Project number: 826276

CPS4EU

Cyber Physical Systems for Europe

D8.8 – Validation results report (industry automation use case)

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1. INTRODUCTION

1.1. Purpose

This document is related to Task 8.4 of WP8 concerning the Test and Validation of the prototypes of industrial use cases.

In task T8.1 the use case requirements of the industrial use cases in CPS4EU have been elicited and established, as captured in deliverable D8.9.

In task T8.2 those use cases were analysed to produce the use case model and high level design. Deliverable D8.4 describes the use case components that are envisaged to satisfy use case needs, how they work together, and the components where CPS4EU modules/PI-ARCHs are used.

In Task 8.3 the use case components are implemented to produce a prototype of the CPS according to the use case design in Task 8.2 in order to address the requirements identified in T8.1.

Task T8.4 deals with the verification and validation of those prototypes. Verification and validation (also abbreviated as V&V) are independent procedures that are used together for checking that a product, service, or system meets requirements and specifications and that it fulfils its intended purpose. The main goal of industrial use-cases in CPS4EU is to demonstrate & evaluate the technology developed in other work packages (namely components from WP1-4, PI-Archs integrated or packaged from components in WP6 or Tool clusters by WP5), as a key enabling technology for industry automation and - more generally - for industry 4.0, to gain high levels of efficiency in the use of resources.

In D8.7 a description of the general strategy and the details of test and validation plans of prototypes implemented in WP8 was presented. Particularly use case prototypes are tested and validated against the user requirements established in D8.9.

This document is the validation result report of the industrial use cases in CPS4EU. It reports the validation results of the adoption of technology from the CPS4EU project in a few industrial use case to demonstrate it enables the implementation of a wide range of solutions for the manufacturing industry, aimed to optimise the production chain and to enable post production services.

1.2. Scope

The following WP8 Industry Automation Use Cases are addressed:

- UC4 - Automatic Vacuum System (LEONARDO)
- UC5 - Trimming Quality Improvement (LEONARDO)
- UC7 - Aircrafts Health Management System (LEONARDO)
- UC8 - Material Flow Analytics and Simulation (TRUMPF)
- UC9 - Mobile CPSs (WIKA)

UC6 Thermoplastic Production Line Monitoring (LEONARDO) is not included as the implementation of a prototype of that use case is outside the scope of the project, as per amendment AMD-826276-26 accepted on 15/02/2022.

1.3. Document structure

The document is organized in chapters for the different use cases. Each chapter reports the results of the evaluation of a use case covering the following aspects:

- The high level description and objective of the use case
- A schematic description of the use case prototype that is evaluated and how it works

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- what CPS4EU components (technological modules, Pi-Archs, Tools) are used in the prototype, at what stage in the process and how they are instantiated/used/configured/extended for that specific use-case
- how the component positions with respect to other off-the-shelf similar components and how many features/modules/aspects of that component are actually used vs. what is not used directly in this use-case prototype;
- how the prototype was tested: prototype deployment, test environment, test phases and test results with reference to the test strategy and test cases defined in D8.7 (The detailed results of test cases execution is provided in annex);
- the metrics adopted to evaluate the success of the use case (i.e. the use case reached its objective) and the measures of those metrics obtained evaluating the use case prototype;
- the benefit achieved using the CPS4EU component/tool/PIArch vs. developing the same (or a similar) use-case without it;
- feedback on the adopted CPS4EU component (usability, performance, fitness of that component) with respect to the target TRL of the prototype.

1.4. Link to other documents/tasks

ID	Description
D8.9	Use case requirements v3
D8.4	Use design and modeling v2
D8.6	Use case prototype v2
D8.7	Test and Validation plan
D4.5	Specification of prototypes of the framework

1.5. Definitions, acronyms, and abbreviations

Acronym / abbreviation	Description
ADC	Analog-to-Digital
BLE	Bluetooth Low Energy
CI/CD	Continuous integration/Continuous deployment
CMSD	Core Manufacturing Simulation Data
CNC	Computerized Numeric Control
CNN	Convolutional Neural Network
COTS	Common Off the shelf
CPS	Cyber-Physical System
CRISP-DM	Cross-industry standard process for data mining

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ER	Entity Relationship
ETL	Extract Transform Load
HAL	Hardware abstraction layer
HMI	Human Machine Interface
IoT	Internet of Things
IIoT	Industrial Internet of Things
JSON	JavaScript Object Notation
M2M	Machine to Machine
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
OPC-UA	Open Platform Communications Unified Architecture
OSGi	Open Services Gateway initiative
OT	Operations Technology
PI-ARCH	Pre-Integrated Architecture
REST	Representational state transfer
RSSI	Received signal strength indicator
RUL	Remaining useful life
UWB	Ultra-Wide Band
VM	Virtual Machine

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1. FOREWARD

One of the objectives of CPS4EU is:

enabling the creation of innovative European CPS products that will strengthen the leadership and competitiveness of Europe for both large enterprises and SMEs.

The key result to achieve to reach the objective is the adoption and experimentation of the advanced key enabling CPS technologies into new products and industrial production lines.

WP7, WP8 and WP9 on CPS4EU are focused on developing use cases and applications in different sectors by large enterprises & SMEs.

In a first phase use cases leaders have provided requirement specifications of the required technology and in a second phase they instantiated technological modules developed in CPS4EU in dedicated use cases from strategic application domains (automotive, smart grid and industry automation) to validate the new CPS modules in stringent industry contexts to achieve innovative products to be marketed or to be used internally (production sites). WP8 concerns use cases of the Industry automation domain.

Main objectives of WP8 are the definition, testing and validation of the CPS4EU architectures and modules using them as a key enabling technology for industry automation and - more generally - for industry 4.0, to gain high levels of efficiency in the use of resources and integration of smart resources (sensors, robots, cobots, etc.) thus reducing set-up time and downtime and improving quality, while cutting down prototyping time

This document concerns the validation phase and describes the results of the validation of the CPS4EU modules that large companies (Leonardo and Trumpf) and SME (Wika) have integrated in Industry automation use cases.

Particularly these use case have been demonstrated and validated:

- UC4 - Automatic Vacuum System (LEONARDO)
- UC5 - Trimming Quality Improvement (LEONARDO)
- UC7 - Aircrafts Health Management System (LEONARDO)
- UC8 - Material Flow Analytics and Simulation (TRUMPF)
- UC9 - Mobile CPSs (WIKA)

Each use case has specific objectives that show the implementation of a wide range of solutions for the manufacturing industry, aimed to optimise the production chain and - going beyond that – to enable post production services (remote services such as predictive & prescriptive analytics, remote monitoring).

This document describes the results of the validation of the use case prototypes against the initial requirements and objectives set for those use cases.

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2. VALIDATION RESULTS OF UC4 - AUTOMATIC VACUUM SYSTEM (LEONARDO)

2.1. Background of the use case

The use case deals with a specific assembly process on large composite structures and aims to automate drilling activities on such structures that currently are human driven.

During drilling activities, the human intervention is twofold: one person drills while the other – positioned on the opposite side of the large structure – has to vacuum the carbon fibre dust that is produced by drilling. The use case will automate the movements of the vacuum system to "follow" the drill position.

The objective of this use case is to move the vacuum automatically to precisely follow the position of the DRILL to vacuum the carbon fibre dust without manual intervention.

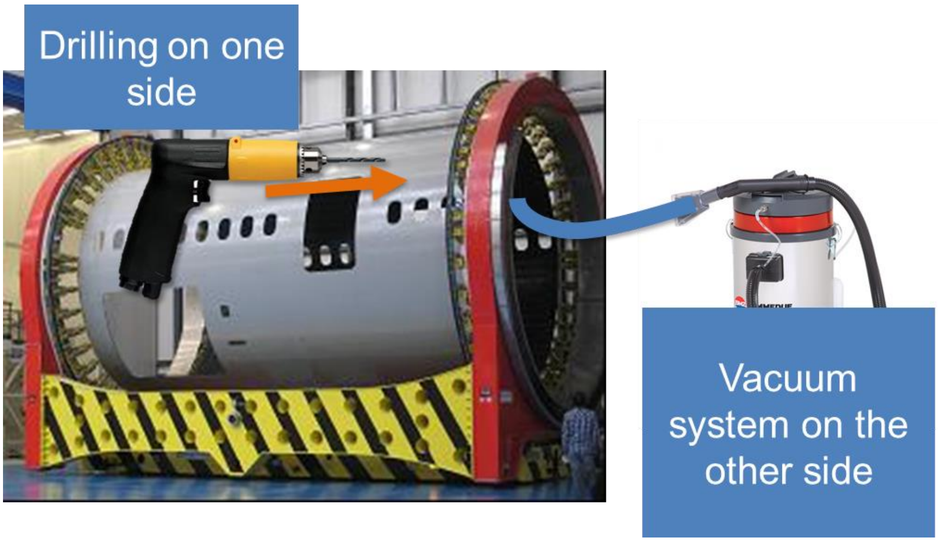

Figure 1 - UC4 overview.

More information on the background and use case requirements can be found in D8.9.

2.2. The use case prototype under evaluation

The use case prototype is made of different components as described in D8.4, encompassing architectures and technological modules developed in CPS4EU and specific components, namely:

- the Drill add-on that includes several modules for drill tip proximity detection, localization, interaction with the drill operator;
- a gateway based on an industrial computing platform with an IoT integration framework, as a field interconnection module that hosts the control logic and supports the communication between the drill and the vacuum;
- a vacuum positioning system based on a cobot that moves the vacuum hose with its anthropomorphic arm
- an enterprise data analysis platform where the main events of the drilling process are collected, which exposes the Monitoring interface that shows the progress of the process
- tool Wear module: a stand-alone system that is able to detect the wearing of the cutting edges of the drill tip.

The picture below shows the components of the tested use case prototype and how they are interconnected. For additional details on the prototype implementation see D8.6.

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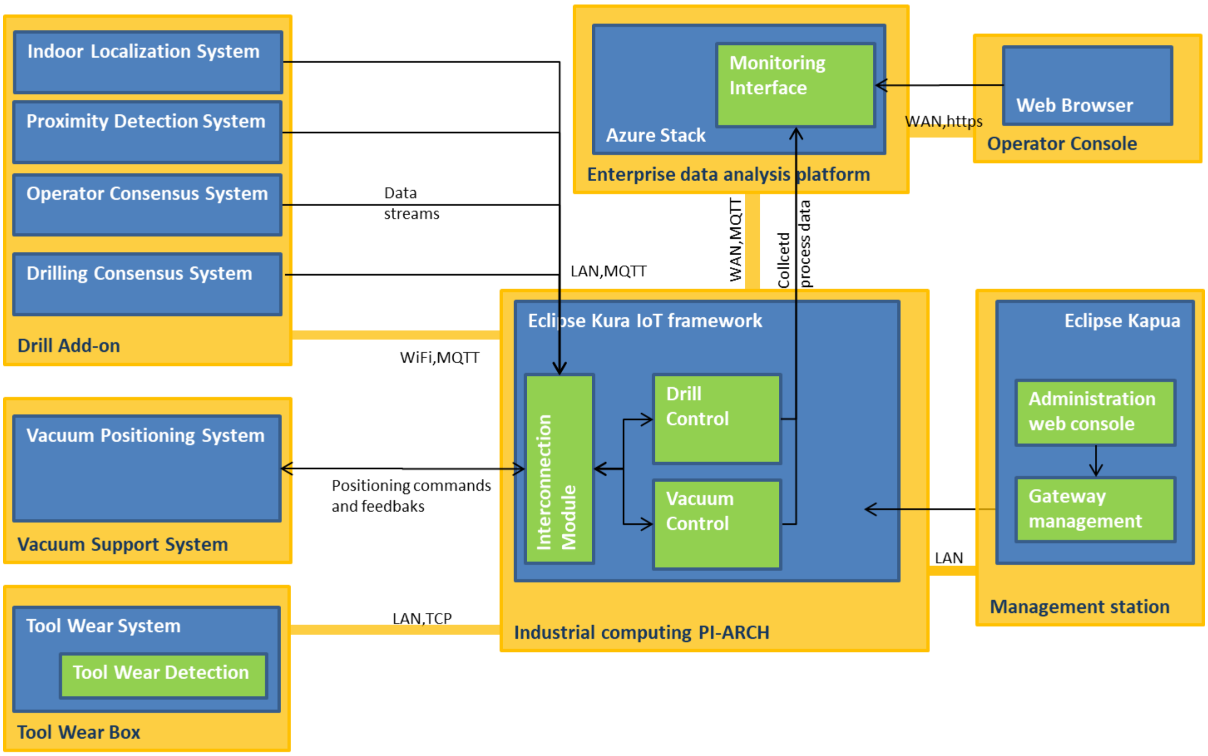

Figure 2 – Use case Architecture

2.3. Adopted CPS4EU technology and links with other CPS4EU WPs

The following table lists the technology developed in other work packages (namely components from WP1-4, PI-Archs integrated or packaged from components in WP6 or Tool clusters by WP5) that is used in the prototype and where it is used.

CPS4EU technological component	Source WP	Where it is used in the prototype
Industrial computing and connectivity PI-Arch (by Eurotech)	WP6	Implements the industrial gateway running the use-case specific business logic that controls the drill and vacuum and enables the communication and interaction between them. The use case implementation exploits the following hardware and software features of this PI-ARCH: - Hardware abstraction layer - Mqtt Information broker - Kura IoT framework - Azure connector - security features (TPM, Secure Boot, physical anti-tampering, authentication and authorization framework, software change detection)
Kura IoT tools	WP5	The engineering, development and testing of the use case prototype leveraged the tools that come with the Kura IoT framework available on the Industrial computing and connectivity PI-Arch. Namely tools for: - functional design: Kura WIRES supports the dataflow programming model allowing to graphically define dataflow graphs where the nodes

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		represent specific abstraction of the devices or of any specific unit of work; - simulation of the Industrial gateway: Kura provides a Device Virtual Twin that allowed to simulate the industrial gateway before the hardware platform was ready; - configuration, Monitoring and remote control of the gateways via the Kura administration web console.
cooperative PI-Arch	WP6 WP4	The cooperative PI-ARCH design pattern (by WP4) was adopted and instantiated in the implementation of the cooperation between the components of the use case prototype i.e. drill, cobot, industrial gateway and enterprise platform. For more detail on how it is instantiated in this use case see D4.5.
Sensing and perception technology (by UniSA)	WP3	The tool wear module of the use case prototype uses the technological module with image recognition for the perception and interpretation of the drill bit wear proposed and experimented by UniSA in WP3 (Task 3.1.2).
Localization technology (by UniSA)	WP3	The drill add-on features the localization technology based on tags experimented by UniSA in WP3 (Task 3.1.2).

Furthermore, the use case prototype architecture adopts the distributed processing architecture defined in WP1 and the drill/vacuum control logic running on the edge on the industrial gateway implements the smart data management paradigm of WP3 transforming the signals received from the drill and the vacuum into actionable data.

2.4. Test and validation results

2.4.1. Test results

Following the strategy for test and validation set in D8.7 the use case prototype components have been developed and tested separately at the development labs of the partners involved, namely:

- University of Salerno (drill add-on subsystem);
- Eurotech dev labs (Industrial edge computing platform)
- Leonardo plant in Grottaglie (Vacuum support and positioning subsystem).
- Leonardo labs in Genoa (monitoring HMI);

Then the use case prototype components have been deployed for integration and testing/validation on Leonardo Aerostructure plant in Grottaglie to test the use case prototype in the work environment and check it meets the working conditions and operational constraints of the production process. The picture below shows the final deployment of the use case prototype:

- the drill add-on is mounted on an air drill in the working area of Leonardo plant in Grottaglie;
- Wi-fi network connections have been set to enable the drill add-on modules communicate via MQTT with the gateway PI-ARCH;
- The vacuum support and positioning system is deployed in the working area of Leonardo plant in Grottaglie and a wired Ethernet connection is established to enable it to communicate via TCP/IP with the gateway PI-ARCH;
- the industrial computing Pi-ARCH is installed in a rack in the communication room of Leonardo plant in Grottaglie;

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- The gateway PI-ARCH is connected via the Finmeccanica Unified Network (WAN) to Leonardo labs in Genoa hosting the Azure Stack platform where process events are collected and the HMI monitoring application is executed;
- The Monitoring station of the process supervisor is connected to the HMI monitoring application running on the Azure platform hosted in Leonardo labs in Genoa;
- The administration management station in Genoa is connected on a separate management network to the administration console of the gateway Pi-ARCH in Grottaglie.

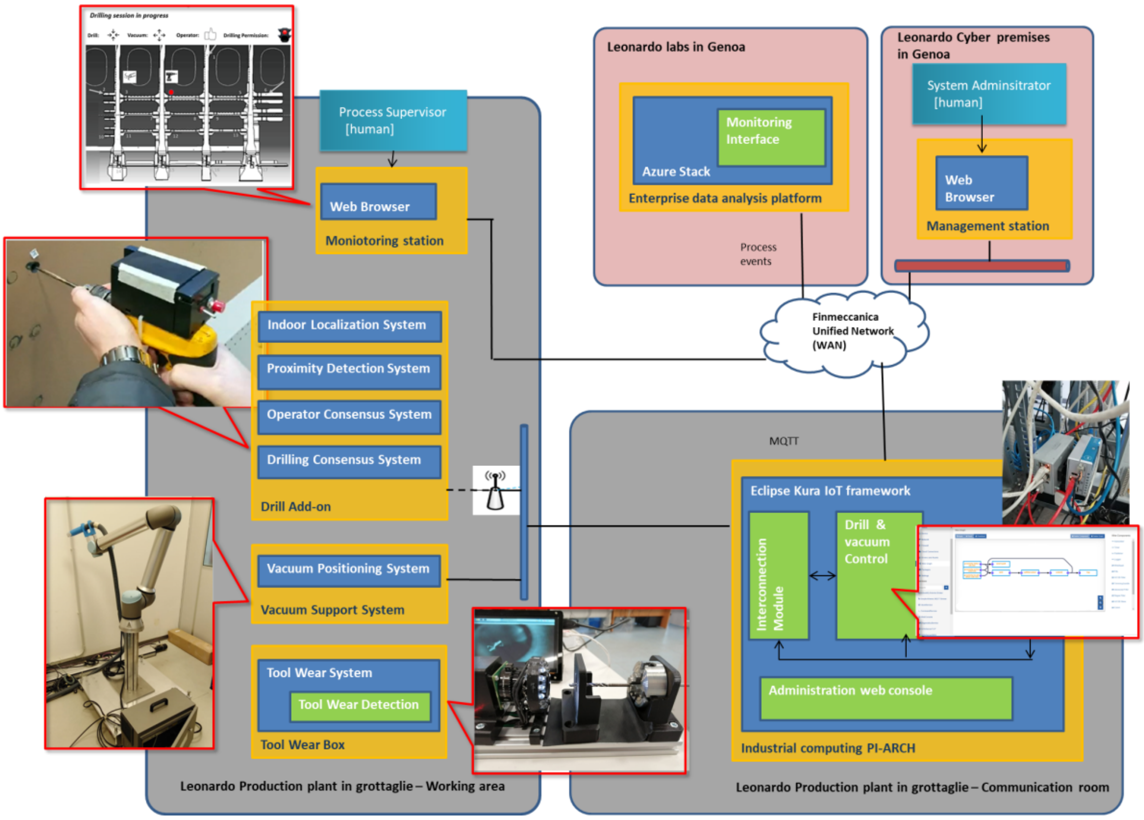

Figure 3 –Deployment of the use case prototype

Several test sessions were carried out on Leonardo production plant in Grottaglie to check the CPS prototype behaviour. The test results can be summarized as follows:

- the cobot is able to move and drive the vacuum to reach the requested target position on the fuselage, also taking into account the shape of the fuselage section and avoiding protruding stringers. The cobot can move the vacuum to reach target positions covering on all fuselage working area. The cobot stops to move if an object is found or comes up on the trajectory of the cobot arm.

- The drill add-on is able to read the coordinates of the hole where the drill tip has been positioned; it is also able to detect the proximity of the drill tip to the fuselage and allows to capture when the operator is ready to drill.

- The drill add-on is able to exchange with the gateway messages indicating the proximity of the drill tip to the fuselage, if the operator is ready to drill and the detected position where he wants to drill, if drilling is allowed at that position.

- The gateway is able to exchange with the cobot messages to direct it to the target coordinates, monitor its positioning and finally obtain feedback when the cobot has reached the target position.

- The gateway is able to coordinate the work of the drill operator and the cobot so that they cooperate: it moves the cobot to the target position after the operator is ready to drill at that position and displays on the drill add-on the consensus to drill when the cobot has reached the target position. The consensus to drill is displayed at most within 6 secs after successful reading of the tag by the drill operator (i.e. operator ready to drill), which meets the target of this prototype. In the elapsed time the cobot reaches the target position.

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- The monitoring HMI allows the supervision of the drilling process cycle showing the steps of the drilling process while they occur.
- The tool wear module is able to tell if drill tip has an acceptable remaining useful life; however, in a few cases it returned contradictory results (false negatives) likely due to wrong setup of the experiments (background setting of the tool and/or drill tip position): repeating the experiment the results were good (see output of tests 8.1.12 and 8.1.13 in Annex par. 8.1.1) .

The table below lists the tests executed and if they were successfully executed. Tests definitions can be found in D8.7.

Test name	Test level	Test ref.	Req.ID	Executed	Success	Notes
Vacuum positioning	Component	8.1.1	UC4-FNC-02 UC4-FNC-03	yes	yes	
Vacuum coverage of fuselage area	Component	8.1.2	UC4-FNC-01	yes	yes	
Drill localization	Component	8.1.3	UC4-FNC-03	yes	yes	
Drill close to the fuselage	Integration	8.1.4	UC4-FNC-04	yes	yes	
Operator ready to drill at the position	Integration	8.1.5	UC4-FNC-04	yes	yes	
Vacuum positioning command	Integration	8.1.6	UC4-FNC-04	yes	yes	
Vacuum positioning feedback	Integration	8.1.7	UC4-FNC-04	yes	yes	
Consensus to drill	Integration	8.1.8	UC4-FNC-04	yes	yes	
Vacuum positioning after the operator is ready to drill	System	8.1.9	UC4-FNC-04	yes	yes	
Positive consensus to drill	System	8.1.10	UC4-FNC-05 UC4-FNC-06	yes	yes	
Negative consensus to drill	System	8.1.11	UC4-FNC-05 UC4-FNC-06	yes	yes	
Drill tip wear estimation (good tip)	Component	8.1.12	UC4-FNC-07	yes	yes	with false negatives
Drill tip wear estimation (worn out tip)	Component	8.1.13	UC4-FNC-07	yes	yes	
Dynamic Obstacle perception	Component	8.1.14	UC4-FNC-08	yes	yes	
Static Obstacle perception	Component	8.1.15	UC4-FNC-08	yes	yes	
Vacuum Positioning time	System	8.1.16	UC4-PRF-01	yes	yes	

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Drilling process cycle	System/Acceptance	8.1.17		yes	yes	

Table 1 – Test results summary.

2.4.2. Evaluation of the use case prototype

The objective of this use case is to move the vacuum automatically to precisely follow the position of the drill to vacuum the carbon fibre dust without manual intervention.

To evaluate the success of the use case, following the goal question metric approach, the use case objective was decomposed in questions and metrics to measure if the prototype successfully answers those questions.

UC "automatic vacuum system" reached its goal if at least 2 out of the 3 questions are successful.

The following table summarizes the values achieved for the metrics associated to those questions.

Question	Target/Success Criteria	Metric achieved	Success
matching of vacuum position with drill position	vacuum position matches the drill position in at least 98% of the cases (before 92%)	100%	Yes
automation of vacuum work	vacuum positioning is automated, including: - localization of drill tip - target coordinates are sent to the cobot - cobot moves the vacuum to the target position - feedback that vacuum reached the target position	100%: - OK - OK - OK - OK	yes
enable post-production services	digital information for both vacuum and drill processing is available for post-production services	100% digital information on drill processing: OK digital information on vacuum processing: OK	yes

Table 2 – UC4 – metrics achieved.

Based on the results above UC "automatic vacuum system" reached its goal (two out of three questions successfully answered).

Below are some comments/grounds /evidence on the values of the metrics achieved.

Question	Comment on the results achieved
matching of vacuum position with drill position	The localization approach using tags stuck above each hole and pre-loaded with hole coordinates ensured error free-localization, also when target holes are quite close (distance less than 2.5 cm) - see test 8.1.3. However, this approach relies on careful positioning of the tags and an accurate tag reading operation.
automation of vacuum work	The use case prototype was deployed on the plant in Grottaglie to test and demonstrate all phases of the drill life cycle, including the steps required to automatically move the vacuum to the target position where the drill operator wants to drill:

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	- localization of drill tip – see test 8.1.3 - target coordinates are sent to the cobot – see test 8.1.5 - cobot moves to the target position – see test 8.1.9 and 8.1.1 - feedback that vacuum reached the target position –test 8.1.17 The automation of the vacuum movement was finally tested with success within the whole drilling cycle reproducing a drilling session of the drill operator –test 8.1.17. A video (confidential) is available that shows the whole drilling process cycle. The operator receives the consensus to drill within six seconds since he communicated the target coordinates where he is ready to drill, which meets the required expectations – see test 8.1.16. Initially drill cycles were prudently experimented operating the cobot at a reduced speed to check there were no collisions and avoid damages, obtaining a consensus response on average in 6 seconds. Then the experiments were repeated with the cobot operating at normal speed obtaining a consensus response between 3 and 5 seconds depending the on the distance between the start position and the target position.
enable post production services	During the testing of the drill cycle - see test 8.1.7 – the edge gateway PI-ARCH edge was able to handle the interactions with the drill and vacuum and to identify relevant events of the drilling process cycle that are displayed on the monitoring HMI of the process supervisor. The gateway sends those events to an enterprise data analysis platform where the HMI web application is executed. Those data are collected on the enterprise data analysis platform where they are available for further analysis of the drilling process. A video (confidential) is available that shows the HMI output while drilling process cycle takes place.

2.4.3. Validation of CPS4EU technology

Industrial edge computing PI-ARCH + Kura IoT tools and cooperative PIARCH

The implementation of the CPS prototype of this use case demonstrated the industrial edge computing PI-ARCH is well suited to work as a gateway on the edge: the PI-ARCH was able to support the connection with the drill-add-on and the cobot on the edge; to manage the interactions with them via mqtt protocol; to implement the control logic to coordinate the work of the drill and the vacuum; to identify relevant events on the edge and communicate them to the remote central platform where those events are collected and displayed on the supervision HMI while the drilling process occurs.

Leveraging the "Industrial edge computing" PIArch and the Kura IoT framework featuring predefined connectors that come pre-integrated on it, the application logic for the drill and vacuum use-case was developed two times faster than implementing embedded software as in previous projects.

The industrial edge computing PI-ARCH was able to meet Leonardo IT security policy and the settings required to support a secure communication on the field, with the remote central data analysis platform and for remote management. The Industrial Edge computing and connectivity PIARCH features enhanced cybersecurity at the hardware level by offering full support for TPM, Secure Boot and a physical anti-tampering system that is active also when power is off. The security is increased also at the software level by providing intrusion detection through file changes monitoring and by introducing a centralized authentication and authorization framework which allows to define and store identities and permissions

Thanks to the hardware and software security features and enhanced architecture of the Industrial edge computing and connectivity PI-ARCH we could benefit of a platform compliant with Industrial security standards and able to satisfy the cybersecurity and edge computing requirements of this industrial automation scenario.

The adoption of the cooperative Pi-Arch design pattern served as a guideline to consistently develop the components supporting the interactions between the drill, industrial gateway, vacuum (cobot) and central data

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platform, ensuring modularity and maintainability of the cooperative interactions between those entities and working as a reference for the implementation by different partners.

Overall, although the logic implemented on the gateway should be made more robust to be adopted in production, the TRL7 concept developed of this use case showed that the industrial edge computing PI-ARCH is able to satisfy the requirements of the use case scenario. Possible areas of improvement are:

- additional Ethernet port: the two Ethernet ports featured by the gateway are not enough when separate IT an OT network connections have to be managed, and a separate network is adopted for remote management connections; the requirement was satisfied in the use case scenario using an USB to Ethernet adapter;
- configurability: some settings (e.g. https connections and authentication certificates) should be manageable via the gateway web administration interface (currently by line commands only);
- remote management: some features are not available from the gateway web administration interface but require the gateway cloud console available through the open source project Eclipse Kapua;
- lost settings: some network configurations were lost after restarting the gateway; this issue was fixed in the second release of the prototype of the gateway. For the adoption in a production environment the platform is mature and ensures that no settings are lost.

