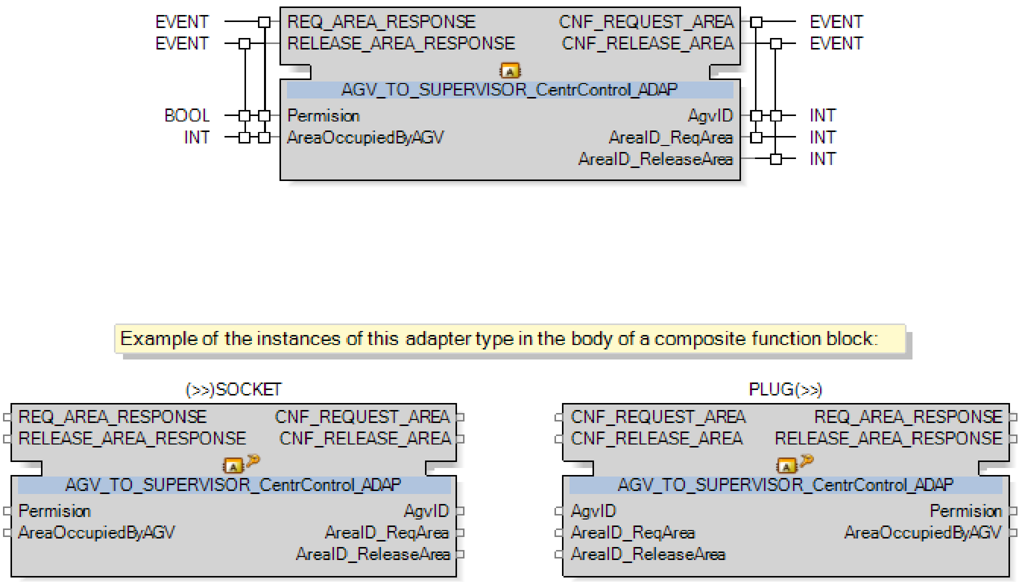


Figure 41: Adapter concept for a bidirectional communication

IEC 61499 Basic FB: The Basic FB is used to store all relevant information for a system. For a centralized architecture, this FB is placed within AGV_Supervisor FB and by decentralized architecture it is placed within AGV_Decentralized FB.

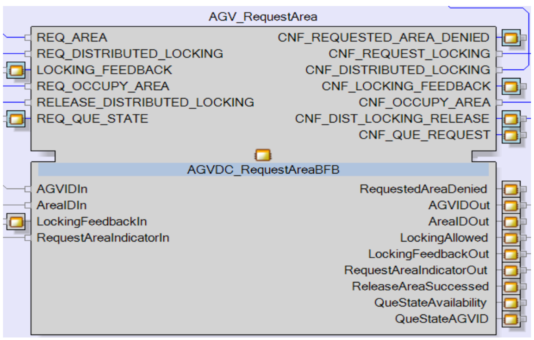


Figure 42: Basic FB -Information Storage

IEC 61499 Service FB: Beside adapters, which are used to connect two FBs and transfer data between them, and Basic FBs, an HMI block (*IEC 61499 Service FB Type*) is also used as a component of the AGV FB, which enables the visualization of the system and observation of process data (Figure 43).

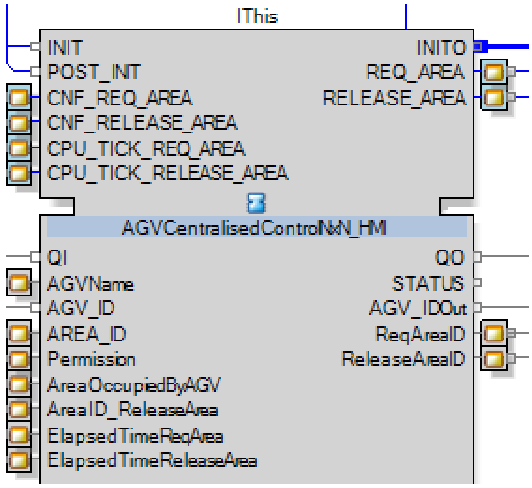


Figure 43: CAT-HMI block

This HMI FB serves as a connection between NXT HMI runtime and NXT ECO runtime (executable environment), exposing process variables to the HMI Interface (Figure 44, Figure 45).

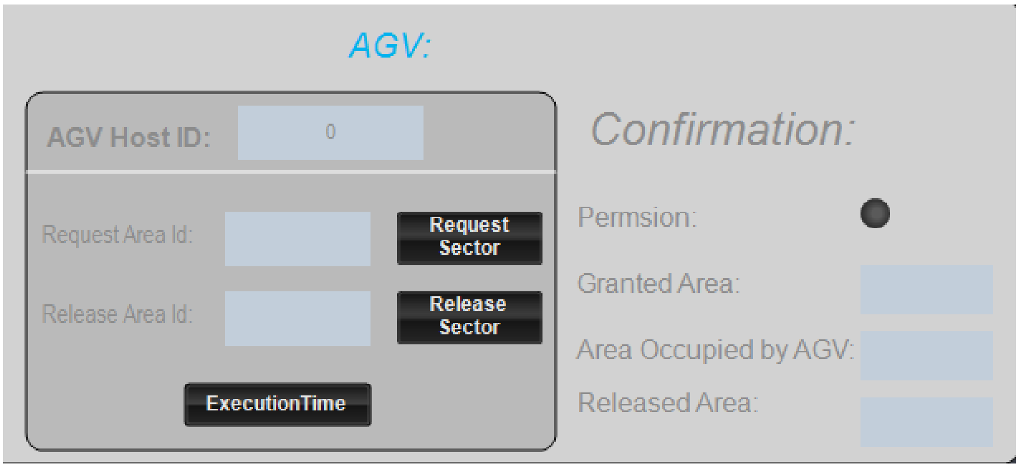


Figure 44: AGV HMI Interface

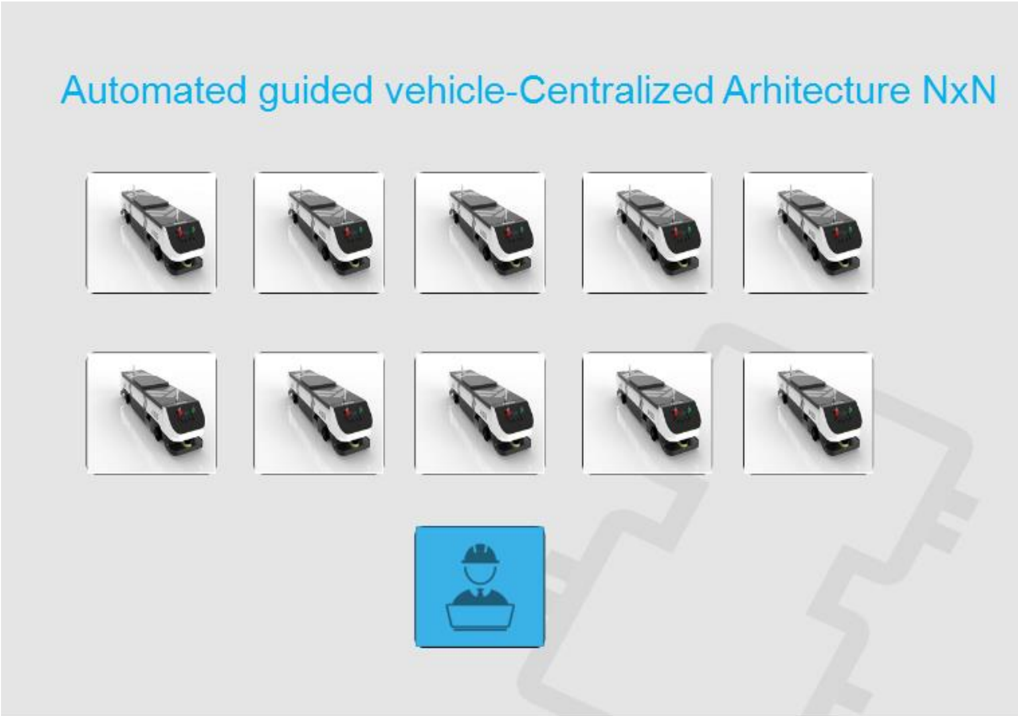


Figure 45: NXT HMI- Overview of all AGV in a system

Figure 46 and Figure 47 present the overview of the composite AGV FB for a decentralized and centralized architecture.

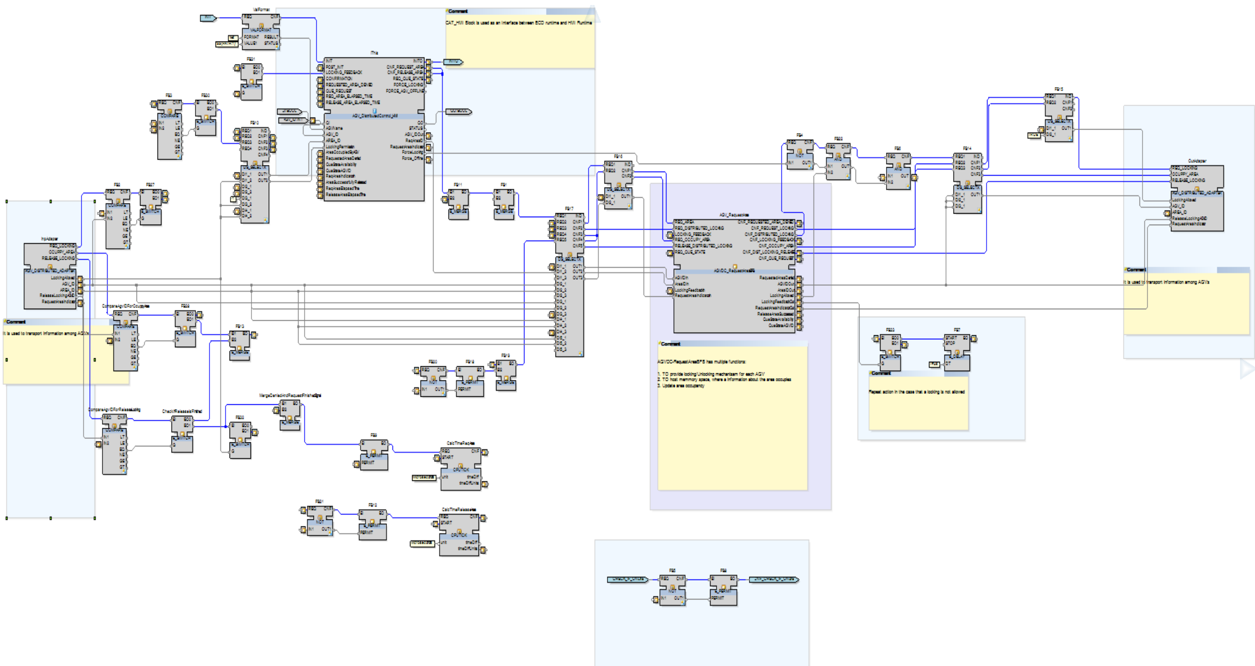


Figure 46: AGV_Decentralized FB- Composite view

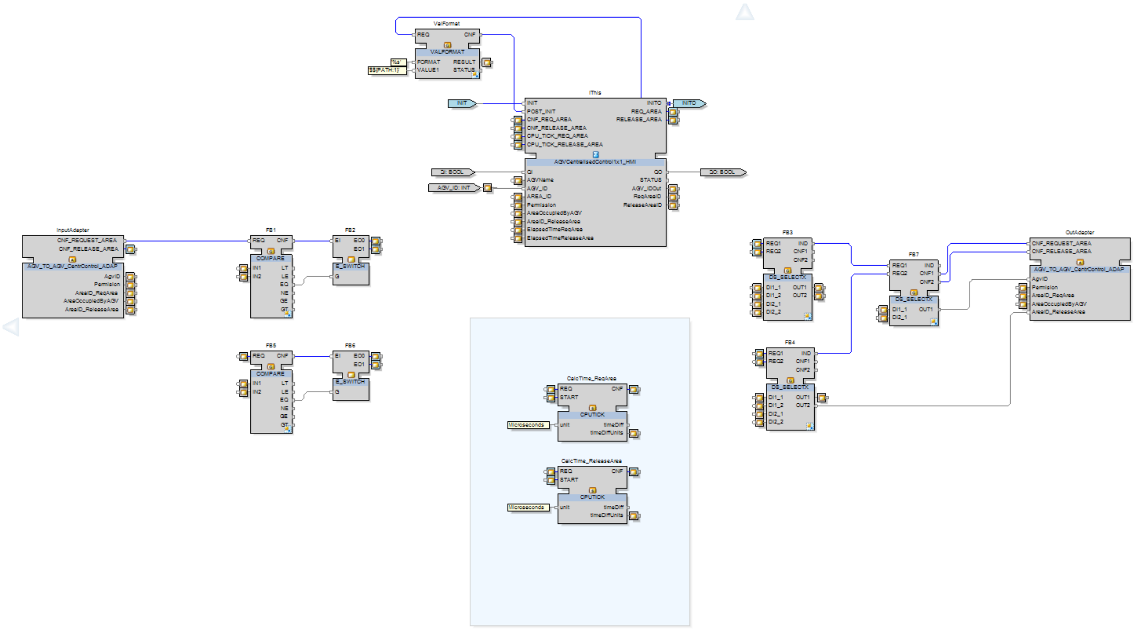


Figure 47: AGV_Centralized FB Composite view

2.4.5.3 Data Input

The control application is the one sending data to the system and the AGVs. It needs to get feedback information from the system to know that an AGV has arrived at the sector or section it was controlled to. Also, the application gets data from other HW devices that interact with the AGVs.

2.4.5.4 System Integration

The integration of the control application with the other parts of the system is currently being carried out by ASTI at their laboratory using two AGVs and an IEC 61499 based control HW that will be controlling a traffic light, elevator or another machine that needs to interact with the AGVs. The EcoRT was ported to 2 raspberry pies that are mounted on the AGVs and are responsible for executing the IEC 61499 control application and for establishing the distributed communication between them.

2.4.5.5 Deployment

The prototype application was deployed to the dedicated HW on the AGVs and the controller of the additional infrastructure (traffic light) using the NxTTech IDE at ASTI laboratory. The control application is being executed and the IEC 61499 based communication is tested in that system set up. The next step will be part of WP7, where the control application will be applied to a new system configuration which involves removing one of the AGVs and adding a Robot. The control application will be adapted accordingly while adding minor changes. For now it is foreseen that this setup will also be deployed at ASTI.

2.4.5.6 User Interaction

If the user is the operator of the system then he/she can interact with the system via the HMI block IEC 61499 Service FB Type. If the user is an application developer then he/she can adjust or extend the application using the NxTTech IDE. It is also possible to use the online change feature of the EcoRT to change the application while it is running.

2.5 AUTOWARE Composable Digital Shopfloor Verification and Validation Framework

2.5.1 Overview

Automation is one of the technology domains in which advances during these past decades are most evident, with the rise of computing and robotics. However, when it comes to improving their processes by implementing components, customer factories demand tailor-made solutions and already tested compliance with several key standards.

Overall, the scope of the verification and validation process of these components, in what comes to automation, includes: Designing and implementing testing environments, Coordinating test processes. Defining test tasks, Formal documentation reviews, Code reviews, Integration and unitary tests, Acceptance and functional tests, Dynamic and static methods, Implementing Security and Quality Standards and Training customer’s staff.

SQS has developed a framework for the testing, verification, validation and eventual certification of automation technological components. Thanks to this framework, components can be tested against relevant standards, these tests can be automated and any bug or potential issue can be detected in the design and product configuration process, before eventual implementation at customer premises. If the product undergoes these testing without any incidence and complies with the requirements demanded, it may also be finally certified against defined usage scenarios.

2.5.2 Background Technologies

TestWorkflow is a key tool behind the development of Q-Digital Automation and Q-IDSA, namely, the technologies developed and used in QU4LITY. TestWorkflow is a tool designed to help throughout the software verification process, by helping the user to automate tests and manage the associated requirements, testing and documentation.

This tool integrates the definition and management of requirements, the organization of the testing process, the automatic execution of test cases, the analysis of results and the generation of multiple reports.

The existing relationships between test cases, requirements and executions are recorded at all times, which guarantees traceability throughout the process. The intuitive interface of SQS

TestWorkflow allows any type of user to understand the validation process and become familiar with it without the need to be a specialist. The tool is based on a methodology that also allows structuring the test processes. It enables the following features:

Definition and Management of Requirements: One of the keys to a successful validation process lies in the good management of the system requirements.

The requirements define the behaviour of the system. Each of them models a function of the same, in such a way that the complete set of requirements must cover its complete functionality.

When performing the validation of a system, it must be ensured that all the requirements are verified. This is achieved by relating requirements and Test Cases.

With SQS TestWorkflow the requirements are defined using a table template that contains all relevant information allowing easy management and administration. Requirements can be grouped to show similarities or dependencies between them and organized by drag and drop.

The implementation of new requirements or the modification of existing ones is done in a simple way.

Organization of Tests: The tests are organized in a hierarchical tree structure that consists of the following elements: *Test Class*, *Test Sub-Class*, *Test Case* and *Test Data*.

Test Class: The Test Class is the element located at the highest level of the structure. Contains one or more Test Sub Classes. A Test Class represents a logical grouping of system requirements.

Test Sub-Class: The Test Sub Class is a subset within a Test Class. In a complex system, the number of requirements is too high for a division into Test Classes to be sufficiently precise. Therefore, Test Sub Classes are used to refine the requirements in smaller subsets.

Test Case: A Test Case is used to check a specific functionality of the system. All requirements must be contained in at least one Test Case, although a Test Case can cover more than one requirement.

Test Data: A Test Data consists of specific data for a Test Case, essential for its execution. Every Test Case, understood as the logical definition of a requirement, contains a set of Test Data. The set of Test Data must cover any possible combination of the Test Case to which it belongs. The specific values of a Test Data depend directly on the implementation of the system.

The executable elements of a Test Data are called Steps. Each Step carries out an action in the system, such as pressing a button, generating an entry, or requesting information from the system. In SQS TestWorkflow there are initialization and execution steps.

Starting from an initial state of the system that, if necessary, can be reached by executing the corresponding initialization steps, the Test Data launch the execution steps that will take the system to its final state.

Steps can be grouped into Macros. A Macro is a sequence of Steps that is usually executed frequently. A typical Macro example would be a part of an initialization sequence that it should be run identically for most Test Data.

Test Data can be grouped into series and stored as a Test Procedure. There are two types of Test Procedures: Collections and Use Cases.

A Collection consists of a series of Test Data independent of each other. It can be Test Collections, in which case Test Data are selected from a testing-oriented point of view, or Requirements Collections, where Test Data are selected based on requirements.

A Use Case consists of a series of Test Data that simulate the behaviour of a user. These Test Data execute the actions that a user would carry out in the system following a specific order.

Execution of Tests: Once the Test Data have been defined, the execution of the tests can be launched. Tests can be executed automatically although the user has the option to control the execution manually (semi-automatic execution).

In both cases, SQS TestWorkflow creates a 'logs' file to store the test results.

An individual Test Data can be selected for an execution, although the most common will be that an execution consists of a set of several Test Data selected to test a set of Test Cases or Requirements.

In SQS TestWorkflow there are the following types of executions:

- Execution by Tests
- Execution by Test Procedures
- Execution by Requirements

Analysis of Test Results: SQS TestWorkflow also evaluates the results of test execution.

In an automatic execution, the tool evaluates the results obtained to determine if they coincide with the expected.

In a semi-automatic execution, the tool shows the results generated by each Test Data so that the user can decide if they comply with those expected.

The full set of tests is then evaluated globally according to the system's acceptance criteria.

Reports on Tests: The user has various reports with which to obtain information about the current state of the organization and the execution of the tests at any time.

These reports display detailed information about the system and facilitate traceability.

In order to provide a simple and standardized document with which any user can work, these reports are exported to Microsoft Word.

Some typical reports are:

- Test Design Specification, details the structure of the tests in Test Classes, Test Sub Classes and Test Cases.
- Requirements Specification Report, shows all the system requirements and their relationships.
- Executed Tests Report, lists all the elements of a test and the execution of the associated Test Data. It also provides statistics about the system including a count of the Test Data and their associated statuses: “passed”, “failed” or “not executed”.

The user also can define and customize their own reports.

2.5.3 Envisioned Industrial Innovation

The platform will provide QU4LITY with the tools, methods and approaches required to validate the safe introduction of technological components deployed at the different Pilots’ or Experimental Facilities’ premises, and, eventually, these will go-to-the-market credited by having undergone a certification process by a trusted, honest third party, as it is the case of SQS. The platform is conceived to validate:

- Basic technology enablers or components, such as Edge boxes for data processing.
- Solutions: Functional implementations based on the integration of technology enablers or components.
- Implementations: Effective integration of solutions in pilots or real uses cases.

The interface with the users/beneficiaries of the platform (technology or solution developer, solution integrators) is granted through a UI developed in Mango App. This tool allows the users to view all the tests that have been designed and run, as well as the status of the execution, in short, customers can see the status of both the certification and the tests that have been designed and executed.

- This platform adopts a "Fit for Purpose" approach. Therefore, the validation will be adapted to the SUT need.
- Privacy is guaranteed, since each component to be validated has its own project defined in MangoApps.
- It is safe because a user and password are provided for each client, and it is reliable because the customer can see, the status of the certification, as well as the tests that have been executed.

In the particular case of IDS components, the experience from the work carried in 2019 and 2020 has brought new expertise to SQS. In this time, as part of the activities lead by Innovalia and the Spanish IDSA Hub, which was inaugurated in December 2019, SQS has become the only credited Evaluation Facility until the present. These Evaluation Facilities are key for the Certification process, as can be seen in Figure 48.