Localization technology and drill add-on

The drill add-on integrates a normal tag reader and standard tags stuck above each hole and pre-loaded with hole coordinates are used. This is a consolidated and mature technology that proved to meet the requirement of a resolution of 2.5 cm. The approach was adopted after the experiments in WP3 on localization based on the triangulation of BLE signals were not satisfactory because of the insufficient resolution adopting state of the art Ultra Wide Band technology (see WP3 test results). Using tags stuck above each hole and pre-loaded with hole coordinates ensures potentially error free-localization provided the tags are positioned correctly (i.e. the tag is above the hole at the coordinates loaded in the tag) and so that it can be scanned with the laser beam of the drill add-on without mistakes (i.e. reading the wrong tag). Therefore, this approach relies on careful positioning of the tags on the fuselage. For the use in production a solution should be implemented to avoid mistakes in tag positioning and tag reading: it is suggested the adoption of mask covering the fuselage, where the tags are pre-attached at the appropriate positions.

Overall, the concept of the drill add-on developed for this use case showed that the selected technology is suited to support sensing on the drill (localization ad proximity); to support the interaction with the drill operator (push button and message display), to manage the communication and exchange of messages with the vacuum via the gateway on the edge (Wi-Fi and mqtt support), and then to satisfy the needs of the use case scenario. For a final product to be used on the production plant the following aspects should be considered:

- drill add-on size: the add-on should be more compact so that it can be mounted on top of the drill enhancing the usability of the tool during the drilling operations;
- the add-on casing should be shaped to better adhere to the top of the drill
- reengineering of electronic components may be necessary to reduce the size of the case
- battery level: an indicator of the battery level should be added;
- ergonomics: the components integrated in the drill add-on (button, display, laser beam) should be positioned to improve the operator’s user experience;
- increased autonomy/battery life: the drill-add on must work for a complete drilling session where several holes are made; the adoption of Bluetooth low energy transmission should be considered to increase the operational autonomy even with batteries of reduced size.

Perception technology and Tool wear module

The tool wear module prototype setup by UniSa in WP3 and tested at their labs was experimented in WP8 with several drill tip sets from the production plant in Grottaglie showing different wear level. Those experiments proved the approach based on image recognition of the drill edge profile can be adopted to estimate the drill tip wear level. However, some false negative estimations showed the current concept developed at the Unisa Lab needs to be further improved and engineered to be adopted and operated in production. Particularly the following aspects should be considered:

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- auto-centering: the current prototype requires careful adjustments when the drill tip is positioned in the tool so that the images taken are in focus; an auto-centering mechanism should be added to ensure the drill tip is always set and blocked in the right position with no need to open the tool box and check the drill positioned correctly, and so to have repeatable and consistent results of the output estimations;
- usability: the current prototype requires the drill tip is unmounted from the drill to be positioned in the tool; in order to be adopted in production to estimate if a drill tip can be used for the next drilling session or should be replaced, the tool wear module should work as a box where the operator can enter the drill tip without unmounting it from the drill. Besides the system should be re-engineered to make it more compact, robust and to produce the output estimation in less time so that it can be operated in the fuselage production area where the drilling sessions take place. Green and red lights that show the outcome of the estimation should replace the video screen to have an immediate feedback for the operator.

2.5. Conclusions

Great satisfaction was expressed by the staff of Leonardo Aerostructures on the plant in Grottaglie for the success of the use case and the possibility of engineering it in the short term so that it can be used in production. The prototype has been demonstrated in an operational environment (TRL7), using real sections of fuselage. From a technological point of view, the components developed by UNISA, Eurotech and Leonardo proved to be successful for the use case.

The system is intended mainly for internal use in Leonardo. Early next year the strategy of Leonardo aims at the industrialization and generalization of the prototype in order to deploy the product in the other production sites of Leonardo.

In addition to the improved efficiency of the process (in fact the operator previously dedicated to the vacuum cleaner can now be dedicated to other activities, with a cost reduction of at least 30%) it is important to note also the impact on the process quality. In fact, the experimentation of image processing technologies confirmed it is possible to check automatically the consumption of the tips which has a direct impact on the quality of the holes made. On this aspect an evolution is foreseen to make the tool wear module more usable/compact and reliable for a quick use during the drilling sessions.

On a more general level, the experience gained in this context can be certainly replicated in other production situations where two subjects (human and / or machine) must collaborate to achieve the production purpose.

As a final consideration, this use case gave Leonardo, Unisa and Eurotech the opportunity to share technological, methodological and process knowledge and to establish good relationships as project partners.

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3. VALIDATION RESULTS OF UC5 - TRIMMING QUALITY IMPROVEMENT (LEONARDO)

3.1. Background of the use case

During trimming/milling activities delamination can be experienced on parts, caused by different phenomena that are difficult to be managed because of the high complexity and high numbers of variables (vibration, detachment of the part being cut, tool wear, speed, humidity, temperature, air pressure, etc.).

The objective of this use case is to collect data coming from sensors and numerical control machines (CNC), analyse them with a quality statistic algorithms and understand the main root causes of defects and then provide real time information in order to change the setting of machine parameters to reduce the risk of damage or defect.

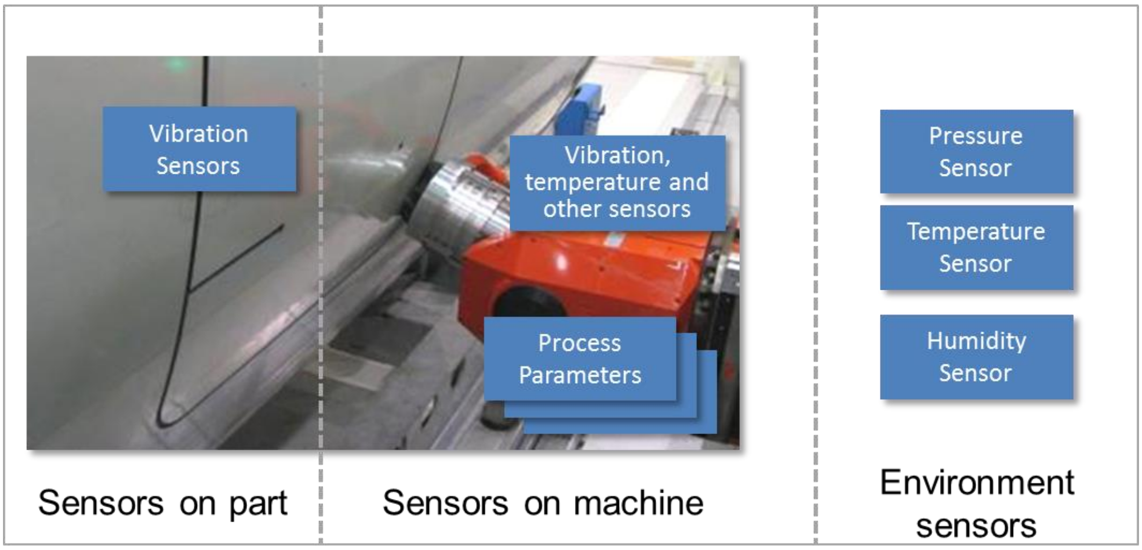

Figure 4 - UC5 overview.

More information on the background and use case requirements can be found in D8.9.

3.2. The use case prototype under evaluation

The use case prototype is made of different components as described in D8.4, encompassing architectures and technological modules developed in CPS4EU and specific components, namely:

- a distributed sensing layer with several smart sensing nodes of various data sources, that are responsible for turning sensor signals into a time series of data for the relevant process variable, with samples at the appropriate frequency; this layer features:
  - Distributed measurement system for the work part parameters, measuring the vibrations the vibrations during the trimming of the window area of the fuselage;
  - Distributed measurement system for the trimming hood parameters, measuring the flux and the temperature of the airflow that the trimming machine hoovers while trimming a fuselage window;
  - Distributed measurement system for the trimming head parameters, measuring the vibrations of the head of the trimming machine during the trimming of the window areas of the fuselage;
  - Trimming parameters acquisition chain, that is responsible of the acquisition of the vibrations of the trimming machine mandrel and of the trimming process parameters (e.g. forward feed and rotation speed of the machine) during the trimming process;
  - Distributed measurement system for the working area parameters, measuring temperature, pressure and humidity of the work environment where the trimming occurs.
- a gateway based on an Industrial computing platform with an IoT integration framework, responsible for collecting the data streams from the distributed sensing nodes and of sending them

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to the remote enterprise data analysis platform; it also runs the defect prediction model on the edge;
- an enterprise data analysis platform where the data scientist can analyse the process data collected from the plant to discover correlations and produce/update a prediction model of the risk of defect using machine learning techniques;
- the Operator interface that shows in real-time the process variables and alerts raised in real-time by the prediction model

The picture below shows the components of the tested use case prototype and how they are interconnected.

Due to the covid-19 pandemia and its impact on the aircraft market, the aircraft fuselage production faced a heavy reduction (the plant in Grottaglie was stopped for several months). Only a limited amount of data could be collected with very few records of defects: the collected dataset was not representative enough to train a reliable prediction model of defects. The prediction model of the risk of defect was emulated with a stub function.

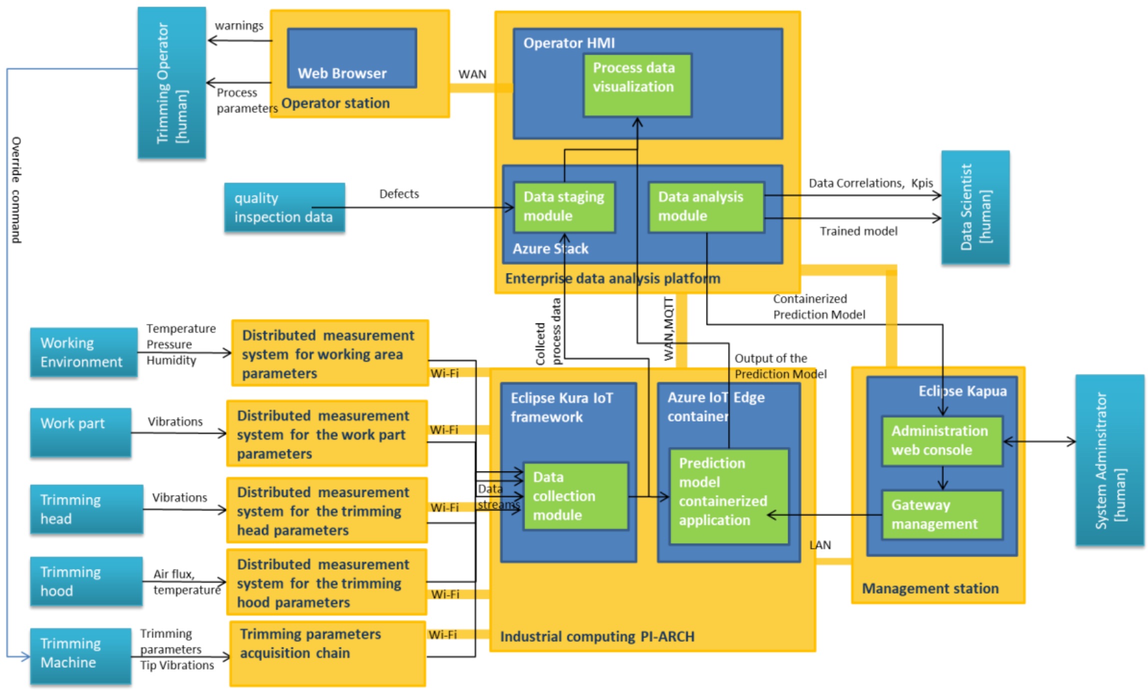

Figure 5 – Use case architecture: the components of the use case prototype.

3.3. Adopted CPS4EU technology

The following table lists the technology developed in other work packages (namely components from WP1-4, PI-Archs integrated or packaged from components in WP6 or Tool clusters by WP5) that is used in the prototype and where it is used.

CPS4EU technological component	Source WP	Where it is used in the prototype
Industrial computing and connectivity PI-Arch (by Eurotech)	WP6	Implements the industrial gateway running the use-case logic that collects the data streams of process variables on the plant and sends the data to the enterprise data analysis platform. Also runs the prediction model on the edge that feeds it in real time with the variables collected on the field and sends those variables along with the output risk index to

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		the enterprise data analysis platform to feed the Operator HMI. The use case implementation exploits the following hardware and software features of this PI-ARCH: - Hardware abstraction layer - Mqtt Information broker - Kura IoT framework - Predefined data collection blocks available in Kura - Azure connector - Docker container - security features (TPM, Secure Boot, physical anti-tampering, authentication and authorization framework, software change detection)
Kura IoT tools	WP5	The engineering, development and testing of the use case prototype leveraged the tools that come with the Kura IoT framework available on the Industrial computing and connectivity PI-Arch. Namely tools for: - functional design: Kura WIRES supports the dataflow programming model allowing to graphically define dataflow graphs where the nodes represent specific abstraction of the devices or of any specific unit of work; - simulation of the Industrial gateway: Kura provides a Device Virtual Twin that allowed to simulate the industrial gateway before the hardware platform was ready; - configuration, Monitoring and remote control of the gateways via the Kura Administration web console.
cooperative PI-Arch	WP6 WP4	The cooperative PI-ARCH design pattern (by WP4) was adopted and instantiated in the implementation of the cooperation between the components of the use case prototype i.e. distributed measurement nodes, industrial gateway and enterprise platform. For more detail on how it is instantiated in this use case see D4.5.

Furthermore, the use case prototype architecture adopts the distributed processing architecture defined in WP1.

3.4. Test and validation results

3.4.1. Test results

Following the strategy for test and validation set in D8.7 the use case prototype components have been developed and tested separately at the development labs of the partners involved, namely:

- University of Salerno (various distributed measurement nodes);
- Eurotech dev labs (Industrial edge computing platform)
- Leonardo plant in Grottaglie (Trimming parameters acquisition chain).
- Leonardo labs in Genoa (enterprise data analysis platform and operator HMI);

For the component testing stubs ad emulators have been setup to emulate the interactions with other components of the CPS and the load/interactions of the use case scenario.

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Then the use case prototype components have been deployed for integration and validation on Leonardo Aerostructure plant in Grottaglie to test the use case prototype in the work environment and check it meets the working conditions and operational constraints of the production process. The picture below shows the final deployment of the use case prototype:

- the smart sensing nodes of the distributed measurement systems have been deployed in the working area of Leonardo plant in Grottaglie;
- the industrial computing Pi-ARCH has been installed in a rack in the communication room of Leonardo plant in Grottaglie;
- Wi-fi network connections have been set to enable the smart sensing nodes communicate with the gateway PI-ARCH;
- The gateway PI-ARCH is connected via the Finmeccanica Unified Network (WAN) to Leonardo labs in Genoa where the Azure Stack platform implementing the enterprise data analysis is deployed;
- The station of the Trimming operator is connected to the HMI application running on the data analysis platform hosted in Leonardo labs in Genoa;
- The administration management station in Genoa is connected with a separate management network to the administration console of the gateway Pi-ARCH in Grottaglie.

As it was not possile to train a prediction model of the risk of defects, it was emulated with a stub application that returns predefined values of the prediction result, as a risk index. The stub application has been deployed as a Docker containerized application on the industrial edge comptuting gateway. In that way we managed to test the functions related to the phase of the use case concerning the real time application of the quality prediction model, that is:

- real-time feed of process data into the prediction model
- real-time execution of the trained prediction model
- supervision and alerting on the trimming process (operator HMI), based on the ouptu of the prediction model.

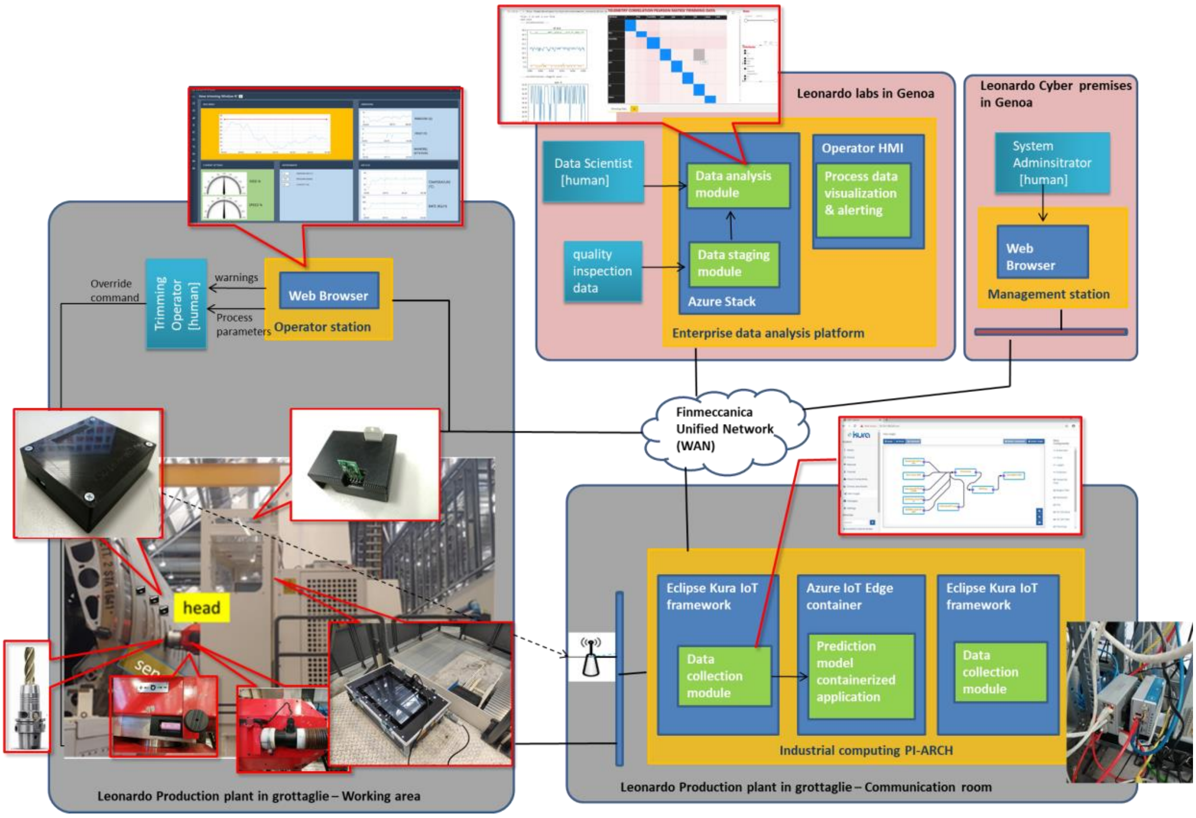

Figure 6 –Deployment of the use case prototype

Several test sessions were carried out on Leonardo Aerostructure production plant in Grottaglie to check the CPS prototype behaviour. The test results can be summarized as follows:

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- the distributed smart sensing nodes are able to measure the various process variables, synchronize them with a common ntp server and send via wi-fi to the industrial gateway mqtt messages containing data packets of the measured variables; data concerning the position of the trimming tip have been anonymized to hide the geometry of the window (customer confidential information);
- the gateway is able to collect the mqtt messages containing measures taken on the field, to buffer those data and to package them for data transfer to the enterprise data analysis platform for post-production investigation, correlating the variations of those variables with the reported defects;
- the data analysis platform supports the visualization of the collected process variables and the investigation of correlations between them and the reported defects;
- the gateway is able to collect the mqtt messages containing measures taken on the field, and to feed the prediction model running locally as a containerized docker application with a rolling window of those variables and then to transfer those variables along with the output risk index obtained from the model to the enterprise data analysis platform for real-time display on the operator HMI;
- The Operator HMI application is able to show the trend of the risk index of defects while the trimming process occurs, along with the variations of the process variables measured on the field.

Given the limited number of window trimming sessions of fuselage sections where data could be collected, the amount of data and defects was not enough to train and validate a machine learning model able to predict the risk to have defects from the ternds of process variables.

The table below lists the tests executed and if they were successfully executed. The definitions of the referenced tests can be found in D8.7.

Test name	Test level	Test ref.	Req.ID	Executed	Success	Notes
environment parameters measurement	Component	7.2.1	UC5-FNC-01	yes	yes	
Collection on the field of environment parameters measures	Integration	7.2.2	UC5-FNC-06	yes	yes	
Worked part vibration measurement	Component	7.2.3	UC5-FNC-02	yes	yes	
Collection on the field of the worked part vibration measure	Integration	7.2.4	UC5-FNC-06	yes	yes	
Trimming head vibration measurement	Component	7.2.5	UC5-FNC-02	yes	yes	
Collection on the field of the Trimming head vibration measure	Integration	7.2.6	UC5-FNC-06	yes	yes	
Trimming tool tip vibration measurement	Component	7.2.7	UC5-FNC-02	yes	yes	
Collection on the field of the Trimming tool tip vibration measure	Integration	7.2.8	UC5-FNC-06	yes	yes	
Trimming air flow measurement	Component	7.2.9	UC5-FNC-02	yes	yes	

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Collection on the field of the Trimming air flow measure	Integration	7.2.10	UC5-FNC-06	yes	yes	
Trimming machine work parameters acquisition	Component	7.2.11	UC5-FNC-02	yes	yes	
Collection of Trimming machine work parameters	Integration	7.2.12	UC5-FNC-06	yes	yes	
Communication of collected measures to the enterprise data analysis platform	Integration	7.2.13	UC5-FNC-06	yes	yes	
Data staging of measures collected from the field	Component	7.2.14	UC5-FNC-06	yes	yes	
Data collection of relevant trimming process parameters from the field	System / Acceptance	7.2.15	UC5-FNC-06	yes	yes	
Data Loading of quality inspection data	Component	7.2.16	UC5-FNC-06	yes	yes	
Data analysis	Component/ System / Acceptance	7.2.17	UC5-FNC-06	yes	yes	
Prediction model validation	System / Acceptance	7.2.18	UC5-FNC-06 UC5-FNC-09	no		Not enough data to train and validate the model
HMI display	Component	7.2.19	UC5-FNC-07	yes	yes	
Communication of the collected measures and prediction output to the HMI	Integration	7.2.20	UC5-FNC-07 UC5-FNC-08	yes	yes	
Trimming process monitoring	System / Acceptance	7.2.21	UC5-FNC-07 UC5-FNC-08	yes	yes	
Real-time execution of the prediction model	System	7.2.22	UC5-PRF-01	yes	yes	

Table 3 – Test results.

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3.4.2. Evaluation of the use case protoype

The objective of this use case is twofold:

a) to collect data coming from sensors and numerical control machines (CNC), analyse them with a quality statistic algorithms and understand the main root causes of defects and then
b) to provide real time information in order to change the setting of machine parameters to reduce the risk of damage or defect.

To evaluate the success of the use case, following the goal question metric approach, the use case objective was decomposed in questions and metrics to measure if the prototype successfully answers those questions.

UC "trimming quality improvement" reached its goal if at least 2 out of the 3 questions have successful answers.

The following table summarizes the values achieved for the metrics associated to those questions.

Question	Target/Success Criteria	Metric achieved	Success
enable data collection of the trimming process variables from different sources	data are collected and centrally archived from at least 4 out of 5 between the following sources: - work environment - part being worked - trimming machine parameters - trimming tip - trimming head	100%: - temp, pressure, humidity -> OK - Window part vibrations -> OK - Rotation, fwd speed ->OK - Tip vibrations -> OK - Trimming head vibrations , trimming hood air flow -> OK	Yes
enable data analysis with quality statistics algorithms	a platform is implemented where: a) the collected variables are organized for data analysis and b) statistics algorithms and machine learning techniques are available to support the discovery of correlation models Success if both a) and b) are satisfied	100%: - Input of quality defects: OK - dataset building: OK - dataset browsing: OK - correlation analysis: OK - machine learning algorithms available: OK	Yes
enable defects prediction	a) a model is trained and validated able to predict the risk of defects b) real time warning during the trimming process is displayed to the trimming operator when there is a concrete risk to have defects according to the model Success if both a) and b) are satisfied	50% - feature engineering: preliminary - model trained: not OK - model validated: not OK - real time warning on HMI: OK	No

Based on the results above UC "trimming quality improvement" reached its goal (two out of three questions successfully answered).

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Below are some comments/grounds /evidence on the values of the metrics achieved. For the definition of the referenced tests see D8.7.

Question	Comment on the results achieved
enable data collection of the trimming process variables from different sources	Each distributed sensor nodes deployed on Leonardo plant in Grottaglie was able to measure the relevant variables (tests 7.2.1, 7.2.3, 7.2.5, 7.2.7, 7.2.9, 7.2.11) and to transmit those data through the industrial gateway on the edge (tests 7.2.2, 7.2.4, 7.2.6, 7.2.8, 7.2.10, 7.2.12) to the central data analysis platform (test 7.2.13) where they are stored to be analysed (test 7.2.14). More information and examples of the staging of collected data files can be found in D8.6. The data collection process was successfully tested with all sensing nodes in place while the trimming process occurred on the plant (test 7.2.15). A video (confidential) is available that shows the data collection during the windows trimming sessions.
enable data analysis with quality statistics algorithms	The data files of measure flows received from the field and stored on the data analysis platform are processed and decoded according to the data flow specification and can be separately viewed on tables (test 7.2.14). The data analysis platform is able to import from a file the defects found by the post production quality inspection on the trimmed windows. (test 7.2.16). The different data flows are combined to build a single dataset and joined with the defects manually reported on file by the quality inspection to obtain the complete dataset for the analysis. The complete dataset can be viewed and explored with Power BI dashboards and graphical charts (test 7.2.15). The data analysis platform can produce Pearson matrix the allows the user to analyse the correlation over a stretch of time between selected process variables collected during the trimming process (test 7.2.17). The data analysis environment setup features tools and technologies like Azure Machine Learning designer, Jupyter notebooks, frameworks such as PyTorch, TensorFlow, and scikit-learn, MLflow, ML Ops and other no-code tools to visually manipulate datasets and build ML models without writing any code. More information and examples of the data analysis features available on the data analysis platform can be found in D8.6.
enable defects prediction	Due to the impact of covid pandemia and reduced fuselage production on plant in Grottaglie , only a limited amount of data was collected and that was not enough to setup an experiment and train and validate a model able to predict the reported defects adopting a machine learning supervised approach (test 7.2.18). However, a preliminary analysis on the available data was performed adopting an unsupervised approach to find anomalous patterns and identify variables that could have an influence on the output quality. More information on the results of that preliminary analysis can be found in Annex par.8.2.1. The emulation of the prediction model with a stub application allowed to demonstrate the feasibility of the real time adoption. The stub application was deployed on the plant in Grottaglie as a containerized docker application running on the industrial gateway. The industrial gateway fed the stub of the prediction model with a rolling window of the variables measured on the plant by the sensor nodes during the window trimming process. The operator HMI shows how the trimming process variables change during the window trimming and the risk of

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	defect produced by the stub prediction model. (test 7.2.9). A video (confidential) is available that shows the HMI display while the windows trimming session occurs.

3.4.3. Validation of CPS4EU technology

Industrial edge computing PI-ARCH and cooperative PIARCH

As for UC4 (Automatic vacuum system) the implementation of the cps prototype of this use case demonstrated the industrial edge computing PI-ARCH is well suited to work as a gateway on the edge and support a data collection scenario: the PI-ARCH was able to manage the connection with the various source nodes deployed on the edge; to manage the interactions with them via mqtt protocol; to buffer and package the data streams received and transfer them as data files to the remote central platform where they are stored and analysed. Besides the industrial edge computing PI-ARCH successfully worked as a Docker container to host the execution of the prediction model and the logic to feed it with the variables measured on the plant by the sensor nodes during the window trimming process.

Leveraging the Eclipse Kura IoT software framework available on the PI-Arch, particularly the configurable and reusable blocks that come with it (i.e. subscriber nodes that receive the messages that sensor nodes publish on the Kura information broker, Azure connector) the data collection logic for the use-case was developed more than three times faster than implementing embedded software as in previous projects.

As already explained for UC4, the industrial edge computing PI-ARCH was able to meet Leonardo IT security policy and the settings required to support a secure communication on the field, with the remote central data analysis platform and for remote management (see par. 3.4.2).

Thanks to the hardware and software security features and enhanced architecture of the Industrial edge computing and connectivity PI-ARCH we could benefit of a platform compliant with Industrial security standards and able to satisfy the edge computing, connectivity and cybersecurity requirements of this industrial automation scenario.

The adoption of the cooperative Pi-Arch design pattern served as a guideline to consistently develop the components supporting the interactions between the sensor nodes, industrial gateway, and central data analysis platform, ensuring modularity and maintainability of the interactions between those entities that cooperate in the data collection scenario and working as a reference for the implementation by different partners.

Overall the TRL7 concept developed of this use case showed that the industrial edge computing PI-ARCH is able to satisfy the requirements of the use case scenario. Concerning the feedback on the PI-ARCH technology see what already reported for UC4 at par. 3.4.2.

Kura IoT Tools

The Eclipse Kura IoT software framework available on the PI-Arch proved to be very useful for the design and testing of the data collection logic running on the PI-ARCH and the remote administration/monitoring of the gateway implementation:

- the Kura WIRES interface allowed to rapidly setup the data collection logic, defining graphically the dataflow graph of the processing nodes involved in interconnecting the sensing source nodes that publish their measurements with the remote data analysis platform;
- setting up the Kura IoT platform on a virtual machine we could benefit of a digital twin of the industrial gateway that allowed to test the developed data collection logic and to test the integration of the gateway with the other components of the use case far before the prototype of the hardware and software platform of the Pi-Arch was ready;
- the Kura Administration web console allowed to remotely configure the settings of the industrial gateway based on the PI-Arch and was very helpful during the integration test to monitor the active processes on the gateway and remotely start/stop them in order to reproduce specific situations or to investigate specific issues.

As reported for UC4 where the same tools were used, possible areas of improvement are:

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- configurability: some settings (e.g. https connection settings and authentication certificates) should be manageable via the gateway web administration interface (currently by line commands only);
- remote management: some features are not available from the gateway web administration interface but require the gateway cloud console available through the open source project Eclipse Kapua.

<u>Distributed sensing nodes</u>

The distributed processing nodes developed/integrated to implement the perception layer of the CPS according to the distributed processing architecture defined in WP1, proved that the concept of a distributed infrastructure that is able to support the collection of process variables from the plant is feasible. The sensing nodes implemented in the prototype could be improved in these areas:

- adoption of a case more robust and dust resistant;
- the size of the air flow measurement system should be more compact;
- addition of an indicator of the battery level;
- the configuration of network settings, DNS and ntp servers should be simplified
- the sensorized mandrel kit should use wi-fi connection (instead of radio frequency) and also provide measures of the temperature close in the trimming zone (these aspects have been already shared with the provider of that technology.

3.5. Conclusions

This use case turned out to be very complex for the development of sensors, network configurations, IT security, integration with production systems and the use of innovative devices (such as the sensorized mandrel by Schunk).

Laboratory tests allowed to validate the individual components and the integration between them through the use of simulators.

A prototype has been demonstrated in an operational environment (TRL7), on real sections of fuselage. To carry out the system/acceptance test it was necessary to involve Leonardo Aerostructure production department without interfering with the activities on the fuselage sections.

Due to the limited production windows of the Grottaglie plant in the past two years (caused by the pandemic and the consequent drastic downsizing of the civil aviation market) the data acquisition campaign could not be completed.

Consequently, the amount of data gathered during the trimming process was not sufficient to build a model able to anticipate possible defects with a supervised machine learning approach and identify the correlations among different variables. Despite this situation, an investigation has been carried on, with encouraging results.

A different approach has been adopted. Unsupervised analysis using anomaly detection COPOD algorithm has been performed on available data, allowing to identify the most affecting variables affecting the quality of the trimming process.

Although the objective of the analysis was not achieved completely, as soon as more data will be available in the next months, the work team is confident to identify a model to predict an anomaly situation, such as delamination. Anyway this use case prototype validated the concept of an infrastructure that is able to support the collection of process variables from the plant and make them available for post-production analysis and ready to provide real time warnings while the trimming process occurs.

After the project conclusion, Leonardo will undertake actions for industrialization in order to deploy the solution in the plant of Grottaglie and other plants with similar needs. Leonardo believes the solution, once installed in the production cycle, can save at least 10% of costs thanks to better quality control of the production process.

Though the solution is mainly intended for internal use, the Cyber & Security Solutions of Leonardo is going to generalize the data acquisition architecture (smart sensors, gateway, networking, data analysis platform) to propose a solution applicable to similar contexts on the external market, with the support of the project partners UNISA and EUROTECH.

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4. VALIDATION RESULTS OF UC7 - AIRCRAFTS HEALTH MANAGEMENT SYSTEM (LEONARDO)

4.1. *Background of the use case*

The Aircraft Health Management System (AHMS) is devoted to gathering, collecting and analysing data concerning aircraft fleet maintenance.

The overall system (depicted in the figure below) consists of different modules, located both on-board and on-ground, providing data and HW / SW framework.

The objective is to collect and correlate data from the aircraft (failures, removed items and performance data), warehouse and other sources (knowledge base, manuals) to support AHMS users in:

- failure troubleshooting (Maintenance Operators);
- monitoring aircraft systems performance and anticipating possible failures (Department Engineers);
- procurement decisions, anticipating spare parts demand (Logistic Operators).

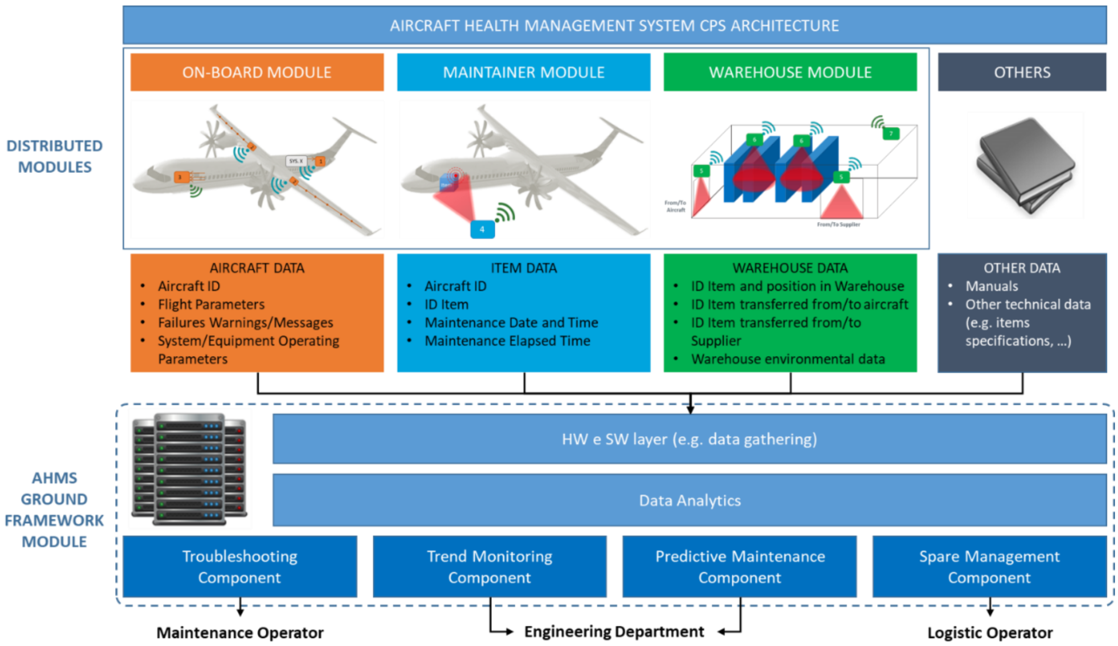

Figure 7 - AHMS CPS – overall picture

More information on the background and use case requirements can be found in D8.9

4.2. *The use case prototype under evaluation*

The prototype implemented in the project is focused on the Ground framework of the AHMS and particularly the scope is limited to the Troubleshooting and spare management components of the Ground Framework. As described in D8.4, it is centred on an enterprise data analysis platform based on Azure Stack technology featuring:

- a data gathering module that is responsible of collecting and loading Aircraft, Item and Warehouse data as well as complementary information from other sources, so that it is available for the processing of specific components;
- Troubleshooting and a Spare Management components where specific dashboarding and analytics functions are available to satisfy the requirements of the Maintenance operator and logistic operator, respectively.

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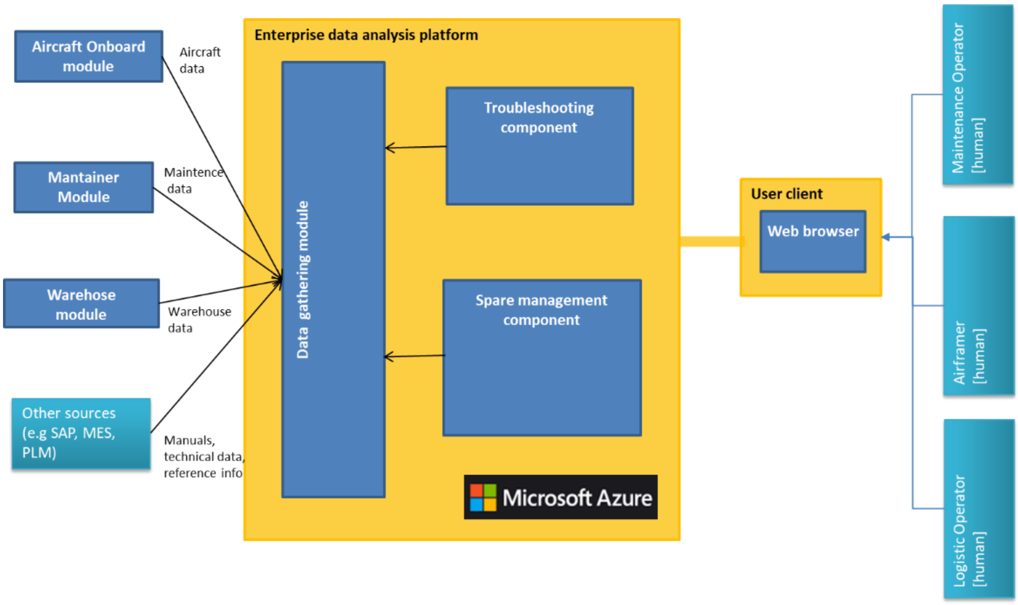

Figure 8 – AHMS architecture.

The prototype of the AHMS Ground Framework has been developed in cooperation between the domain users (Leonardo Aircraft Division) and Software experts (Leonardo Cyber & Security Solutions Divisions).

For additional details on the prototype implementation see D8.6

4.3. Adopted CPS4EU technology

The implementation of the central enterprise data analysis platform of the Ground Framework is based on the Azure Stack Platform. It mainly relies on Azure services and open-source data analysis tools that are integrated with custom development. Given the limited scope addressed in CPS4EU of this CPS, no specific technological modules from CPS4EU are used for the implementation. Future implementation of the full CPS would benefit from the adoption of CPS4EU technology e.g. the industrial edge computing and connectivity PI-ARCH to collect and transfer the data originated in the aircraft on board module.

However, the collaborative PI-ARCH design pattern from CPS4EU has been adopted to support the data collection paradigm of the CPS entities involved in the use case scenario, namely the Central data analysis platform of the AMHS Ground Framework and the various data sources (aircraft module, maintainer module, warehouse module) that send data to the Ground Framework.

CPS4EU technological component	Source WP	Where it is used and how much of it is used
cooperative PI-Arch	WP6 WP4	The cooperative PI-ARCH design pattern (by WP4) was adopted and instantiated in the implementation of the Data receiver and Data staging components of the Data gathering module. For more detail on how it is instantiated see D4.5.

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4.4. Test and validation results

4.4.1. Test results

Following the strategy for test and validation set in D8.7 the use case prototype components have been tested to verify that the features implemented in the Troubleshooting and Spare Management components satisfy the use case requirements for those components as captured in D8.9 “Use case requirements v3”.

As depicted in the picture below the Enterprise data analysis platform developed to implement AHMS Ground Framework components is hosted in the labs of Leonardo Cyber and Security Solutions Division on Azure Stack technology. The platform is interconnected, via the Finmeccanica Unified Network (WAN), with the end-user clients on Leonardo Aircraft Division site in Turin where domain experts play the different user roles.

The “physical” components of the CPS (i.e. aircraft on-board module, maintainer modules, warehouse module) have been simulated as source files for the data that are originated in those components. Leonardo Aircraft division provided a set of real customer data previously recorded over one year about: aircraft flight parameters, removed items, spare parts. The data have been anonymized and preliminary filtered before using them as an input to the data analysis platform of the Ground Framework.

Additional resources required to simulate the use case scenario (e.g. reference maintenance data on aircraft parts, foreseen flight hours, spare parts supply lead time, as well as other configuration information like failures catalogue, material required for maintenance intervention) have been pre-configured on the platform reading them from dedicated source files.

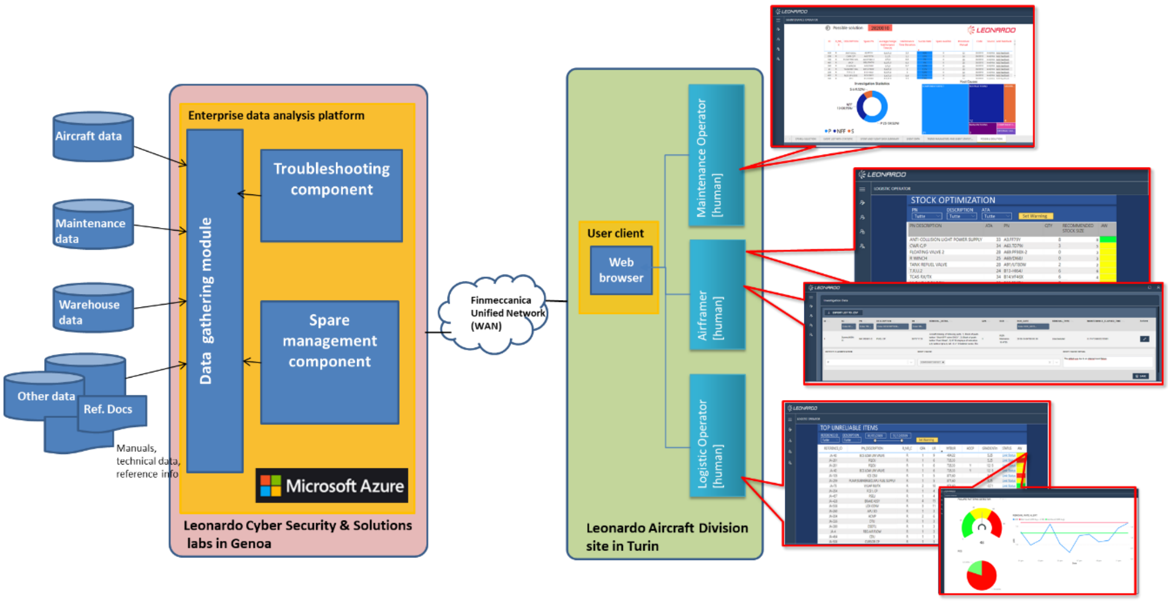

Figure 9 –Deployment of the use case prototype

Test sessions were carried out first at component level tests aimed at verifying that the features implemented in the Troubleshooting and Spare Management components satisfy the use case requirements for those components (see D8.9), particularly the requirements that have high priority. Acceptance tests were executed to check the prototype satisfies the patterns of usage to support the goals of the final users (maintenance operator, logistic operator, airframer). As reported in the table below most tests were executed successfully excepts a few where partial results were achieved, but not concerning high priority requirements. The test results can be summarized as follows:

The table below summarizes the results of the tests executed and if they were passed. The test results can be summarized as follows:

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- The AHMS Troubleshooting component fulfils the high priority requirements that this CPS preliminary prototype was expected to satisfy to proof it is able to support the goals of the maintenance operator and of the airframer;
- The AHMS Spare Management component fulfils the high priority requirements that this CPS preliminary prototype was expected to satisfy to proof it is able to support the goals of the logistic operator and of the airframer;
- The data gathering component supports the collection of relevant data from different sources (aircraft failures, aircraft flight parameters, item removals, troubleshooting manuals, warehouse in/out tracking)

Additional information on the output of the execution of the use case acceptance test can be found in paragraph 8.3 in Annex.

<u>Troubleshooting test results</u>

Test name	Test level	Test ref.	Req.ID	Executed	Success/notes
Collection and managing of aircraft failures data	Integration/ Component	8.3.1	UC7-FNC-73	yes	passed
Collection and managing of aircraft flight parameters	Integration/ Component	8.3.2	UC7-FNC-73	yes	Passed
Collection and managing of items removals	Integration/ Component	8.3.3	UC7-FNC-74	yes	Passed
Collection and managing of troubleshooting manuals	Integration/ Component	8.3.4	UC7-DSG-17	yes	Passed
Troubleshooting component access by Maintenance Operator	System/ Component	8.3.5	UC7-OPR-11	yes	Passed
Troubleshooting component access by Airframer Operator	System/ Component	8.3.6	UC7-OPR-12	yes	Passed
List of fault events and event selection	System/ Component	8.3.7	UC7-FNC-80 UC7-FNC-81 UC7-FNC-95	yes	Passed
Flight parameters chart interaction	System/ Component	8.3.8	UC7-FNC-83 UC7-FNC-84	yes	Partial: scale and formatting of the chart are automatically defined by the software, not by the user (UC7-FNC-84)
List of possible solutions for fault event	System/ Component	8.3.9	UC7-FNC-76 UC7-FNC-77 UC7-FNC-78 UC7-FNC-79 UC7-FNC-82 UC7-FNC-85 UC7-FNC-86 UC7-FNC-87	yes	Passed

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			UC7-FNC-91 UC7-FNC-97 UC7-FNC-98 UC7-DSG-15		
Insert of Maintenance Operator Notes	System/ Component	8.3.10	UC7-FNC-90	yes	Passed
Insert of Airframer Notes	System/ Component	8.3.11	UC7-FNC-89 UC7-FNC-92	yes	Passed
Association between Failures and Removals	System/ Component	8.3.12	UC7-FNC-93	yes	Passed
Correlation analysis between failures and flight parameters	System/ Component	8.3.13	UC7-FNC-94	yes	Passed
Calculation of Investigation Statistics	System/ Component	8.3.14	UC7-FNC-96	yes	Passed
Maintenance Statistics visualization	System/ Component	8.3.15	UC7-FNC-102 UC7-FNC-103 UC7-FNC-106	yes	Partial: actual Maintenance Elapsed Time reported. Deviations between design and actual values are not automatically reported (UC7-FNC-103)
Export of maintenance activities report	System/ Component	8.3.16	UC7-FNC-108	yes	Passed
Export of flight debrief report	System/ Component	8.3.17	UC7-FNC-107	yes	Passed
Troubleshooting	Acceptance	8.3.18	-	yes	Passed
Investigation Data	Acceptance	8.3.19	-	yes	Passed
Analytics	Acceptance	8.3.20	-	yes	Passed
Troubleshooting Optimization	Acceptance	8.3.21	-	yes	Passed
Identification of Valid Correlations	Acceptance	8.3.22	-	yes	Passed

Table 4 – Troubleshooting - Test results.

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Spare management test results

Test name	Test level	Test ref.	Req.ID	Executed	Success/notes
Collection and managing of warehouse data	Integration/ Component	8.3.23	UC7-FNC-113	yes	Passed
Collection and managing of warehouse in/out tracking data	Integration/ Component	8.3.24	UC7-FNC-116	yes	Passed
Collection and managing of Flight activity data	Integration/ Component	8.3.25	UC7-FNC-115	yes	Passed
Spare Management component access by Logistic Operator	System/ Component	8.3.26	UC7-OPR-11	yes	Passed
Spare Management component access by Airframer Operator	System/ Component	8.3.27	UC7-OPR-12	yes	Passed
List of scheduled maintenance activities	System/ Component	8.3.28	UC7-FNC-114 UC7-FNC-120 UC7-FNC-121 UC7-FNC-141 (also in next test)	yes	Passed
List of top unreliable items	System/Com ponent	8.3.29	UC7-FNC-119 UC7-FNC-122 UC7-FNC-123 UC7-FNC-124 UC7-FNC-125 UC7-FNC-141 (also in previous test)	yes	Partial: - It is possible to change the observation period, nut not the period typology (UC7-FNC-123) - Last Reliability Analysis Date is not shown, since the calculations are performed when the dashboard is opened; the date is always equal to the date of the dashboard opening) UC7-FNC-124 - Does not allow to change the number of Top Unreliable Items included in the list (UC7-FNC-125)
Updating of Reliability KPI	System/ Component	8.3.30	UC7-FNC-126	yes	Passed
Calculation of Availability Warning and relevant performance indicators	System/ Component	8.3.31	UC7-FNC-127 UC7-FNC-128 UC7-FNC-129 UC7-FNC-130 UC7-FNC-134	yes	Passed

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Modification of weights and thresholds	System/Com ponent	8.3.32	UC7-FNC-131	yes	Passed
Insert of AOG event	System/Com ponent	8.3.33	UC7-FNC-132	yes	Passed
Recommendation of weights and thresholds	System/ Component	8.3.34	UC7-FNC-133	yes	Passed
Visualization of performance indicators	System/ Component	8.3.35	UC7-FNC-135 UC7-DSG-17 UC7-DSG-18 UC7-DSG-19	yes	Passed
Calculation of recommended stock size	System/ Component	8.3.36	UC7-FNC-136	yes	Passed
Exporting of parts availability report	System/ Component	8.3.37	UC7-FNC-138	yes	Passed
Exporting of scheduled activities report	System/ Component	8.3.38	UC7-FNC-139	yes	Passed
Exporting of top unreliable items report	System/ Component	8.3.39	UC7-FNC-140	yes	Partial: it is possible to set filters on a subset of fields; it is not possible to select a number of Top Unreliable Items
New Orders by	Acceptance	8.3.40	-	yes	Passed
Top Unreliable Items	Acceptance	8.3.41	-	yes	Passed
Scheduled Maintenance	Acceptance	8.3.42	-	yes	Passed
Activities administration	Acceptance	8.3.43	-	yes	Passed
Stock optimization	Acceptance	8.3.44	-	yes	Passed

Table 5 – Spare management - Test results.

4.4.2. Evaluation of the use case protoype

The objective of the use case is to collect and correlate data from the aircraft (failures, removed items and performance data), warehouse and other sources (knowledge base, manuals) to support AHMS users in:

- failure troubleshooting (Maintenance Operators);
- procurement decisions, anticipating spare parts demand (Logistic Operators).

To evaluate the success of the use case, following the goal question metric approach, the use case objective was decomposed in questions and metrics to measure if the prototype successfully answers those questions.

The use case reached its goal if at least 4 out of the 5 questions defined are successful.

The following table summarizes the questions and the values achieved for the metrics associated with those questions.

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Question	Target/Success Criteria	Metric achieved	Success
enable data collection in AHMS from different sources	Success if data are collected and centrally archived from at least 4 out of 5 between the following sources: - aircraft failures - aircraft flight parameters - item removals - troubleshooting manuals - warehouse in/out tracking	100% - aircraft failures OK - aircraft flight parameters OK - item removals OK - troubleshooting manuals OK - warehouse in/out tracking OK	Yes
enable data analysis in AHMS with quality statistics algorithms	Success if a platform is implemented where the collected variables are organized for data analysis and machine learning techniques are available to support the discovery of correlation models	100%: - datamart building OK - correlation analysis OK - machine learning available OK	yes
enable the identification of valid correlations of aircraft failures	Success if the data analysis model is able to discover 3 known or new valid correlations	2 known correlations 1 new correlation	yes
The AHMS Troubleshooting component is functional and fulfils its requirements	Success if 80% of requirements listed in D8.9 with High priority and means of validation "By Demonstrator" are validated	98%	yes
AHMS Spare Management component is functional and fulfils its requirements	Success if 80% of requirements listed in D8.9 with High priority and means of validation "By Demonstrator" are validated	97%	yes

Based on the results above UC "Aircrafts Health Management System" reached its goal (5 out of five questions successfully answered).

Below are some comments/grounds /evidence on the values of the metrics achieved.

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Question	Comment on the results achieved
enable data collection in AHMS from different sources	The implemented data gathering component was able to take data from input files and load them on the central data platform to feed the Troubleshooting and Spare management component where they can be analysed - see the result of tests 8.3.1, 8.3.2, 8.3.3, 8.3.4 and 8.3.23, 8.3.24, 8.3.25.
enable data analysis in AHMS with quality statistics algorithms	The input data from source files are stored on a data lake based on Azure Blob Storage and then loaded into a data model set up in Sql server Analysis Services (SSAS), the analytical data engine that provides the capabilities for business intelligence, data analysis, and reporting in Power BI. Power BI dashboards using the SSAS data model and analytics correlation engine show the results of the analytics and insights that the system offers to support the decisions of the logistic operator, maintenance operator and airframer users. The analytics support that the system offers can be found in: - the automatic association algorithm between the Fault Code and the item Removals that is used to identify the most probable faulty item and to calculate the success rate of a possible solution (see Possible solutions dashboard of the Troubleshooting component) - Pearson Correlation Matrix are available to the Airframer user in Correlation and Patterns section, to investigate the correlation (-1; +1) between two selected variables e.g. between flight parameters (Telemetry), Fault Codes and Telemetry-Fault Codes - The recommended Weights and Thresholds settings that the Spare Management Component suggests to the Logistic Operator to calculate the Availability Warning, the predictive KPI which estimates the possibility of facing lack of spare parts to support maintenance operations. Additional information on those analytics features can be found in Annex 8.3.3.
enable the identification of valid correlations of aircraft failures	The Pearson Correlation Matrix available to the Airframer user in the Correlation and Patterns section were used to test the data analysis model offered in the Troubleshooting Component. First the analysis focused on known correlations, to check if the model is able to correctly identify engineering proven relationships; then new correlations were explored. Valid correlations have been identified in terms of Telemetry vs Telemetry, Fault Code vs Fault Code and Telemetry vs Fault Codes. Item Removals have been used to support or validate the analysis. Three examples of the valid correlations found to answer this question (2 known correlations in terms of Fault Code vs Fault Code and 1 new correlation in terms of Telemetry vs Items Removals) are given in Annex 8.3.4.
The AHMS Troubleshooting component is functional and fulfils its requirements	The table in the Annex at par. 8.3.5 shows for each requirement set in D8.9 that are relevant to answer this question (i.e. with High priority and means of validation "By Demonstrator"), what tests have been successfully performed to prove the requirement is satisfied.
AHMS Spare Management component is functional and fulfils its requirements	The table in the Annex at par. 8.3.6 shows for each requirement set in D8.9 that are relevant to answer this question (i.e. with High priority and means of validation "By Demonstrator"), what tests have been successfully performed to prove the requirement is satisfied.

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4.4.3. Validation of CPS4EU technology

N.A.

4.5. Conclusions

For the AHMS use case an overall Architecture was defined, encompassing:

- Several Distributed modules (On-board, Maintainer, Warehouse)
- an AHMS Ground Framework central module.

First, a detailed analysis and definition of the requirements for all the modules of the system was performed in order to define the complete scenario to support the maintenance of the aircraft and increase aircraft performance in terms of reliability, duration and availability flight safety.

Given the time and resources left for the implementation of the use case prototype after the decision to quit the development of UC6 Thermoplastic Production Line Monitoring (as per amendment AMD-826276-26 accepted 15/02/2022) the implementation of this use case prototype was limited to the Ground Framework, particularly on the Troubleshooting and Spare Management components, focusing on the development of a prototype of those components showing all the most relevant functionalities to support the Airframer, Maintenance Operator and Logistic Operator in their objectives.

The implementation of Ground Framework leveraged the "Enterprise data analysis platform" based on Azure Stack technology (the same used in the "Automatic Vacuum System" and "Trimming quality improvement" use cases) and was validated with real data for the telemetry and failures recorded during the flights of a customer fleet, scheduled and unscheduled items removals occurred during maintenance operations performed and registered spare parts availability.

The team made up of personnel from the Aircraft division and personnel from the "Cyber & Security Solutions" division of Leonardo, worked closely adopting an agile approach and managed to meet the expectations of the domain experts. The prototype was validated with real data obtained from an operating environment reaching TRL 6. Advanced data analytics techniques have been adopted.

Although functionally satisfying the expressed requirements, the prototype needs a subsequent deployment phase on a production infrastructure. The two divisions of Leonardo, downstream of the project, will agree on an effective way for the release of the system to end users.

The target market of this system for Leonardo Aircraft Division is:

- inside Leonardo (internal market): engineers will be able to analyse in-service data to identify new patterns from analytics with benefits for Leonardo and his customers;
- outside Leonardo (even if an external sale of the AHMS is not currently planned): future potential customers will be able to take advantage of the analytics results to optimize their troubleshooting procedures and improve the spare management processes.

With the AHMS Leonardo expects to improve customer satisfaction thanks to an overall control of the customer service processes based on real in-service data. Leonardo will gain from the AHMS for:

- Optimization of the Fault Isolation process, speeding up failure resolution (estimation: at least -10%)
- Reduction of No Fault Found events (estimation: at least -5%)
- Reduction of Aircraft on ground events due to missing parts (estimation: at least -10%)

Significant investments of Leonardo are planned in next years to develop the remaining modules of the AHMS CPS.

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5. VALIDATION RESULTS OF UC8 - MATERIAL FLOW ANALYTICS AND SIMULATION (TRUMPF)

5.1. Background of the use case

The main objective of UC8 is summarized as a flexible production management of complex processes on the shop floor. A shop floor is the area of the production hall, where the machines are located. The main feature of UC8 is the realization of a digital twin of the shop floor. The digital twin (cyber component) is the digital representation that describes the shop floor (physical component). The digital twin can then be used together with simulation models and live data from the shop floor. The main goals are the reduction of efforts to set up a simulation model and to get data from indoor localization systems to capture process times for manual processes and transport times.