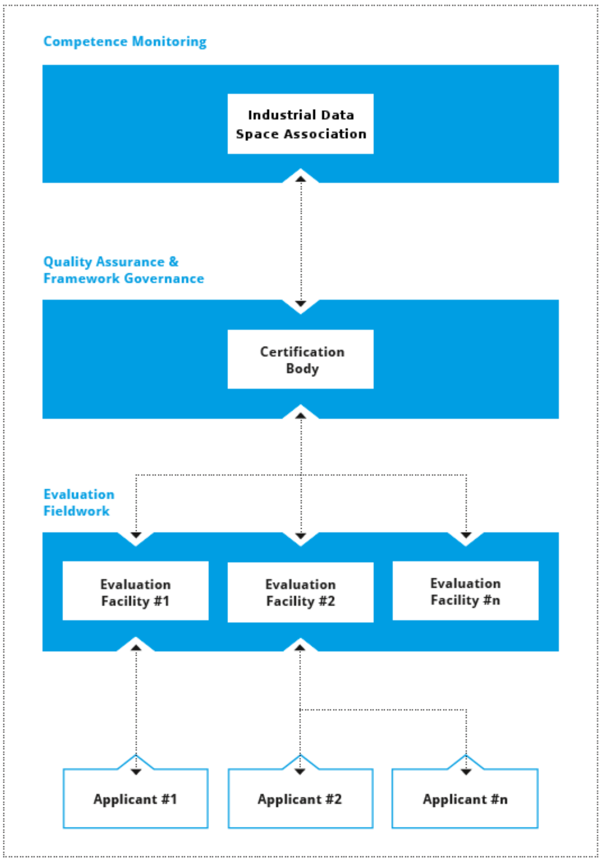


Figure 48: Governance for the IDS Certification process

For this purpose, a monthly or bi-monthly event, called the "IDSA Integration TestCamp" kicked off in early-to-mid 2020, organized by SQS, as has held several editions since.

The Integration TestCamp is a service, in the form of an online event, open to all the public, in which the remote access to an IDS-credited infrastructure is provided, thanks to which the participants can test the interoperability of their pre-commercial components in a similar environment/scenario to the one corresponding to the Manufacturing stage, and through which their components' functionalities can be tested – in a previous stage to the one corresponding getting certified by the International Data Spaces Association (IDSA).

2.5.4 Pilot Description

The AUTOWARE Composable Digital Shopfloor Verification & Validation is implemented in two Pilot cases within QU4LITY. These are:

Real-time Cognitive Hot Stamping Furnace 4.0 (GHI Pilot): 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.

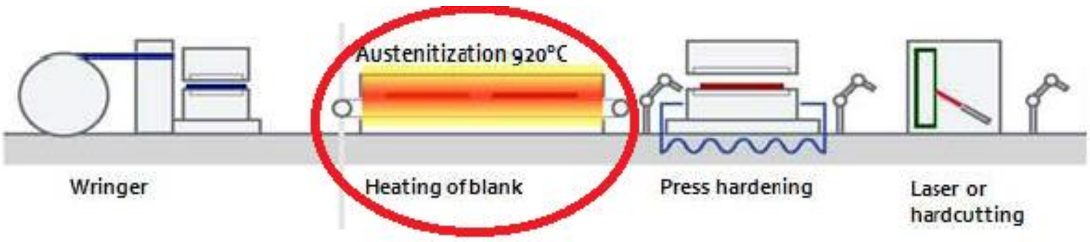


Figure 49: GHI Pilot in the hot stamping production line scheme

The use case aims at smart monitoring and cognitive control towards optimized heating of parts for zero defect hot stamping. Zero-Defect Manufacturing in these systems are related to the development of smart connected furnaces with the ability for real-time connected and smart closed loop monitoring & control. Closed loop quality control on the furnace heating control in relation to the press stamping parameters such as spring bass, press, frequency and mould & die ware out.

Figure 50: Hot stamping production line

Figure 51: Example of other machinery involved: Rolling beam furnace, Transfers and the Stamping press

Within QU4LITY, GHI aims to provide a universal ZDM framework for the development of the Furnace 4.0 family of products that the company delivers to a large number of markets. The picture below shows the large variety of furnaces GHI delivers to their customers. Moreover, the increasing demand of highly tailored industrial furnace solutions demands that the ZDM capabilities of the furnace as part of a complete production process are standardized.

The objective is to reduce defective parts manufacturing, especially crack formation on parts. This is intended to be achieved through increased control and also thanks to the monitoring of the industrial furnace operating parameters. The system demonstrates Zero-Defect Manufacturing in automotive hot stamping of safety critical parts in automotive, where quality is at the highest standards in the sectors in terms dimensional, surface and structural characteristics of the manufactured part.

This is where the support by Innovalia and SQS, both technology providers within the Pilot case, is needed:

- Autonomous Quality framework's definition: Innovalia Association contributed to the development and integration of the ZDM framework, and, in particular, of the cognitive digital twin service (long-term learning and pattern analysis) and deep streaming analytics framework for real-time analysis. The final product is to be dimensionally analyzed, once it has gone through all the production steps of the hot stamping process, so as to feedback the eventual analysis to be performed in the second phase of the Pilot experiment.
- Integration and interoperability of Data Space connectors: SQS contributed to the integration and interoperability of connectors for the creation of secure and trusted data spaces. The information, thus, is to be shared in a safe way, through IDS connectors, between GHI and Innovalia or other partners in the future. It will provide technological solutions for the integration and seamless interworking of the digital enablers of the autonomous quality paradigm. The AUTOWARE Digital Shopfloor Automation V&V is utilized here to verify and validate the IDS connectors by providing remote access to a trusted infrastructure composed of certified IDSA components.

Another objective is related with the production optimization, taking into account the part quality results obtained and counting on the "know-how" and expertise by GHI and its final customer, Gestamp. The holistic approach given by this performed control platform will provide a balance between the different elements' interactions. These performances will lead to a sustainable production.

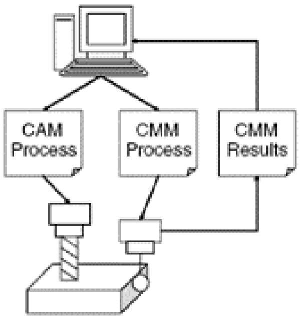
Finally, another objective is the possibility to obtain a modular solution: extensible, scalable, customizable and, replicable system that could be transferable to other process industries; e.g., steel industry.

Provision of Advanced Metrological Services within a Machine Tool (M3MH Solution by UNIMETRIK at the AIC Experimental Facility and Implementation at the GF Pilot: This kind of solution consists of the integration of a metrological software, so that the machine tool itself is enhanced with the capability to act as a quality control device for dimensional inspection. Through this solution, the machine tool is allowed to feed back the information captured in real time, to dynamically update the manufacturing process of mechanical components, thereby improving direct control over the machining process, as well as improving the dimensional accuracy of the products obtained.

Therefore, a software solution for machine tool measurement allows actions to be carried out to verify the state of the machine, set it up and measurement operations for three-axes and five-axes machines, with controls that incorporate open communication protocols, in semi-connectivity mode and for all types of geometries.

However, in order to carry out all these tasks, the critical point lies in the need to adapt this software solution to each machine, rather than to each Computer numerical control (CNC) language in which the machine operates with. Adequate integration is required for communication between both devices (PC with software / CNC) to generate an adequate control loop.

In the figure below, the control loop architecture of the solution can be observed:



The architecture used for the metrological capability gets the data from the points that the sensor (touch probe) points on. This touch probe is connected mechanically with a piezoelectric that sends electric signals to the analogical input. Each of the electrical inputs will be a point measured and will be processed to transform it into a digital point that will have a three-dimensional position. When there are more points, a digital point cloud can be constructed, one which will reflect the shapes of the object.

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 which the communication is established with. For example, conversion instructions have been implemented with the "G" code, characteristic of some numerical machining controls.

In this way, through the development of a series of connectors that generate that conversion of instructions for different communication protocols with which each CNC operates, an effective communication and information transfer has been established, guaranteeing the interoperability between the software and the CNC in order for this to interchange the cutting tool used for machining for a machining probe, for instance. Thanks to advances in data collection and connectors, the current system makes use of the following workflows, represented in the Figure 52 below:

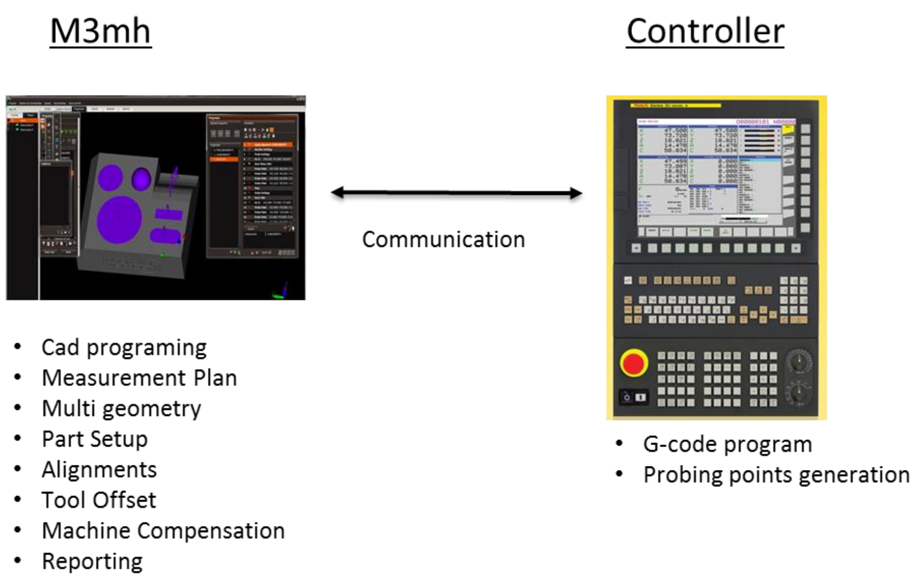


Figure 52: M3MH Communication

Below, in Figure 53, a diagram of the connectivity requirements for the M3MH solution is shown:

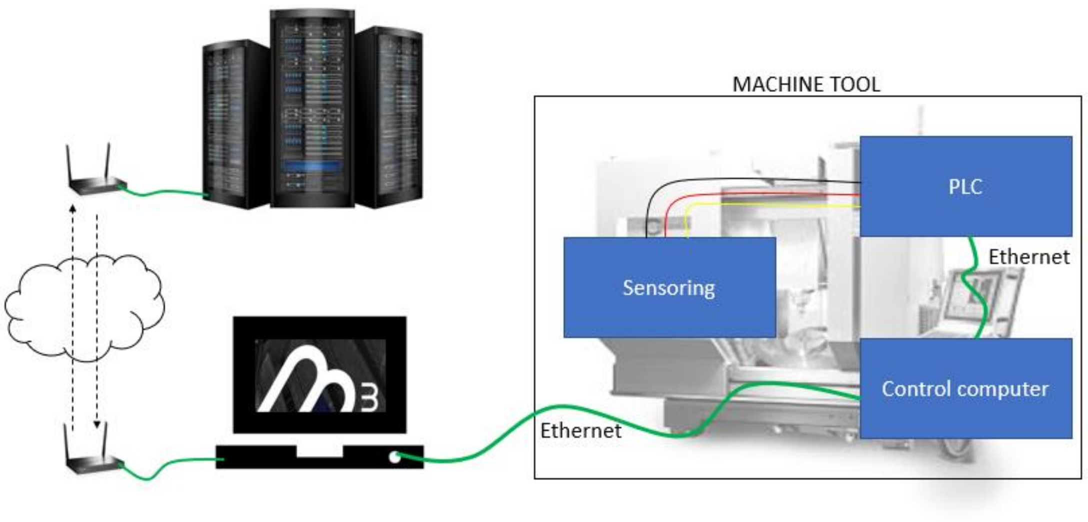


Figure 53: M3MH connectivity architecture

The M3 software is run from a PC connected with the CNC via Ethernet. 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.

The next step for the configuration between the M3MH software and the machine tool is to define the workspace volume. This has to be set-up from the software.

In order to indicate in which Experimental cases this solution is now deployed, at M33 of the Project, the following must be stated:

- M3MH has been deployed at the AIC Experimental Facility, for demo purposes, in a 3-axes machine tool.
- Also, M3MH is one of the solutions to have been deployed at +GF+ premises in Biel (Switzerland), within a 5-axes milling machine, as part of the solution sets implemented there.

Here, the work by SQS, through its AUTOWARE Composable Digital Shopfloor V&V framework, has been focused on verifying that the M3MH software effectively fulfils and is fully compliant with the QIF Standard (ISO 23952:2020), which is used as Model-Based framework for unique part traceability and data interoperability, because the M3 software uses QIF-compliant .XML format files for importing and exporting dimensional part quality results. This has been successfully achieved as of M33 of QU4LITY.

2.5.5 Technology Implementation and Deployment

2.5.5.1 Technology Description

The components developed and utilized during the QU4LITY Project are the following:

Q-Digital Automation: A certification framework where core components are certified for concrete usage scenarios.

Q-IDSA: A "branch", or particular case of Q-Digital Automation, still under development currently, consisting right now in monthly events in which the online access to a remote infrastructure is granted, so as to partners pursuing to get their IDS components certified can test them. A commercial product will be developed in the near future.

M3MH software and QIF Standard: In order to transform a company into a ZDM Model-Based Enterprise (ZDM-MBE), in the quality control field, the Digital Metrology Standards Consortium (DMSC) and also many companies have been working for many years in the development of Quality Information Framework (QIF). QIF is an open unified .XML framework standard for CAD quality measurement systems that enables the effective exchange of metrology data throughout the entire manufacturing quality measurement process: from product definition, inspection planning, execution, to the final analysis and reporting. The goal of the QIF specification is to facilitate the interoperability of manufacturing quality data between system software components.

The intention behind this framework, is, therefore, to solve the metrology interoperability problem, and, in this way, benefitting the manufacturer by avoiding wasted resources spent on non-value-added costs of translating data between the different components of manufacturing quality systems.

The flow of QIF data typically starts with the generation of CAD + PMI data exported as QIF MBD (Model-Based Definition) application data. QIF data complies or guarantees data quality. This means that all data/information in the QIF standard are defined correctly, completely, and unambiguously.

The QIF standard is not only a data structure; but, also, a set of formal rules for data interaction with that structure. By virtue of its implementation in XML schema language and standard checks available in the XSLT language standard, QIF transfers much of the burden of data/information quality from the application implementer to the standard itself.

Regarding the QIF data structure, The QIFDocument is the highest-level element of all QIF instance files. It can be used to generate many different sorts of instance files including information from one or more application areas.

All elements other than the required QPId element are optional; however, it is recommended that a QIFDocument contains at least a Header and one or more of the MeasurementResources, Product, Plan, Results, Rules, and Statistics application areas.

QIF is constructed to enable a seamless flow of information from upstream applications to downstream applications and to enable tracking information through a product's lifecycle.

The primary mechanism for identifying the same information independent of location and instance is by the use of permanent persistent identifiers (IDs). QPID is a short form of QIF Persistent Identifier and is the QIF implementation of a universally unique identifier (UUID), as standardized in ISO/IEC 9834-8. These persistent IDs provide a mechanism for QIF to preserve connections to data objects in external QIF files and data objects in the world outside of QIF.

As described before, a QIFDocument instance file can contain any one of the applications or any combination of them, but the most natural combinations in a single instance file are those that contain a sequence along the workflow: A Product element from the Define Product activity, a QIFPlan element from the Define Measurement Process activity, and a Results element from the Execute Measurement Process activity. Those elements would reference information common to all three of them contained elsewhere in the QIFDocument, such as:

- File units
- Datum definitions and datum reference frames
- Measurement resources
- Feature definitions, nominals, and items
- Characteristics, definitions, nominals, and items

Throughout the QIFApplications/QIFDocument.xsd XML schema files the QIF MBD is defined. QIF MBD defines a digital data format to convey part geometry (typically called the "CAD model") and information to be consumed by downstream manufacturing quality processes, about the essential characteristics of the product.

The QIF MBD data format defines manufacturing information to form a "digital bridge" connecting CAD processes for product design and downstream manufacturing quality processes that generate physical products. The QIF MBD data model provides a vendor-neutral format and ensures that software solutions that support it, by either writing or reading QIF instance files, can exchange manufacturing quality data efficiently and accurately.

The QIF MBD model is designed to support the transfer of model-based definition information between a variety of types of applications as shown in the following Figure 54:

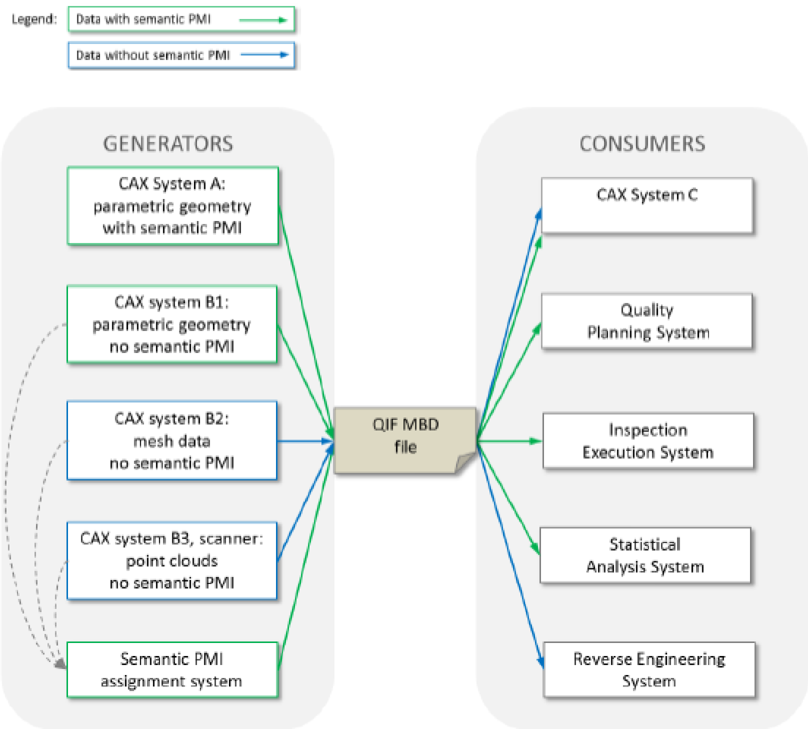


Figure 54: Workflow of QIF MBD Information

As it has been described above, QIF standard defines an integrated set of information models which enable the effective exchange of metrology data throughout the entire manufacturing quality measurement process.

The validation process of this standard is performed as follows. In order to check if QIF instances are following the standard, two validation actions will be taking into account:

1. If the design of the QIF schema is followed correctly.
2. If the contents of the fields are in range.

Checking the QIF Schema: In order to validate that a XML file is following the QIF schema the following resources will be used:

- A XML editor.
- Binding source code created by the QIF Community.

Just applying some of the resources provided by the QIF community, as for example the QIF3 Schema Browser or the Source Code Bindings, it is easy to identify if there is any error committed on the QIF schema definition, but also, these tools are quite useful to ease this work for every QIFDocument.

Below, in Figure 55, an image can be found regarding a QIF schema test, where an error is found as Names is found instead of Name, as the field is called on a common QIF schema.

Figure 55: QIF schema validation test

Content Verification Process: In order to certificate the content of the QIF files the following resources will be used:

- XSLT templates available through qif standard website.
- XSLT processor.

XSLT (Extensible Stylesheet Language Transformations) is a language for transforming XML documents into other XML documents, or other formats such as HTML for web pages, plain text or XSL Formatting Objects. QIF uses XSLT to perform robust checks on a QIF instance file.

XSLT scripts can be executed on any modern operating system and provide much richer validation than the XSD schemas can. For example, with this XSLT scripts, some things that can be checked:

- Valid ID references to external documents
- Correct unit vector length
- Data integrity checks for array sizes

To develop this validation task, SQS has adapted Q-Digital Automation to create and test a tool to ensure that QIF instances are following the QIF standard. This tool includes both validations activities, the QIF schema check and the QIF instances content verification, and enormously simplifies the validation activities to the final user.

The is now able to upload a QIF file and the tool automatically will report if there are any errors in the QIF instance.

2.5.5.2 Technology Architecture

The Architecture of the core of this V&V automation solution, which is, indeed, Q-Digital Automation, is shown in Figure 56.

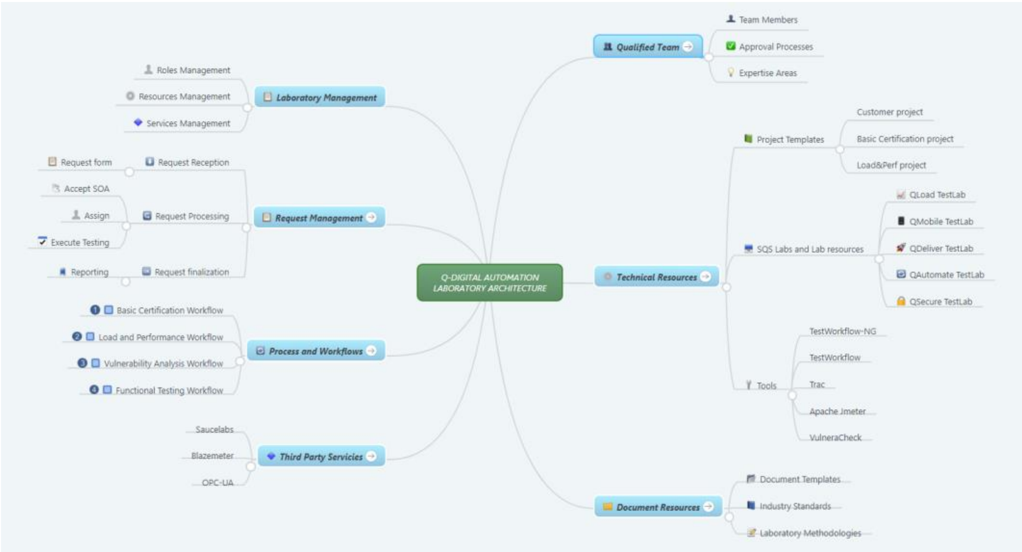


Figure 56: SQS TestLab Architecture

Also, a special tool has been developed in order to remotely validate IDS components, such as IDS connectors, which is depicted in Figure 57.