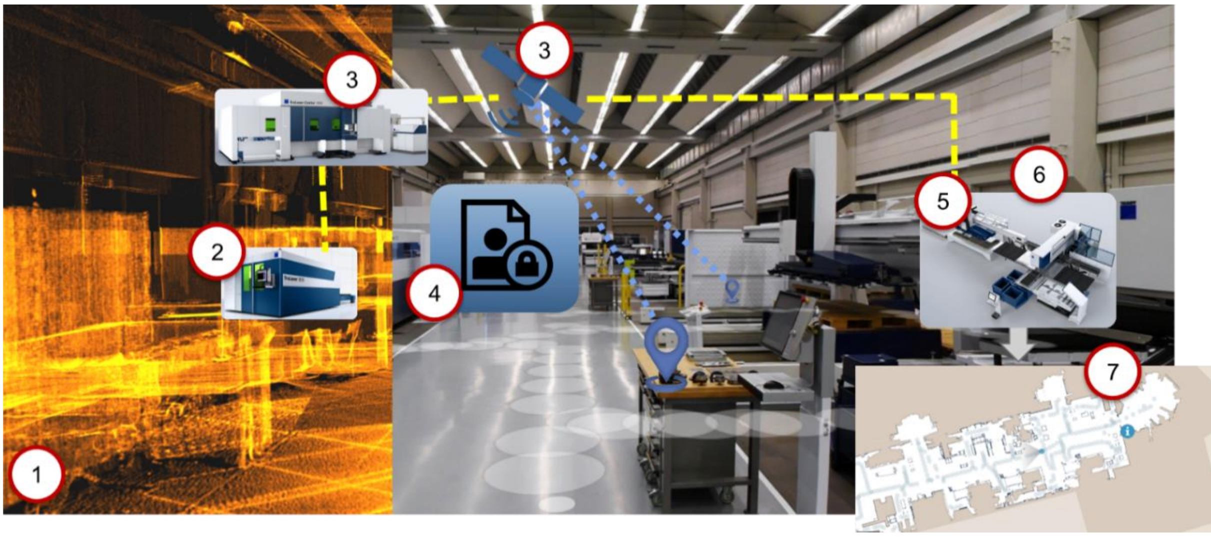

Figure 10 Overview over the major functions of UC8

The major functions of the CPS that is realized in UC8 are depicted in ***Figure 10***: The pointcloud (1) that is generated by a 3D shopfloor scan, the enrichment of the model with semantics (2), the provision of an accurate material flow tracking system (3), the assessment w.r.t. ethical requirements (4), the automatic creation of a simulation model (5), the continuous adaption of the shop floor model based on this data (6) and finally the usage of the simulation results for real-time re-scheduling, re-routing and re-nesting (7). The test and validation of the overall use case will be demonstrated in the TRUMPF Customer Center in Ditzingen that is depicted in the background of ***Figure 10***.

5.2. The use case prototype under evaluation

The final prototype deployment state is depicted in ***Figure 11***. The pointcloud and the raw images from the 3D shop floor scanner are processed by the semantic enrichment module on premise. The results are shown in the shopfloor validation GUI and can be validated and manipulated. The shopfloor description is transferred to the simulation model generator as a json file.

A prototype of the UWB tracking system is installed at the TRUMPF customer center in Ditzingen. The indoor localization data from the UWB tracking system is stored to a cloud database and processed on premise. The results like manual process times or shift models are imported to the simulation configurator.

Unlike initially planned we did not achieve a fully functional deployment of the simulation environment in the Microsoft Azure cloud. We have reported the successful deployment of some components in the cloud in D8.6 but could not fix all issues in the meantime. The reasons are the underestimated complexity of developing cloud applications and capacity issues in the IT department. This however does not impede the functionality of the prototype. The deployment on a cloud infrastructure will however be necessary to offer simulation services as a product to a customer.

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The testing environment for the prototype is the TRUMPF customer center in Ditzingen. We have conducted a 3D shop floor scan with the new scanner from Navvis and we have an UWB tracking system installed.

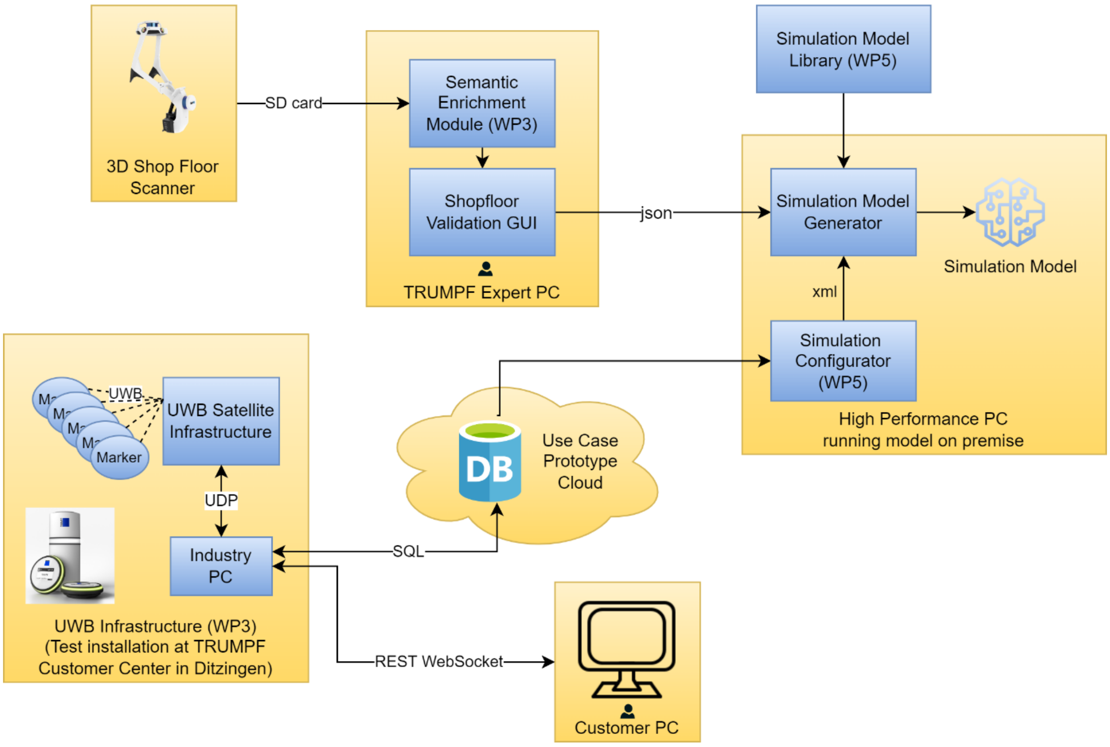

Figure 11 UC 8 Final Prototype deployment

For additional details on the prototype implementation see D8.6.

5.3. Adopted CPS4EU technology

The prototype of a digital factory twin builds on components and tools developed in WP3 and WP5. The material flow simulation library and the simulation configurator from WP5, the semantic enrichment module as well as the UWB tracking system from WP3 were combined to create a prototype of a digital factory twin for a sheet metal manufacturing plant. The tools and components that are adopted form other CPS4EU work packages is shown in ***Figure 12***.

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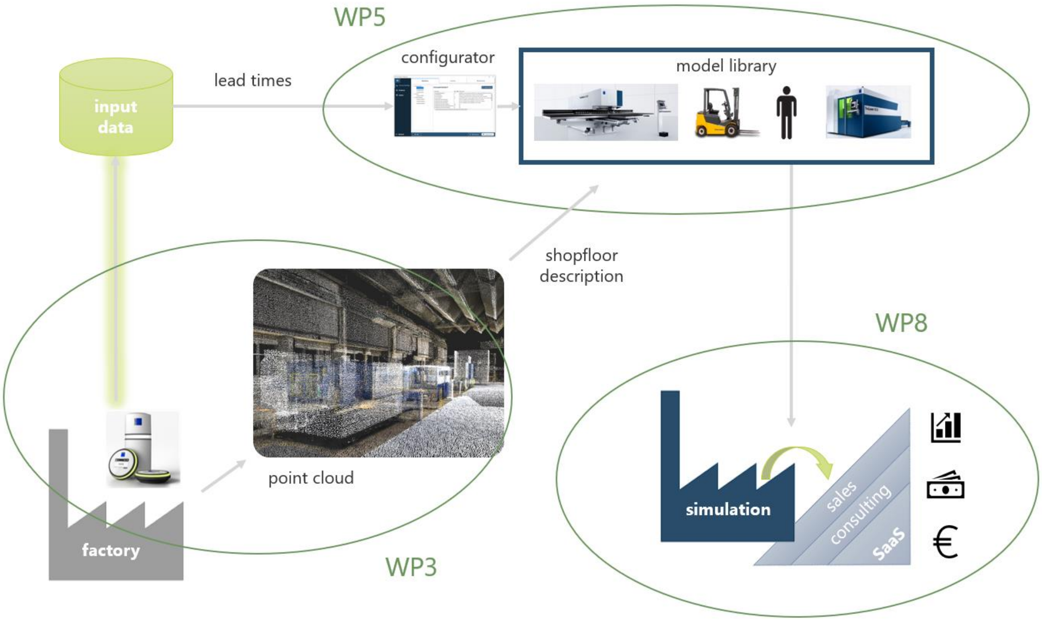

Figure 12: Tools and components adopted from other work packages

Our prototype builds on architectural patterns from a few CPS4EU PI-ARCHs.

The implementation of this prototype relies on the cooperative pre-integrated architecture PI-ARCH (WP4) for the interconnection and organization of the different components. Besides utilizing the architectural patterns and paradigms (e.g. synchronization, data fusion, consensus), it was successfully used to analyse the use-case prototype regarding the collaboration mechanisms and possible failure scenarios (cf. D4.2).

The use-case further builds on the industrial computing and connectivity PI-ARCH (WP6) and implements the corresponding patterns and methods (e.g. isolation of networks and services) for the UWB infrastructure system uplink from shop floor to the cloud. While we could not directly build on the WP6 reference hardware (i.e. the industrial edge gateway) as we needed a more powerful appliance (TRUMPF IPC) for the localization and simulation loads, we also see a strong need for more light weight edge gateways for enabling machine connectivity at our customers for a range of products.

Finally, some modules of our use-case are related to the Perception PIArch and Localization PIArch. For the Localization PI-ARCH our UWB system provides another sensor to increase the localization accuracy indoors. The Perception PIArch on the other hand, is strongly focussed on autonomous driving and therefore only few architectural and requirement overlaps are present e.g. 3d point cloud reconstruction for recognition.

Table 6 shows the modules used from CPS4EU project in the implementation of the prototype.

CPS4EU technological component	Source WP	Where it is used and how much of it is used
Simulation Configurator	WP5	The simulation configurator is a graphical user interface that simplifies the creation of different simulation scenarios. It is deployed on a TRUMPF expert PC. It can be filled with different data sources. One possible data source is the lead times derivation from tracking data.
Material Flow Simulation Library	WP5	The simulation model library is the basis for the realization of UC8. It is deployed on a TRUMPF expert PC. Nearly all parts of the model library are used here. In order to reduce the complexity for the model generation algorithm we created production cells that consist of multiple simulation model units.

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Semantic Enrichment Module	WP3	The semantic enrichment of the shopfloor scan is essential for the automatic generation of factory simulation models.
UWB Infrastructure	WP3	The UWB tracking system provides reliable data for manual processes and transport that cannot be gathered reliably from another source. This is particularly important as manual processes still play an important role for small and medium sheet metal manufacturers.

Table 6: Technological Components from other WPs used in UC8

5.4. Test and validation results

5.4.1. Test results

According to the test and validation strategy defined in D8.7 multiple tests on the component, integration and system level were carried out. The detailed test descriptions and their respective results can be found in Annex 8.4. The test results can be summarized as follows:

1. **Semantic Enrichment Module Test (component test)**

   The Semantic Enrichment Module was tested with a 3d point cloud from the TRUMPF Customer Center in Ditzingen. The accuracy of the detection of a machine (producer, machine series and machine name) reached the required level. The localization of machines achieved an IOU of 97% and thus exceeded the required level.

2. **UWB Infrastructure Test (component test)**

   As reported, TRUMPF installed the UWB infrastructure from WP3 on its own premises. Using this installation, the system was evaluated and improved in various aspects. The required localization accuracy, localization latency, the transfer to the cloud server and the association of product and order information was successful.

   In addition to the on-site installation in TRUMPF Ditzingen, the system was also rolled out to more test customers. In order to understand the system usage and operation, the cloud monitoring was implemented.

3. **Simulation Model Unit Tests (component test)**

   The simulation model units, namely machines, automation units, storage systems and transport devices like Automated Guided Vehicles (AGVs) have been verified and validated. The testing procedure consists of automated software unit tests that ensure the logical validity and prevent bugs and validation experiments that ensure the validity regarding cycle times. The detailed validation procedure that has been developed and published can be found in [1]. The software unit tests as well as the cycle time validation fulfilled the requirements.

4. **Simulation Model Generation Test (system test)**
   Similar to the simulation model unit tests, automatic system tests have been developed. In the first stage we used a synthetic shopfloor description in order to validate a larger variety of possible systems.

5. **Overall Use Case Test (system test)**

   The shopfloor description that was created by the semantic enrichment module and manually corrected using the validation GUI could successfully be imported to the simulation model generator. The data analysis from the UWB tracking system proved to be far more complex than expected. We did not achieve a fully automatic pipeline from the UWB tracking system to the simulation. The steps in between still have to be executed manually. The results are currently inserted in the simulation configurator tool from WP5 that feeds the simulation model with production data in an xml document. The functionality of the overall use case could be proved although it could not be deployed on the target infrastructure.

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An overview over the test results is given in Table 7 below.

Test name	Test level	Test ref.	Req.ID	Executed	Success	Notes
Semantic Enrichment Module Test	component	8.4.1	UC8-FNC-01 UC8-FNC-02	yes	yes	
Interface Test	integration	8.4.3	UC8-INT-01	yes	yes	
Ethical requirements validation	Does not apply	Does not apply	UC8-ETH-01 UC8-ETH-02 UC8-ETH-03	yes	yes	
Selection and test of hall scan provider	-	-	UC8-OPR-01 UC8-PFR-01	yes	yes	
UWB infrastructure test	component	8.4.2	UC8-OPR-02	yes	yes	
Simulation model unit test	component	8.4.4		yes	yes	
Simulation model generation test	system	8.4.5	UC8-FNC-03 UC8-FNC-04	yes	yes	
Simulation model performance test	component	8.4.6	UC8-PFR-02	yes	yes	
Overall use case test	integration	8.4.7	UC8-INT-02	yes	yes	prototype not deployed on target infrastructure

Table 7 – Test results.

5.4.2. Evaluation of the use case prototype

The objective of the use case is to realize a prototype of a digital factory twin that represents the real material flows and allows experiments with the virtual system. To make this service available for many of our customers the most important part is the reduction of efforts for the creation of the simulation model. Our approach was to recognize the machine types and their respective positions automatically from a 3d hallscan. The use case reached all important objectives.

The feasibility of the concept was shown through the demonstrator. Especially the simulation model generator and the simulation configurator that can also be used without the semantic enrichment reduced the efforts tremendously.

Question	Target/Success Criteria	Metric achieved	Success
Is a 3d scan of the shop floor at TRUMPF headquarter available and satisfies all requirements?	3d scan is available 2d images of scanner are available annotated shopfloor plan is available	100 % 100 % 100 %	yes

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Does the semantic enrichment of the scan provide positions, orientations and machine type recognition for at least 3 asset types?	Positions are available (given by an oriented bounding box) and can be modified by user Orientations are available (given by an oriented bounding box) and can be modified by user Classification results of machines are available (producer, machine series and machine name) and can be modified by user	97% 97% 98%	yes
Can the creation of a simulation model be reduced by at least 50 % by using the simulation framework ?	percentage of time reduced for setting up a whole factory simulation model with at least 4 machines	~8h to ~2h -> -75%	yes
Are simulation models for all machine types in the TRUMPF customer center available?	TruPunch 5000 + SheetMaster automation TruLaser (1030, 3030, 5030) TruLaserCenter 7030	100 %	yes
Can at least 3 simulation input types be derived from UWB tracking data ?	shift models machine process times residence times in storage geo fences	100%	yes
Is the system able to visualize KPIs to the user?	Is one dashboard with 3 different KPI's calculated from simulation output and 2 different types of diagrams available?	100 %	yes
Did the use case reach its goal?	goal is reached if metrics above are successful	all metrics are successful	yes

Table 8: UC8 KPI Overview

Based on the metrics achieved displayed ***Table 8*** the use case "Material Flow Analytics and Simulation" reached its goal.

In ***Table 9*** are some comments/grounds /evidence on the values of the metrics achieved.

Question	Comment on the results achieved
Does the semantic enrichment of the scan provide positions, orientations and machine type recognition for at least 3 asset types?	The data set provided contained 9 TRUMPF machines of which all were detected and correctly classified. Due to the absence of a sufficiently large data base of point clouds, the recognition of the machine’s actual orientation was rendered impossible. Instead, the position and orientation of a machine consists of an oriented bounding box enfolding the three-dimensional points belonging to a machine. In rare instances where this does not suffice a correction can be done in the user interface.
Can the creation of a simulation model be reduced by at least 50 % by	However, this metric only applies to systems with components that come off the shelf. As we often deal with customized production solutions, manual efforts are still required.

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using the simulation framework ?	
Are simulation models for all machine types in the TRUMPF customer center available?	All required simulation models are available in the model library. All simulation model unit tests have been executed successfully and after some adjustments in the model parameters the models fulfilled the validation criteria.
Can at least 3 simulation input types be derived from UWB tracking data ?	Algorithms for the derivation of simulation inputs have been developed and published in scientific research papers: [2], [3], [4]. These papers were mainly focused on determining process times and lead times but we also achieved to determine the shift model and validate the results against customer ERP data. Nevertheless, indoor localization data requires a lot of data cleaning and some results could not be validated to a full extend.
Is one dashboard with 3 different KPI's calculated from simulation output and 2 different types of diagrams available?	Each machine tool simulation model unit comes with a dashboard that displays its KPIs in various diagrams. Furthermore multiple dashboards on the system level and for the automatic storage system or the AGV fleet exist. An example dashboard can be found in Annex 8.4.8.
Did the use case reach its goal?	The use case reached its goal regarding the intended functionality. However, as the prototype is still deployed on a local PC and not on a cloud infrastructure the solution is not yet scalable for customers. Manual efforts for executing different scripts and manual adjustments in the creation of the simulation model are still required.

Table 9: Comments on KPI evaluation

5.4.3. Validation of CPS4EU technology

Due to the modular approach of the CPS4EU project TRUMPF was able to realize a prototype of a digital factory twin by assembling the developed components to a new product. The material flow simulation library and the simulation configurator from WP5, the semantic enrichment module as well as the UWB tracking system from WP3 were combined to create a prototype of a digital factory twin for a sheet metal manufacturing plant.

Simulation Model Library and Simulation Configurator (WP5 – TRUMPF)

The simulation model library is the basis for UC8. It was intended to be flexible and adaptable to many configurations which made the automatic model generation very complex. Therefore, production cells that consist of a machine tool and a certain set of automation units had to be created.

The simulation configurator as easy to use graphical interface proved to be very helpful to create datasets for testing and creating scenarios from analysed process times.

Semantic Enrichment Module (WP3 – acs-plus)

The semantic enrichment module helps to gather information of the actual shopfloor with quite low efforts. Often the layout plans are not kept up to date and are therefore not a reliable data source. However, the results show some weaknesses as mentioned above. The results of the semantic enrichment always have to be validated and augmented manually but the positioning information however is very valuable and reliable.

UWB tracking system (WP3 – TRUMPF)

The UWB tracking system enabled us to determine especially manual process times that could have previously not be determined on a large scale and had to be replaced by assumptions. However due to many outliers in the data the efforts for data cleaning are extremely high and do sometimes still produce inconsistent or implausible results.

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The UWB tracking system builds on some PiArch architectural patterns. However, some changes had to be made to meet all our requirements. Details can be found in chapter5.3 and D4.2.

5.5. Conclusions

Participating in the CPS4EU project enabled TRUMPF to develop a first prototype of a digital factory twin. The integration of cyber-physical systems brings the material flow simulation to a new level. On one hand the automatic layout and simulation model creation makes the solution scalable. On the other hand, the analysis of indoor localization data allows to create reliable input data for manual processes that could only be estimated previously. Nevertheless, bringing the prototype to a level that is suitable for industrial purposes is still a long way to go.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

6. VALIDATION RESULTS OF UC9 - MOBILE CPSS (WIKA)

6.1. Background of the use case

Collaborative Lifting is a use case provided by WIKA Mobile Control GmbH for this project. It deals with the use of at least two mobile machines, i.e. cranes, to lift a huge object that cannot be lifted using a single mobile crane.

Nowadays, the planning of such a complex process is done either by classical methods for some cases (Pen & Paper) or using a planning and modelling software for others. Nevertheless, the execution of such a process still represents a challenge among the crane operators and fleet managers.

To accomplish a collaborative lifting process, it is mandatory that a lifting supervisor/ planer looks at the lifted object and at the machines and makes sure that the lifting is performed according to the plan. In many cases, the crane operators can have a restricted sight on the obstacles, humans and maybe other machines present on site, due to the size, volume and shape of the object lifted e.g., or due to complex movements that have to be performed. Thus, the lifting supervisor has to give instructions or hints to the crane operators via Walky-Talky or other means of communication to ensure a damage free lifting.

WIKA is proposing an innovative way to accomplish such complex task, relying on well-established technologies such as modelling, simulation, collaborative algorithms and new innovative technologies such as digital twins, AI-powered algorithms, real-time capable communication interfaces and cloud services. The integration and adaption of such technologies will make it possible to deliver the instructions for the collaborative lifting process on an HMI placed in the crane cabin and the lifting process will be supervised and monitored by a server (it can be local server on site or remote such as a cloud).

A drone is also used a visual sensor to provide feedback on the position of the lifted object.

6.2. The use case prototype under evaluation

The initial plan of the use case prototype was to use a co-simulation (Cranes in Simulink and Drone in Gazebo) but due to the lack of resources the updated plan called for a separate simulation for the drone and the crane. ***Figure 13*** shows that the testing of the crane and the drone will be carried out separately with no mutual communication.

The main goal is to showcase the capabilities of the drone and crane separately in a simulation of collaborative lifting, that could be later connected together through the ROS infrastructure as shown in ***Figure 14***. Both the crane and the drone simulation can be taken as ROS nodes which can use the ROS communication channels (such as topics) to exchange information. The communication between the two systems will be taken as a task for the future.

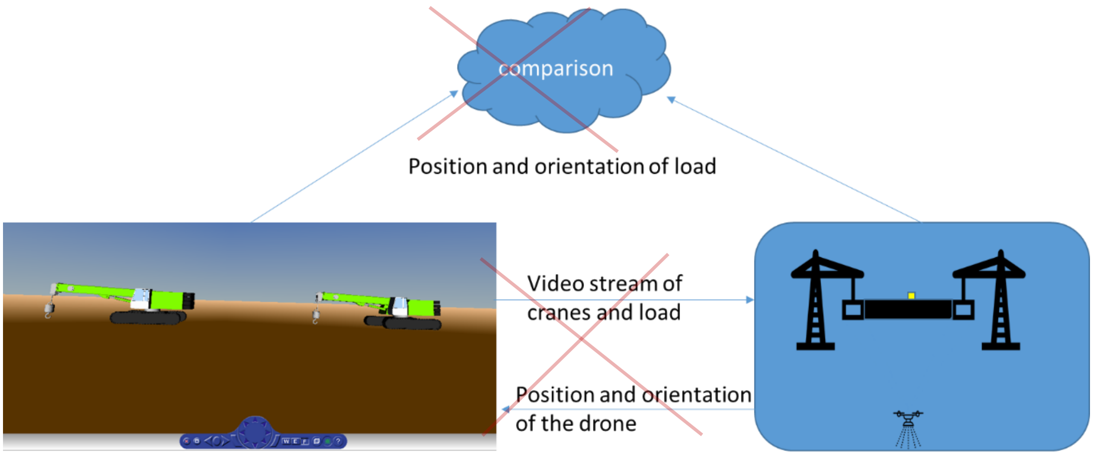

Figure 13 - Crane and Drone Simulation

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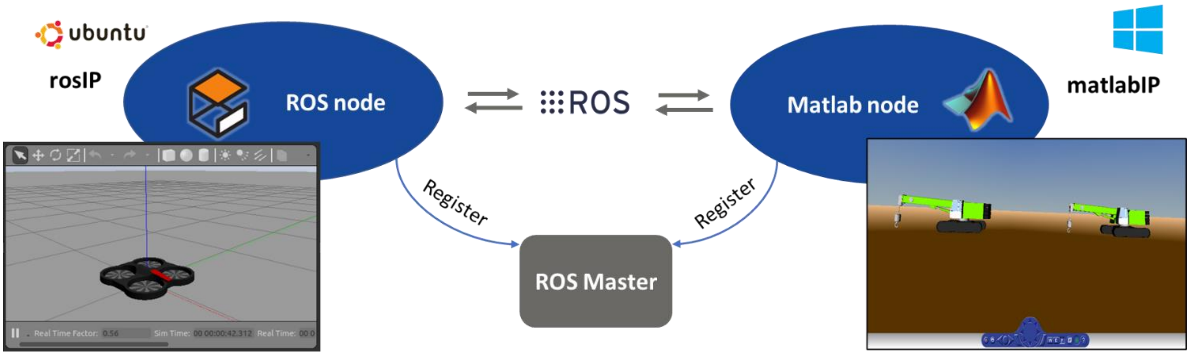

Figure 14 - ROS Infrastructure for Matlab and Gazebo Simulation

<u>Cranes digital twin</u>

The use case prototype simulates a lift of an object with two cranes within a MATLAB Simulink program. To accomplish that we implemented the communication between the physical model and the MATLAB model. The cranes in MATLAB simulation is behaving like the physical model. The prototype is a MATLAB simulation running on a PC. The simulation will be provided with commands. The same commands are given to the physical model crane. The resulting sensor values of the two parts are sent to relayr cloud and then checked by the anomaly detection.

To test the monitoring in the cloud we implemented an anomaly detection in a docker container, enabling us to execute it either at the crane or in any other edge device or server. The anomaly detection algorithm is a part of that project and will be validated in a master thesis written at WIKA.

The picture below shows the test scenario.

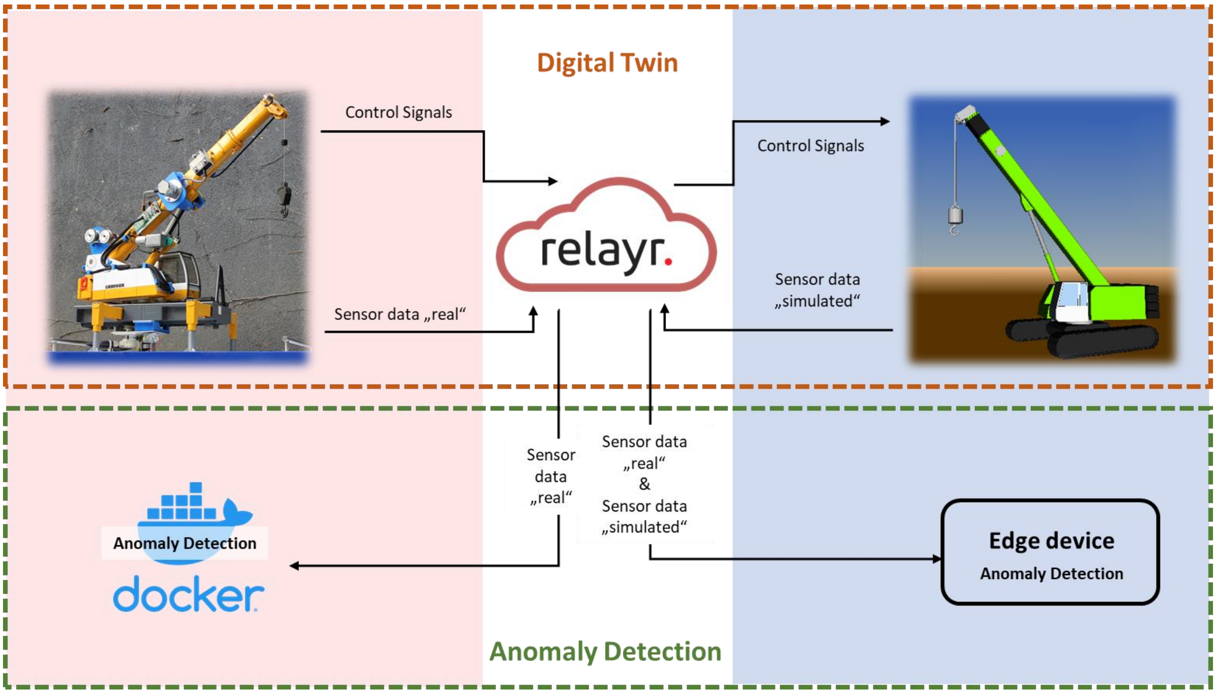

Figure 15 - Crane Testing

The table below recalls the test cases are planned to validate the prototype. A reference to the use case requirements that the use case is intended to test can be found. The test definitions and results that can be found at par. 8.5 in ANNEX.

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System part / Test Type	Coverage	Comment
MATLAB-simulation of cranes	This will be the system providing sensor values and position data, according to the control input.	This can be used to plan the lift in real world.
Anomaly detection	This process will compare the calculated sensor values from the MATLAB simulation to the values of the physical model crane	This will test the accuracy of the anomaly detection.
Measure delay between the two simulations	A method to measure the time delay has to be developed.	The delay shall be smaller than 0.5s

Table 10 – Cranes digital twin validation tests.

Drone simulation as additional sensor

To supplement collaborative lifting process, a complementary drone simulation was proposed in the earlier deliverables. The drone was to navigate to the location in front of the object detect the position of the markers on the object and send its position back to the crane. The crane would adjust the alignment of the lifted load accordingly.

The Gazebo simulator simulates the Drone and its navigation and object detection algorithms developed using Robot Operating System (ROS). The simulation consists of a drone, dummy object to be lifted, some static objects (trees and buildings) that are used as obstacles during navigation. The drone navigates to the specified location before the object, detects the markers on it and displays the estimated position with respect to itself. In the co-simulation this would have been sent to the crane to calculate the object alignment to adjust the position of the load.

The picture below shows the scenario of drone testing.

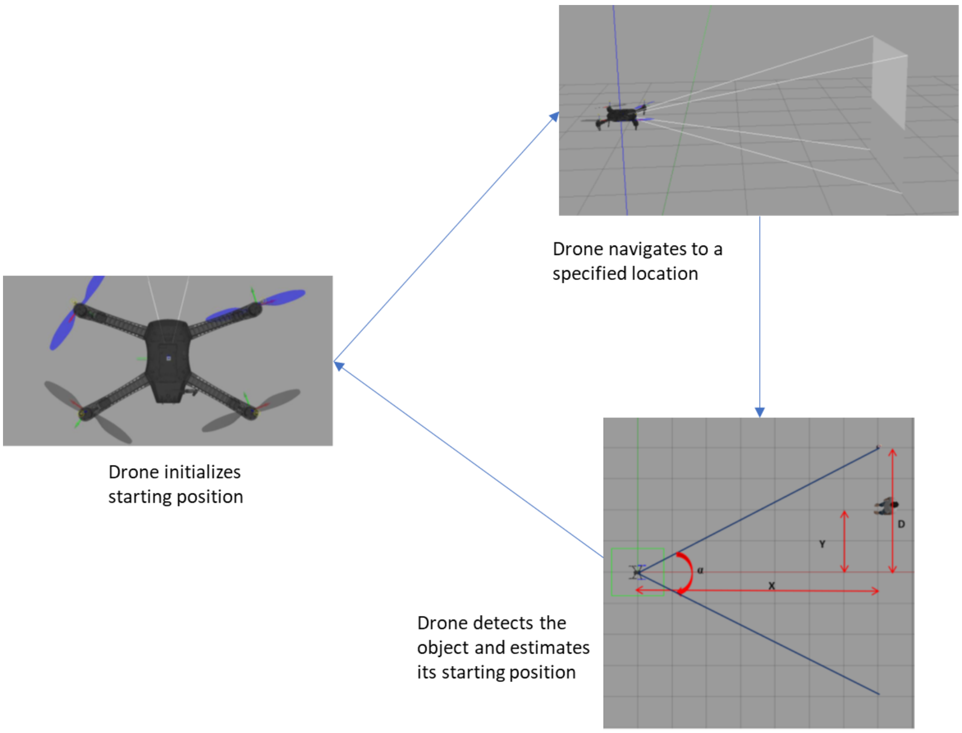

Figure 16 – Drone testing

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The table below recalls the test cases planned to validate the drone prototype. A reference to the use case requirements can be found. The test definitions and results that can be found at par. 8.5 in ANNEX.

Test name	Test level	Test ref.	Req.ID	
Drone Navigation	Component	8.5.4	UC9-FNC-10	Generate logs that will report the drone position and detects if the drone crashes with the obstacle
Object marker position estimation	Component	8.5.5	UC9-FNC-10	Measure the difference between the actual position of the markers in simulation and compare it with the generated position of markers

Table 11 – Drone simulation validation tests.

6.3. Adopted CPS4EU technology

Given the reduced implementation scope WikA was not able to use the Cooperative PiARCH as planned.

However, the MoCoAnalyzer tool by UnA was adopted and used on parts of the use case prototype.

CPS4EU technological component	Source WP	Where it is used and how much of it is used
MoCoAnalyzer (by UnA)	WP5	UnA supported WIKA with this tool during their modelling of the use case and the following analysis activities. The MoCoAnalyzer was developed during WP5 activities including a modelling editor and supports multiple analyses on architecture and at code level. Further information on the tool can be found in D5.6.

6.4. Test and validation results

Each component was tested on separate PCs. The tests performed can be summarized as follows:

MATLAB-simulation of cranes

The simulated cranes in MATLAB received the control inputs from the Relayr cloud. The resulting orientation and position data of the cranes was then send to the cloud. The time between the sending of the control data and the receiving of the expected results was measured in the Relayr cloud.

The results were at 1.1s in average. This showed that the cloud communication with Relayr is too slow for a real world application. Nevertheless, the objective of this proof of concept is considered achieved.

Anomaly detection

The setup and tests results are described at par.6.4.1.

Drone simulation

The Drone was tested for successful execution of navigation algorithm and object detection and position estimation algorithm. The drone should be able to navigate to specified position while avoiding the objects and

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should reach the specified position (x,y,z) as well as the specified orientation(roll, pitch, yaw). The drone's camera should detect the markers on the object and then calculate the position of the markers with respect to the drone and the accuracy was calculated. The test results are provided at par. 6.4.2 and 6.4.4

The table below summarizes the results of the tests executed and if they were passed.

Test name	Test level	Test ref.	Req.ID	Executed	Success	Notes
Move simulated crane	system	7.5.1	UC9-FNC-01 UC9-FNC-10	yes	yes	
Send the sensor values	system	7.5.2	UC9-FNC-01 UC9-FNC-10	yes	yes	
Measure delay	system	7.5.3	UC9-FNC-01 UC9-FNC-10	Yes	partly	In part outside of desired range
Check anomaly detection	system	7.5.4	UC9-FNC-01 UC9-FNC-10	Yes	yes	
Drone Navigation	Component	7.5.5	UC9-FNC-10	Yes	Yes	
Object marker position estimation	Component	7.5.6	UC9-FNC-10	Yes	Yes	

Table 12 – UC9 Test results.

6.4.1. Anomaly detection

The diagram below shows the setup to communicate the sensor data and control data to the relayr cloud and check anomalies.

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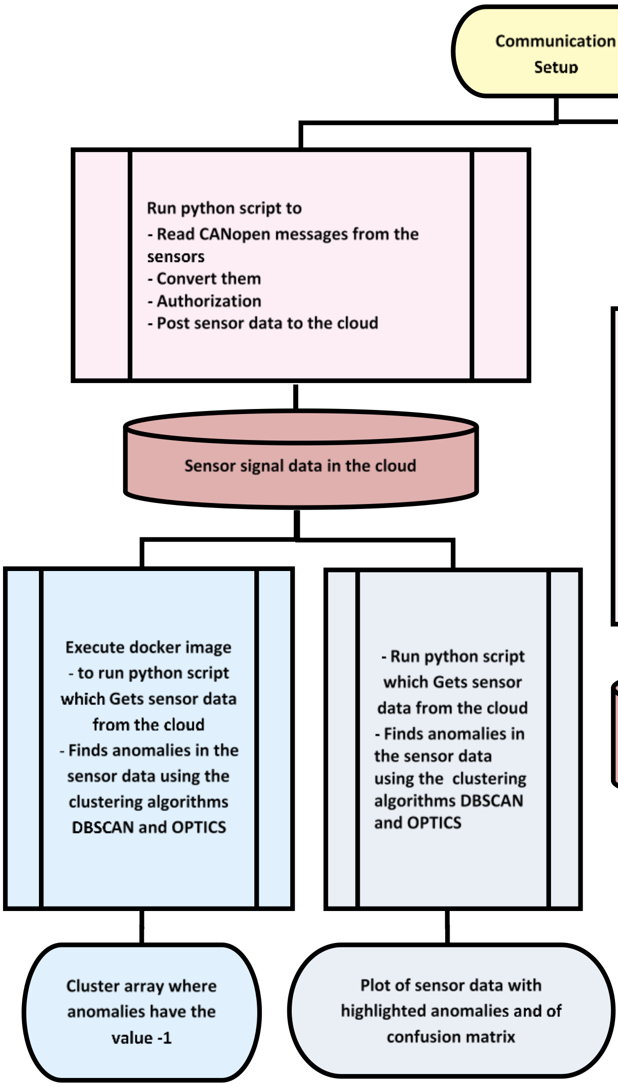

Figure 17 Communication Setup

WIKA implemented the communication setup in the diagram above (see ***Figure 17***) based on hardware and software scenario described in the picture below (see ***Figure 18***) using sensors for inclination and rotation in space.

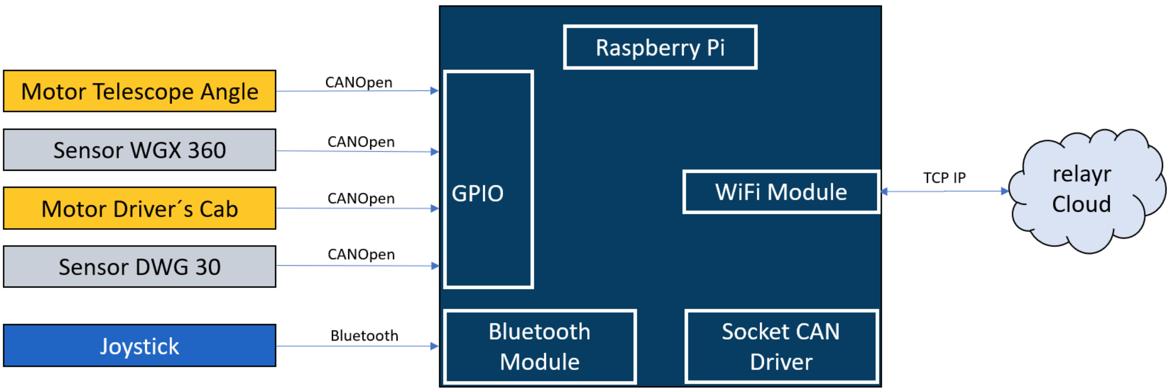

Figure 18 Block Diagram Hardware/Software Setup

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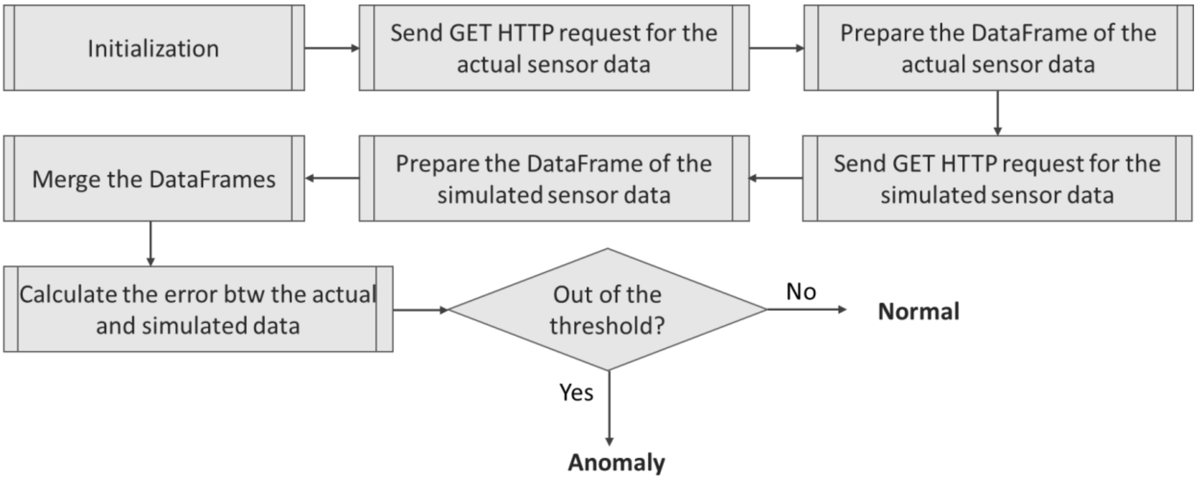

Figure 19 Anomaly detection algorithm, logical view

WIKA used a proprietary algorithm for detection of anomalies for certain combination of involved sensor elements. Originally, sensors for inclination, space orientation and relative pressure were planned to be correlated in one unit. WIKA did measurements with inclination and space orientation units within this project. This part of investigation will be continued in the future.

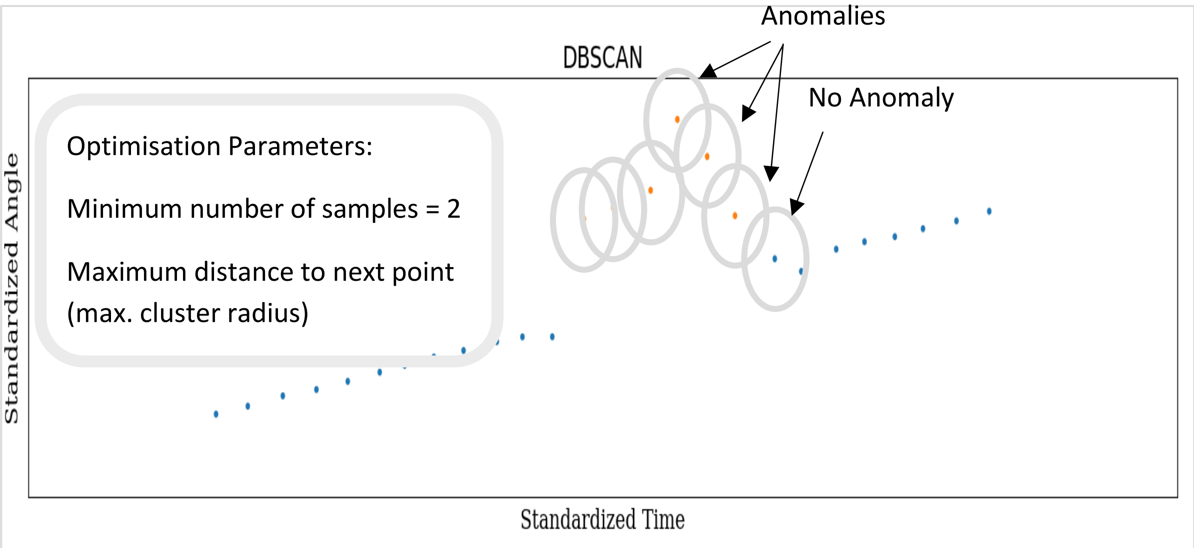

Figure 20 DBSCAN Methods for recognition of anomalies

WIKA used DBSCAN as well OPTICS algorithms for recognition and evaluation of anomalies for certain sensors.

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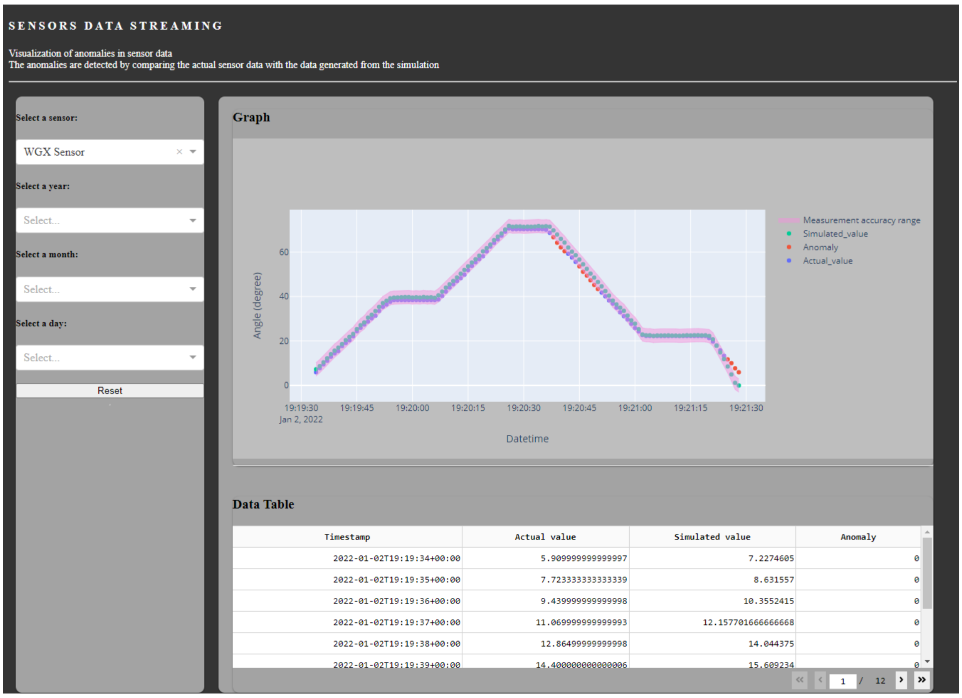

Figure 21 Measurement of accuracy range for an inclination sensor

Example: WIKA inclination sensor has been analyzed according to its anomalies in various dynamic movement situations. This sensor should be used as a part of object localization unit placed on the lifted object.

6.4.2. Drone Navigation Test Results

Before the drone can successfully detect the objects' markers and return their estimated position, the drone must be able to navigate to the specified position and position itself properly in front of the markers. The drone should be able to avoid any obstacles in between. The drone will be asked to change its position quite frequently following the lifting of the load object.

The internal sensors and the simulation drone status were tracked during all the test cases, and the drone did not crash even once for all the tests. The collected output and Sample screen for the test cases are shown below. The details of the test case are given in the annex par. 8.5.

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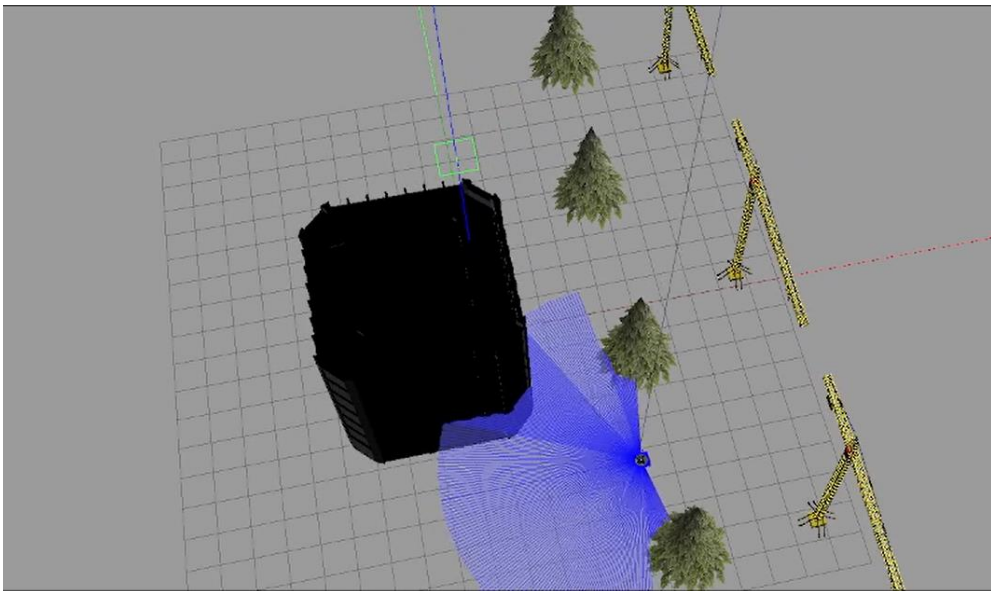

Figure 22 - Drone Navigation with Building, Trees & Crane

The scenario in the figure above shows a drone navigating while avoiding a building and trees and reaching a position in front of dummy cranes. Different combinations of objects were used to verify the navigation of the drone. The drone did not crash even once in all test cases and reached the required position with an average difference of 0.03m across all coordinates. A sample snippet of a test case across one scenario is shown below.

Target Goal			Target Achieved			Error		
x	y	z	x	y	z	x	y	z
-6	3	3	-5,9119	3,032	3,02255	-0,0881	-0,032	-0,02255
-6	-15	4	-5,904684	-14,90977	3,939	-0,09532	-0,09023	0,061
-10	15	5	-9,925	14,9918	4,8777	-0,075	0,0082	0,1223
9	-24	10	8,8815	-23,9221	9,868151	0,1185	-0,0779	0,131849
-39	-24	10	-38,87952	-23,93766	9,91907797	-0,12049	-0,06234	0,080922
18	7	10	17,97189	6,92533	10,08662	0,02811	0,07467	-0,08662
0	7	3	-0,107159	6,87111	2,93291	0,107159	0,12889	0,06709
9	0	3	8,9912	-0,121635	3,02749	0,0088	0,121635	-0,02749
0	0	8	-0,003326	0,095944	7,353045	0,003326	-0,09594	0,646955
36	18	10	35,9285	17,991845	9,907702	0,0715	0,008155	0,092298

Table 13 – Results of navigation in a test scenario.

6.4.3. Object Detection and Position Estimation Test Results

Once the drone is positioned in front of an object, e.g. a beam, the drone's camera can detect the markers placed at the end of the beam. The drone calculates the position of the markers (centre point) with respect to itself. The object was kept at a steady position and the drone was moved around. The error was calculated using the difference of the actual position vs the real position of the markers. The error ranged from 0.2m to 0.7 m with an average of 0.45m. The screenshots below showcase the testing scenario. Sample results from this scenario follow the screenshot.

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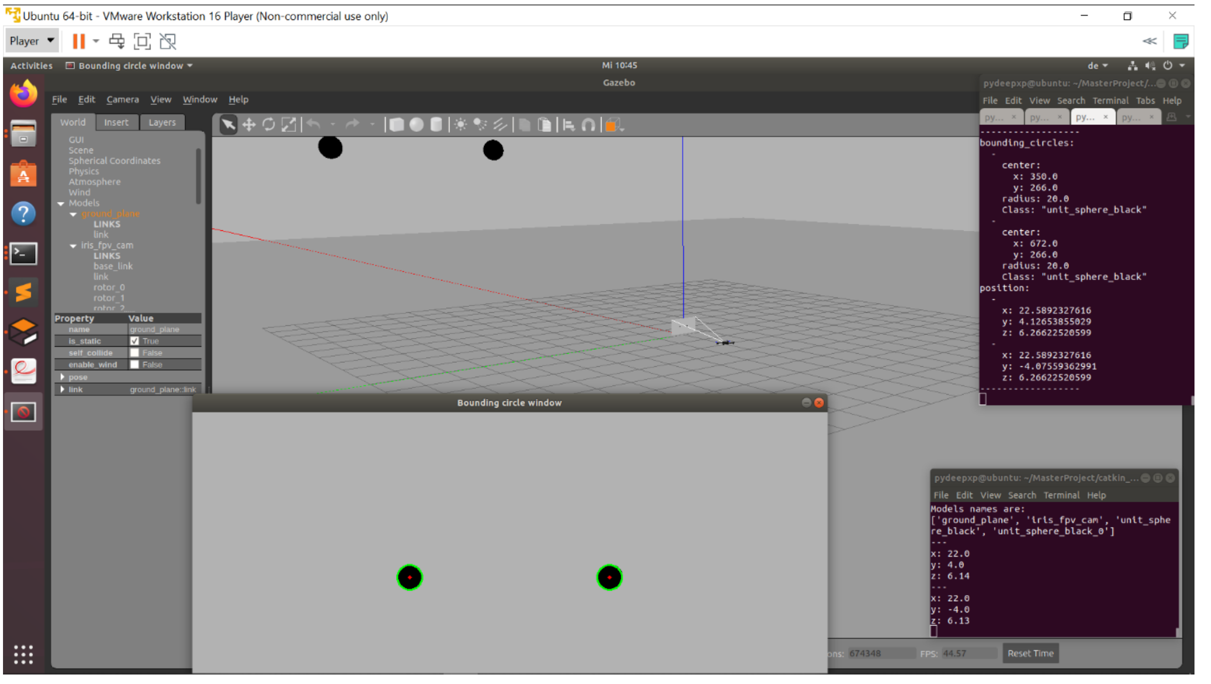

Figure 23 - Drone detecting the two markers

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Actual(exact) positions of the 2 markers in meter(m)		Estimated positions of the 2 markers in meter(m)			
P'	P'	P	P	Error= distance(P',P)	
[29.0 2.0 5.07]	[29.0 -2.0 5.06]	[28.31 -1.92 4.92]	[28.31 1.98 4.92]	0.71	0.71
[31.0 2.0 5.07]	[31.0 -2.0 5.07]	[30.24 1.98 4.91]	[30.24 -1.91 4.91]	0.78	0.78
[33.0 2.0 5.08]	[33.0 -2.0 5.07]	[32.57 -1.98 4.99]	[32.57 1.98 4.99]	0.44	0.44
[35.0 4.0 1.16]	[35.0 -0.0 1.15]	[35.38 4.07 1.12]	[35.38 0.0 1.12]	0.38	0.39
[35.0 2.0 4.75]	[35.0 -2.0 4.74]	[35.38 2.07 4.55]	[35.38 -1.99 4.55]	0.42	0.44
[14.0 2.0 5.3]	[14.0 -2.0 5.29]	[13.37 1.93 5.07]	[13.1 -1.83 4.94]	0.67	0.98
[14.0 -1.0 5.31]	[14.0 -5.0 5.3]	[13.1 -0.89 4.94]	[13.64 -4.92 5.2]	0.38	0.98
[13.0 2.0 5.31]	[13.0 -2.0 5.3]	[13.1 -2.04 5.35]	[13.1 2.04 5.35]	0.11	0.12
[11.0 2.0 5.31]	[11.0 -2.0 5.3]	[11.36 -1.97 5.46]	[11.36 2.0 5.48]	0.4	0.4
[9.0 2.0 4.66]	[9.0 -2.0 4.65]	[9.62 -2.23 4.71]	[9.62 2.04 4.79]	0.63	0.66
[14.0 2.0 2.47]	[14.0 -2.0 2.47]	[13.37 1.93 2.32]	[13.37 -1.9 2.32]	0.65	0.66
[21.0 2.0 2.44]	[21.0 -2.0 2.43]	[21.44 -2.13 2.61]	[21.44 2.18 2.61]	0.49	0.5
[22.0 2.0 2.57]	[22.0 -2.0 2.56]	[22.59 2.09 2.6]	[22.59 -2.04 2.6]	0.59	0.6
[26.0 2.0 2.45]	[26.0 -2.0 2.45]	[25.37 1.95 2.35]	[25.37 -1.95 2.35]	0.64	0.64
[33.0 2.0 2.44]	[33.0 -2.0 2.43]	[32.57 -1.98 2.35]	[32.57 1.98 2.35]	0.44	0.44
[38.0 3.0 5.36]	[38.0 -2.0 5.36]	[38.77 3.06 5.42]	[38.77 -2.01 5.42]	0.77	0.77
[38.0 4.0 5.38]	[38.0 -4.0 5.37]	[38.77 4.11 5.51]	[38.77 -4.02 5.42]	0.77	0.79
[11.0 4.0 6.17]	[11.0 -4.0 6.16]	[10.56 3.71 5.98]	[10.29 -3.6 5.82]	0.56	0.88
[43.0 4.0 5.94]	[43.0 -4.0 5.94]	[42.85 -3.96 5.9]	[42.85 4.06 5.9]	0.16	0.17
[39.0 4.0 5.95]	[39.0 -4.0 5.94]	[38.77 4.02 5.86]	[38.77 -3.93 5.86]	0.25	0.25
[39.0 7.0 5.95]	[39.0 -1.0 5.95]	[38.77 -0.96 5.86]	[38.77 6.99 5.86]	0.25	0.25
[39.0 8.0 4.96]	[39.0 0.0 4.96]	[38.77 7.96 4.9]	[38.77 0.0 4.9]	0.24	0.24
[39.0 8.0 1.96]	[39.0 0.0 1.96]	[38.77 0.0 1.92]	[38.77 7.96 1.92]	0.23	0.24
[39.0 8.0 -1.02]	[39.0 0.0 -1.03]	[38.77 7.96 -1.05]	[38.77 0.0 -1.05]	0.23	0.24
[38.0 8.0 -1.87]	[38.0 0.0 -1.88]	[38.77 0.0 -2.01]	[38.77 8.22 -2.01]	0.78	0.81
[36.0 8.0 -1.86]	[36.0 0.0 -1.86]	[35.38 0.0 -1.84]	[35.38 7.9 -1.84]	0.62	0.63
[35.0 8.0 -2.0]	[35.0 0.0 -2.0]	[35.38 0.0 -2.07]	[35.38 8.14 -2.07]	0.39	0.41
[27.0 8.0 -1.44]	[27.0 0.0 -1.45]	[26.7 0.0 -1.63]	[26.7 7.95 -1.63]	0.35	0.36
[25.0 8.0 -2.03]	[25.0 0.0 -2.04]	[25.37 0.0 -1.77]	[25.37 7.78 -1.77]	0.46	0.5
[22.0 8.0 -1.41]	[22.0 0.0 -1.42]	[22.59 0.0 -1.53]	[22.59 8.25 -1.53]	0.6	0.65
[22.0 8.0 -0.2]	[22.0 0.0 -0.21]	[22.59 0.0 -0.31]	[21.44 7.83 -0.24]	0.59	0.6
[22.0 8.0 4.01]	[22.0 0.0 4.01]	[22.59 0.0 4.08]	[23.35 8.43 4.16]	0.59	1.42
[22.0 12.0 4.14]	[22.0 4.0 4.13]	[22.59 4.13 4.23]	[23.35 12.64 4.32]	0.61	1.5
[22.0 8.0 4.06]	[22.0 0.0 4.06]	[22.59 0.0 4.08]	[22.59 8.2 4.08]	0.59	0.62
[22.0 4.0 4.07]	[22.0 -4.0 4.06]	[21.96 4.01 4.01]	[22.59 -4.13 4.13]	0.07	0.61
[22.0 0.0 4.1]	[22.0 -8.0 4.1]	[22.59 0.0 4.13]	[21.96 -7.97 4.01]	0.1	0.59
[22.0 -1.0 4.58]	[22.0 -9.0 4.56]	[22.59 -1.02 4.64]	[23.35 -9.58 4.84]	0.59	1.5
[22.0 -2.0 4.57]	[22.0 -10.0 4.55]	[22.59 -2.04 4.08]	[21.0 -9.57 3.74]	0.77	1.36
[22.0 -2.0 0.98]	[22.0 -10.0 0.97]	[22.59 -2.04 0.97]	[23.35 -10.53 1.0]	0.59	1.45
[22.0 -2.0 2.06]	[22.0 -10.0 2.06]	[22.59 -2.04 1.99]	[22.59 -10.19 1.99]	0.6	0.62
[22.0 -2.0 3.26]	[22.0 -10.0 3.25]	[22.59 -2.04 3.21]	[21.44 -9.72 3.05]	0.59	0.66
[22.0 -2.0 4.66]	[22.0 -10.0 4.66]	[21.96 -1.98 4.61]	[21.96 -10.0 4.66]	0.04	0.07
[22.0 -2.0 5.99]	[22.0 -10.0 5.99]	[22.59 -2.04 6.11]	[21.0 -9.52 5.73]	0.6	1.14
[22.0 -1.0 6.05]	[22.0 -9.0 6.04]	[21.96 -0.99 5.99]	[21.0 -8.62 5.68]	0.07	1.13
[22.0 2.0 6.05]	[22.0 -6.0 6.04]	[21.96 2.03 5.99]	[22.59 -6.11 6.16]	0.08	0.61
[22.0 4.0 6.05]	[22.0 -4.0 6.05]	[22.59 -4.08 6.16]	[21.96 4.01 5.99]	0.07	0.61
[13.0 4.0 6.16]	[13.0 -4.0 6.16]	[11.9 3.78 5.55]	[12.57 -3.8 5.95]	0.52	1.28

Table 14 – Actual vs Calculated position of the markers.