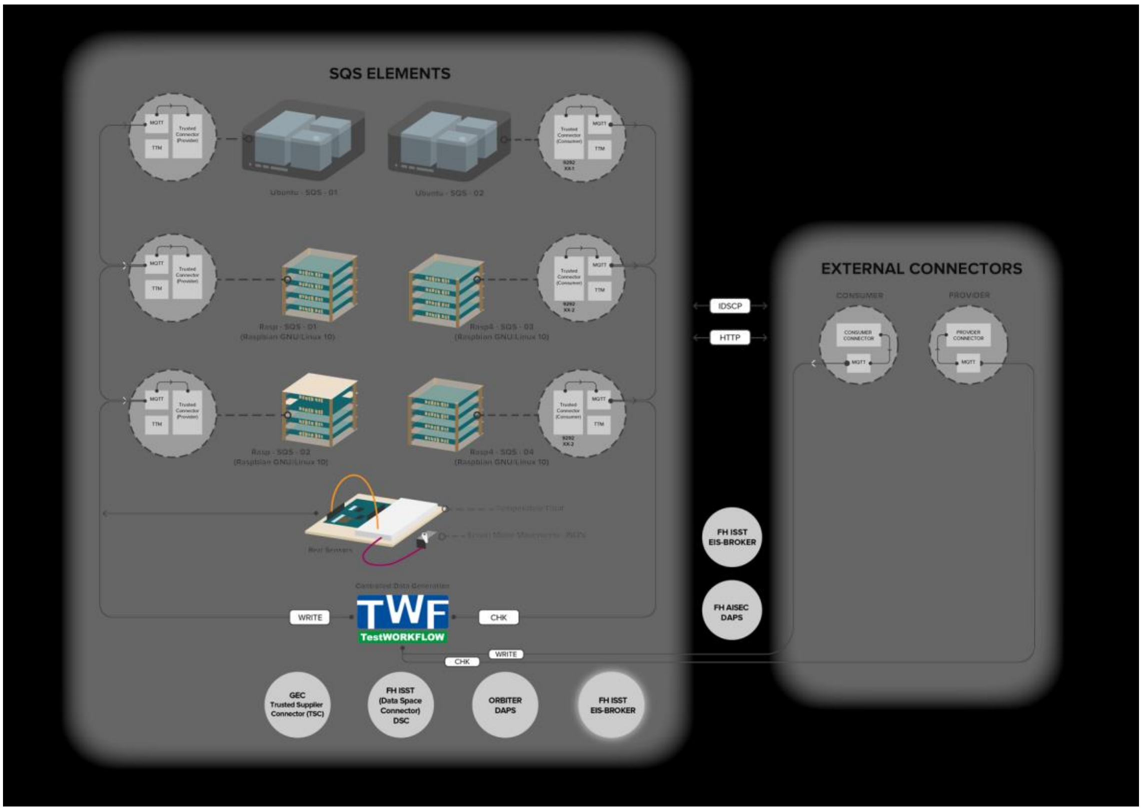


Figure 57: Architecture of the SQS IDS Integration TestCamp

2.5.5.3 Data Input

As it has been described in the previous section, SQS has developed a tool that allows the validation process to be carried out. The main part of this tool, offered as a service, is called Q-Digital Automation.

This service is based on the idea of a Digital Automation Validation Laboratory, in order to provide a certification framework that advocates for a modular approach, where core components are certified for concrete usage scenarios and the specific adaptation, to tailor the solutions deployed, is actually validated or certified at the factory shopfloor.

It consists, then, of a certification laboratory flexible to validate performance, scalability, OT/IT safety and security of Industry 4.0 base technologies and can be customized to the validation of application specific deployments in any industrial sector. Among the different industrial sectors targeted by Q-Digital Automation are: Manufacturing, Production Facilities, Metrology, Industrial Automation, Railway and Pharma. And, among the different possible technologies, are the following: Industrial Communications, Fog/Edge Computing, Robotic Systems, Cybersecurity & Safety, Cloud Computing, Big data and analytics and Mobile Solutions.

In a specific scenario, for example, for the case of M3 software, or in M3MH, it has been adapted for the QIF instances validation process for industrial communication on the Metrological sector, but as mentioned before, Q-Digital Automation is now qualified for the validation of new standards, technologies and sectors.

To carry out this validation process through Q-Digital Automation, it has been necessary to follow a series of steps defined by this certification framework. The validation process is made up of the following phases:

1. The owner of the component requests the certification and the acceptance request is registered in MangoApps, which is a platform like a workplace (portrayed in Figure 58) that integrates the applications that SQS uses along the whole validation process.

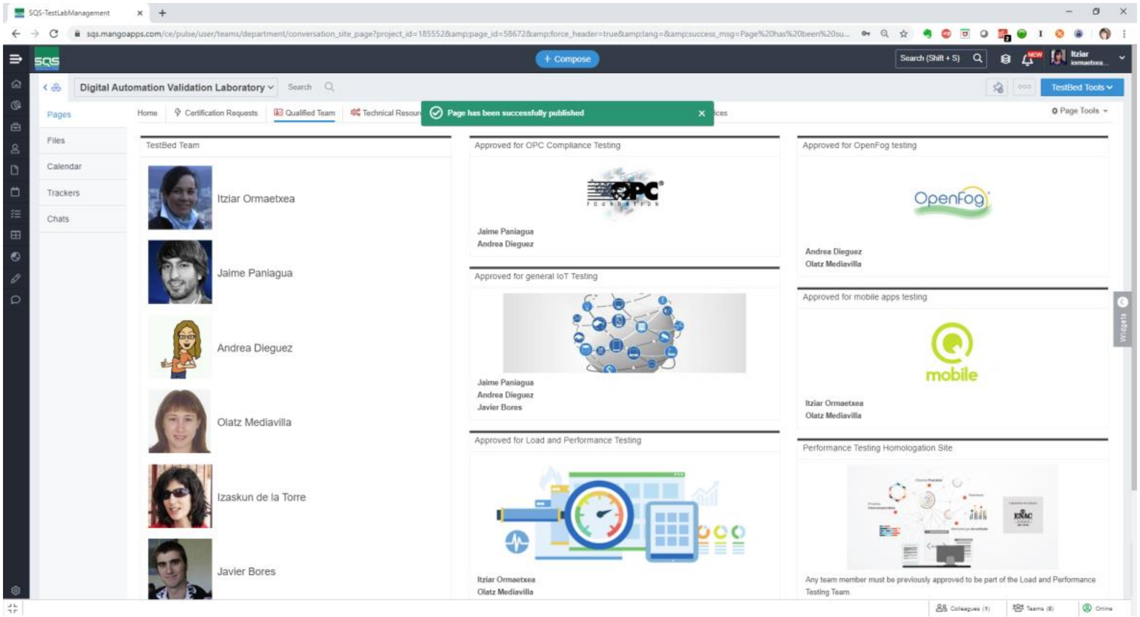


Figure 58: MangoApp Interface

2. The next step is the conformity assessment. The SQS TestLab Manager receives the request and begins the certification procedure, accepting the assignment.
3. The next step is to upload the documentation and make the Hardware/Software request. The SQS TestLab Manager assigns the specific tasks to the SQS team and uploads the certification templates. Afterwards, the declaration of applicability is sent to the client and when final approval is obtained, the component is requested to be sent to be tested.
4. The next step is the installation and configuration of the component for test development in the SQS lab (and not at Pilot premises: this is important). The SQS TestLab Team configures the component so that testing can begin. The architecture of the TestLab was already shown in Figure 56.
5. The next step consists of reviewing the documentation generated in the previous steps and determining: the certification strategy, the work team in the certification process and the selection of the necessary tools to carry it out.

6. Component testing begins. The first is called White-Box testing, which consists of a review of the internal structure, design and code of the software. It mainly focuses on verifying the flow of inputs and outputs through the application, improving the design and usability, strengthening security. Through these tests, the code evaluation report is generated, reporting the errors identified.

7. The next test is the functional assessment. Bump testing is a quality assurance (QA) process that bases your test cases on the specifications of the software component under test. Through this test, the functional evaluation report is generated.

8. The final tests are related to vulnerability analysis and consists of penetration tests. These tests are intended to exploit vulnerabilities in a system to determine if unauthorized access or other malicious activity is possible and to identify which cracks pose a threat to the application. Through this test, the Vulnerability Assessment Report is generated.

9. Finally, the SQS TestLab Manager collects all the previous reports, reviews them and generates the final validation report of the component, determining if it meets the established requirements. This report is sent to the client through MangoApps.

The deadlines established to carry out this entire validation process depend, in general, on the complexity of the component and what needs to be validated, for this, and summarized in the chart of Figure 59, three possible scenarios have been established, from the faster to the most conservative one, giving a deadline for each phase of the process where Owner means that this step depends on the customer, for when they decide or manage to do it. This means that it is not actually inherent to SQS.

Phase	Low (days)	Medium (days)	High (days)
Phase 0: SOA	Owner	Owner	Owner
Phase 1: Conformance	2	4	5
Phase 2: Upload	Owner	Owner	Owner
Phase 3: Installation	1	3	5
Phase 4: Documentation	3	5	7
Phase 5: White Box (if req.)	3	7	10
Phase 6: Functional	5	7	10
Phase 7: Vulnerability	5	5	10
Phase 8: Reporting	3	5	7
Total (days)	22	36	54

Figure 59: Possible Scenarios for the Validation Process

2.5.5.4 System Integration

The AUTOWARE Composable Digital Shopfloor Verification & Validation framework, in its Q-Digital Automation form, is not integrated at Pilot premises as if it were a “usual” component, mappable in the QU4LITY Reference Architecture, but, rather, it is part of the Innovation Journey of component development, namely, the last part before going to the market, as may be seen further below in Figure 60 within the next subsection.

2.5.5.5 Deployment

The AUTOWARE Composable Digital Shopfloor Verification & Validation framework, in its Q-Digital Automation form, is not deployed at Pilot premises as if it were a “usual” component, mappable in the QU4LITY Reference Architecture, but, rather, it is part of the Innovation Journey of component development, namely, the last part before going to the market.

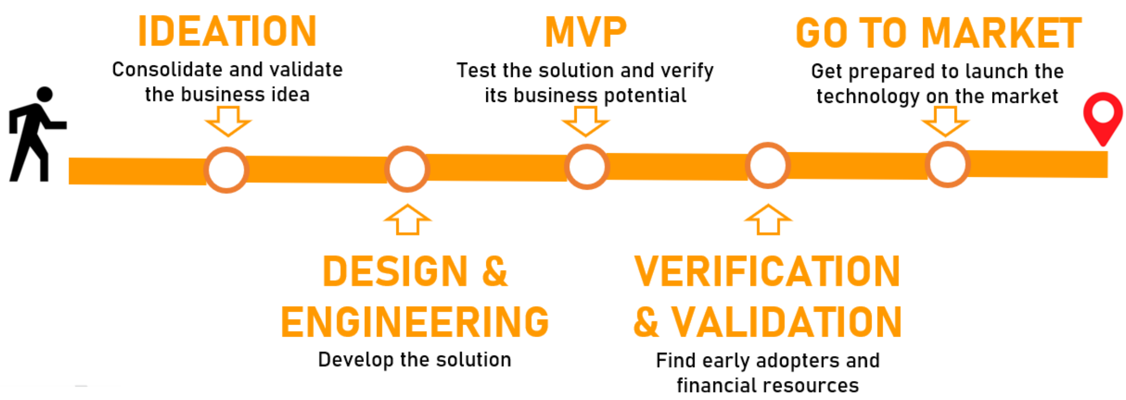


Figure 60: Depiction of a (Generic) Customer Journey for Technology Providers

In the case of Q-IDSA, SQS intends to develop a commercial component from the experience of 2020 and 2021 free-of-charge and open Integration TestCamps, something which will be possible in 2022, at the end of the QU4LITY project.

During 2020 and 2021, more IDS-certified components have been developed by third-party agents from the IDSA ecosystem, and many of them have been added to the remote infrastructure for which SQS grants access. Apart from that, more are planned, as can be observed in Figure 61, since some components that make part of the IDSA ecosystem are under development, this being the specific case of the AppStore (in a higher maturity level right now) and the Clearing House, or the transaction registry.

Component	Communication Protocol	Status	Hosted at SQS	Hosted at Third Party
Provider Connector	IDSCP	✓ Running	✓ Yes	
Consumer Connector	IDSCP	✓ Running	✓ Yes	
Provider Connector	HTTP	✓ Running	✓ Yes	
Consumer Connector	HTTP	✓ Running	✓ Yes	
Broker	HTTP	✓ Running	✓ Yes	✓ Yes
DAPS	HTTP	✓ Running	✓ Yes	✓ Yes
App Store	HTTP / IDSCP	Planned for future ITC	Planned for future ITC	
Clearing House	HTTP / IDSCP	Planned for future ITC	Planned for future ITC	

Figure 61: Status of the V&V tests that currently take place or are planned to be hosted at the SQS Integration TestCamp

2.5.5.6 User Interaction

As noted in previous Sections, the user of the component (whether Q-Digital Automation or Q-IDSA) does not interact with the user straightaway through an interface, as it would be in the case of partners who develop automation software products and implement them in a factory.

MangoApps interface, through which the Q-Digital Automation tool functions, was shown in Figure 58 of Section 2.5.5.3 – Data Input, along with the full description of all the phases of the Validation process of an automation component.

Also, in order to provide evidence for the celebration of past Integration TestCamps in which a variety of companies could test, attached are Figure 62, Figure 63 and Figure 64.

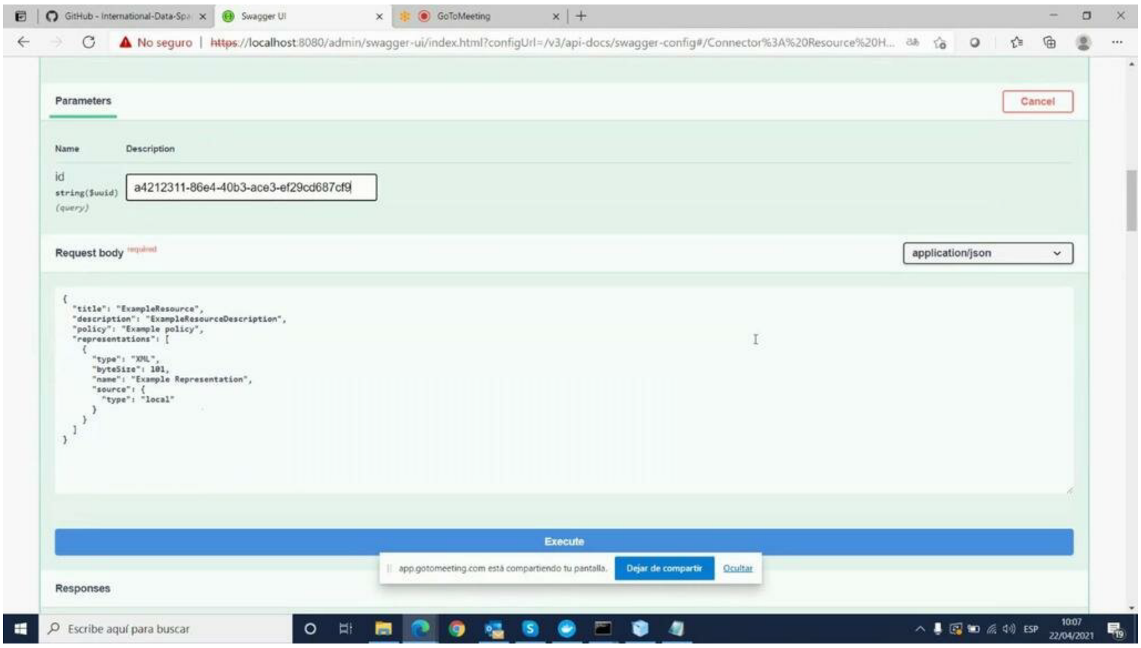


Figure 62: Integration TestCamp event on April 21st and 22nd, 2021 (1)

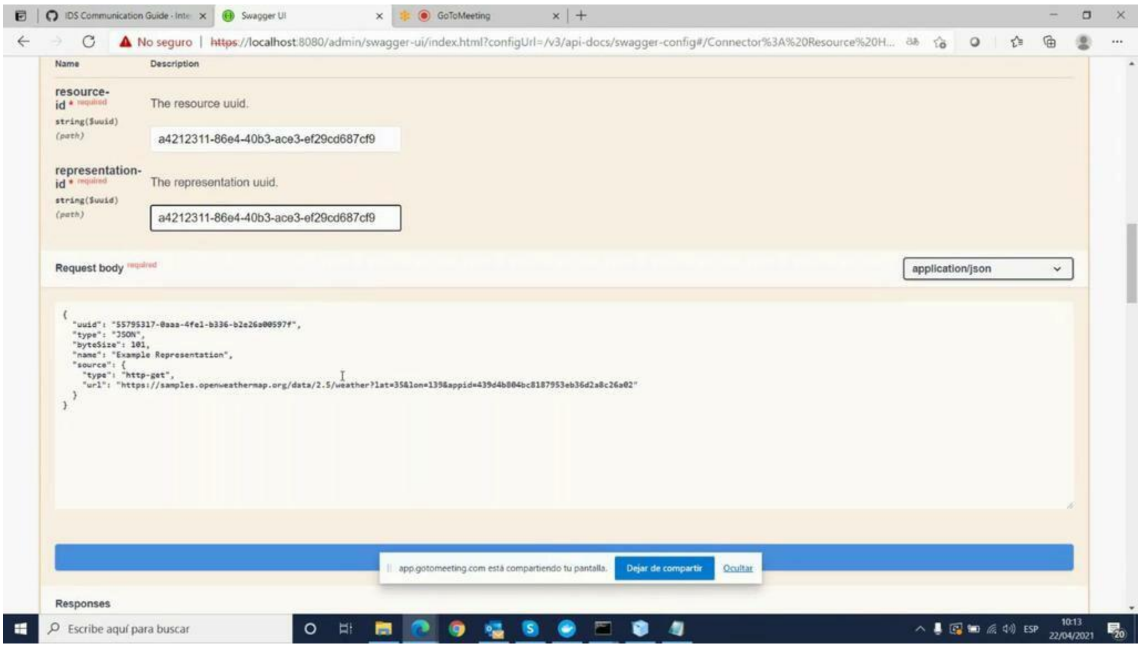


Figure 63: Integration TestCamp event on April 21st and 22nd, 2021 (2)

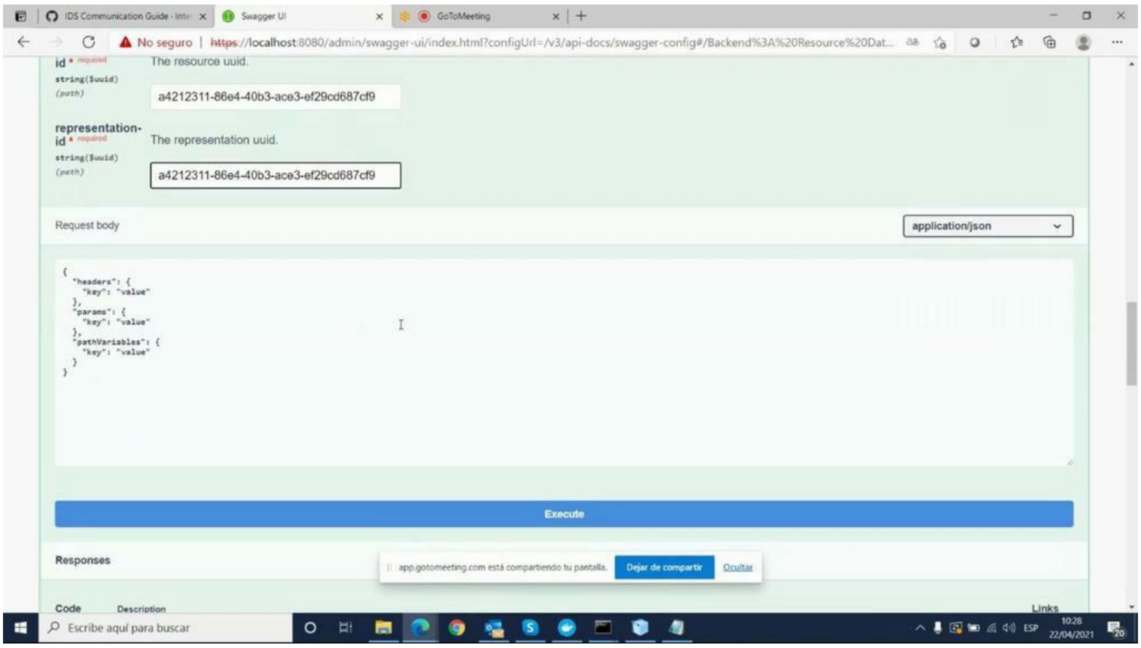


Figure 64: Integration TestCamp event on April 21st and 22nd, 2021 (3)

2.6 Pacelab WEAVR Augmented Reality for Operational Support

2.6.1 Overview

Leveraging Augmented Reality (AR) technology for operation support on top of machines for training operators to get familiar with new acquired machines and new processes is what brought inspiration and innovation to Continental's Plant.