6.4.4. Test results on the code analysis (UnA)

UnA supported the evaluation of code by confirming the absence of code weaknesses in parts of the use case. The test is detailed at par. 8.5.1. in Annex.

In summary, the test was performed in several steps, each step relying on the capabilities of the MoCoAnalyzer. Firstly, two models were built based on structural information of the use case and program code provided by WIKA. Then, the model was evaluated by performing UnA's three code-based analyses as detailed in D5.6. However, only the first code-based analysis was applicable to the use case as these analyses follow an iterative process.

Table 15 below shows the results of the first code-based analysis. The results confirm the absence of the code weaknesses listed in the table.

CWE	MoCoAnalyzer	
	Warnings	Reachable
Out-of-bounds Read	0	0
Use After Free	0	0

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NULL Pointer Dereference	0	0
Out-of-bounds Write	0	0

Table 15 - Results of the code-based analyses

6.4.5. Evaluation of the use case protoype

The objective of the use case is to enable a collaborative lifting process based on CPS technologies; particularly using a cloud solution for a digital twin of the lifiting process.

To evaluate the success of the use case, following the goal question metric approach, the use case objective was decomposed in questions and metrics to measure if the prototype successfully answers those questions.

The following table summarizes the values achieved for the metrics associated to those questions.

Question	Target/Success Criteria	Metric achieved	Success
MATLAB simulation working?	Simulation received control values from cloud.	100 %	yes
	Simualtion moved the crane according to the control data	100 %	
	Simualtion send geometry and sensor values to the cloud	100 %	
Does the anomaly detect work?	Detection of prepared invalid data	100%	yes
Do the physical and the cyber system work synchronously	The delay between sending and receiving of the data to the MATLAB simulation shall be smaller that 0.5s	50% (deleay is in average 1.1s)	partly

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6.4.6. Validation of CPS4EU technology

MoCoAnalyzer

The MoCoAnalyzer was developed during WP5 and subsequently WP1 activities and can identify flaws on the architectural and code level of a system. Here, the tool was mainly used to identify flaws on the code level (see test 8.5.6). The output of the analysis with the tool confirmed the analysed code provided by WIKA is free from code weaknesses.

To validate the result, two static code analysis tools were additionally used to find weaknesses in the source code. These were likewise not able to find any of the weaknesses (see Table 16).

CWE	MoCoAnalyzer		Cppcheck	Clang Static Analyzer
	Warnings	Reachable	Warnings	Warnings
Out-of-bounds Read	0	0	0	0
Use After Free	0	0	0	0
NULL Pointer Dereference	0	0	0	0
Out-of-bounds Write	0	0	0	0

Table 16 - Results of static code analysis tools on code from WIKA

The experiment made on the code from Wika confirmed the analysis implemented in the tool is correct as it returns the same output obtained with similar tools.

6.5. Conclusions

The planned complexity of the use case could not be fully achieved, due to missing project resources, as explained before. Nevertheless, we achieved to have a working proof of concept that a physical crane can be simulated with data provided by the cloud. And anomalies in movement and sensors can be detected, even though the timing constraints are not met yet.

The plan is to use another type of cloud system and maybe extend to time sensitive networking to minimise the delays. WIKA is member of the OPC/UA over TSN working group in the OSADL. Also the cooperation with TUC to get a real drone test setup is considered. The MoCoAnalyzer tool can also be applied to application developments to ensure cyber security in our development.

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7. CONCLUSIONS

On four out of five use cases the implemented prototype was validated in an industrially relevant environment or in a real operational environment (TRL 6-7) and reached their objective: they proved the concept of the use case is valid and the technology adopted is fit for the purpose in a real scenario and/or with real data.

The Use cases implementation demonstrated the benefits that can be achieved both in terms of production results and in savings on the development efforts and maintainability of the solution. All use case leaders plan to further invest to develop these concepts to exploit these advantages.

Finally, the use case gave the opportunity to share technological, methodological and process knowledge and to establish good relationships between the CPS4EU partners involved.

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8. ANNEXES

8.1. UC4 Test case results details [LEONARDO]

Here are some details of the output of the tests performed on the Tool Wear module.

8.1.1. Results of drill tip wear estimation

Test Name	Drill tip wear estimation (good tip)
Test ID	8.1.12
Test Type	Component
Test purpose	Verify that the system returns that drill tip is still suited for drilling when the tip that is subject to the wear control cycle has an acceptable remaining useful life.
Test input	Three different tips have been tested several times: a brand new tip, a tip with 50% RUL and a tip very close to null RUL.
Test description	Test prerequisites: tool wear module, drill tips Switch on the tool wear module Mount a drill tip on the support of the tool wear module Adjust the drill tip on the support to ensure centering and alignment with the camera of the wear module. Start the wear control cycle and wait for the completion of the cycle Check the outcome of the control on the display of the tool wear module. Repeat the test for each drill in the input set.
Expected output	For brand new tip and for each drill tip in the input set the outcome of the wear control is that the drill tip can still be used.
Test output	The tool wear subsystem always returned positive feedback for brand new and 50% RUL tips showing also a correct and different level of usage. For the tip close to be scrapped but still usable, the system first returned negative feedback suggesting to discontinue the tip. Repeating the experiment and setting operations (tip alignment and background setting) the result was positive showing a high level of wear.

Test Name	Drill tip wear estimation (worn out tips)
Test ID	8.1.13
Test Type	Component
Test purpose	Verify that the system returns that drill tip is still no more suited for drilling when the tip that is subject to the wear control cycle does not have an acceptable remaining useful life.
Test input	Three different tips have been tested several times, showing different wear levels but all deemed to have an unacceptable remaining useful life.

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Test description	<u>Test prerequisites</u>: tool wear module, drill tips Switch on the tool wear module Mount a drill tip on the support of the tool wear module Adjust the drill tip un the support to ensure centering and alignment with the camera of the wear module. Start the wear control cycle and wait for the completion of the cycle Check the outcome of the control on the display of the tool wear module. Repeat the test for each drill in the input set.
Expected output	For the worn out tip and for each drill tip in the input set the outcome of the wear control is that the drill tip is not good for drilling.
Test output	The tool wear subsystem showed an unacceptable wear for all drills and tests for further drilling operations. The analysis showed that wear often causes the loss of helical geometry by highlighting chipping on at least one of the two cutting edges.

8.2. UC5 Test case results details [LEONARDO]

8.2.1. Results of the preliminary analysis on the collected data

Due to the limited fuselage production on Leonardo Aerostructure plant in Grottaglie last year, the amount of data collected during the trimming process of fuselage windows was not sufficient for applying a supervised machine learning approach, in order to train and validate a model able to anticipate possible defects and identify the correlations among different process variables. Despite this situation, Leonardo investigated the available data to identify anomalies that could lead to a defect. Unsupervised analysis using anomaly detection COPOD algorithm has been performed with encouraging results, as described below.

Before the data analysis, a visual check of the trimmed surface of the windows has shown not really a delamination but a roughness increase of the surface in two different zones for two different windows. This phenomenon anticipates a real delamination effect.

First of all, the data analysis was addressed to identify the base line where the quality of the trimmed surfaces is acceptable.

Most of the sessions in the dataset where the process quality is acceptable show a standard behaviour, with parameter values into confidence ranges; however, for two sessions (where an increase of the roughness of the surface was reported), anomaly detection found some strong deviation at certain time windows.

The algorithm generates a score index. For the standard cases, the score index lies below a threshold, while for irregular cases with anomalies, the analysis highlighted the growth of the score index and the presence of bumps above the threshold at the two time windows where deviations were found.

The result of this preliminary analysis is that the variables most affecting the quality of the trimming process are presumably a combination of vibration data (from spindle, windows and trimming machine head), feed speed and spindle speed. This relationship is confirmed by domain experts.

This analysis is preparatory for the identification of the variables that most affect the quality of the trimming output and for the evaluation of the weights of each variable and to drive the feature engineering on those variables. This can result very useful in order to design a predictive model with a supervised approach.

The right combination and weights of each variable is still under investigation.

The paragraphs below provide more details on the analysis performed.

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8.2.1.1. Dataset preparation

The available data collected from the field, consists of 20 datasets from different working sessions; two of them concern sessions that led to an increase of the roughness of the surface (as found after a visual check; this phenomenon can anticipate a real delamination effect) and we will refer to them as “slow” and “fast” anomaly cases – because in the first the speed slowed down in a time frame while in the second a speed increase was recorded in another time frame (variations not found in standard production activities where no issues have been reported).

Variables involved in the analysis are:

- Window vibration data, for each axis x,y,z; [counts]
- Vibration of the head of the trimming machine, for each axis x,y,z; [counts]
- JOBS Process Data: ROW VIBRATION ARRAY v (spindle vibrational data); [counts]
- Spin speed of the trimming tool [rpm];
- Feed speed of the trimming tool [cm/s];
- Remaining Useful Life of the tool (start value for new tools: 1800 s) [s];
- Part Program Sequence (a sort of discrete curvilinear abscissa which identifies some sectors – numbered from 1 to 250 – along the edge of the window);
- Air flux from vacuum tool [kg/h];
- Air flux temperature [°C];
- Environmental data such as air temperature [°C], air pressure [mbar], air humidity [%].

Vibrational data are in units of 16-bit signed counts. In order to convert those data in units of g = 9,81 m/s^2, you have to multiply the measured quantities by a factor of $\frac{1}{2^6}\frac{15.6\ mg/LBS}{1000}$.

Resampling was operated during dataset preparation in order to get the same sampling rate (108 Hz) for each variable.

8.2.1.2. Plots of datasets

The following plots show the trend of the physical quantities measured during the sessions. A “standard” session has been selected as reference case and two anomaly cases, respectively the “slow” and the “fast” irregular one, has been distinguished among the analyzed sessions. For the “slow” case, anomalies approximatively occur between samples 5250 and 5610 (i.e. on the lapse between 48.6 s and 51.9 s); for the “fast” case, anomalies are roughly in the range of samples 2890 – 3250 (i.e. on the lapse between 26.7 s and 30.1 s).

On x axis is always the progressive number of samples (with a rate of 108 samples per second – i.e.: a sample has been recorded every 1/sampling_rate seconds).

Trivial plots for physical quantities such as Remaining Useful Life (which has a linear decreasing trend in time) and environmental data (air temperature, pressure, humidity show an almost constant trend during the sessions) are not included in this paragraph.

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Windows vibrations

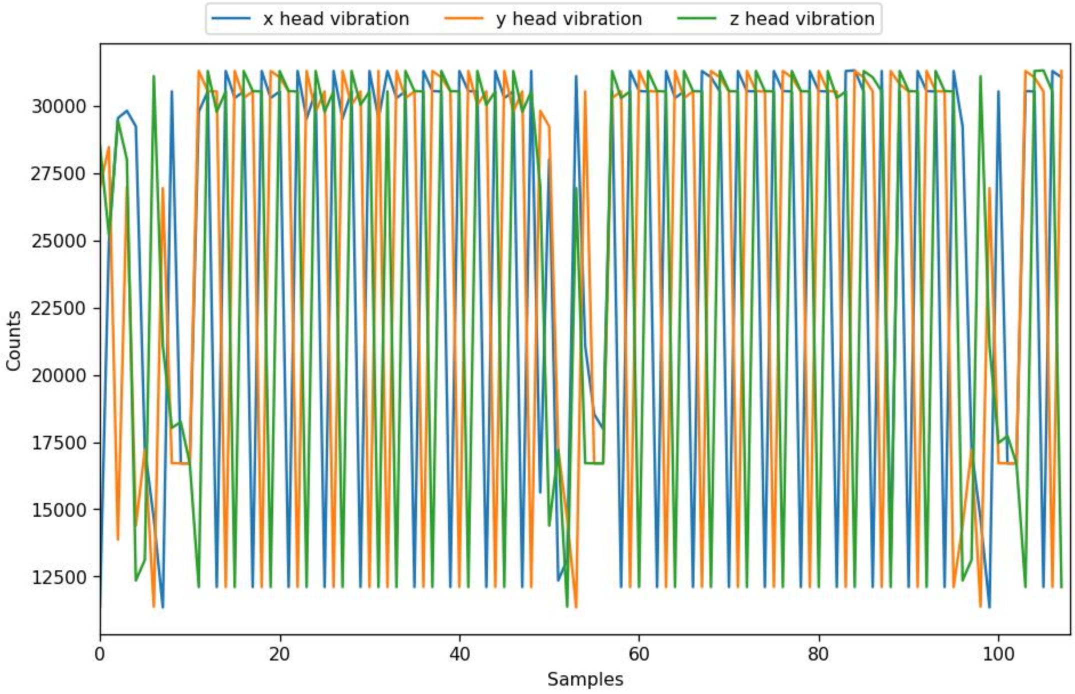

Figure 24 Window vibrations, first second in a standard session.

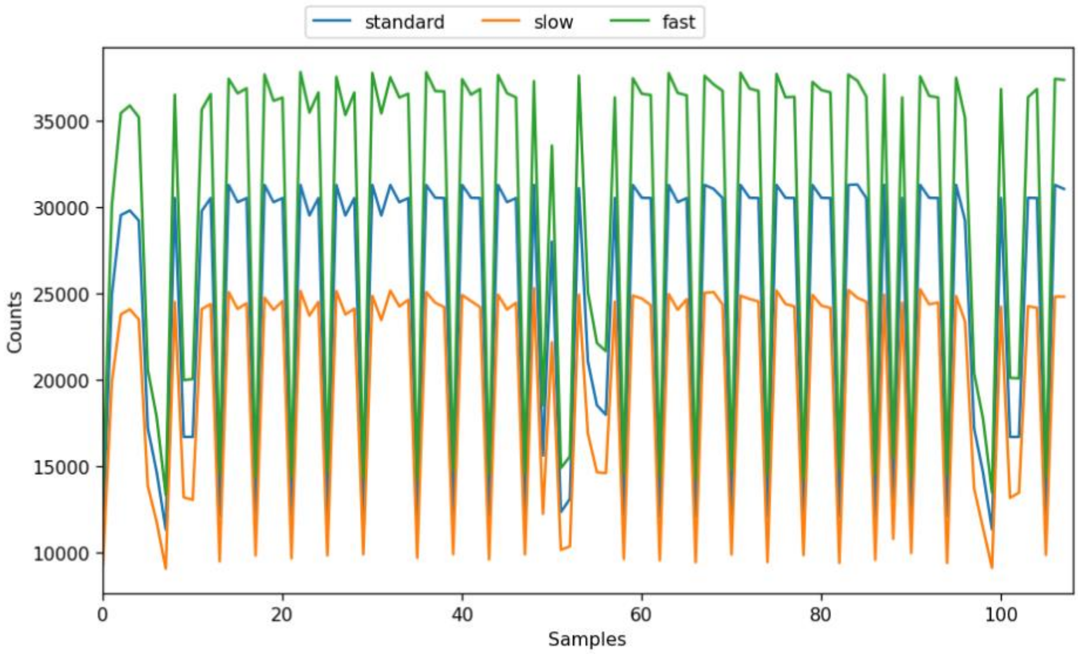

Figure 25 Window vibration on x axis - first second for standard, slow and fast sessions.

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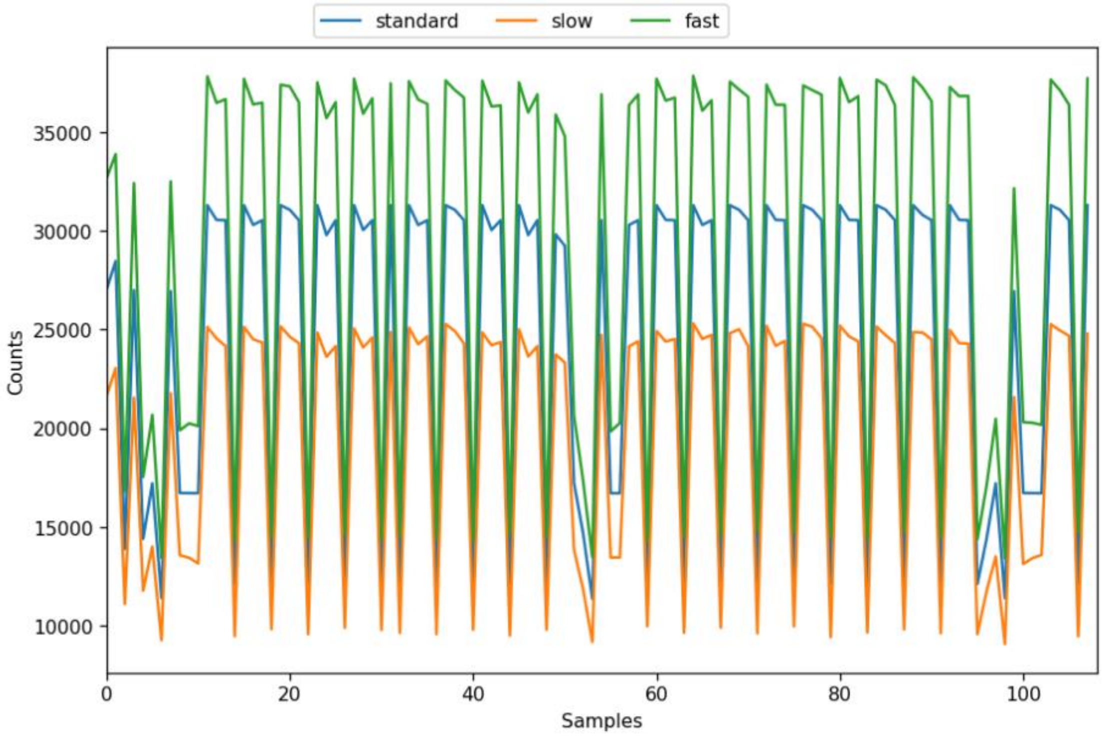

Figure 26 Window vibrations on y axis - first second for standard, slow and fast sessions.

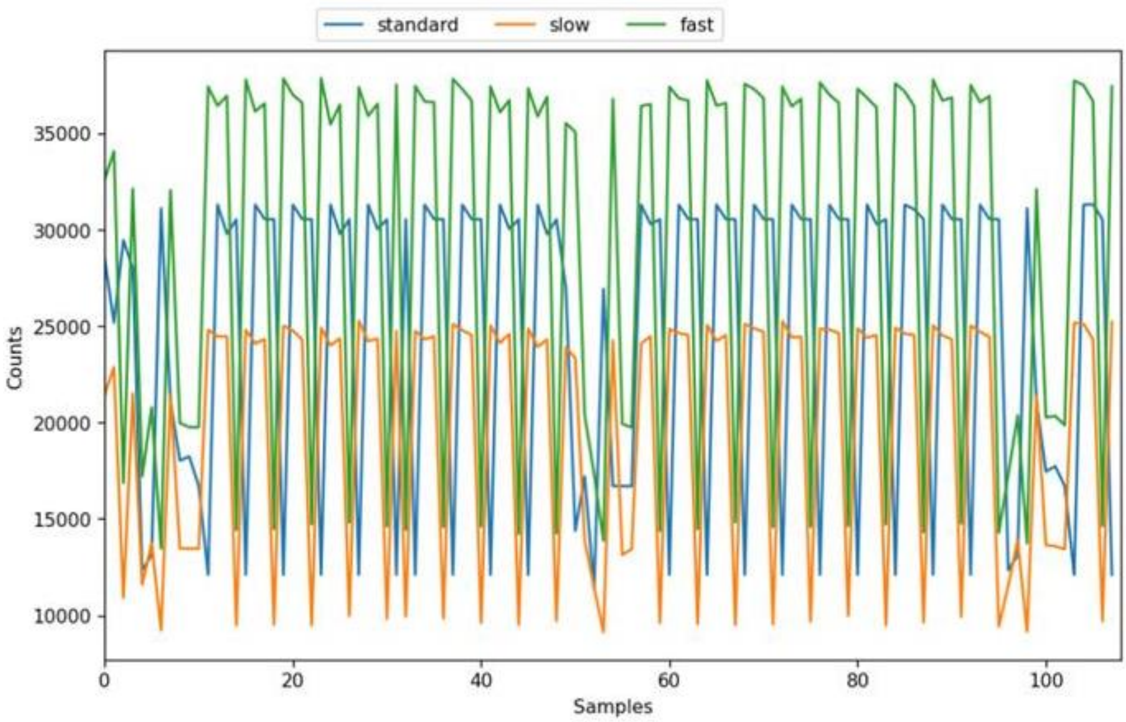

Figure 27 Window vibrations on z axis - first second for standard, slow and fast sessions.

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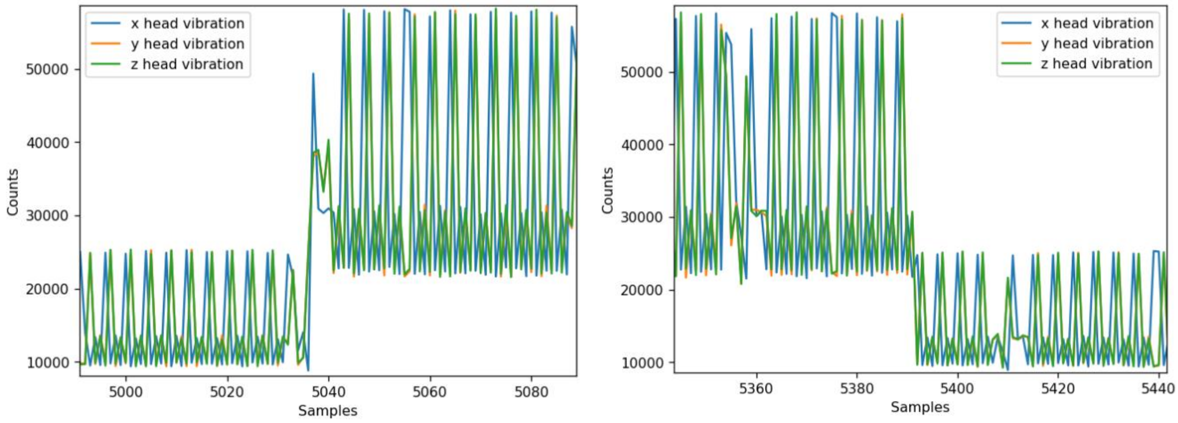

Figure 28 Anomalous window vibrations in the "Slow" session. The plot on the left shows the start of the anomaly, while the plot on the right shows when the anomaly condition ends.

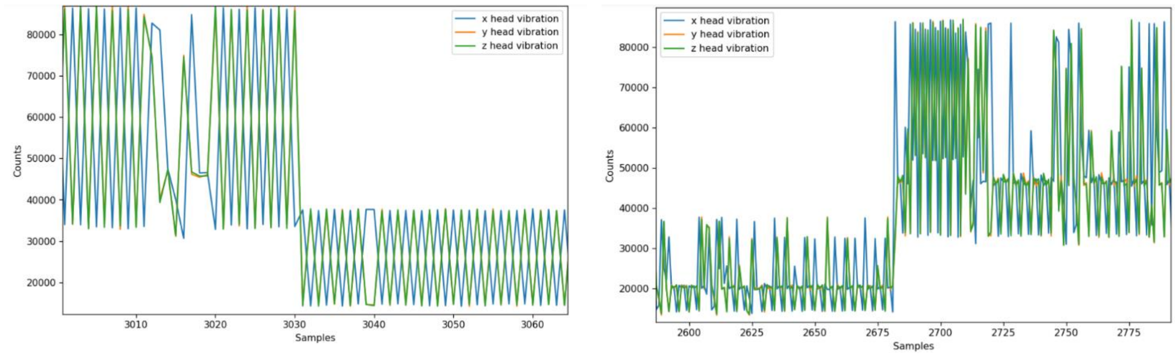

Figure 29 Anomalous window vibrations in the "fast" session. The plot on the left shows the start of the anomaly, while the plot on the right shows when the anomaly condition ends.

Head vibrations

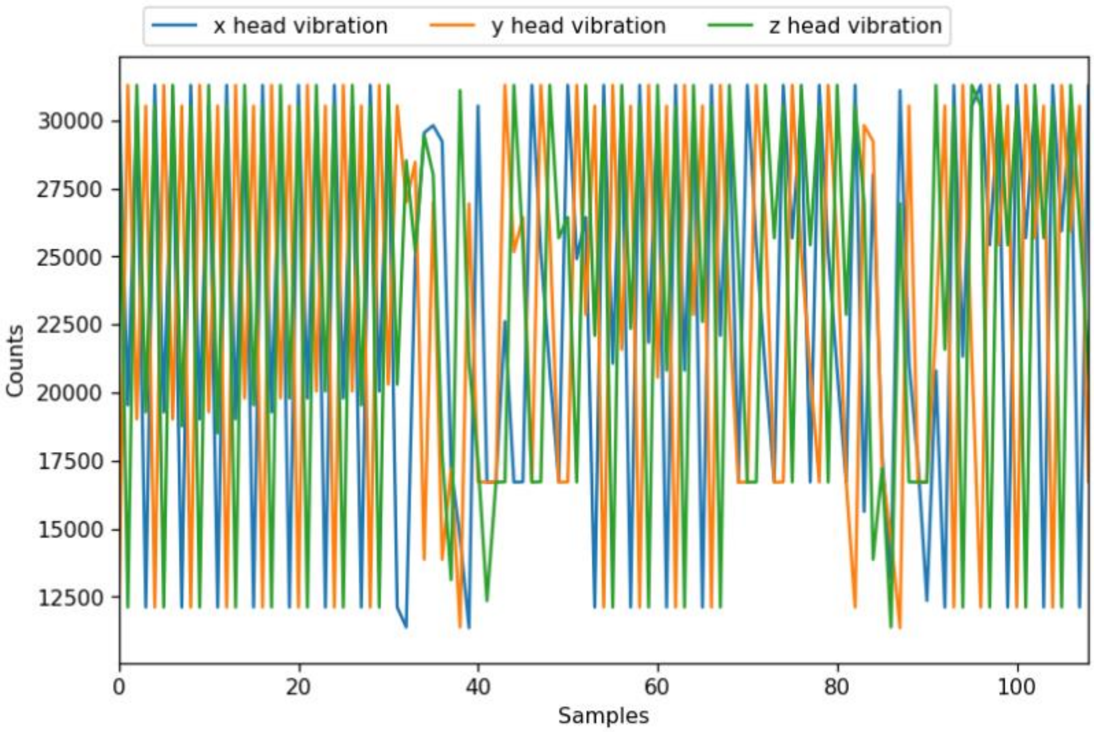

Figure 30 Head vibrations - first second of a standard session.