Traditionally, operators & maintenance technicians are required to read and follow guidance from user manual printed papers to perform specific operations on the machine. This happens to decay the process of the operation time needed and increase the human error risk that could cause severe damage to the machine that would require maintenance.

To resolve the issues, we will be leveraging AR technology to provide step by step operation guidance as overlaid messages and annotations to reduce the human risk and increase the safety level of the operation. This technology will utilize the Pacelab WEAVR platform solution.

To ensure to have the optimal experience in leveraging AR technology for operation support, we have to improve and update some main features of our product modules to meet the requirements and contribute to the state of the art of the Pilot.

2.6.2 Background Technologies

The background technology needed to create the envisioned prototype implementation on the Pacelab WEAVR platform is:

Unity: Unity is a cross-platform engine developed by unity Technologies. The engine can be used to create three dimensional, two-dimensional, virtual reality, and augmented reality, as well as simulations and other experiences. The engine has been adopted by industries outside video gaming, such as film, automotive, architecture, engineering and construction.

.NETCore: .NETCore is a free and open-source, managed computer software framework for Windows, Linux, and macOS operating systems. It is a cross-platform successor to .NET Framework.

Docker: Docker is a set of platforms as a service product that uses OS-level virtualization to deliver software in packages called containers. Containers are isolated from one another and bundle their own software, libraries and configuration files; they can communicate with each other through well-defined channels.

Azure: Microsoft Azure, commonly referred to as Azure, is a cloud computing service created by Microsoft for building, testing, deploying, and managing applications and services through Microsoft-managed data centers.

AWS: AWS is a subsidiary of Amazon providing on-demand cloud computing platforms and APIs to individuals, companies, and governments, on a metered pay-as-you-go basis. These cloud computing web services provide a variety of basic abstract technical infrastructure and distributed computing building blocks and tools. One of these services is Amazon Elastic Compute Cloud (EC2), which allows users to have at their disposal a virtual cluster of computers, available all the time, through the Internet. AWS's version of virtual computers emulates most of the attributes of a real computer, including hardware central processing units (CPUs) and graphics processing units (GPUs) for processing; local/RAM memory; hard-disk/SSD storage; a choice of operating systems; networking; and pre-loaded application software such as web servers, databases, and customer relationship management (CRM).

2.6.3 Envisioned Industrial Innovation

The innovative features that we envision to implement within our prototype solution in the 3 major modules are the following:

WEAVR Creator Module: One of the main envisioned goals of using WVR Creator is to empower inexperienced developers and non-programmers to develop AR content applications seamlessly as simple as writing a user guide manual or PowerPoint. Therefore, after several iterations and development of AR content applications, there have been some challenges in encapsulating data as a sub-information in a simplified view which can be reused for deployment for other different platforms like PC, Android, IOS etc., as well enabling dynamic workflows that would simplify and decrease the number of steps needed to complete the procedural workflow content of an AR application.

In other words, as an analogy, the concept is to have the procedure represented as a chapter that has sub-chapters/section which includes the tasks for each sub-chapter/section just like a written user guide manual. In technical words, currently the defined AR content is named as a procedure. The procedure consists of steps that are linked together to form the shape of a complete procedure workflow, and each step consists of tasks divided into entry actions, exit condition, and exit actions.

The innovative update that will impact the process of developing AR application content is to have:

“Sub-procedure” of the “main procedure”: This will impact the process of developing AR content for the “use-case 1” of using Zevac rework Onyx29 machine, and for “use-case 2” ARS5/SRR5 housing opening, rivet removal, and PCB extractions as well for other machineries where similar machines have common initial setups but slightly different operations during the process. Therefore, from development perspective, when we define the initial “procedure” to setup the machine; instead of rewriting the same “initial procedure” over and over again for similar machineries, this “initial procedure” will remain as the main setup process of the machine and we will create and write a “sub-procedure” that will be the operation of that particular machine. This allows the reusability of data for other use-cases and simplifies the process of development which enhances the application performance.

“Super-step” of several “steps”: The idea is to encapsulate and group several steps under one bigger step. This will give a higher-level overview for the developer, subject matter expert about what is the main task in the operation with the possibility to view the sub-tasks flow. This also comes back to the concept of empowering non-programmers and inexperienced developers or the subject matter expert to define and write the AR content for operation support in the form of user manual guide or PowerPoint that has chapters with sub-chapters/sectiosn – main task with sub-tasks.

“Dynamic flow”: this feature improvement will allow any developer to be able to define the dynamic flow of the procedure content rather than just having it as a linear approach. This is helpful in a way and applicable to the Pilot use-case when encountering a new error type during the operation. This would allow the operator to trigger the “troubleshooting procedure” which will guide the operator to perform a generic troubleshooting process for the machine in a way that is related to the input provided by the operator in the application, the system then will provide guidance necessary to ensure a successful troubleshooting process throughout the operation. From a technical perspective, this will allow to have multiple exit conditions for each step that would be linked to another step that will generate a sophisticated dynamic procedural workflow.

WEAVR Manager Module (Server): Currently the WEAVR server is the center of communication between the WEAVR Creator & WEAVR player to manage the content data of the application distribution and to store basic data about the performance of a operator in the backend system. The envisioned plan of feature update is to upgrade the UI of the Frontend system for a better user experience with the ability to add four main features in the WEAVR Manager portal itself.

- *User Management*: The operator manager/trainer will be able to manage his team of operators/technicians by assigning them specific roles in the WEAVR Manager, group the technician team in relation to their machineries responsibilities/operational task, assign them the correct procedure/AR application related to the production line/machine they are responsible for. This feature will provide a high-level overview about the active operators who working on their operational tasks as well with the possibility of managing the team remotely as well by redefining their major focus and interchanging their responsibilities on several use-cases in the manufactory.
- *Procedure Management:* The operator manager will be able to define and assign the correct AR application for each operator or group of operators, define descriptions of each AR application, and manage the history version of each AR application based on the platform & hardware supported. This feature will simplify the process of managing several AR content applications for different use-cases in the shop-floor.
- *Collaboration Management*: The operator manager/subject matter expert will be able to create a collaboration session where he will be able to communicate and see what the operator sees in the field to provide additional remote instructions to help the operator in shop-floor.
- *Analytics*: The operator manager will be able to observe the data that represents the overall performance of the operator upon the completion of the operation using the AR step-by-step guidance. This functionality will simplify the process of managing the operators and monitor their performance to measure the ROI of utilizing AR technology in the field of operation.

WEAVR Player Module: Currently this module is for hosting and running the AR applications that have been developed within the WEAVR Creator. The envisioned plan of updating this module is by upgrading the UI for a better user experience where AR applications are organized automatically in relevant to the use-case operation field that has been defined initially by the operator manager via the WEAVR Manager. As well, through this module, the Operator will initiate a collaboration room where it would require 2 or more operators to be working together on a specific operation on the machine. Therefore, the collaboration functionalities will be developed to be interconnected with the WEAVR Manager to bring over the remote instruction needed from subject matter expert to stream back and record what is happening on the shop-floor.

2.6.4 Pilot / Use Case Description

At Continental's plant in Ingostaldt, there has been a challenge in guiding the operators & technicians to learn and perform an operation using a new machine that has been acquired for the specific use-case. The current difficulty that Continental is facing is the skill challenge in performing the correct operation without error on the Zevac Rework Onyx29 machine "Use-case 1" and on performing the operation of housing & Radome opening for ARS5/SSR5 following a complete rivet removal and PCB extractions "Use-case 2", as the process has high risk of causing injuries to operators and possible damages to the machines and PCB devices if the operational process wasn't followed precisely.

The ONYX 29 combines operating comfort, precision and process automation. Due to the integrated vision-system the precise orientation of components is guaranteed. The multifunctional hot gas heater head can be used for serial processes due to the highly integrated automation features to solder components, to remove components, to site clean (contactless removal of residual solder) and optional as a dispenser for dispensing applications. In addition, many unique options for several additional processes that are available.

The Onyx29 machine has a wide range of applications that are used in Continental's plant; it is mainly used for selective soldering and desoldering of SMD components. The high-performance unit onyx 29 guarantees high reliability and ease of operation. It is equipped with a special vision system for accurate alignment of all SMD's and fine pitch components and is ideal for:

Repairs: Misaligned devices can accurately be repositioned, and defective components can reliably be replaced.

Prototyping: The onyx 29 simultaneously assembles and solders prototypes. It allows expensive components to be desoldered and re-used.

Post-Assembly: Components that are missing at assembly time can be placed and soldered later. Individual devices which cannot be handled by available production resources can be retrofitted.

Assembly: The onyx 29 is the most accurate tool for assembly, from the simplest to the most densely populated boards.

2.6.5 Technology Implementation

2.6.5.1 Technology Description

PACE is providing in the project its own expertise and software product (Pacelab WEAVR as reported in T2.3 catalogue of ZDM assets technologies) about extended (augmented-mixed-virtual) reality application. The supported use case is "Operation Support" in which the goal is to support workers during their job with new augmented technologies and new wearable devices (example: MS HoloLens) and handheld devices (tablets and smartphones).

Pacelab WEAVR is a powerful software suite to streamline the authoring, management and execution of extended reality (XR) applications for operations, maintenance and training. Pacelab WEAVR enables you to create, deploy and execute a wide array of virtual, augmented and mixed reality solutions from the same set of technical data, creating a seamless and consistent experience from basic familiarization exercises to advanced, interactive field support. Its template-based, visual approach requires little to no programming or scripting skills, allowing subject matter experts to model tasks and procedures efficiently and without involving 3D developers or software engineers.

Pacelab WEAVR provides an integrated set of modules including an editor platform, a server application for collaboration and content distribution, as well as a run-time environment empowered by mixed, virtual and augmented reality technology. Its unique set of features and modules enables companies to create, manage, and implement a wide array of operation (setup, maintenance, etc.) and training applications from the same set of technical data, creating a seamless and consistent experience from basic familiarization exercises to advanced, interactive shop floor and field support. The solution is designed for subject matter experts to easily create content; for trainees and long-term employees to acquire new know-how and skills and get assistance for their day to-day assignments; and for supervisors and instructors to monitor and support these activities. Pacelab WEAVR comprises of three main modules (Editor, Server, and Runtime) and four optional modules (Developer Simulation Hub, Reporting, Remote Collaboration, and Run-Time Simulation Hub).

- I-house Editor: editor for creating and updating training contents
- High extensibility: Flexible integration of in-house and/or third-party models and tools
- Modular architecture: Easy setup and update
- Cutting-edge 3D game engine: 3D models and scenarios for fully immersive environments
- Multi-platform approach: Consistent learning experience across devices and channels

The prototype solution that will be provided, is a digital AR application on iPads/Mobile-phones/HoloLens that is providing step-by-step guided procedure for operators on the shopfloor for Zevac rework Onyx29 “Use-case 1” machine as well for ARS5/SRR5 Housing & Radome opening, rivet removal, and PCB extractions “Use-case 2”. The solution will be developed & deployed using our WEAVR platform and will be hosted on private isolated network BPA or via our cloud service that ensures privacy policies of the end-user and allows accessibility & private distribution via App Store & Play Store.

2.6.5.2 Technology Architecture

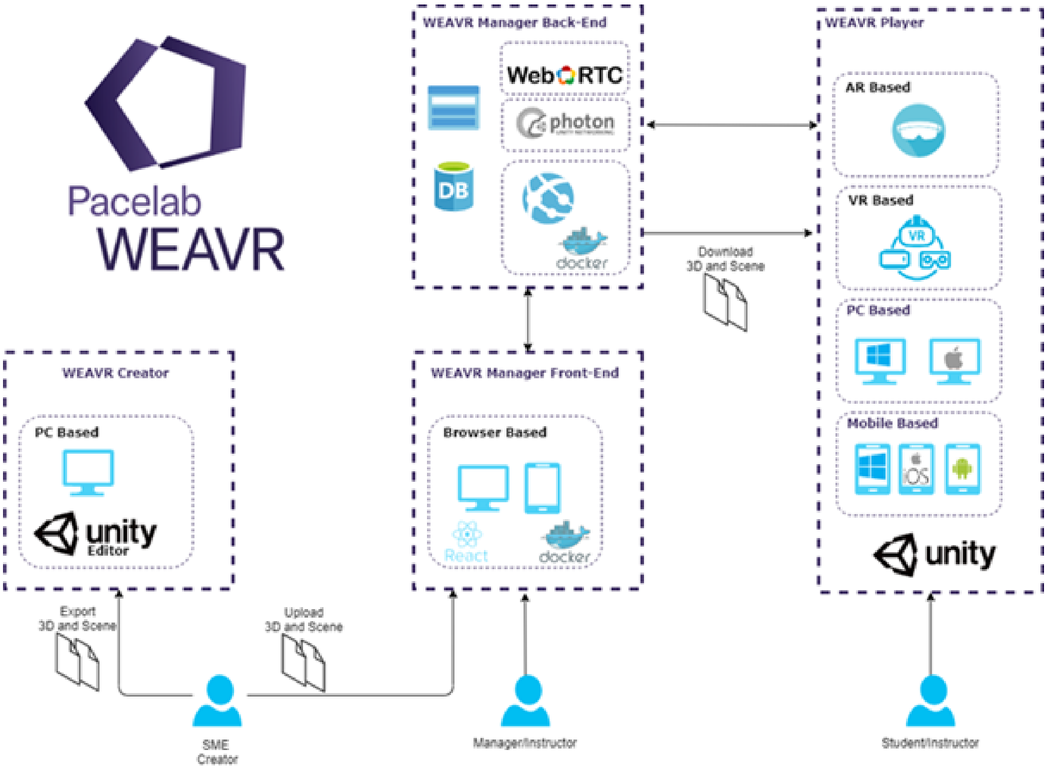


Figure 65: Pacelab WEAVR Architecture

WEAVR Creator: A plugin SDK built on top of unity3D engine, it is the authoring tool that allows users/technical writers/designers to create extended reality training content with simple Drag-and-drop visual programming where they do not need to have coding knowledge to build AR or VR applications. It has a set of unique features that leverages ARCore, XR foundations and all necessary interaction behaviours to interact with 3D objects and interface it in the AR mode on top of physical machineries or provide immersive virtual operational training.

WEAVR Manager: It is a web portal that acts as the central nerve of the platform by linking the Authoring and Execution module together. This web module collects and distributes content and basic functionalities to supervisors and instructors, enabling the handling of users, groups and job assignments and controlling real-time monitoring. Pacelab WEAVR Manager is an open system supporting the integration with 3rd party assets such as MES, PLM, LMS/TMS and more.

The module provides:

- Periodic reports summarizing activities, also using xAPI log;
- Remote collaboration allowing more parties to share the same view (immersive or augmented) and exchange information.

WEAVR Player: This is a player to access, select, and execute the available procedures in different modalities. Pacelab WEAVR Player is available across various systems including desktop PC, mobile; VR devices and AR devices such as HTC VIVE and Oculus, browser-based cloud applications and Microsoft HoloLens. Functionalities include to create, execute and continuously update of procedures in the shop floor,as well as troubleshooting and problem solving and training on the job.

2.6.5.3 Data Input

The Data input needed to develop the optimal step-by-step guidance AR application for the "use-case 1" Zevac Rework Onyx29 machine and for "use-case 2" ARS5/SRR5 housing opening, rivet removal, and PCB extractions are the following:

- CAD file of the machine. Pictures from top, back, sided views.
- Screen recordings of the software program used from PC to operate the machine.
- User Manual documentation coming from the manufacturer.

2.6.5.4 System Integration

The system integration for the WEAVR Creator will be through providing a WEAVR Creator SDK package and Unity v2019.4 software or higher and have it installed a PC based installation.

The WEAVR Player will be provided as an APK file that is compliant with Continental security policies on smart devices like iPads, tables and AR HoloLens device.

The WEAVR Manager web portal system integration will be done through exchange of APIs being a RESTful for application and providing automated terraform script for AWS deployment in compliance with Continental server and IT policies.

It's a set of Installations that will be integrated and compliant within the firewall protected continental environment, following continental security procedures.

2.6.5.5 Deployment

The integration can be done in two ways depending on the IT infrastructure of Continental use and their preferences. Ideally, the WEAVR Manager shall be hosted on-premises utilizing virtual machines or to be hosted on Continental AWS cloud server that is already in use.

For the first test, the WEAVR Manager will be deployed and hosted on PACE cloud AWS service and will provide credential access to Continental pilot.

Below is a list of services/tools required to correctly deploy and run WEAVR Manager on AWS cloud instances:

Amazon Elastic Container Registry (ECR): This service is used to store the containers of WEAVR Manager. By default, it is not possible to have multiple versions of the same container and the container with the "latest" tag is used as default.

Amazon Elastic Container Service (ECS): This service is used to create WEAVR Manager services from tasks defined for each container. Each task has its own defined environment variables and options. Among variables, there are the URIs of other services and connections to the databases.

Amazon Elastic Compute Cloud (EC2): This service is used to start the (Amazon Machine Image) AMI instances with the WEAVR Manager containers and configure an Application Load Balancer (ALB) to handle external as well as internal communication. The Docker images require an ARM equipped AMI preferably with a Linux OS. The terraform script will configure a load balancer to handle the instances, by default only one always running instance is used.

Amazon Simple Email Service (SES): This service is used to send emails to invite new users or reset passwords. A verified identity should be specified in the task and this email address should be SPF and DKIM compliant. A standard WEAVR invitation email is used right now, but a template will be used in future releases.

Amazon Simple Notification Service (SNS): This service is used to handle the asynchronous messages between WEAVR services.

Amazon Simple Queue Service (SQS): This service is used to store and enqueue asynchronous messages coming from WEAVR services.

Amazon Simple Storage Service (S3): This service is used to store various persistent data in buckets, such as:

- Log files coming from various WEAVR services and the configured AWS services. Private access is imposed for this bucket.
- Procedure files needed to preview and run the procedures. Some files are accessed privately by WEAVR services (e.g. asset bundles, procedure definition files) and others (e.g. procedure pictures) can be accessed publicly.
- Front-end part of WEAVR Manager. This bucket has public access since it should provide the Single Page Application (SPA) resources to browsers.

Amazon Relational Database Service (RDS): This service is used to store the databases needed for WEAVR services. The required engine is PostgreSQL. Every service has its own schema which is not accessible by others.

Amazon CloudWatch: This service is used to aggregate and inspect logs coming from various WEAVR services.

Other Components: There are other AWS components required for a correct deployment like VPC, Subnets, etc. but those are automatically handled by the deployed terraforms script.

On the other hand, the WEAVR Player will be deployed to AppStore (IOS) & Play Store (Android) as well for HoloLens and PC version to support different platforms for the same use-cases.

2.6.5.6 User Interaction

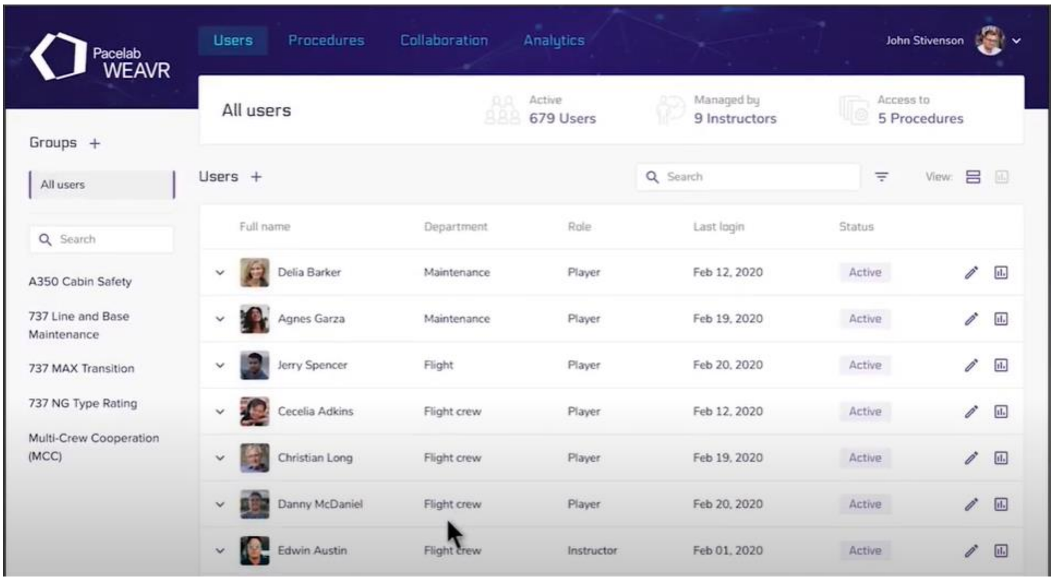


Figure 66: WEAVR Manager portal

As the WEAVR Manager is designed for managers/instructors and being used on the web portal, the user will be able to assign the correct maintenance procedure to the end-user/operator on the shopfloor.

On the other hand, the operator will be using the WEAVR Player on his/her handled/wearable devices, they will receive a notification that will inform them about the operation task that is required to be executed. Hence, they will open the WEAVR Player app and launch the maintenance procedure that has been assigned to them by their managers and will be able to follow the step-by-step guided procedure to perform the operation and necessary actions accordingly.

Figure 67: WEAVR Player – Zevac Onyx29 use case

2.7 Improved Failure Classification Enabler

2.7.1 Overview

Customers are increasingly demanding electronic components with high quality, which forces companies to continuously fulfil these requirements. This leads to a high number of inspection gates with high inspection severity and a high number of pseudo defects. Double inspections by process experts reduce the aforementioned defects as they develop process know how. Based on this process understanding, accurate assessments of the products can be made. However, the evaluation requires a high level of expertise from the process experts and at the same time leads to high inspection costs.

This challenge can be met by autonomous learning inspection gates, which enable product inspections with a high degree of inspection severity. Machine learning algorithms are particularly suitable for autonomous learning of process states. In the context of the technology described below, such algorithms are therefore adapted and integrated into an inspection gate in order to reduce pseudo errors in particular and to relieve process experts during double inspections.

2.7.2 Background Technologies

Within the “function-blocks” different Python libraries are necessary, as listed in Table 4.

Table 4: Relevant Python libraries

Package name	(short) Description
pandas	data analysis and manipulation tool for DataFrames[11]
numpy	mathematical functions[12]
psycopg2	PostgreSQL database adapter[13]
pandas.io.sql	Read SQL query or database table into a DataFrame[14]
feather	portable file format for storing Arrow tables or data frames[15]
scikit-learn	Library of ML-Algorithms[16]
xml.etree.ElementTree	API for parsing and creating XML data[17]

2.7.3 Envisioned Industrial Innovation

The general objective of the considered use case is to improve the overall product quality rate as well as to increase the testing efficiency. In the chosen scenario, the vision is to reduce the pseudo error rate significantly by changing from predefined static testing parameters to a refined quality assessment procedure based on processing parameters and prior testing results. Following a closing-the-loop approach, data and results from the overall line are collected and investigated to identify failure sources. It is furthermore intended to gain experience and improve the transparency of the manufacturing process by applying data mining and machine learning.

To increase the overall product quality rate as well as the testing efficiency, information about the final product quality need to be obtained during the ongoing manufacturing process.

2.7.1 Pilot / Use Case Description

At Amberg, Siemens' Digital Factory Division is manufacturing its SIMATIC products. The core of the manufacturing process is the production of the circuit boards, which are later assembled with the housing parts to form the final product.

As typical in electronics production, a high effort is put into non-value adding processes for testing the manufactured products to guarantee high product quality. As of today, all products are tested in different testing steps (marked orange in Figure 68).

[11] https://pandas.pydata.org/
[12] https://numpy.org/
[13] https://www.psycopg.org/docs/
[14] https://pandas.pydata.org/pandas-docs/version/0.14.1/generated/pandas.io.sql.read_sql.html
[15] https://arrow.apache.org/docs/python/feather.html
[16] https://scikit-learn.org/stable/
[17] https://docs.python.org/3/library/xml.etree.elementtree.html

Figure 68: Circuit board manufacturing line with test stations

At Solder Paste Inspection (SPI), the volume and geometry of the solder paste are measured and compared with predefined threshold values provided by the machine vendor. If the measurement of any single solder pad is not within the tolerance, the location of the pad is registered, and the panel consisting of four circuit boards is classified as “DEFECT”. It is then automatically extracted from the actual manufacturing flow and is moved to a buffer, and an operator is notified to check the measurement results. After manually checking the effected soldering pad, the operator classifies it as “GOOD,” leading to the result that the inspection is “PASSED.” Classifying as “DEFECT” results in removing the panel from the line to perform rework. The current inspection process is illustrated in Figure 69.

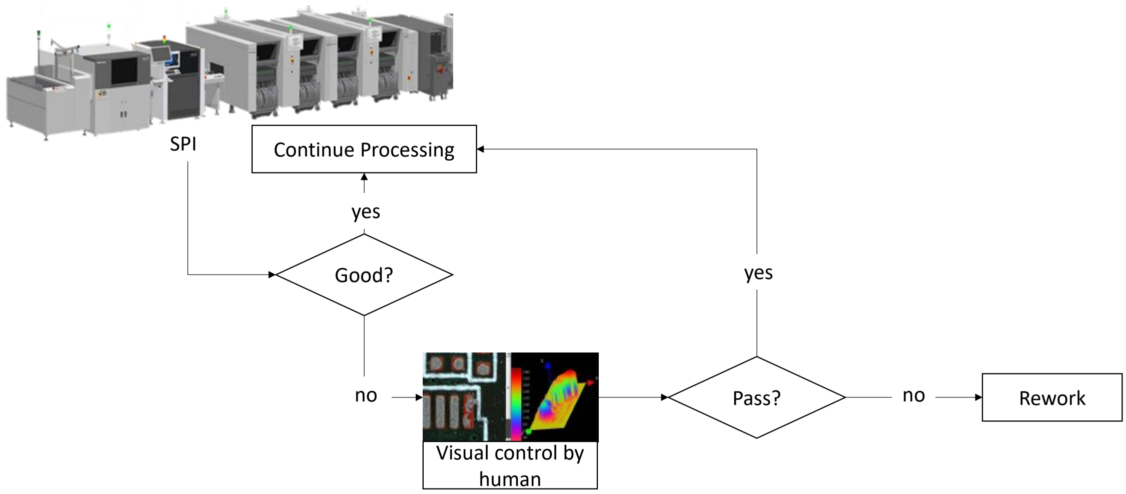


Figure 69: Current inspection process flow within the Pilot

As illustrated in Table 5, the “PASSED” result is treated as a pseudo error. At every test station a similar procedure is in place today, leading to a comparable situation: the pads are tested and compared with predefined threshold values provided by the machine vendor, being classified as “DEFECT” and moved to a manual re-testing sub-line/buffer.

Overall, this results in a lower as possible efficiency of the line. Since pseudo errors are a significant percentage of the overall test results and require additional work for the operator, gaining a deeper understanding of (pseudo) error is a necessary basis for further optimization of the entire process chain.

Table 5: Solder paste inspection station - Error table

Machine Test Result	Operator Test Result	Overall Result	Interpretation
GOOD	---	GOOD	No Error
DEFECT	GOOD	PASSED	Pseudo Error
DEFECT	DEFECT	FAILED	Rework

Since each pseudo error requires an operator to perform additional evaluation of the test results, the aim of the business scenario is the reduction of pseudo errors to reduce unnecessary evaluation steps. In this context, the propagation of defects or product properties throughout the entire process chain is of particular importance. Based on this, a defined future business scenario is the reduction of pseudo errors by an “Improved Failure Classification”.

2.7.2 Technology Implementation and Deployment

2.7.2.1 Technology Description

Based on the description of the current process flow, it can be seen that knowledge of pseudo errors is inherent with the employees. The aim is to identify and extract this knowledge to implement the findings in the process flow to reduce pseudo errors. The basis for this is an implementation of models, trained by machine learning algorithms, in the existing production process. These models will be used to automatically and continuously recognize patterns that distinguish real errors from pseudo errors.

Within the first integration stage, limit values for the products installed on the SIMATIC are automatically identified, which do not influence subsequent manufacturing processes or impair product quality. In particular, the identification process is generalized by artificial intelligence in such a way that no humanitarian evaluation (by an operator) is required for the identification of pseudo faults in the future. This aspect forces the objectification of quality inspection processes by avoiding humanitarian inspections so that an objective and constant quality of product monitoring is achieved.

Within the second integration stage, the "normal" process behaviour is monitored, so that in the case of unusual process behaviour (for example, an increasing number of product defects), the quality deviation is indicated by models, trained by machine learning algorithms.

With the third integration stage, the first two integration stages are integrated into each other: Based on the monitoring of normal process behaviour and reliable detection of pseudo faults, correlations between process changes and upstream production steps are automatically identified. From this, process adaptations such as changes in monitoring limits are derived. The integration of these models is intended to take place in the solder paste inspection.

2.7.2.2 Technology Architecture

The module consists of four layers. These layers take on different tasks and are linked to each other.

The Communication Layer: This layer links the automatic measuring system with the other layers of the module. Via this layer, the automatically recorded measurements are transferred to other layers. In addition, the results of the other layers are fed back into the automatic measuring system via the Communication Layer.

Data Preparation Layer: In this layer, the measurements are processed and prepared for further analysis.

Data Analysis Layer: The pre-processed data from the Data Preparation Layer are analysed within the Data Analysis Layer for patterns hidden in the data. Various machine learning algorithms are used to train corresponding models. Furthermore, the models are optimised and validated in the layer.

Testing Layer: Out of these optimised models the best models are selected and integrated into the Testing Layer. This layer enables a classification of new and unseen products in GOOD and DEFECT in order to reduce pseudo errors.

The Module is established by different "function-blocks" within Python. These "function-blocks" are connected to each other as illustrated in Figure 70.

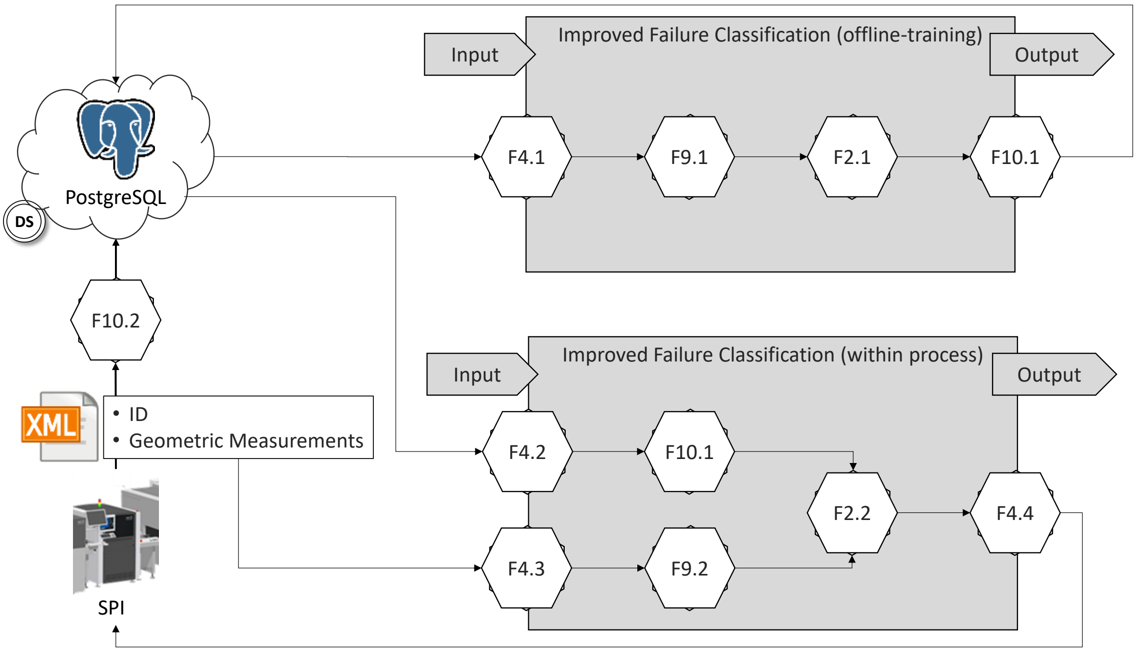


Figure 70: Insight in the module

A description of the in Figure 70 presented "function-blocks" can be found in Table 6.

Table 6: Used function-blocks within the module

ID	Function	Description
F2.1	Analytics	Train and optimize Machine Learning Models
F2.2	Analytics	Use Machine Learning Models to determine good and defect products
F4.1	Communication	Retrieve data from database
F4.2	Communication	Retrieve stored model
F4.3	Communication	Retrieve data via XML
F4.4	Communication	Send results to SPI / humans
F9.1	Preprocessing	Data cleaning / selection of features / feature generation
F9.2	Preprocessing	Data cleaning / selection of features / feature generation (identical to F9.1)
F10.1	Storage	Store trained model in cloud
F10.2	Storage	Store data in Database

2.7.2.3 Data Input

The module must be able to process numerical measured values in order to distinguish GOOD products from DEFECT products. The numerical measured values include position properties of the solder joints and measurements of geometrical properties.

Furthermore, it is considered to process image data, if the exclusive use of numerical measured values is not sufficient for classification.

2.7.2.4 System Integration

The module uses automatically recorded process data from Solder Paste Inspection (SPI). These include geometric measurement data of the applied solder paste at defined pin positions. Figure 71 represents the data flow of the module.

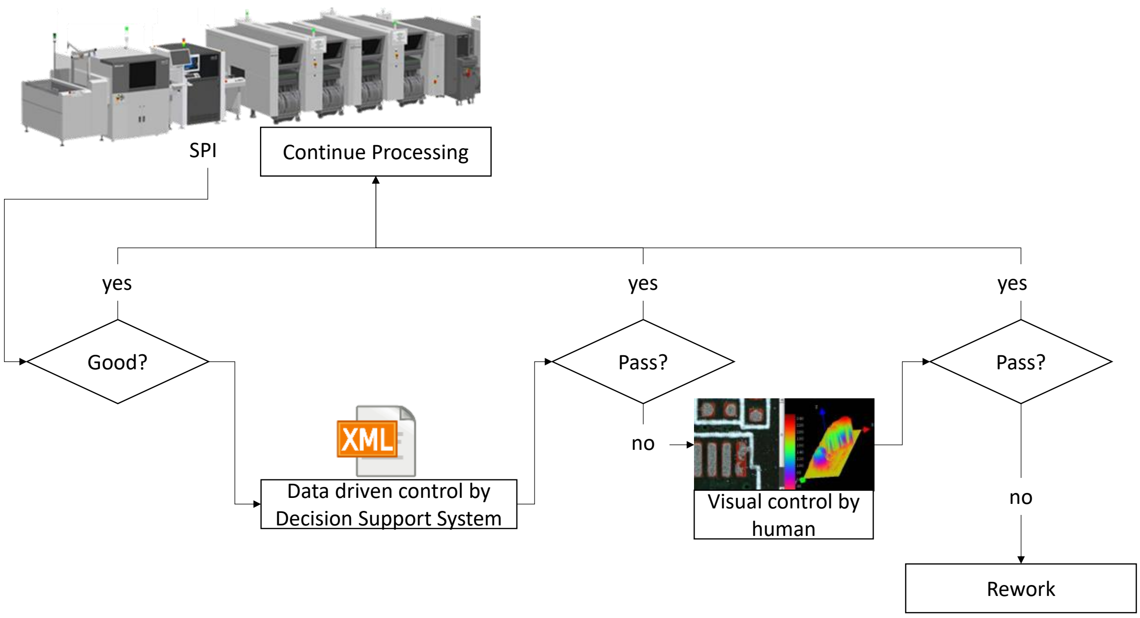


Figure 71: Prototype interactions with other systems within the pilot

The objective of the module (mentioned as Decision Support System in Figure 71) is an objective identification of defective pins. For this purpose, supervised and unsupervised machine learning algorithms are used: Machine Learning Algorithms are used to build up models which can differentiate between GOOD and DEFECT on the basis of recorded measurement values. The decision is made within the SPI: If a product is classified as DEFECT, this product is rejected and reworked. In case of a classification as GOOD, the tested product is further processed according to Figure 68.

In general, the Module is able to use automatic measurement results to predict DEFECT and GOOD products. By visualizing the decision made by the module and comparing them with the real expert labels, the module can be validated to ensure long-term use in the product line.

2.7.2.5 Deployment

As described above, products rated as DEFECT are verified by humans. It is planned to integrate the module into the SPI, so that if a DEFECT product occurs, the module is used to distinguish between GOOD and DEFECT instead of humans. In case the module evaluates a product as DEFECT as well, only these products will be verified by humans (as illustrated in Figure 71).

2.7.2.6 User Interaction

By implementing the module, various interaction possibilities between humans and the module arise: The actual state of production (e.g. counts of errors and locations with higher error amount) can be visualised within a dashboard. From this, process experts can derive information for process improvements and evaluate historical process developments. Furthermore, process experts can evaluate the module regarding its topicality, for example, to verify its function after process adjustments have been made.

2.8 Data Analytics Tool for Additive Manufacturing

2.8.1 Overview

The Data Analytics Tool for Additive Manufacturing is developed around the requirements of the PRIMA pilot, where it will be integrated.

The main goal of the tool is to process a set of KPIs that are representative of the process quality and that can support the operator in the identification of roots for possible problems in the quality of the manufactured parts.

The overall system is developed by different partners involved in the PRIMA pilot. In the scope of Task 5.3, we focused on the development of an analytics tool to elaborate a set of KPIs based on the data monitored, which are exploited, on the one hand, by the operators to evaluate and get an insight into the manufacturing process and, on the other hand, by a Decision Support System (DSS) for further elaboration and the triggering of possible corrective/preventive actions.

2.8.2 Background Technologies

To develop the Data analysis tool for Additive Manufacturing components from some open source projects are exploited in order to leverage largely available and well maintained pieces of source code as well as to focus on the added value and customization features instead of “reinventing the wheel”.

The list of technologies that is going to be leveraged is almost definitive, even if it could be possibly modified in the coming period, while the developments of the pilot and of all the other technologies involved in that use case.

One core technology is MQ Telemetry Transport (MQTT) messaging protocol. Such a technology was already introduced in D5.5 and therefore the reader should refer to that document for further details on the MQTT technology.

Concerning the storage of the information collected in the pilot, the Data analysis tool for Additive Manufacturing makes use of a DBMS optimized for time series data, in order to speed up the access to the database for reading/writing operations on the data collected from the manufacturing process. InfluxDB is an open source database that can satisfy the needs for the PRIMA pilot use case.

To provide better and easier access to the information, the Data analytics tool is enhanced with a visualization functionality that presents the most relevant information about the process quality through a dashboard. The implementation of such a functionality leverage an open source technology named Grafana, which enables to develop good quality dashboard effectively, and easily accessible via web-browsers applications.

2.8.3 Envisioned Industrial Innovation

The Data Analytics Tool actively contributes to the process of managing the quality of the production process, in cooperation with the other components of the overall system, each specialized on its functionality. A relevant innovative role of the Data Analytics tools is represented by the aggregation of information produced by different sources, collected by leveraging the widely accepted standard MQTT to simplify communication and semantic issues. The system implements a more general approach of data streaming processing, which helps in analysing the continuous flow of data generated by various sources, without the overhead of unnecessarily storing them, if not needed.

The specific approach for the storage of data and metadata managed by the Data Analytics Tool has been defined and implemented in a first prototype running at lab scale, at SYN premises. Additionally, an auxiliary tool has been implemented to generate artificial data and enable the testing of the prototype while the developments proceed.

The Data Analytics Tool is also complemented by the optional possibility to store the processed data, for a future further analysis, with an automatic retention time based on the implicit generation timestamp.

In addition to provide relevant data and KPIs to the DSS, the Data Analytics Tool also enables the operator to be informed about the overall information collected and associated to a specific manufacturing task. All the data will be stored in a time-series based database management system (DBMS) and they will always be accessible by the user whenever it is needed. To provide better and easier access to the information, the Data Analytics Tool is enhanced with a visualization functionality that presents the most relevant information about the process quality through a dashboard.

2.8.4 Pilot / Use Case Description

Prima Additive is the new division of PRIMAs Industrie, which develops, manufactures, sells and distributes metal Additive Manufacturing systems. The PRIMA pilot builds around one of their additive machine tool products, a Power Bed Fusion (PBF) system. The main goal of the pilot is to enhance the machine with advanced monitoring capabilities and other features that enable to increase the quality of the production.

Figure 72: Print Genius250

The additive manufacturing system that will be enhanced with the technologies of QU4LITY is a Genius250 model, with a laser power of 2x500W and capable to process a wide range of metal powders: stainless steel, maraging steel, cobalt chromium alloy, aluminium alloy, titanium alloy and high temperature nickel base alloy, etc.

Several enhancements are planned for the additive manufacturing system:

- A vision system and a real time image processing system will enable the monitoring of the quality while the different layers of the part under manufacturing are ongoing.
- A 3D visualization tool will present to an operator a detailed vision of the manufactured part and will enable the investigation of possible defects recognized by the vision system previously mentioned.
- A simulation tool will be exploited to simulate the manufacturing process before the actual processing of the real part. The results of such a simulation will provide an estimated duration for the manufacturing of the part.
- A Decision Support System (DSS) will be leveraged to support the management of the machine tool providing relevant indications about the actions to be performed in order to keep the system within the expected production quality performance range.
- An augmented reality (AR) system will be integrated into the machine tool to support the operator during maintenance tasks.

While all these enhancements are developed by other partners involved in the PRIMA pilot, SYN focused on the development of an analytics tool to elaborate a set of KPIs based on the data monitored and collected from the process. The performance indicators and other metadata will be exploited both by the operators to evaluate and get an insight about the manufacturing process as well as by the DSS for further elaboration and the triggering of possible corrective/preventive actions.

2.8.5 Technology Implementation and Deployment

2.8.5.1 Technology Description

The additive manufacturing process is a very complicated process where many factors play a role simultaneously in the final quality of the part manufactured.

The Data analytics tool for Additive Manufacturing monitors different types of process parameters while manufacturing process is running and stores the data in a database management system (DBMS).

In order to elaborate KPIs that can consider the overall spectrum of information, which are associated to the manufacturing process and the manufactured part, the Data analytics tool for Additive Manufacturing collects metadata also from other sources. Details about the manufactured part defectivity are collected from the image processing system, while the information about the estimated processing duration is gathered from the simulation tool.

Additional metadata are collected from the 3D visualization tool that the operator uses to investigate the quality of manufactured parts, providing relevant hints to the computation of KPIs based on his experience. The human skills are indeed exploited by the analytics tool to provide more refined and relevant KPIs about the process quality.