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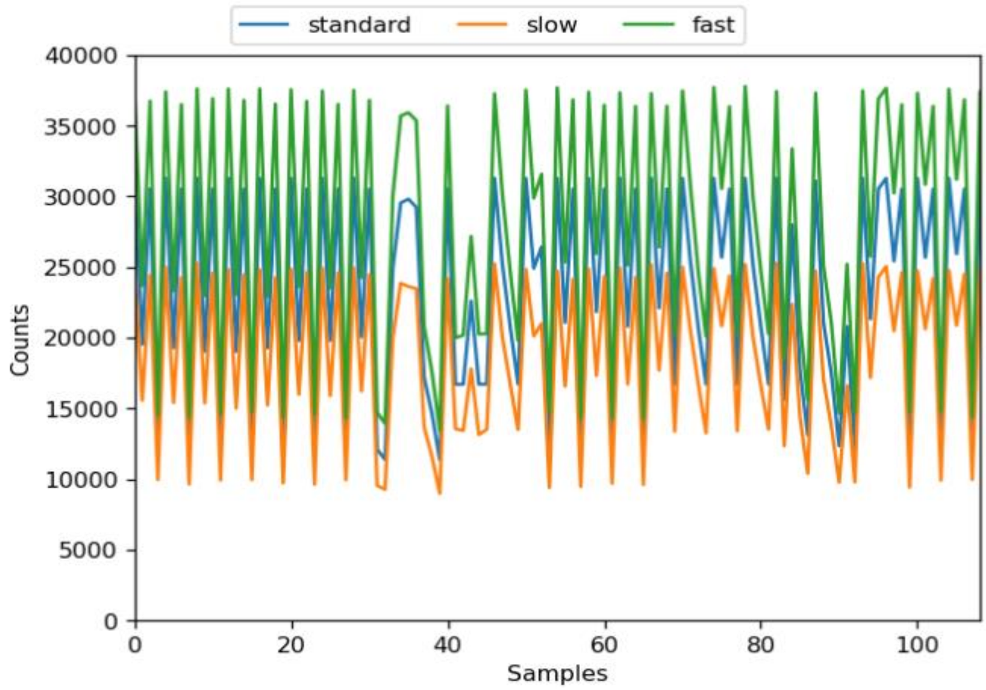

Figure 31 Head vibrations on x axis - second for standard, slow and fast sessions.

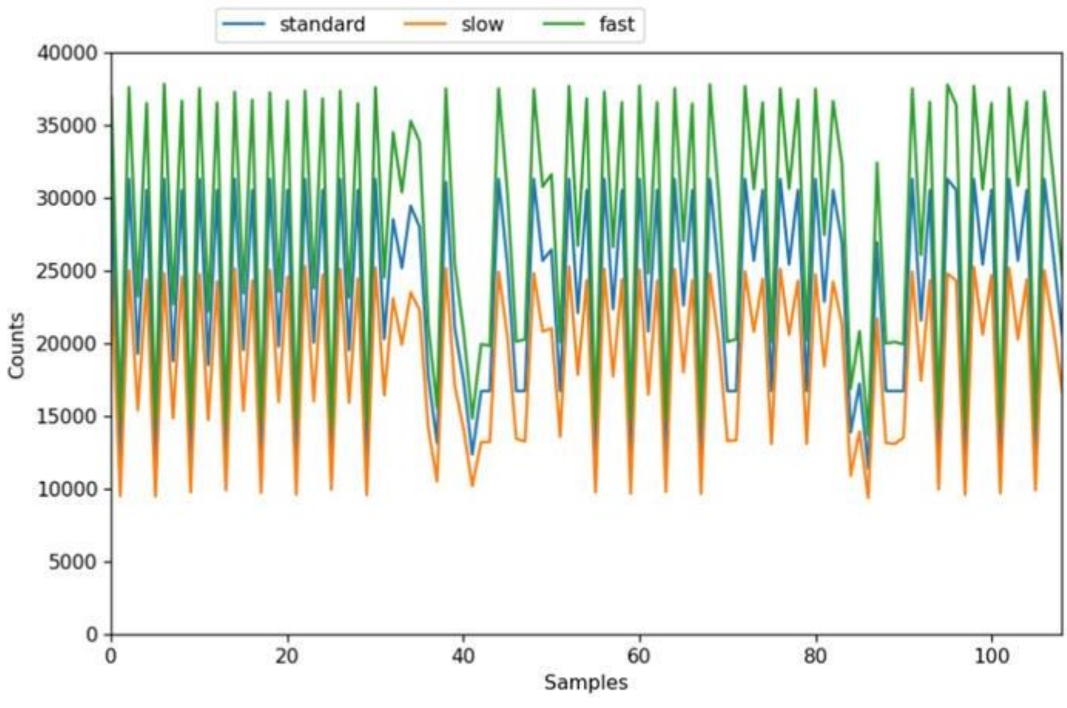

Figure 32 Head Vibrations on y axis - first second for standard, slow and fast sessions.

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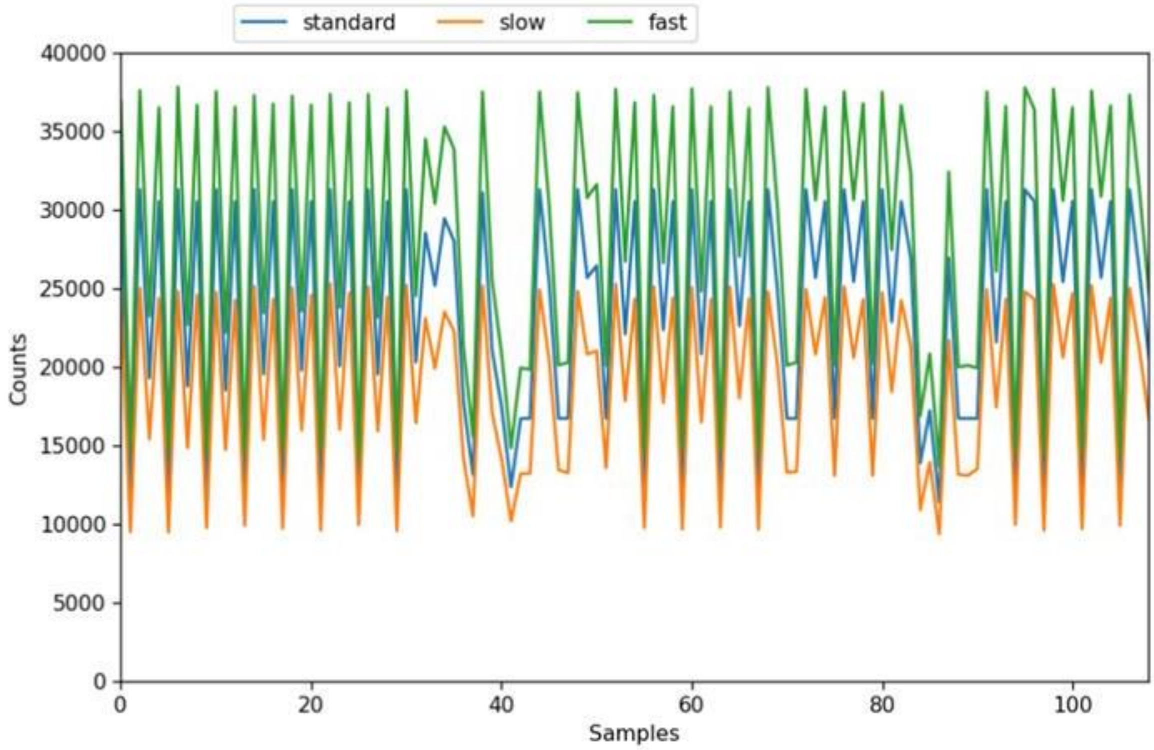

Figure 33 Head vibrations on z axis - first second for standard, slow and fast sessions.

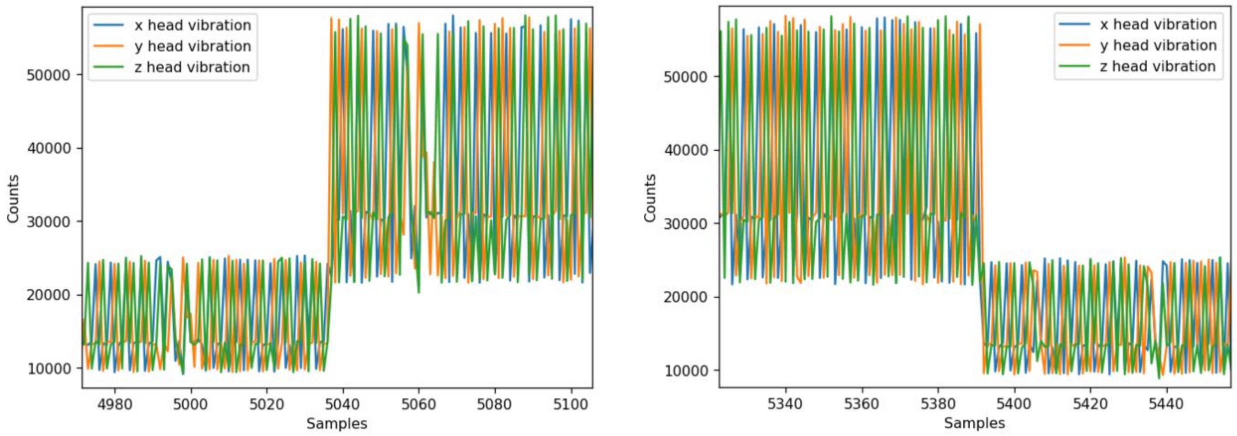

Figure 34 Anomalous head vibration in the "slow" session. The plot on the left shows the start of the anomaly, while the plot on the right shows when the anomaly condition ends.

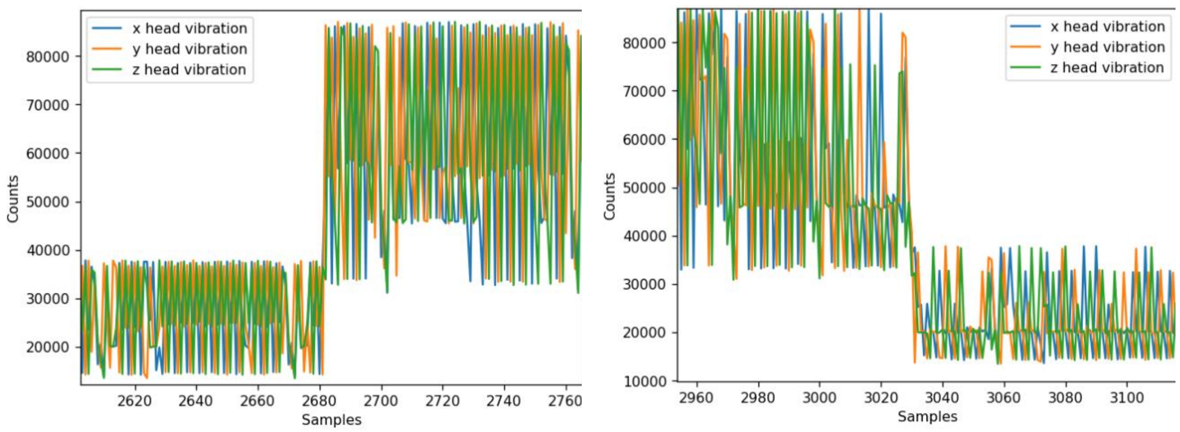

Figure 35 Anomalous head vibration in the "fast" session. The plot on the left shows the start of the anomaly, while the plot on the right shows when the anomaly condition ends.

Spindle speed of the trimming tool

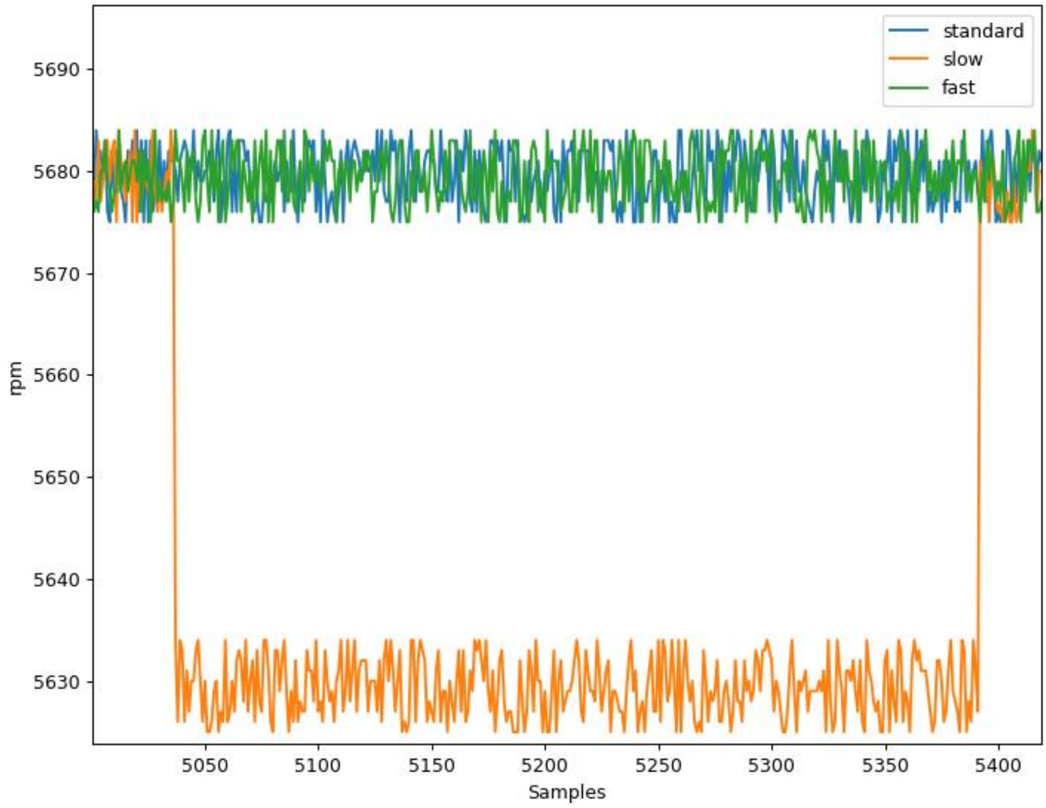

Figure 36 Slow session: anomaly in the spindle speed of the trimming tool.

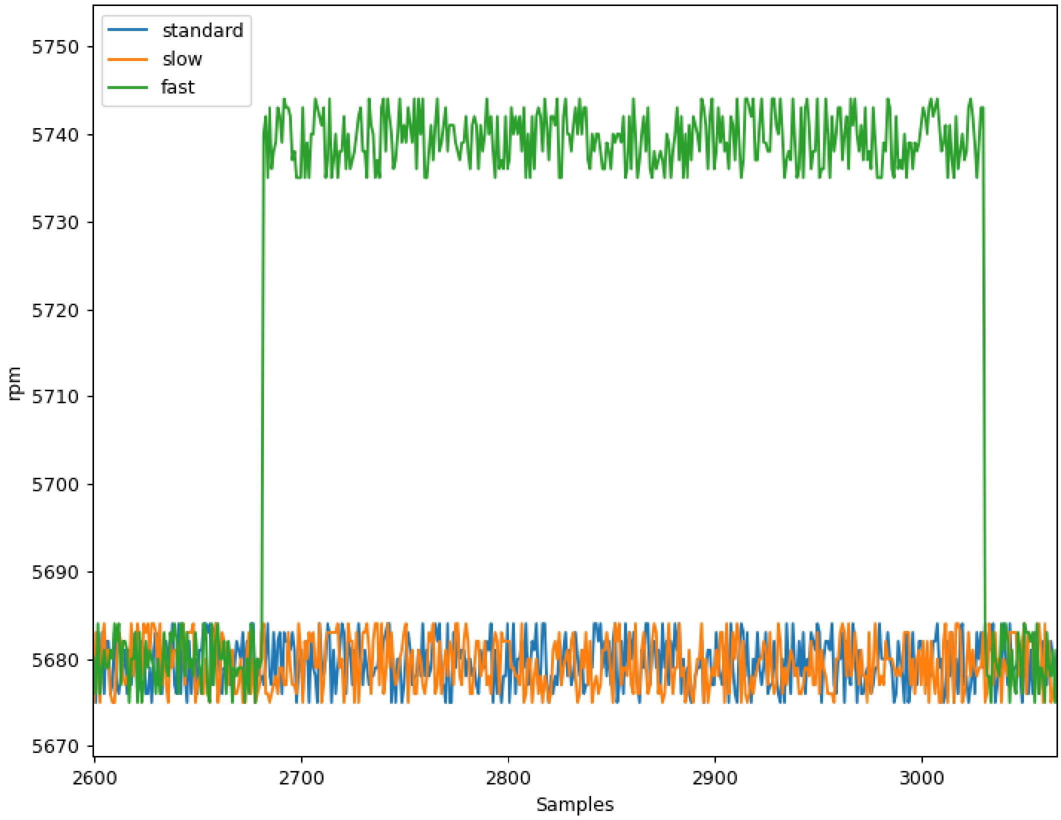

Figure 37 fast session: anomaly in the spindle speed of the trimming tool.

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Feed speed of the trimming tool

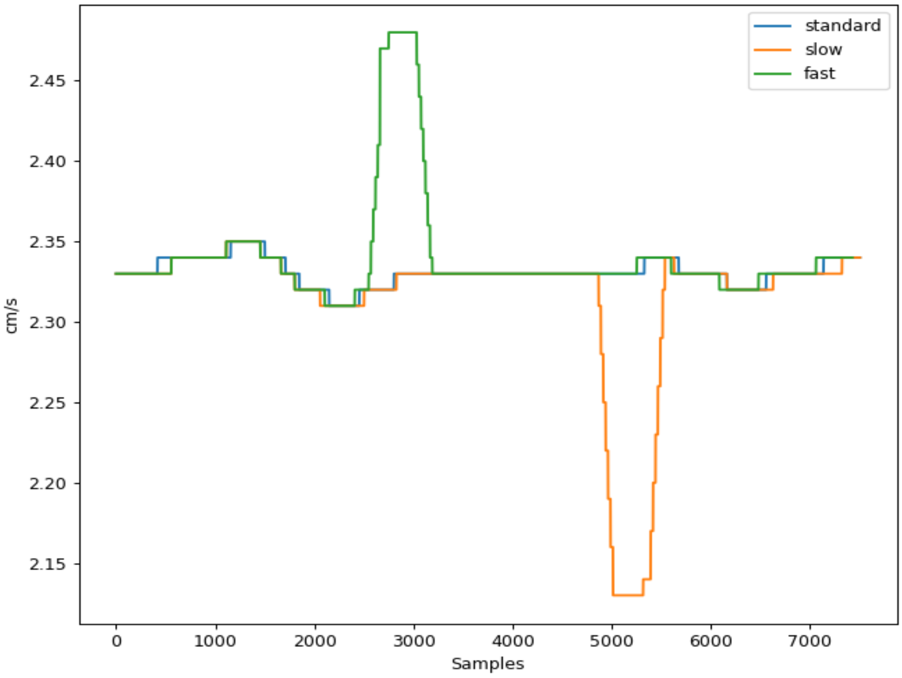

Figure 38 Feed speed of the trimming tool

Spindle vibrations

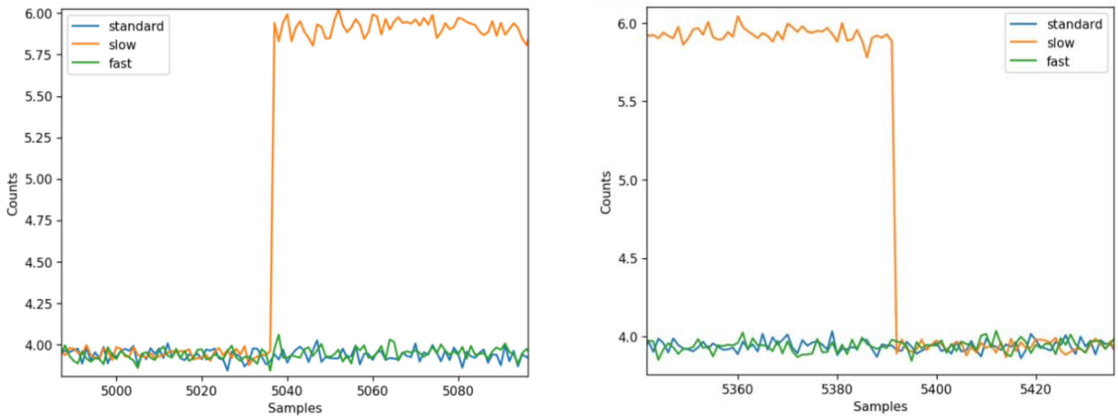

Figure 39 "Slow" session – anomalous spindle vibrations. The plot on the left shows the start of the anomaly, while the plot on the right shows when the anomaly condition ends.

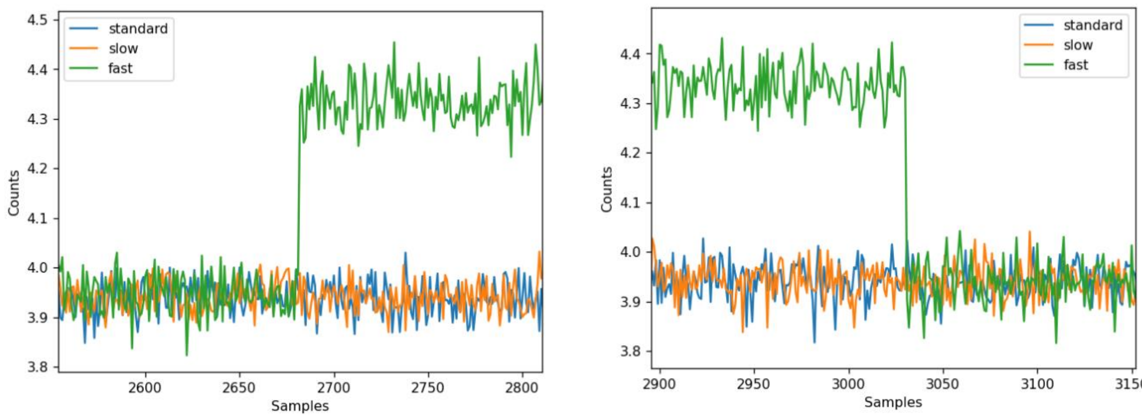

Figure 40 "Fast" session – anomalous spindle vibrations. The plot on the left shows the start of the anomaly, while the plot on the right shows when the anomaly condition ends.

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Air flux

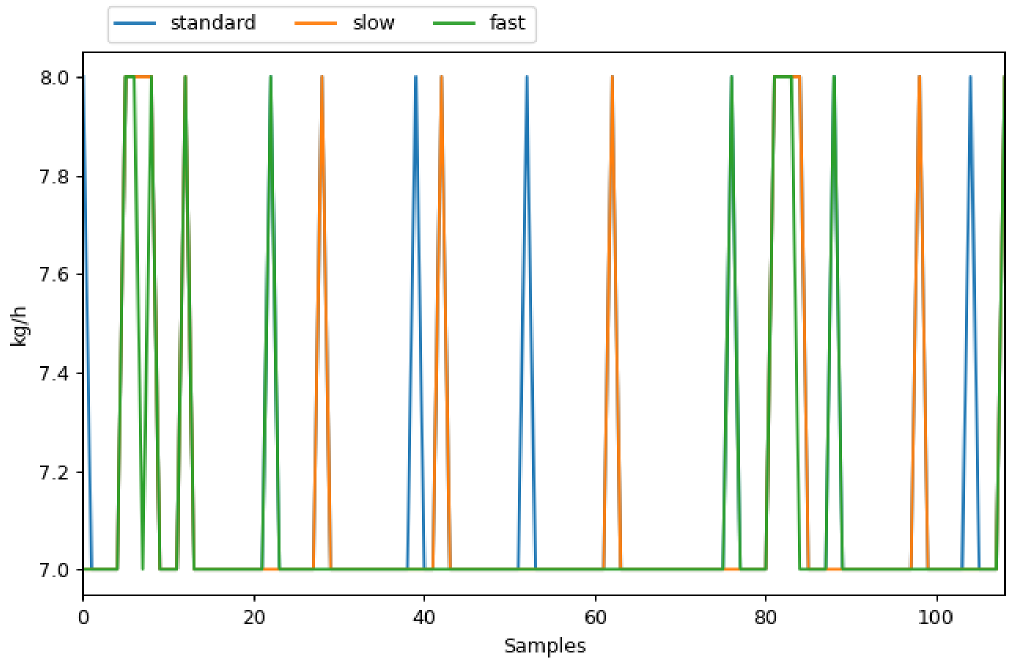

Figure 41 Air flux – samples of the first second of the session.

Air flux temperature

The diagrams below show the anomalies found in the air flux temperature samples of the fast and slow trimming sessions.

The anomalies found in the air flux temperature are shifted forward with respect to the anomalies found on other variables due to the delay when the heat transfers through the air.

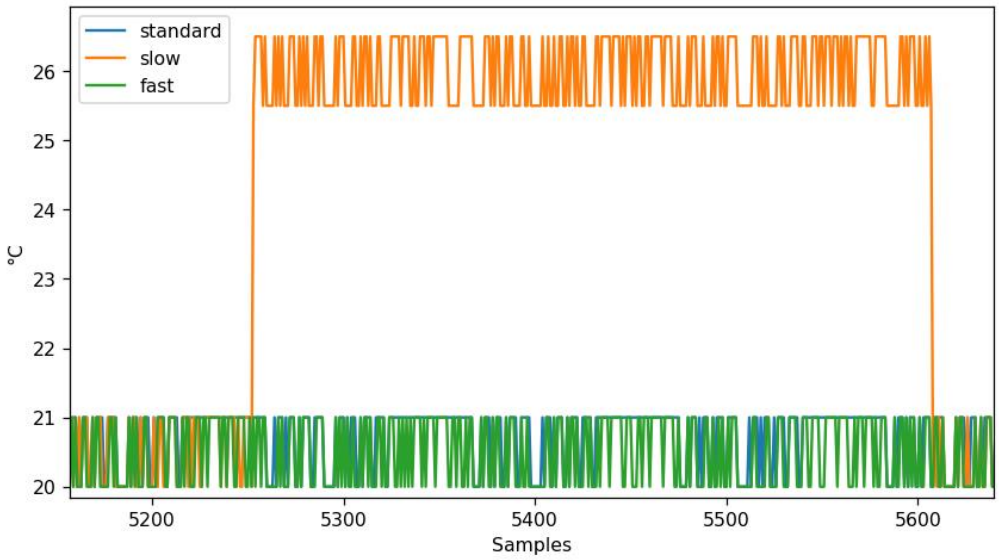

Figure 42 Slow session - anomalies on air flux temperatures [°C]

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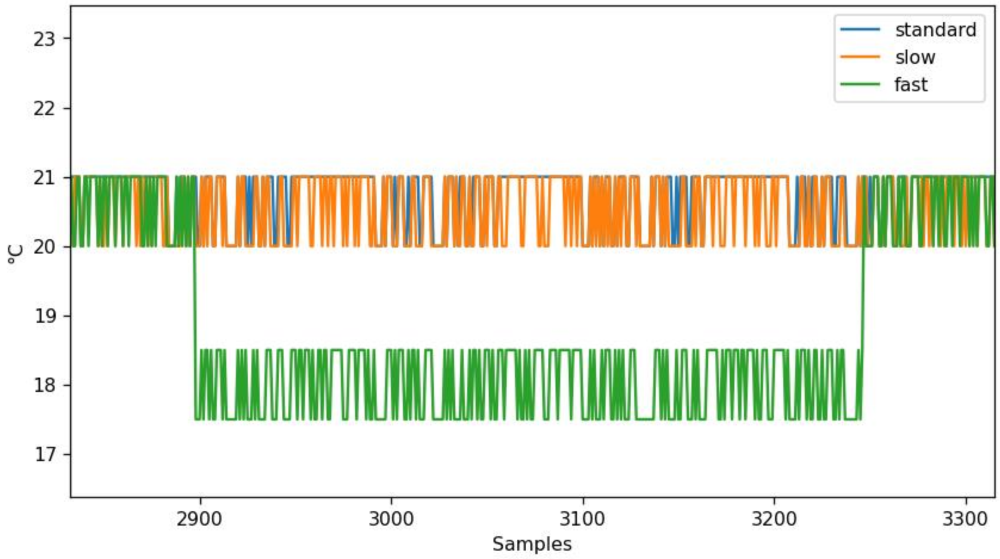

Figure 43 Fast session - anomalies on air flux temperatures [°C]

8.2.1.1. Anomaly detection with COPOD

The main concept in our analysis can be expressed as follows: suppose you have to check the behaviour of the parameters involved in a working process (e.g. the variables in the previous paragraph). Standard cases (with no issues in the process) usually show values of parameters in certain ranges. Looking at "slow" and "fast" cases – those that can potentially lead to delamination – and performing specific analysis of outlier detection on them, we found that, in specific time windows, some parameters considerably deviate from the standard case (i.e., some anomalies – or outliers – have been found).