2.8.5.2 Technology Architecture

The Data analytics tool for Additive Manufacturing is hosted in a device that provides the required resources in terms of memory, storage, processing and networking capabilities. From an architectural perspective, the tool runs at Edge level.

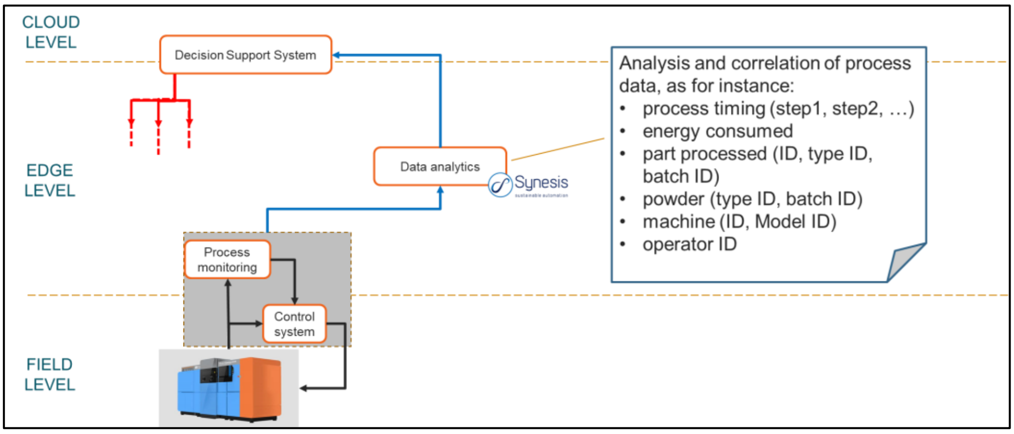


Figure 73: Deployment layers of PRIMA pilot

The Data analytics tool for Additive Manufacturing is designed to be hosted in an Edge device, provided with some sort of virtualization features. The components of the Data analytics tool will be allocated to one or more virtual machines.

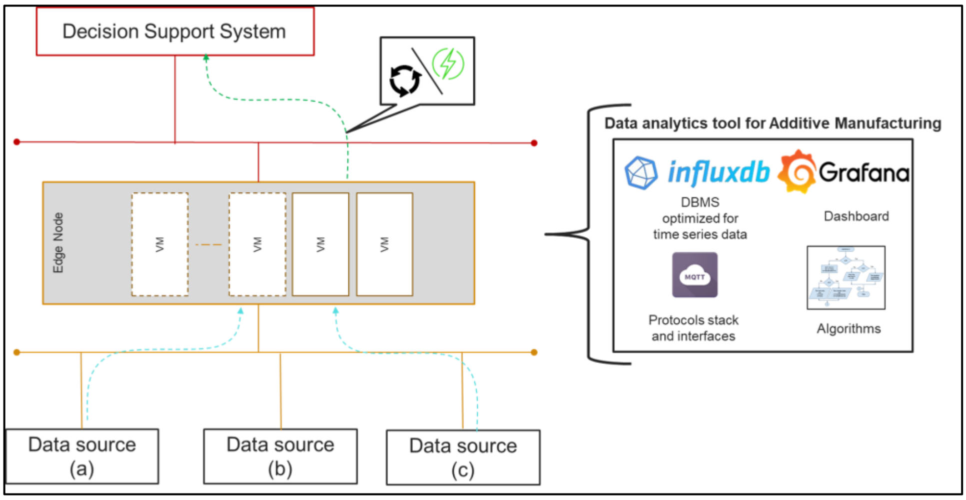


Figure 74: Hosting schema of PRIMA pilot

In addition to the elaboration module, dedicated to the computation of KPIs and basically built on top of a set of dedicated software algorithms, the Data analytics tool will be composed by other components dedicated to provide the different functionalities required. Within the PRIMA pilot there is a database management system that the pilot owned already uses for his production. However, to avoid performance bottlenecks that can affect the data collection and storage of the system, a dedicated DBMS will be used for the needs of the Data analytics tool.

InfluxDB is a high performance DBMS optimized for the storage of time series data and therefore suitable for the implementation of the Data analytics tool, which has to monitor the process parameters of the machine tool while the manufacturing task is ongoing.

The connectivity with the other systems of the pilot is implemented leveraging the MQ Telemetry Transport protocol. The protocol stack is integrated within the Data analytics tool to enable the effective exchange of data from the many data sources and to provide relevant information to the Decision Support System.

To provide a visual feedback to human operators, with presentation of real-time data charts and trends about KPIs, SYN also implements a graphics dashboard dedicated to the visualization of the information elaborated by the analytics tool. Such a functionality is developed leveraging technologies proposed by big and well known open source communities. In particular, the data analytics tool is enhanced with the Grafana technology to develop graphics dashboards accessible via any web browser tool.

2.8.5.3 Data Input

The Data analytics tool for Additive Manufacturing interacts with many systems and tools in order to collect the information that is needed to provide an aggregated form to the several parameters associated to a specific manufacturing task, and then to elaborate the pre-configured KPIs that can highlight quality performance indicators and possible roots of defectivity on the manufactured parts.

The first source of information is the machine tool from where the Data analytics tool collects several process parameters along with the manufacturing task. The definitive set of parameters to be monitored is not defined yet but will be composed of process values measured by the different sensors that equip the machine tool.

Another source of information is the simulation tool from TTS that will provide an estimation for the processing of a part.

The vision acquisition and image processing tool from FHG-ILT will provide different metadata associated to each layer of the manufactured part. Such information will provide insight into the defectivity of the part.

Also the 3D visualization tool from FHG-IGD should enable a person to provide the Data analytics tool with evaluations of the part's quality directly leveraging the skills of the experienced operator.

2.8.5.4 System Integration

Many systems and tools interface to the Data analysis tool in order to provide some kind of data or to collect the information processed by the tool.

A draft schema about the systems/tools involved and the main path of data flow is represented in the following figure.

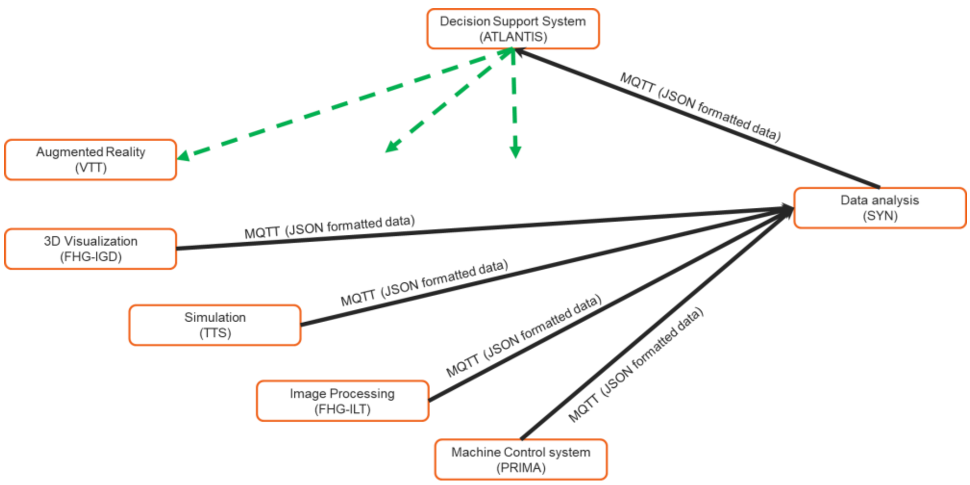


Figure 75: Main data flow paths that involve the Data analysis tool

2.8.5.5 Deployment

The system is designed to be deployed on an edge node. This would simplify the connection with other systems in the overall configuration, which could be constrained by their physical implementation.

As illustrated in the following picture, the system is expected to communicate with both the field level, where the Process monitoring and Control system, and the cloud level, where the Decision Support System is implemented.

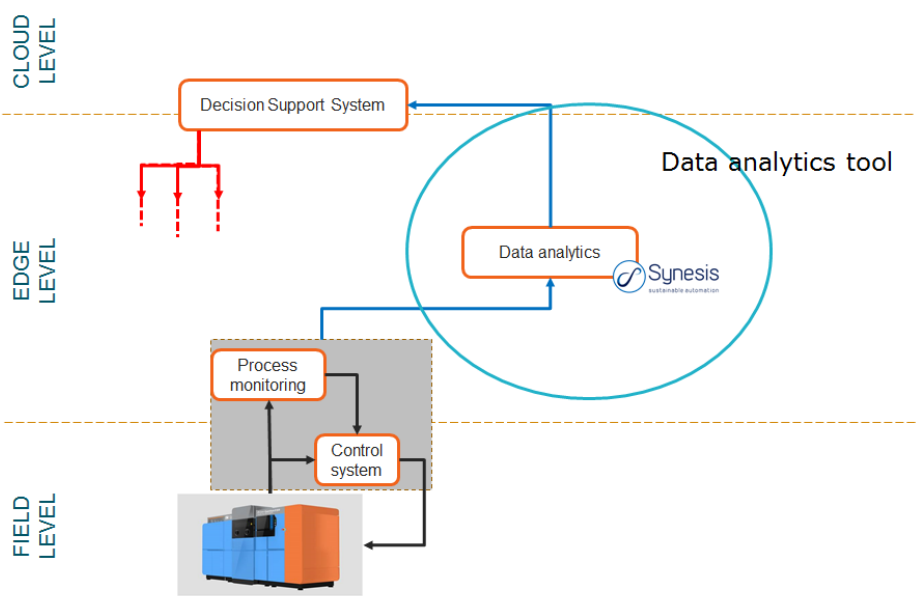


Figure 76: Data Analytics Tool deployment

2.8.5.6 User Interaction

The human operator can have access to a graphical dashboard accessible via a web-browser tool. The dashboard reports different charts associated to the KPIs evaluated by the Data Analytics Tool.

3. Technology Evaluation

3.1 Context Awareness Framework

3.1.1 Pilot Requirements

Functional Requirements: The pilot-specific technological requirements for each component of the Context Awareness Framework are as follows:

- Context Monitoring: The system is able to connect to the RDS datalake and periodically execute SQL queries to retrieve the relevant test measurements in CSV Format.
- Context Extraction: The downloaded data needs to be processed and transformed into the required format, which can be processed by the Big Data Analytics python script. The system executes the script, processes the results and stores them in a MongoDB.
- Context Provision: The results of the analysis are made available via a RESTful API.
- User Interface: A browser-based interface (SPA) allows users to view, search and export the relevant data.

Furthermore, we have defined KPIs to measure the fulfilment of functional requirements of the system.

- Percentage of units that can be monitored and checked for errors
- Percentage of faulty units detected with the monitoring/extraction and analysis solution
- Accuracy of outliers detected by Data Analytics vs Customer Returns

Non-Functional Requirements: From a non-functional perspective, the user interface needs to be accessible and understandable for users inside Continental. It should provide the information in a close to real-time scenario, as well as for retrospective analysis.

3.1.2 Evaluation

The system was designed with quality managers from Continental as the primary end users in mind. Having said this, for the preparation of the evaluation process, a Quality Manager from a Continental production site, identified products and test steps to focus on:

- The first product investigated is a camera. For instance, assembly line tests that measure the power supply were considered relevant by the expert in relation to an issue that has caused customer complaints in the past.
- In order to retrieve the relevant test measurements, the data in the Continental datalake tables being assessed, links relevant data from different tables, meaning that e. g. test measurements are already linked to the process data.

Table 7 describes in detail the evaluation scenario for real-time analysis which can lead to interference in the production process. Another evaluation scenario is the retrospective analysis of particular faulty units, as described in Table 8.

Table 7: Real-time Analysis Scenario

Test Scenario Name	Check analysis results for the last shift
Actors	Continental Quality Manager
Description	Quality Manager checks if there are potentially defective parts detected by the system
Trigger	Shift is over
Preconditions	- There were units produced in the recently finished shift - Production and testing data was uploaded to datalake with minimal delay - Data has been processed and analyzed by the system
Normal Flow	- Quality Manager opens User Dashboard - Clicks on the batch of units he wants to investigate - Checks for suspicious units - Manually check those units and/or take them out of the assembly line
Alternative Flows	- Quality Manager opens User Dashboard - Click on the batch of units he wants to investigate - Check for suspicious units - No suspicious units found. No intervention necessary
Frequency of Use	Daily, or multiple times a day, depending on the production schedule
Assumptions	- Faulty Units need to be taken out before the batch of units is brought to the warehouse at the end of the shift
Narrative	When the shift is over, the Quality Manager enters the system and checks if there are potentially defective parts detected by the Context Awareness Framework Continental application (the so called Online Data Acquisition and Industrial Data Analytics)
Results of testing	Some issues were observed: - The data-upload to the datalake (see pre-conditions above) can take too long such that the analysis results are not available in time to intervene in the process. - Information needs to be presented in a clear way to allow quick decisions

Table 8: Quality Assurance Scenario

Test Scenario Name	Quality Assurance Investigation of returned products
Actors	Continental Quality Manager
Description	A Quality Manager retrospectively investigates a specific unit or set of units, which have been claimed by customers The Online Data Acquisition and Industrial Data Analytics solution is able to provide meaningful additional information on certain units for the Quality Manager to take into account
Trigger	Customer claims faulty units
Preconditions	- The claimed unit was processes and analyzed by the system
Normal Flow	- Quality Manager opens User Dashboard - Searches for the unit of interest - Checks the analysis for the production batch, which contains the claimed unit
Alternative Flows	- Quality Manager opens User Dashboard - Searches for the unit of interest - Checks the analysis for the production batch, which contains the claimed unit - Use CSV Export functionality to e.g. and discuss the findings with colleagues
Frequency of Use	On demand, whenever there is a customer return that could be related to the issue addressed by the prototype.
Assumptions	The data is stored for long enough
Narrative	The scenario was carried out in the above described flow of events.
Results of testing	The prototype can help to identify previously hidden patterns that faulty units have in common. The user interface could be enriched with further information on each unit (e. g. the shipping status)

KPI Evaluation: The 3 identified KPIs were evaluated and the results are presented as follows.

1. Percentage of units that can be monitored and checked for errors: During the testing of the prototype inside Continental that was done so far, the measurements of over 1 million units have already been analysed. The time needed to process a 4-hour batch of units varies slightly based on the number of units produced in the timespan, ordinarily it takes less than 1 minute for a typical batch of 300-400 units. The testing has shown, that the prototype can provide valuable information in a timely manner on all units of the considered product type and is scalable for practical application.

2. Percentage of faulty units detected with the monitoring/extraction and analysis solution: Of the total 1.058.764 units that were analysed in the testing period, 32.515 were flagged as potentially faulty. This means 3,07 % of all analysed units were considered outliers among similar units, which can indicate future problems with that units.
3. Accuracy of outliers detected by Data Analytics vs Customer Returns: At the time this is written, the evaluation of this KPI is not yet finished. There is still relevant data missing and some inconsistencies that need to be clarified before the evaluation can be considered complete. In order to assess the performance of the pilot implementation based on a confusion matrix, an accurate labelling of the data is needed. Since the data analysed is coming from intermediate production steps, at the time of analysis the final outcome of each unit is unknown.

There are several possibilities:

- Unit is scrapped later.
- Unit is in the warehouse and was not shipped yet.
- Unit is shipped to customer and is not returned.
- Unit is shipped to customer but is claimed.

This means for recently produced units, we cannot yet convincingly determine whether they were correctly or falsely detected as risky units by the algorithm. Therefore, we decided to primarily look at historical data. So far predominantly data from September and October 2020 has been considered, since this is far enough back into the past such that the customer returns have been properly processed. By comparing the customer returns and the units identified as risky by our prototype, we can assess how many actually faulty units were missed by the system (false negatives) and how many were correctly predicted (true positives).

To determine which okay units, were falsely detected by the system (false positives), the true status of each unit needs to be checked, since the unit could have been detected and scrapped in a later step. In that case the prediction was actually correct, but the faulty unit was only caught e. g. by a manual inspection. It is also possible, that the part was not yet shipped to the customer, e. g. is still stored in the warehouse. In this case, it is too early to make a final judgement of that unit. The Process to investigate the true status of the falsely predicted units is still ongoing at Continental.

We can present preliminary results based on the small dataset of customer returns that is currently available. We can calculate the sensitivity by the following formula:

$$Sensitivity = \frac{True\ Positives}{\text{True Positives} + \text{False Positives}}$$

$$Sensitivity = \frac{7}{7 + 140} \approx 4{,}76\%$$

The system will be improved further by fine-tuning the algorithm, e. g. by adjusting the detection threshold. Domain experts can interpret the results to discover weaknesses.

3.2 Ontology-based Data Processing Algorithms and Techniques

3.2.1 Pilot Requirements

Current Scenario in the Company: Different kinds of simulations models are developed and performed at the early stage of an aircraft program but there is a lack of simple solutions supporting Industrial Multi-Model integration, Trade off studies, design space exploration and optimization within the company and with the Extended Enterprise. In addition to that, Industrial architects are taken decisions by optimizing alternatives based on r experiences and judgments, innovative areas are not explored because the way of working does not consider a systematic exploration based on multiple parameters considerations, no integrated platform or way to manage trade off studies of different alternatives. This current state of development of each aircraft program, pushes the company to have dedicated tools for data mining to help industrial architects make more accurate decisions and move towards performance

Description of the Future Scenario: During the development of a program, Industrial Architects are evaluating different industrial scenarios. One of the activities is to perform trade-off to optimize the future industrial architecture using different performance parameters to evaluate different alternatives for a specific decision to make, and to do optimization as part of design space exploration.

The project consists to develop an integrated platform to manage trade study and design space exploration for industrial system model, operations, sequences, planning, assets and layout tending towards both approaches that are Zero Defect Manufacturing and Autonomous quality to ensure a better quality with no nonconformities and an autonomous industrial system to manage the quality.

The integrated quality platform for managing trades and exploring designs include:

- MBSE Models for calculation of manufacturing-related metrics
- Rapid performance evaluations
- Design of experiments and analysis results
- Surrogate models enabling rapid evaluations for a parametric exploration of the design space
- Design space exploration environment that provides design space parameter controls
- Ontology optimization

Trade Study for Different Alternatives Decision Making: The trade-off process, to handle in this platform, shall be based on the following main steps.

1. Define Trade-off (scope, objectives, addressed requirements)
2. Define trade space
3. Define design parameters + ranges + Design of Experiments

4. Define assessment criteria + weighting methods + associated objectives (minimize, maximize)
5. Define alternatives
6. Perform Multi-criteria assessment + Ranking
7. Select Alternatives (or areas of alternatives)

Trade Space Process Scenario: A use case scenario will be produced involving multiple engineering options. This Proof of Concept (PoC) will be developed keeping in mind the need to deploy the solution at a large scale and at a low cost.

Business Objectives: The business objective of the quality integrated platform is mainly based on defining and maturing methods and capabilities description for Trade Space Exploration.

Table 9: Pilot Specific KPIs

N	Common KPI	Do/Can you measure it?	Value prior to QU4LITY	Value after/ with QU4LITY
1	Development time	From Concept Selection to EIS Industrial Maturity at start of the ramp-up.	7 years	5 years
2	Flexibility for late customization	(-50% lead-time for CDF to EIS)	3 years	1,5 years
3	Process leadtime	Time it takes to create a product and deliver it.	36 hours	10 hours
4	Trade-off Feasibility	State or degree of being easily or conveniently done	Disconnected Design study	…
5	Working conditions & Labour Efficiency		Ergonomic value	Ergonomic value
6	Flow efficiency	examines the two basic components that make up your lead time: working time and waiting time	Working time:26h / Waiting time: 10h	Working time: 9h Waiting time: 1h
7	Quality level	Uncertainties characteristics	Product and Industrial Requirements fulfilment	Product and Industrial Requirements fulfilment

From the IT side, the objective is mainly based on defining and maturing needs according to interoperability platform with other systems and solutions with whom the company can interact.

Expected Benefits: The implementation of this project will be beneficial on several levels and mainly in the optimization of the different parameters:

- Quality: Many of the factors that influence products quality will be possible to control by the integrated platform that fits perfectly in the optics of the framework which aims primarily a factory with zero default Manufacturing and with autonomous quality.
- Industrial Asset Cost: Exploration of alternative that can exist will allow us to make a well thought out choice in order to choose the most profitable assets and with a good quality-price ratio. Different type of financial trade will be made by the integrated platform to maintain or increase the scope of charges to save and take care of the business economy which is the most important pillar of the company.
- Labour Cost: Labour cost must be part of the most important parameters used by industrial architects. It is important from the fact that the direct labour cost is taken as the basis of estimating the amount of factory overheads while determining the product cost.
- Lead Time: Lead Time can play a crucial role in determining the financial success of a company. In manufacturing company as AIRBUS, the lead time must be controlled in order to organize the different stages of supply chain.
- Production Ramp up: Inappropriate production ramp up often ends up in short term, and long term productivity deviations. After implementing the integrated platform, many of the factors that influence the outcome of the production ramp up will be possible to control by a well thought thru methods and tools of managing trade off and alternatives.

3.2.2 Evaluation

The ontology-based data processing tool developed in the Airbus pilot contributed to the following sections of the QU4LITY Reference Architecture:

1. **Engineering and Planning Services (CAE):** VisualComponent uses 3D simulation software to simulate both semi-automated and manual assembly processes to compare the differences.
2. **AI/ML Training Analytics and Data-driven Services:** Develop a data model to integrate relevant elements that impact process quality. Use ontology-based knowledge management tools to analyse the results of different trade-off scenarios
3. **Simulation and Visualization Services:** VisualComponent will use 3D simulation software to simulate both semi-automated and manual assembly processes to compare the differences
4. **Cloud:** 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 tool mainly serves the design and planning phase, which concerns the assembly process performance and quality as well. One of the objectives is to achieve a better digital continuity from concept upon industrial system design trade-off and choice with validation in iteration. Current results realized a proper digital continuity from concept design to a simple case of scenarios trade-off end-to-end. Further works will still investigate the evaluation of system concept for trade-off.

In addition, the Airbus pilot also defined a new semantic meta-data model that will comprise cognitive manufacturing concepts, with emphasis on the representation of ZDM and autonomous quality entities and an industrial requirement management concerning requirement traceability. The information representation of various levels (incl. machine, production, product etc.) via OWL is based on the IOF-Core (Industrial Ontologies Foundry), which refers to BFO (Basic Formal Ontology). An application ontology is established for capturing, managing and forwarding the assembly system configurations. The knowledge representation and the integration between centric ontology and other modules representing respective areas (e.g., architecture and requirements) are to be enhanced.

Moreover, the technical reference of the new semantic data model for the area of fuselage joint assembly will be a key enabler for data standardization and knowledge persistence for comparable scenarios of different assembly lines of factories despite the discrepancies of purpose and tools. The approach of tool-agnostic modelling in ontology allows data to be centrally enriched, managed and further used as needed for different engineering activities as services, such DES (Discrete Event Simulation), 3D simulation for design validation, trade-off dashboard for decision support in this pilot. Current results indicate a successful ontology-driven services, which were only possible via gathering dispersed data and coordinating different modelling languages in the past. Nevertheless, further researches will also enhance the functionalities of the services such as the validation and result visualizing in a dashboard for an integrative evaluation of concepts in trade.

The existing parts of the tool are under investigation with regard to their re-usability in the Airbus-case of QU4LITY, and brought in as appropriate. Missing ontology elements concerning concepts and relations for Zero Defect Manufacturing will be developed in discussion with EPFL as needed.

3.3 Adaptive Visual Quality Inspection

3.3.1 Pilot Requirements

The system must reduce the amount of time required for visual quality inspection by at least 20 %, by detecting and excluding the defective items from the final products. Besides the visual quality inspection, other Pilot elements, such as predicting the defects and thus allowing an intervention, can be combined to reduce the scrap rate.

3.3.2 Evaluation

The main aspect of the presented technology deployed at JSI TEF is the adaptive robot trajectory generation for visual quality inspection. Every visual quality check requires different trajectories, which are automatically computed based on the neural network prediction where the errors are most likely to occur. Thus, not all but only some of the vantage points are reached by the robot during each visual quality control check. Two key performance indicators are evaluated:

1. Which motion planning algorithms are the fastest and most reliable in generating collision free trajectories between vantage points.
2. How much time is saved when only a few vantage points for visual quality inspection are visited, instead of all.

Note that the decision which of the possible vantage points should be reached by the robot relies on a deep neural network algorithm, which takes the production parameters of the product as input and outputs the probabilities for a list of errors, associated with the list of the predefined vantage points. This network is described in deliverable D3.4: HPC and Cloud Resources for ZDM, where we also describe how the training of the deep neural networks is offered as a service using HPC infrastructure.

In the following we first evaluate the motion generation aspect. We used the Open Motion Planning Library [12] - OMPL and there provided benchmarks to assess which of the planners is the most suitable for our case. We considered 21 different planners, which generated trajectories between 10 random poses. We then checked various parameters to determine which planner might be most suitable. First, we checked if the planners reach the desired pose and all did.

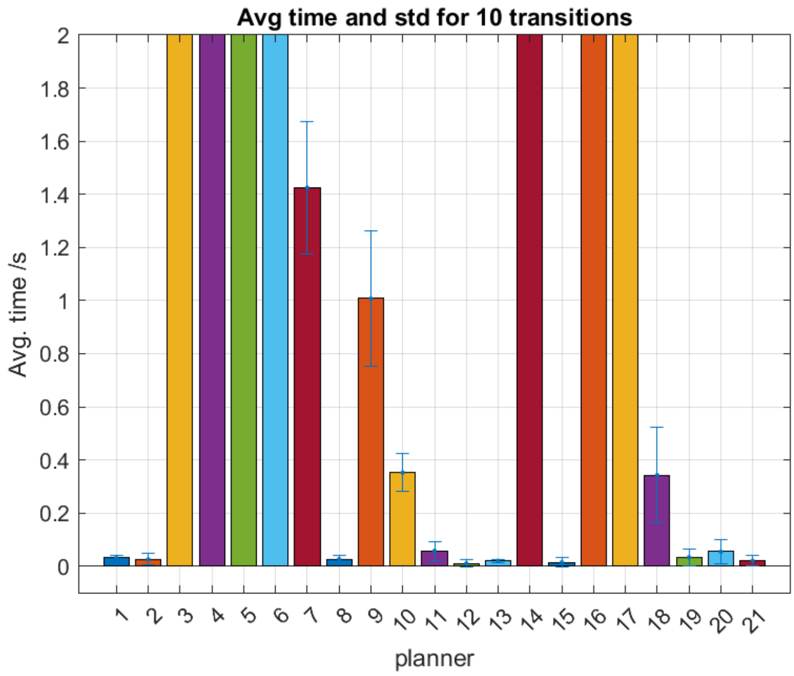


Figure 77 Average times for 10 transitions between 2 random points, for all 21 planners, 5 times per planner

Next we checked the average time required for planning. We can see in Figure 77 that some of the planners took much longer (durations are cut at 2 seconds) and in fact timed out at 10s (predefined time-out). Those were immediately ruled out. Next, we checked trajectory smoothness (closer to zero is better), shown in Figure 78 and length, shown in Figure 79. The planners are for clarity marked with numbers (the corresponding names are given in Table 10).

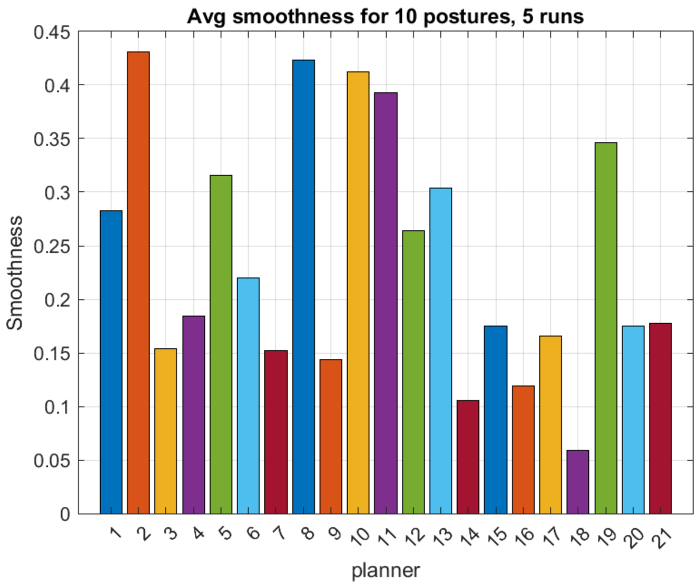


Figure 78 Average smoothness of 10 transitions. Lower value is better

Looking at computational times, we can see that only planners 1, 2, 8, 12, 13, 15 and 21 are worthy of further analysis.

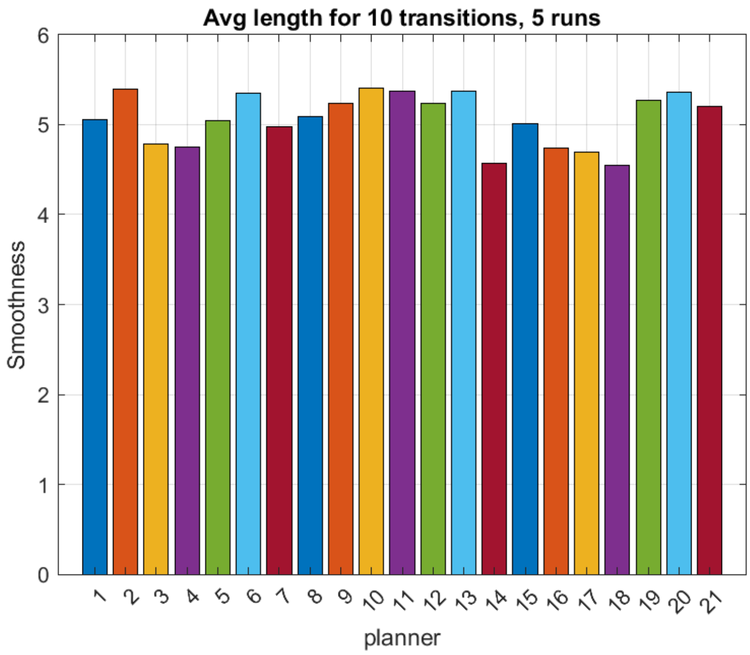


Figure 79 Average length of planned trajectory for 10 transitions for all planners, 5 times per planner

Next, looking at the smoothness and length of these planners, we can see that planner 14, i.e., T-RRT [13] (Transition-based RRT, RRT stands for Rapidly-exploring random tree [14]) is best in both of these categories amongst the remaining 7 planners.

Table 10: Planner names and numbering

Planner #	Planner name
1	BiEST (Bidirectional version of EST)
2	ProjEST (Projection-based version of EST)
3	LazyPRM
4	LazyPRM*
5	SPARS (SPArse Roadmap Spanner algorithm)
6	SPARS2
7	SBL (Single-query, Bi-directional and Lazy Collision Checking)
8	EST (Expansive Space Trees)
9	LBKPIECE (Lazy BKPIECE)
10	BKPIECE (Bidirectionnal KPIECE)
11	KPIECE (Kinematic Planning by Interior-Exterior Cell Exploration)
12	RRT (Rapidly-exploring Random Trees)
13	RRT Connect
14	RRT*
15	T-RRT (Transition-based RRT)
16	PRM (Probabilistic roadmap)
17	PRM*
18	FMT (Fast Marching Tree algorithm)
19	PDST (Path-Directed Subdivision Trees)
20	STRIDE (Search Tree with Resolution Independent Density Estimation)
21	BiTRRT

Thus T-RRT planner was selected. T-RRT combines the exploration strength of the RRT algorithm, which rapidly grows random trees toward unexplored regions of the space, with the efficiency of stochastic optimization methods that use transition tests to accept or reject any new potential state. It does not provide any hard optimality guarantees, but usually results in a short, low-cost path.

Given the selected motion planner, we evaluated how much time can be saved by the proposed system. Without the prediction of the most probable set of vantage points for visual quality control, the robot would need to reach all 10 possible vantage points (the robot postures at these 10 vantage points are shown in Figure 81). The minimum time needed to pass through the shortest paths between all of them, with sufficient time given to capture good quality images, is 33.27s. On the other hand, visiting only 3 vantage points takes on the average 12.04s ± 1.04s. The results for the complete series of vantage points and for 10 transitions between three random vantage points are shown in Table 11. Thus, these results demonstrate that the inspection time can be reduced to 36% ± 3,3 % of the initial duration of visual quality inspection from all 10 vantage points.

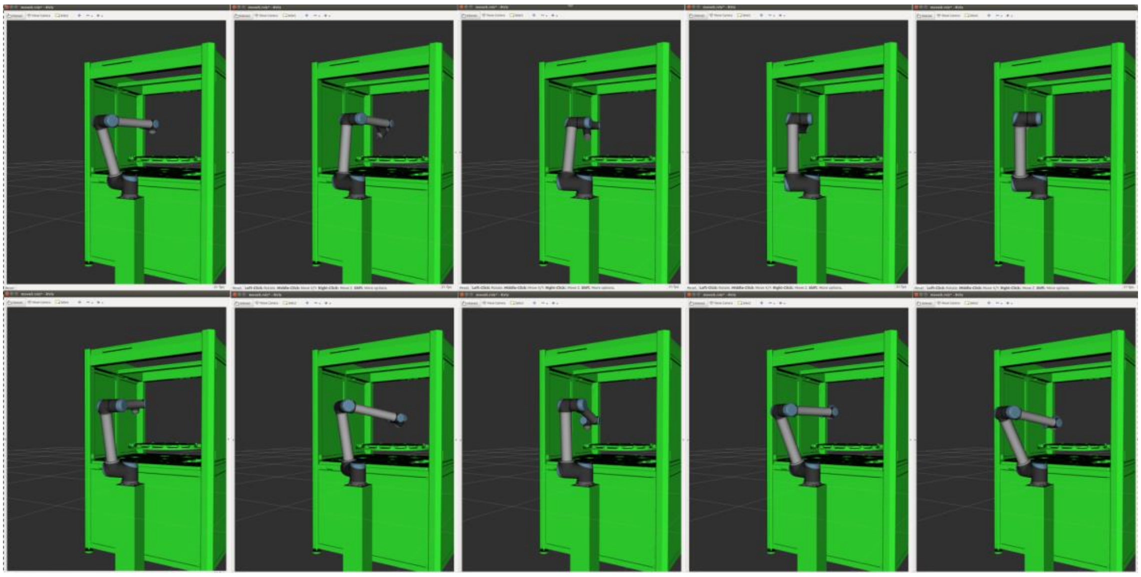


Figure 80: All 10 postures for visual quality control

Table 11: Time of travel between example sets of vantage points

Vantage point #	times / s
1,2,3,4,5,6,7,8,9,10	33,27
10,6,2	12,25
3,5,9	13,69
1,2,3	10,21
7,10,3	11,97
4,9,1	11,35
8,3,5	12,07
5,6,10	12,88
2,4,8	10,98
6,7,8	11,53
9,1,7	13,5
mean	12.04 ± 1.04

The impact of the proposed visual quality control scheme on the scrap rate at the Kolektor production plant will be assessed once the visual quality control cell can be installed there.

3.4 NxTTech IDE and EcoRT Runtime System

3.4.1 Pilot Requirements

The execution of the use case presented in Figure 34 requires the right implementation of the traffic algorithms and the distributed communication between the AGVs to be able to communicate and avoid crashes.

It's necessary to be able to deploy different parts of the control logic to different AGVs. The AGVs should be able to communicate with each other in real-time to notify the others when they are locking or unlocking a field or when they are crossing an intersection. Depending on the number of AGVs involved in the system, there should be different architectures that will provide the best solution in terms of performance but also orchestration.

3.4.2 Evaluation

NxTTech IDE and EcoRT is designed to fulfil the requirement of partially distributing the control logic of the server on the AGVs and the supervisor FB. The control logic for avoiding crashes where different areas can be locked and unlocked, so that 2 AGVs cannot drive to the same area is deployed directly to the AGVs.

As mentioned before, the NxTTech IDE was used to develop the IEC 61499 control application, to distribute and deploy it to the AGVs. Since the IDE is based on the IEC 61499 standard it offers many features that provide adaptability on the shopfloor. For example, it can be used to create libraries of FBs for different domains where each FB presents a real device as a SW object. The FBs from the libraries can easily be used to create control applications where per drag and drop the FBs are taken from the library and connected with each other to create FB-networks. The development of the control application is HW independent and it provides additional flexibility when choosing the HW for the system. If in our use case the AGVs get a new control device then we would not need to change the control application, only the HW configuration.

The HMI developed in our prototype implementation was also created in the IDE and it can be used to monitor the AGVs in the system and to send out control orders. It is a direct connection between the field level and the control level (system operator).

The HMI provides features to test and simulate parts of the system which is very useful when developing a new application or especially when changing an existing one.

The IEC 61499 based runtime system is used to run the IEC 61499 based control applications on the Raspberry Pies that are mounted on the AGVs. A feature of the runtime system that rises the adaptability of IEC 61499 based solutions is the 'online change' feature. It provides the ability to change an application, add or remove FBs and deploy the changes to the running system, without interrupting the execution of the system. In our example it would mean that one or more AGVs can be added to the system without stopping all the other AGVs that are already executing some tasks.

The IEC 61499 base implementation enables a good OT/IT connectivity where data from the shop floor are directly sent to the IT level. Also the other way around, the feedback of the IT level, like new parameters, control data or commands, can be directly sent to the shop floor. This good OT/IT connectivity is given with the event driven nature of the IEC 61499 standard wich is the same as in the IT level.

The NxTTech IDE and the EcoRT are great assets in both the adaptive digital shopfloor automation' and the automation and control domains of the QU4LITY Reference Architecture.

3.5 AUTOWARE Composable Digital Shopfloor Verification and Validation Framework

3.5.1 Pilot Requirements

GHI Pilot: The AUTOWARE Composable Digital Shopfloor V&V framework has focused on guaranteeing the following requirements:

- Ensuring both transmission and quality of the data flowing from the Beyond Platform for data monitoring and analysis to the Cognitive Digital Twin Service for ZDM (the other two components present at the Pilot case), and the opposite way.
- Testing a connector so as the data transmission device to become a plug&produce enhancement equipment.
- Beyond platform services, as visualization tools, to be optimally operational to be functional for users.
- Proper operation of the M3Box by Innovalia, in order to ensure data sharing.
- Ensuring that only the desired part of the dataset is shared on the Orion Context Broker.

GF Pilot: The main requirements are focused on the deployment of M3MH along with Unimetrik. They can be summarized in the following:

- Ensuring data transfer by satisfying the defined security standards.
- Ensuring scalability, reliability and latency on communication between components.
- Dimensional Metrology data quality.

3.5.2 Evaluation

GHI Pilot: The interoperability between connectors (Data provider and Data consumer) has been tested as per the below Figure 81. Data Sovereignty and Governance is ensured all along, as well.

Connector Interoperability	FH DAPS (as a service) GHI Provider – Trusted Connector Provider (IDSCP)
Data Interchange Consumer connector requests data, with a valid DAT, to provider connector. Provider connector verifies DAT and the data is interchanged.	OK
Data interchange – Negative answer Consumer connector tries to get access to a resource from an already known provider connector, with an invalid certificate/DAT. The request is rejected.	OK
Connection failure (only if data flow is continuous) While the provider connector is sending data, the consumer connector is turned off. 2 minutes later it is turned on, the connection is re-established and data flows correctly.	OK
Connection failure (only if data flow is continuous) While the consumer connector is receiving data, the provider connector is turned off. 2 minutes later it is turned on, the connection is re-established and data flows correctly.	OK
Connection with more than one provider (optional) The consumer receives data from more than one provider.	OK
Connection with more than one consumer (optional) The provider sends data to more than one consumer.	Not Tested
Data interchange – with Broker mediation The consumer connector gets the information of a specific resource from a Broker, automatically makes a request to reach it and gets access to it.	NA

Figure 81: Connector-to-Connector Interoperability tests carried for the GHI Pilot case.

GF Pilot: The validation process has been successful and following the guidelines for QIF compliance testing, as thoroughly described in Section 2.5.5.1 – Technology Description for the case of the QIF Standard.

- Encrypted transfer of information between the 5-axis CNC machine and M3MH has been validated.
- Reliable communication validated, linked to the previous requirement.
- In terms of data quality, during the project lifetime, the amount of data generated has been positively tested against different data quality dimensions, such as: accuracy, completeness, consistency, integrity, timeliness, etc. Traceability is also guaranteed thanks to the QPId unique part indicator.

3.6 Pacelab WEAVR Augmented Reality for Operational Support

3.6.1 Pilot Requirements

The requirements of Pacelab WEAVR implementation needed to fulfil the use-case of Continental is to ensure Internet connectivity upon initial setup, have key access to isolated network BPA at Continental's plant for data and privacy policies protection.

To work with paper-based instructions for the operators in a status quo that represent working instructions at the line.

Standard CAD format .dwg, .stp, .fbx, .obj, should be able to be used for setting up digital 3D representation of the equipment.

Standard video formats like MPG, MP4, should be able to be used for guiding the operators and have a real representation of maintenance operation along with the digital 3D models.

Continental was so far not prepared to provide operator instructions and CAD files via digital interfaces to ERP/MES. Therefore, PACE has created 3D models based on pictures and 2D schematics that has been provided to generate AR operational guidance content.

It would be useful for Continental in the near future to have AWS cloud server available to host the AR applications deployed. As in contrary, PACE has provided Continental access to its own AWS account to host the AR content application as a service to facilitate scalability and deployment within Continental Plant.

3.6.2 Evaluation

Referring to the Pilot requirements addressed above and the KPIs required to assess the Pacelab WEAVR platform technology for AR operational guidance and step by step support. It has been successfully evaluated with Continental pilot during the verification and evaluation phase of implementing the use-case at Ingolstadt plant.

The KPIs measures that have been highlighted by the pilot are the following:

1. Personnel cost.
2. Effort percentage of inhouse work content for AR application preparation
3. Usage of standard smart devices (PCs, iPads, smart glasses)
4. 1st pass yield efficiency improvement
5. Enhancement of operational efficiency

Pacelab WEAVR has met the requirements and the KPIs of the Pilot by supporting standard CAD file format import to generate 3D models that can be used for AR guidance, followed the paper-work instruction to create and digitalize a step-by-step AR operational support by creating procedural workflow, and integrated pictures and videos the simulate the actual process as a reference to the operators while being guided through AR smart glasses.

On the other hand, the personnel costs in training, changeover, and maintenance operation have been reduced as the human effort in all three areas have been minimized with the use AR step-by-step guidance. Additionally, the Pacelab WEAVR platform has enabled non-technical/programmers to develop and maintain the AR content application inhouse without heavy dependency on the technology provider neither having the need to hire skilled developers to maintain internal operational AR applications. Moreover, the first pass yield "FPY" and operational efficiency have been significantly improved as during changeover and maintenance operations less failures have occurred due to the help of the digital augmented reality operational support during the operations.

Hence, referencing to the QU4LITY reference architecture, Pacelab WEAVR maps with the following components:

Simulation and Human-centric Visualization Services: Visualization Services take care of displaying data in an easy-to-access and fast-to-understand way. Augmented operational supports using guided visualizations and annotations via PACELAB WEAVR. Interoperability-standard is IoT standards and data exchange formats supported are json, mpeg, AVi.

Control Services: These are microservices executed on a Kubernetes Cluster. Interoperability-standards used are OPC UA, Rest API. Data exchange format used is MQTT.

Digital Infrastructures (Cloud): Cloud acts as a host for manufacturing data lake. An enhanced and protected area is provided for manufacturing services. Data exchange format includes all internet exchange formats.

Assets & Smart Products: These are smart glasses/hololens. Interoperability-standard is WiFi. Data exchange format support Jsons and .weavr.

Engineering and Planning Services: WEAVR AR/VR solution from PACE supporting Planning of Processes in manufacturing like maintenance/setup/repair**.** Interoperability-standard is WiFi. Data exchange format support Json and .weavr.

Coherently, Pacelab WEAVR technology implementation and integration contributes to the Adaptive Digital Shopfloor Automation by enabling the possibility to entail the human in the loop of zero-defect manufacturing in the shopfloor through leveraging AR operational guidance as a human machinery communication interface. This allows maintenance operators to adapt to any identified risk of failure and have a digital guided troubleshooting process to ensure successful operation. Hence, the AR technology is bridging the gap between the physical and digital world where these implications and interactions are fostered within the rest of QU4LITY solutions.

3.7 Improved Failure Classification Enabler

3.7.1 Pilot Requirements

The module uses quality parameters that are recorded in the specific production line. The to-be-developed data collection and analysis solution provides the baseline for machine learning algorithms to train models as illustrated in Figure 82. Beyond the scope of this business scenario, the data collection with these solutions can be continued potentially yielding additional benefits which are not yet considered.

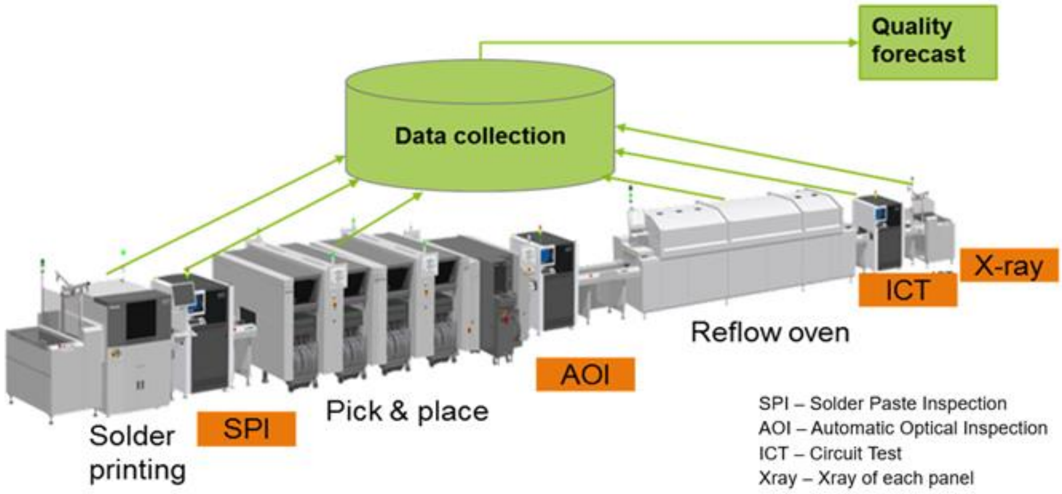


Figure 82: Required Data collection and data storage

However, there are requirements by the pilot for the module: The module must be able to process numerical measured values in order to distinguish GOOD products from DEFECT products. The numerical measured values include position properties of the solder joints and measurements of geometrical properties. Furthermore, the module should have extension possibilities, e.g. to be able to process image data, if the exclusive use of numerical measured values is not sufficient for classification.

Furthermore, the module must secure to not declare defective products as GOOD. It must therefore be ensured that no error slip occurs (slip rate = 0). Moreover, the number of GOOD products which are falsely marked as DEFECT must be reduced. The number of pseudo-defects should thus be reduced. Finally, the module is to be integrated into the Siemens pilot (Figure 68). Thus it must meet the requirements regarding classification speed (time required per classification of a product to be evaluated). An exact indicator is still to be defined.

3.7.2 Evaluation

To develop an improved failure classification Gradient Boosted Trees were trained and implemented into the above described technology. To do so a sufficiently large database was first derived from the real production environment. This was examined with regard to process position and process changes and their significance interpreted using expert knowledge.

Based on the deviations found, adjustments were made directly to the solder paste printing process and at the same time additional features were generated by the technology to enrich the used database: In addition to the numerical geometric properties (e.g. area, height, volume) of the solder deposits already automatically recorded in the SPI, key figures for the surrounding solder deposits were determined for each solder deposit of each Printed Circuit Board (PCB). Based on expert knowledge, the radius was limited to 2 mm to ensure that faulty interactions due to the tool contour were not taken into account. In addition, the average absolute and relative deviations of the geometric properties of neighbouring solder deposits were taken into account.

During the modelling process, the database was divided into a test set (30 %) and a training set (70 %) in order to evaluate the resulting model quality. The derived database exclusively comprised lot depots that were initially declared as defect by the SPI. Within the framework of model building, the hyperparameters *max_depth*, *min_child_weight*, *subsample*, *colsample_bytree*, *gamma*, *eta* and *scale_pos_weight* were optimised using Bayesian optimisation and the results were cross-validated 5-fold on the training set. The resulting prediction results of the trained model on test data not considered during training are shown in Table 12.

Table 12: Confusion matrix of the final classification result

Accuracy 89,39%		**True expert label**		**Class precision**
		Defect	**No defect**	
Predicted label	**Defect**	1.995	258	88,55%
	No defect	104	1.055	91,03%
Class recall		95,05%	80,35%	

The confusion matrix shows that the evaluation of the lot depots by the trained model corresponds to 89.39% of the evaluations of the process experts, with an error slip (11.45%) and pseudo error share (8.97%). It follows that the use of the model can reliably reduce manual testing efforts.

The analysis of the features relevant for the model showed that the *area* and *the percentage filled area of the perpendicular depot* as well as the *average percentage filled area*, the *average perpendicular depot height*, the *maximum perpendicular depot height*, the *average volume and the minimum area of neighbouring perpendicular depots* were particularly relevant for the prognosis. By monitoring the insights to process experts, it turned out that they also take into account neighbouring perpendicular depots for the evaluation of the perpendicular depots and, in particular, the degree of surface filling.

In summary, it could be shown that machine learning processes offer great potential to differentiate automatically between defective and good products in solder paste inspection. This reduces manual inspection efforts carried out by process experts. On the one hand, this relieves the process experts and at the same time reduces line stoppages due to pseudo defects. Furthermore, it is shown that through the application of a GBT, knowledge previously implicit in the data was extracted and validated by means of expert knowledge.

Based on the knowledge gained from this, further research work will follow: The knowledge of the process experts will be used to generate further numerical features as input for the technology. In addition, the use of image data, which the process experts have previously used to verify the supposedly defective products, offers further potential for the creation of autonomous inspection processes. However, when processing image data, it must be taken into account that the rejection of this data can lead to a delay in the cycle time due to the data interfaces used, as the time required for data storage influences the line cycle. In this case, either faster data interfaces are needed, or additional numerical features have to be created that represent the relevant information of the image data sufficiently accurately without affecting the cycle time of the process. This outlines the connection to adaptive digital shop floor automation: in the case of prevailing strict time requirements, decisions about the further production of tested products have to be made with a high degree of decision-making reliability. The model performance, the duration of the decision of a model as well as the needed communication times for data acquisition and the return of decisions made to the SPI determine the required time horizons for the application. However, these time horizons must be at least smaller than the time requirements in order to be successfully applied in production.

3.8 Data Analytics Tool for Additive Manufacturing

3.8.1 Pilot Requirements

The general use case requirements for the PRIMA pilot are:

- The Data analysis tool will collect process parameters by means of MQTT connections while the manufacturing process is ongoing.
- The Data analysis tool will collect metadata from different systems/tools (i.e. simulation tool, image processing system, 3D visualization tool) via MQTT.
- The Data analysis tool will elaborate the pre-configured KPIs and triggers specific messages whenever any pre-configured threshold for those KPIs is overpassed.
- The metadata generated by the FHG-ILT’s tool and the FHG-IGD’s tool will be delivered to the Data analysis tool on layer basis: data will be transmitted/received for each layer of the additive manufacturing process.

- The Data analysis tool will deliver relevant information to the Decision Support System via MQTT.

3.8.2 Evaluation

The Data analysis tool successfully contributes to manage the need of cooperation between independent and heterogeneous tools, each specialized on a specific requirement of the PRIMA pilot. This functionality is realized leveraging the state-of-the-art and widely accepted communication protocol MQTT, as it was in fact introduced and promoted by the QU4LITY Reference Architecture (D5.5 [1]).

Such an architectural aspect, along with other specific functionalities, contribute to fulfil relevant requirements and advantages, also elaborated by the QU4LITY Reference Architecture:

- **Decoupling of the processing between collaborating tools**, which could work asynchronously through coordinated
- **Simplification of the communication issues**, which could exploit the advantage of a widespread standard
- Enabling the **deployment** of each cooperating tool to their elective environment, being **field, edge or cloud**
- Contributing to the definition of a **common ontology**, possibly based on the concept of **topic** (interoperable with the concept of URI) and the widely accepted JSON syntax
- Enabling the enrichment of raw data with **context aware information**, by conforming to the agreed ontology
- Opening the system to the easy **addition of complementary modules** or even to the substitution of existent ones with an alternative implementation.

4. Conclusion

The main achievement of Task 5.3 is the development of a comprehensive toolset of eight tools and technologies that enable and leverage adaptive shopfloor automation and ZDM processes within the QU4LITY Pilots and Use Cases. This deliverable presented each of the tools and technologies from this toolset and evaluated each ones of them with respect to their contribution to the enhancement of adaptive digital shopfloor and ZDM processes based on the pilot requirements that address the adaptability functionalities of digital shopfloor and ZDM processes.

The evaluation of these tools and techniques showed that the toolset developed contributes to various functional domains of the QU4LITY Reference Architecture, hence the goal of Task5.3 is achieved by addressing these functional domains via the different tools in the toolbox. A summary of the functional domains covered by the tools and techniques from Task 5.3 is given in Table 13.

Table 13: Overview of Q-RA functional domains covered by Task 5.3 Tools and Technologies

QU4LITY Functional Domain	Task 5.3 Tools and Technologies
IoT Automation	Context Awareness Framework NxTTech IDE and EcoRT Runtime System Adaptive Visual Quality Inspection
Control Services	NxTTech IDE and EcoRT Runtime System WEAVR Augmented Reality for Operational Support
Data-driven modelling and learning	Ontology-based Data Processing Techniques Adaptive Visual Quality Inspection Data analytics Tool for Additive Manufacturing Improved Failure Classification Enabler
Simulation and human centric visualization	Ontology-based Data Processing Techniques WEAVR Augmented Reality for Operational Support AUTOWARE Composable Digital Shopfloor Verification and Validation Framework Data analytics Tool for Additive Manufacturing
Engineering and planning services	Ontology-based Data Processing Techniques WEAVR Augmented Reality for Operational Support

The toolset solution of Task 5.3 contributes to Autonomous Quality concept of the project and each tool and technology in this toolset brings industrial innovation to its domains. A summary of contributions and industrial innovations is given in Table 14.

Table 14: Summary of Contributions of Task 5.3 Tools and Technologies

Tool / Technology	Contribution	Industrial Innovations
Context Awareness Framework	Collect & deliver context relevant data about processes / equipment / products	The context identified by the Context Awareness Framework and provided to other tools in the shopfloor to automate and adapt certain processes and outputs based on the context in which the products / machines / processes are being used
Ontology-based Data Processing Techniques	Semantic modelling of industrial process line	Model-based industrial system design in operation
Adaptive Visual Quality Inspection	Detect and exclude defected items from final products through visual quality check using adaptive robot trajectory generation	Autonomous visual quality inspection
NxTTech IDE and EcoRT Runtime System	Distributed control solution for AGVs	Automatic enabling of direct communication between AGVs, creation of library of functional blocks, run-time addition of AGVs, hardware independent application
WEAVR Augmented Reality for Operational Support	Adapt to any identified risk of failure using digitally guided trouble-shooting support	Entail the human-in-the-loop of ZDM in the shopfloors through AR operational guidance as a human machinery communication interface
AUTOWARE Composable Digital Shopfloor Verification and Validation Framework	Validation of data transfer between machines, testing of data against data quality dimentions	Data accuracy and data quality during data transmission
Data Analytics Tool for Additive Manufacturing	Enabler for adaptive digital shopfloor and ZDM processes	Aggregation of data produced by different sources

Tool / Technology	Contribution	Industrial Innovations
Improved Failure Classification Enabler	Pseudo error identification and reduction, autonomous learning of process states	Increase overall product quality

List of Figures

List of Tables

List of Abbreviations

AQ	Autonomous Quality
AR	Augmented Reality
AVG	Automatic Guided Vehicle
CPS	Cyber Physical Systems
CT	Cognitive Twin
DBMS	Database Management System
DDS	Data Distribution Service
DMSC	Digital Metrology Standards Consortium
DSS	Decision Support System
ESB	Enterprise Service Bus
GUI	Graphical User Interface
FB	Function Block
HMI	Human Machine Interaction
HW	Hardware
IIoT	Industrial Internet of Things
IoT	Internet of Things
IOF	Industrial Ontologies Foundry
IoT	Internet of Things
MBD	Model-based Definition
MBE	Model-based Enterprise
MES	Manufacturing Execution System
MQTT	MQ Telemetry Transport
MVP	Minimum Viable Product
PLC	Programmable Logic Controller
PoC	Proof-of-Concept
QIF	Quality Information Framework
RA	Reference Architecture
RDS	Relational Database Service
ROS	Robot Operating System
SPI	Soldr Paste Inspection
SW	Software
USM	User Story Mapping
VM	Virtual Machine
VR	Virtual Reality
XML	eXtensible Markup Language
XSLT	Extensible Stylesheet Language Transformations
ZDM	Zero Defect Manufacturing
ZDM-MBE	Zero Defect Manufacturing Model-Based Enterprise

References

[1] QU4LITY Consortium, „D5.5 Tools and Techniques for Adaptive Shopfloor Automation and ZDM Processes (Version 1),“ 2020.

[2] QU4LITY Consortium, „D2.12 Reference Architecture and Blueprints (Final Version),“ 2020.

[3] D. Spath, H.-P. Lentes und J. Lentes, „Towards an ontology supporting the planning of production systems.,“ *Production Engineering. Research and development in Germany. Annals of the German Academic Society for Production Engineering 12 ,* 2005.

[4] N. Guarino, „Formal Ontology and Information Systems.,“ *Proceedings of FOIS'98, Trento, Italy,* pp. 3-15, 1998.

[5] D. Spath und J. Lentes, „An ontology-enabled production-in-the-loop,“ in *In: Bernard, A.: 5th Int. Conf. on Digital Enterprise Technology, DET 2008*, Nantes, 22 - 24 October 2008.

[6] J. Lentes und N. Zimmermann, „amePLM: a platform providing information provision in engineering,“ *International Journal of Production Research,* Bd. 55, Nr. 13, pp. 3832-3841, 2017.

[7] V. (. E. Federation), „Industry 4.0 meets Lean – Guideline to increase added value holistically,“ Industrie 4.0 Forum, pp. 9, 2018.

[8] B. Mrugalska und K. Magdalena, „Towards Lean Production in Industry 4.0,“ in *Procedia Engineering 182*, pp. 466-473, 2017.

[9] S. Kolla, M. Minufekr und P. Plapper, „Deriving essential components of lean and industry 4.0 assessment model for manufacturing SMEs,“ *Procedia CIRP 81,* pp. pp. 466-473, 2019.

[10] G. T. U. A. Bevec R., „Robot-Driven Autofocus Control Mechanism for an In-hand Fixed Focus Camera,“ in *Advances in Service and Industrial Robotics. RAAD 2018. Mechanisms and Machine Science, vol 67*, Bd. Vol. 67. Springer, Springer, 2018.

[11] V. Vyatkin, „IEC 61499 Function Blocks for Embedded and Distributed Control Systems Design,“ *Instrumentation Society of America, USA,* 2006, 2011 (second edition), 2014 (third edition in German and English).

[12] I. A. Ș. L. E. K. Mark Moll, „Benchmarking Motion Planning Algorithms: An Extensible Infrastructure for Analysis and Visualization,“ *IEEE Robotics & Automation Magazine,* p. 22(3):96–102, September 2015.

[13] J. C. a. T. S. L. Jaillet, „Transition-based RRT for path planning in continuous cost spaces," *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems,* pp. pp. 2145-2150, 2008 .

[14] S. K. a. E. Frazzoli, „Sampling-based Algorithms for Optimal Motion Planning," *International Journal of Robotics Research,* Bd. Vol. 30, Nr. No. 7, 2011.

[15] IETF, „The WebSocket Protocol," [Online]. Available: https://tools.ietf.org/html/rfc6455.

[16] QU4LITY Consortium, „QU4LITY D3.7 deliverable - Library of Integrated, Interoperable Digital Enablers," 2020.

[17] „O.Standard, MQTT Version 3.1.1," 2014.

[18] F.A.Fernandes, G. Sestito, A. Dias, D.Brandão und P. Ferrari, „Influence of network parameters on the recovery time of a ring topology PROFINET network," *IFAC-PapersOnLine,* pp. 278-283, 2016.

[19] Y. Han, „A survey of emerging M2M systems: context, task, and objective.," *IEEE Internet of Things Journal,* Nr. 3(6), pp. 1246- 1258, 2016.

[20] „ The Importance of Data," [Online]. Available: https://psu.pb.unizin.org/ist110/chapter/11-3-data-visualization/.

[21] 2. S. Dr. Kishori Lal Bansal, „Data Visualization A Tool of Data Mining," [Online]. Available: http://www.ijcst.com/vol23/1/kishorilal.pdf.

[22] J. D. M. B. S. Stuart T. Kard, Readings in Information Visualization, using vision to think, 1999.

[23] T. Bauernhansl, „Komplexe Märkte erfordern komplexe Fabrik- und Managementstrukturen:," *Interaktiv 1,* pp. 36-39, 2014.

[24] B. Vogel-Heuser, G. Bayrak und U. Frank, „Forschungsfragen in Produktionsautomatisierung der Zukunft: Diskussionspapier für die acatech Projektgruppe „ProCPS - Production CPS," 2012.

[25] R.-S. Guh, „Real-time pattern recognition in statistical process control: a hybrid neural network/decision tree-based approach," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 219,* p. 283–298, 2005, Nr .3.

[26] V. Cherkassky und M. Mulier, „Learning from Data: Concepts, Theory, and Methods," 2. Wiley, 1998.

[27] D. Lieber, „Data Mining in der Qualitätslenkung am Beispiel der Stabstahlproduktion," Technische Universität Dortmund, Dissertation, 2018.

[28] P. Chapman, J. Clinton, R. Kerber, T. Khabaza, T. Reinartz, C. Shearer und R. Wirth, „CRISP-DM 1.0: Step-by-step Data Mining Guide.," 2000.

[29] J. Deuse, J. Schmitt, M. Stolpe, M. Wiegand und K. Morik, „Qualitätsprognosen zur Engpassentlastung in der Injektorfertigung unter Einsatz von Data Mining.," *Schriftenreihe der Wissenschaftlichen Gesellschaft für Arbeits- und Betriebsorganisation (WGAB) e.V.,* p. 1–14, 2017.

[30] S. J. Russel und P. Norvig, „Künstliche Intelligenz: Ein moderner Ansatz," 2. Pearson, 2004.

[31] Qu4lity Consortium, „D2.5 Catalogue of ZDM Assets (version 1)," 2019.

[32] P. Flach, „Machine Learning: The Art and Science of Algorithms that Make Sense of Data," Cambridge University Press, 2012.

[33] R. Gabriel, P. Gluchowski und A. Pastwa, „Data Darehouse & Data Mining," W3l GmbH, 2009.

Partners

INTELLIMECH Consorzio per la Meccatronica
SIEMENS
AtoS
AIRBUS
MONDRAGON
NXT CONTROL
ATB Institut für angewandte Systemtechnik Bremen GmbH
Continental
RIA STONE
UNIMETRIK Metrology and Calibration
Technology Transfer System
EPFL
SQS
FAGOR ARRASATE
TTTech Ensuring Reliable Networks
technische universität dortmund
thyssenkrupp
Jožef Stefan Institute Ljubljana, Slovenia
PRIMA INDUSTRIE
eit Digital
ENGINEERING
PACE a TXT company
innovalia association
Telefonica
Synesis sustainable automation
ghi
UNPARALLEL
DANOBAT
POLITECNICO MILANO 1863
Whirlpool Corporation
VTT
VISUAL COMPONENTS
ASTI
Fraunhofer
cea
INTERNATIONAL DATA SPACES ASSOCIATION
PHILIPS
ATLANTIS
aic Automotive Intelligence Center
KOLEKTOR
INTRASOFT International
SINTEF
+GF+
Technische Universität Braunschweig
TNO innovation for life
TTTech industrial