Outlier detection refers to the identification of rare items that are deviant from the general data distribution. Many existing approaches suffer from high computational complexity, low predictive capability, and limited interpretability. For our analysis we choose to use a novel outlier detection algorithm called COPOD (COPula-based Outlier Detection), which is inspired by copulas for modelling multivariate data distribution.

Copulas are functions that enable to separate marginal distributions from the dependency structure of a given multivariate distribution. In other words, a copula allows us to describe the joint distribution of the random variables involved using only their marginals. This gives high flexibility when modelling high dimensional datasets, as we can model each dimension separately, and there is a guaranteed way to link the marginal distributions together to form the joint distribution.

A dataset from a standard case has been used as reference

COPOD first constructs a empirical copula, and then uses it to predict tail probabilities of each given data point to determine its level of "extremeness". Intuitively, we think of this as calculating an anomalous p-value. This makes COPOD both parameter-free, highly interpretable, and computationally efficient.

Formally speaking, COPOD takes a d-dimensional input dataset (in our case, each dimension is referred to a physical quantity measured during the process)

$$X = (X_{1,i}\ , X_{2,i}\ , \dots\ , X_{d,i})$$

(with i=1,…,n index for samples, where a sample is recorded every 1/sampling_rate seconds) and produces an outlier score vector

$$O(X) = [X_1, \dots, X_n].$$

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Outlier scores are between $(0, \infty)$, and are to be used comparatively. In other words, the score does not indicate the probability of X_i being an outlier, but rather the relative measure of how likely X_i is when compared to other points in the dataset. . The bigger $O(X_i)$ is, the more likely X_i is an outlier.

For further information, the reference article (Li et al., 2020) is available here: https://arxiv.org/abs/2009.09463.

Results obtained with COPOD

For anomalous sessions (fast and slow), the COPOD model found out a number of outliers, as shown in the following figures. Outlier distribution has two bumps in ranges of score 10-30 ca. and 40-50 ca.; the first one can be interpreted as statistical fluctuation of values in a standard context or as occurrences of slight deviance, while the second one shows outliers with strong deviance from standard behaviour.

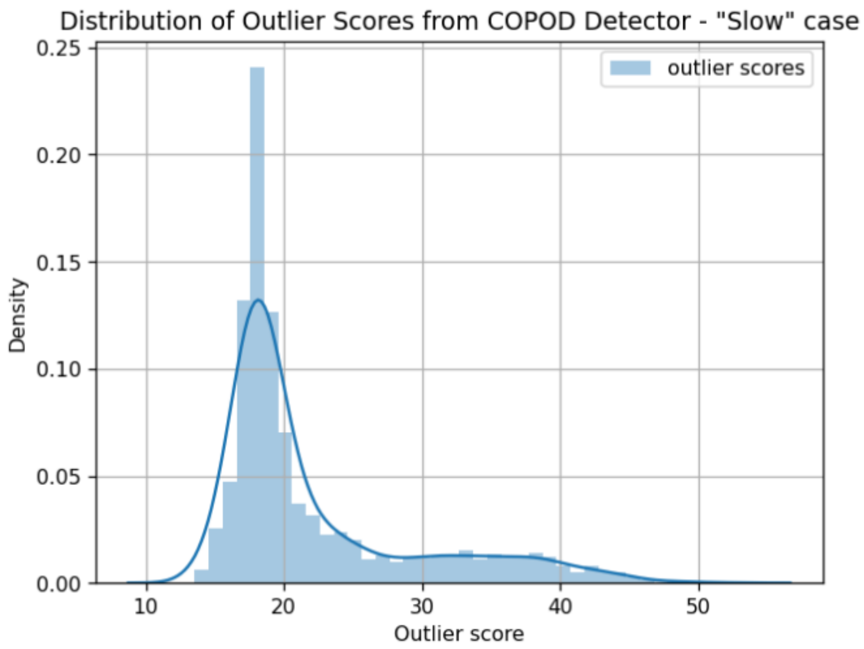

Figure 44 Distribution of outlier scores from COPOD analysis for "slow" session

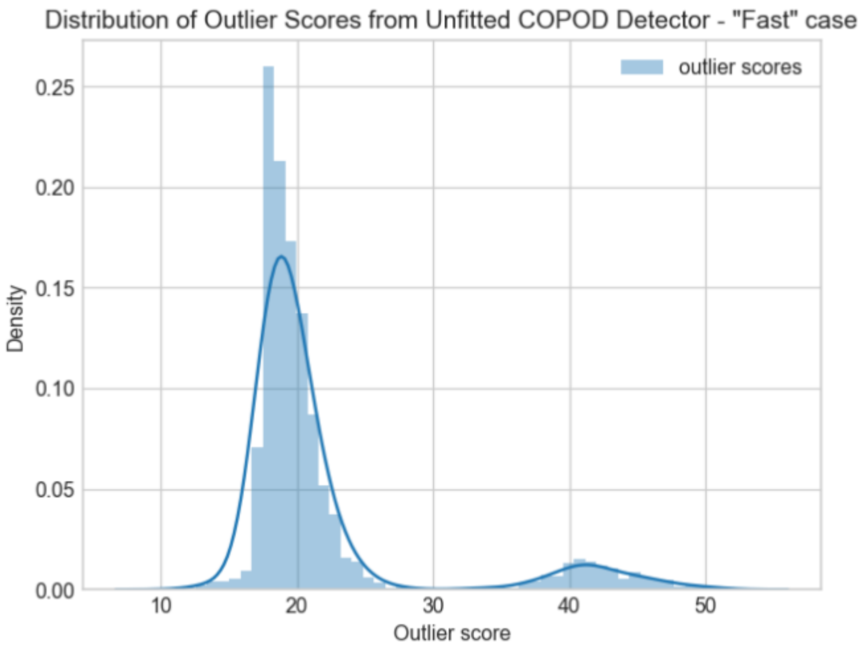

Figure 45 Distribution of outlier scores from COPOD analysis for "fast" session

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The following diagrams show the score calculated by COPOD over the time (the x-axis shows the progressive samples) for the slow session and for the fast session. Each point on the x axis is a "sample" including the values of all the variables involved at that time. On the y axis is the score that quantifies how much the sample deviates from the reference standard behaviour.

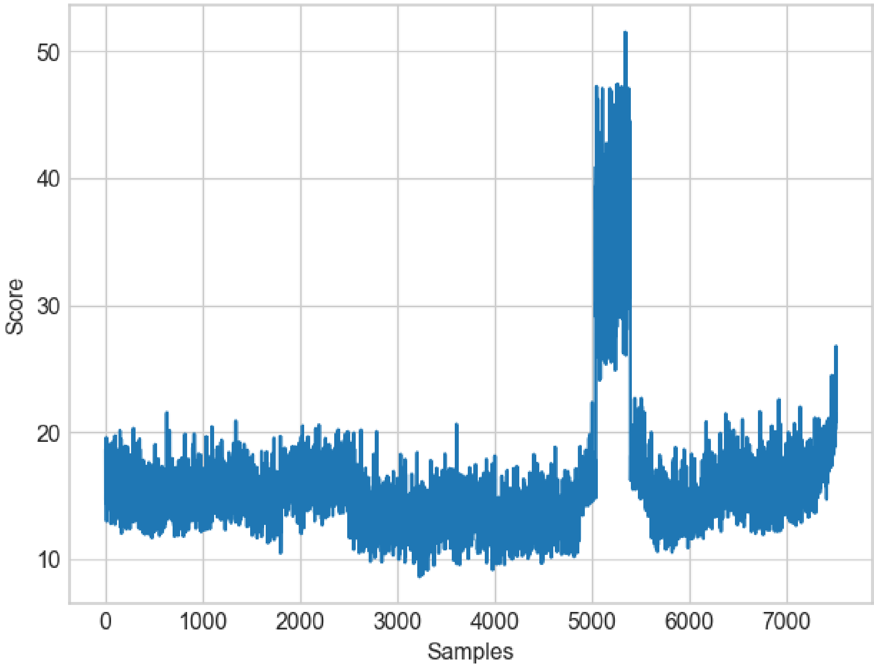

Figure 46 Outlier scores for "slow" session

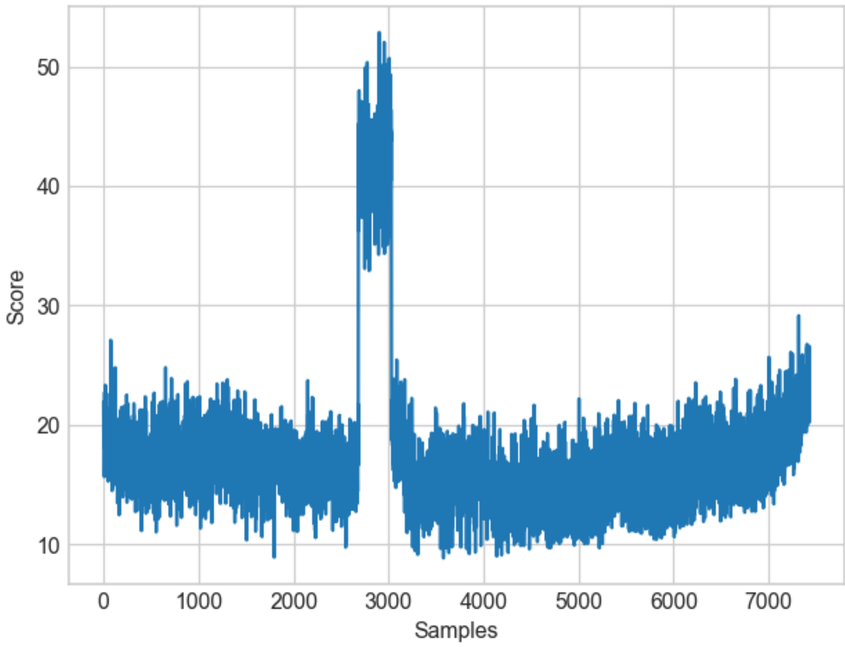

Figure 47 Outlier scores for "fast" session

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8.3. UC7 Test case results details [LEONARDO]

The paragraphs below provide some details on the execution of acceptance test planned on the troubleshooting and spare management components of the Ground Framework of the AHMS

8.3.1. Troubleshooting: Acceptance test results

Test Name	**Troubleshooting**
Test ID	8.3.18
Test Type	Acceptance
Test purpose	Verify that the Troubleshooting Component allows the Maintenance Operator to perform the troubleshooting activity by tracking the maintenance operations performed and recommending the most successful possible solutions obtained from the elaboration of historical data and analytics correlations.
Test input	-
Test description	-Login as a user with Maintenance Operator profile -Select an Aircraft and a Flight **1-Fault Debriefing** -Open Maintenance Operator's section with events list -Look at the events list and choose a Fault Code **2-Fault Isolation and solution identification** -Open section with possible solution -Open Fault Isolation Manual -Select a proposed solution - After the maintenance intervention, add feedback (Maintenance operator's notes) **3-Flight and Maintenance reports exporting** -Export Flight Debrief report -Export Maintenance Activity report
Expected output	1. Events list with relevant timestamp, fault code, event type (fault detected/recovered), flight phase, Average Total Maintenance time, number of occurrences of this event in the last flight and in the last user-defined number of flights 2. Possible solutions list with relevant part number, description, parts available at stock, average/design maintenance time maintenance time deviation and success rate. 3. Flights and Maintenance activity report on file
Test result	An example of the test output is given below. After the selection of an Aircraft and a Flight (Progressive)

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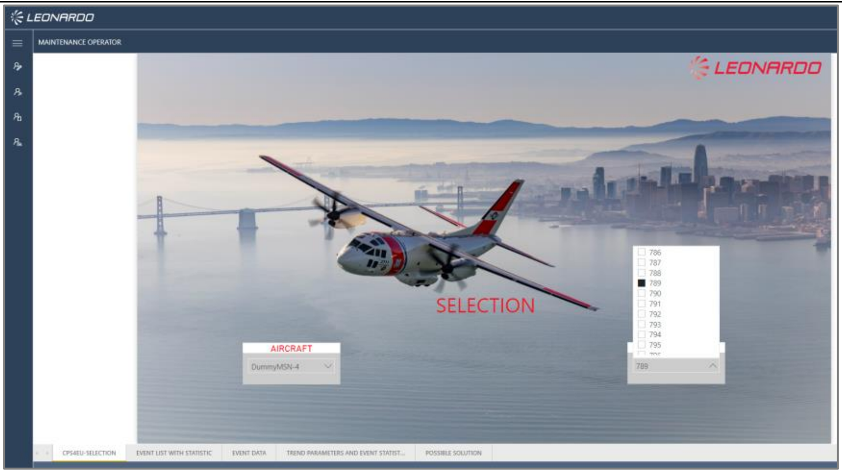
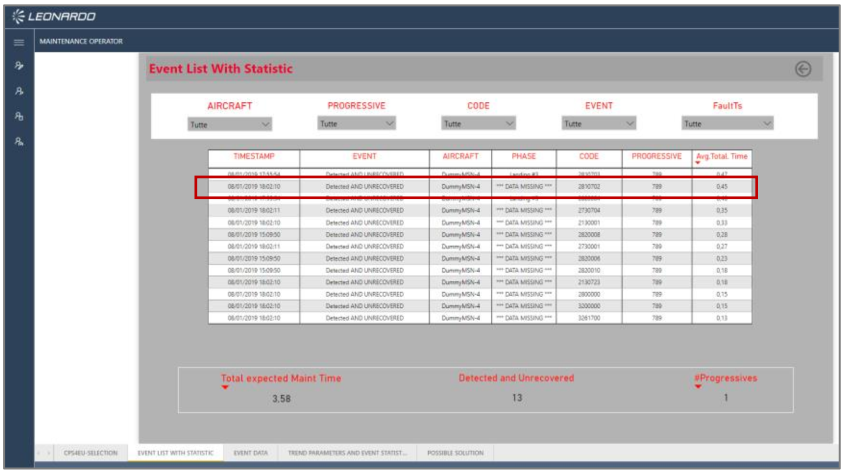
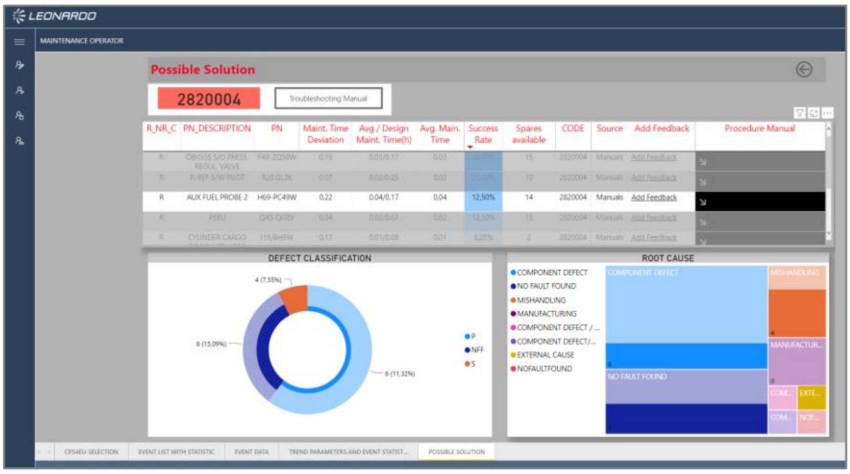


1. The system displays the list of Faults registered during flight that require investigations (Detected and Unrecovered Faults). The Total Expected Maintenance Time, along with the average Total Time estimated for each Fault Code are displayed.



2. For a selected fault event the system provides the possible solutions list with relevant part number, description, parts available at stock, success rate, information on maintenance time and provides a link to the relevant Troubleshooting Manual



After the user solved the trouble following the Troubleshooting procedure, he can pick the solution in the list that proved to be the correct one and add Feedback, including the activity performed, the Removal Reason and insights on resources, maintenance time and skills requested to complete the maintenance task.

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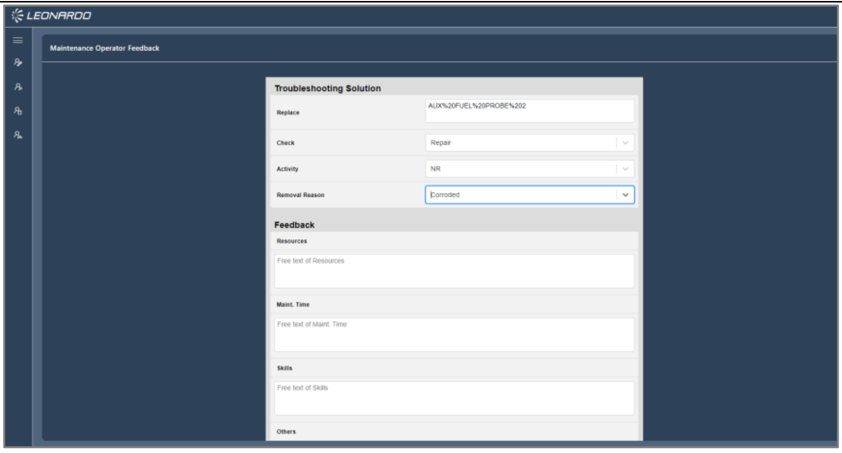
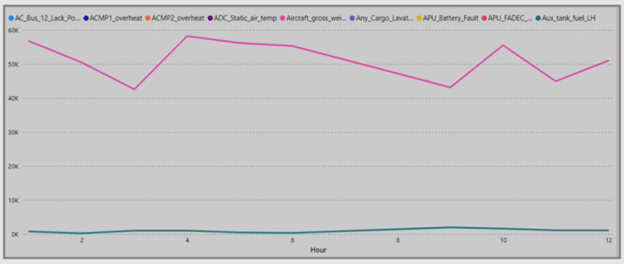


3. Flights and Maintenance activity report on file

The results of the maintenance operations can be exported as tables and charts, and inserted into a debrief report. Below is an example of Flight Parameters vs Time, list of occurred Fault Codes during Flight and selected Solution are reported. Since the investigated Fault Code is relevant to the Fuel System, the user decided to plot the variation of the aircraft mass during the day of the failure, along with the variation of auxiliary tank fuel:

Extracts of Flight and Maintenance activity Debrief Reports — LEONARDO

Flight Parameter vs Time



List of fault events analysed

TIMESTAMP	EVENT	AIRCRAFT	PHASE	CODE	PROGRESSIVE	Avg.Total. Time
08/01/2019 17:55	Detected AND UNRECOVERED	DummyMSN-4	Landing #3	2810703	789	0,466666669
08/01/2019 18:02	Detected AND UNRECOVERED	DummyMSN-4	*** DATA MISSING ***	2810702	789	0,449999988
08/01/2019 17:55	Detected AND UNRECOVERED	DummyMSN-4	Landing #3	2820004	789	0,400000006
08/01/2019 18:02	Detected AND UNRECOVERED	DummyMSN-4	*** DATA MISSING ***	2730704	789	0,349999994
08/01/2019 18:02	Detected AND UNRECOVERED	DummyMSN-4	*** DATA MISSING ***	2130001	789	0,333333343
08/01/2019 15:09	Detected AND UNRECOVERED	DummyMSN-4	*** DATA MISSING ***	2820008	789	0,283333331
08/01/2019 18:02	Detected AND UNRECOVERED	DummyMSN-4	*** DATA MISSING ***	2730001	789	0,266666681
08/01/2019 15:09	Detected AND UNRECOVERED	DummyMSN-4	*** DATA MISSING ***	2820006	789	0,233333334
08/01/2019 15:09	Detected AND UNRECOVERED	DummyMSN-4	*** DATA MISSING ***	2820010	789	0,183333337
08/01/2019 18:02	Detected AND UNRECOVERED	DummyMSN-4	*** DATA MISSING ***	2130723	789	0,183333337
08/01/2019 18:02	Detected AND UNRECOVERED	DummyMSN-4	*** DATA MISSING ***	2800000	789	0,150000006
08/01/2019 18:02	Detected AND UNRECOVERED	DummyMSN-4	*** DATA MISSING ***	3200000	789	0,150000006
08/01/2019 18:02	Detected AND UNRECOVERED	DummyMSN-4	*** DATA MISSING ***	3261700	789	0,13333334

Troubleshooting solution

PN_DESCRIPTION	PN	Maint. Time Deviation	Avg / Design Maint. Time(h)	Success Rate	Stock	Fault Code	Source
AUX FUEL PROBE 2	H69-PC49W	0,22	0.04/0.17	12,5%	14	2820004	Manuals

Test Name	Investigation Data
Test ID	8.3.19
Test Type	Acceptance

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Test purpose	Verify that the Troubleshooting Component allows the Airframer Operator to add the results of dedicated post-removal failure investigations to provide a feedback between the fault and the root cause of the defect, in order to improve the troubleshooting and avoid no fault found events.
Test input	-
Test description	- Login as a user with Airframer Operator profile - Go to Airframer Operator's section about the investigation data - Filter the data by description and/or aircraft and select a removal - Insert notes relevant to the investigation performed on the removed item
Expected output	Investigation performed fields (Defect classification, Root cause, Root cause detail) filled in the relevant removal of the removals list The investigation Information entered (Defect classification, Root cause, Root cause detail is saved on the system and used to calculate the investigation cause statistics.
Test result	An example of the test result is given below. In the section about investigation data The Airframer Operator can see the list of all items removals.  The user can pick an item in the removal list to enter additional notes relevant to the investigation performed during repair by the Supplier: The user can fill three fields: Defect Classification and Root Cause (with pre-defined values) and Root Cause Details (free text)  By clicking on the SAVE button, the data is stored in the system and is available to the future calculations of Investigation statistics.

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Test Name	**Analytics**
Test ID	8.3.20
Test Type	Acceptance
Test purpose	Verify that the Troubleshooting Component allows the Airframer Operator to use analytics models to identify correlations, patterns and statistics from the aircraft and maintenance generated data. The results of these models, once validated, can be exported to support the Maintenance Operator in his troubleshooting activities.
Test input	-
Test description	- Login as a user with Airframer Operator profile - Go to Airframer Operator's analytics section **1-Data analysis** - Select a Fault Code - Look at the results in the correlation matrix and choose a correlation to investigate -Look at the associations between fault event and removals proposed by the system -Look at the failure cause statistics calculated based on investigation data **2-Test and validation** -Test the effects of the selected correlation -Validate the correlation **3-Export the model** -Export the updated correlation table
Expected output	1a. Correlation Matrix between: o Flight parameter vs flight parameter o Fault vs fault o Fault vs flight parameter 1b. Association list between items removals and fault events 1c. For each item, the failure causes statistics that show the distribution of the defect root causes based on Airframer investigation data 2. Updated success rates, possible solutions and investigations statistics and comparison with the old ones 3. Validated values are used in the Troubleshooting Component in order to calculate and show the success rates, possible solutions and the investigations statistics in the Maintenance Operator's section
Test result	An example of the test result is given below. 1. In the Airframer Operator analytics section the Airframer selects a fault code, in this case Fault Code 2331507. An analysis is performed for each aircraft, showing the following pattern:

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A correlation is found between Code 2350010 and Fault 2331507, whenever a specific item, the ICS CSU, is removed. Therefore, the user performs an analysis on the automatic association provided by the Troubleshooting Component, identifying and validating the right Fault Code-Item Removal couple to be associated for each aircraft (an example for aircraft DummyMSN-7 is given below):

CODE	PROGRESSIVE	VALIDATION	AIRCRAFT	PN
2331507	Tutte	Tutte	DummyMSN-7	Tutte

FlightRemovalKey	CODE	AIRCRAFT	Conteggio di ID	PROGRESSIVE	PN	ID	Association Probability
110276107507	2331507	DummyMSN-7	1	1075	T69/UA45W	276	1,68%
110279107507	2331507	DummyMSN-7	1	1075	T69/UA45W	279	1,68%
110284107507	2331507	DummyMSN-7	1	1075	V50/UG9X	284	1,68%
110288107507	2331507	DummyMSN-7	1	1075	Z57.EU36Y	288	1,68%
110278107507	2331507	DummyMSN-7	1	1075	B9-RM30WA	278	0,84%
110254107507	2331507	DummyMSN-7	1	1075	D88.UL24X	254	0,84%
110229107507	2331507	DummyMSN-7	1	1075	D99-LE17W	229	0,84%
110241107507	2331507	DummyMSN-7	1	1075	E28.SU70W	241	0,84%
110300107507	2331507	DummyMSN-7	1	1075	F78-EP4W	300	0,84%

The user can see the investigation statistics relevant to the ICS CSU removals, to check the distribution of the root causes based on the investigation data:

FAILURE CAUSE STATISTICS REPORT

DEFECT CLASSIFICATON	#DEFECTS
P	11
NFF	1
S	0

ROOT CAUSE	#DEFECTS
COMPONENT DEFECT	11
NO FAULT FOUND	1

2-3. After the validation of the new association Fault Code-Item Removal, the success rate calculated in the Possible Solutions dashboard is updated accordingly. The pictures below show the possible solutions dashboard output before and after the new association is validated:

Before:

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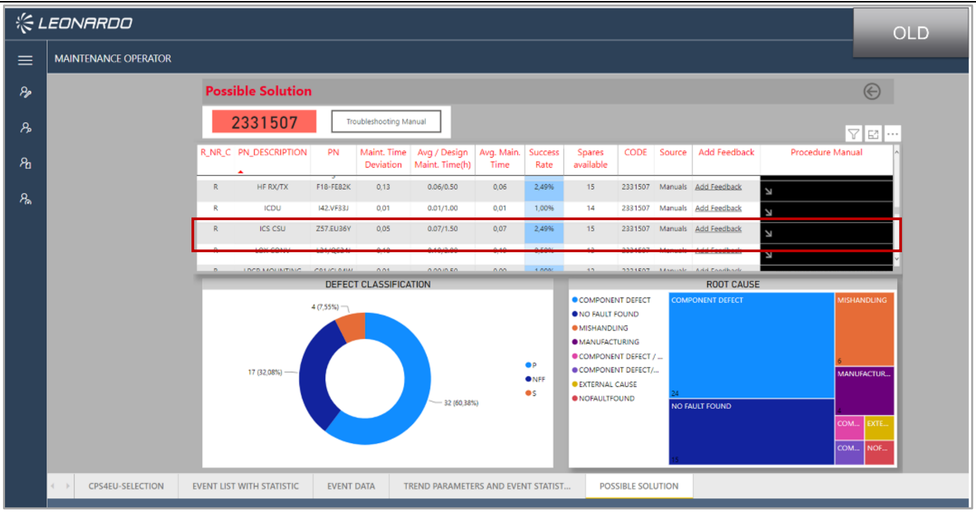
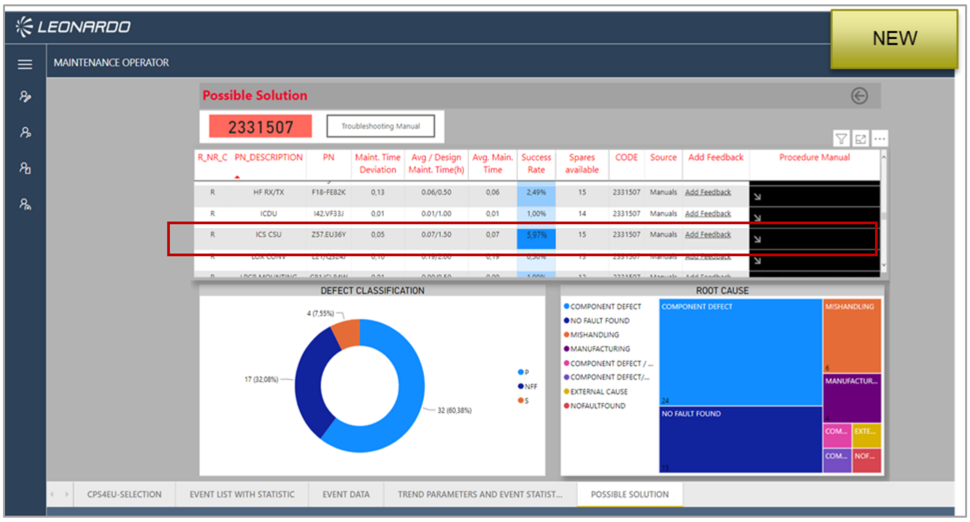


After:



Test Name	**Troubleshooting Optimization support**
Test ID	8.3.21
Test Type	Acceptance
Test purpose	Verify that the Troubleshooting Component allows the Airframer Operator to export Troubleshooting and Analytics results to support Troubleshooting optimizations activities that are performed outside the system
Test input	-
Test description	- Login as Airframer Operator - Go to Airframer Operator's troubleshooting optimization section - Select a Fault Code - Export data

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Expected output

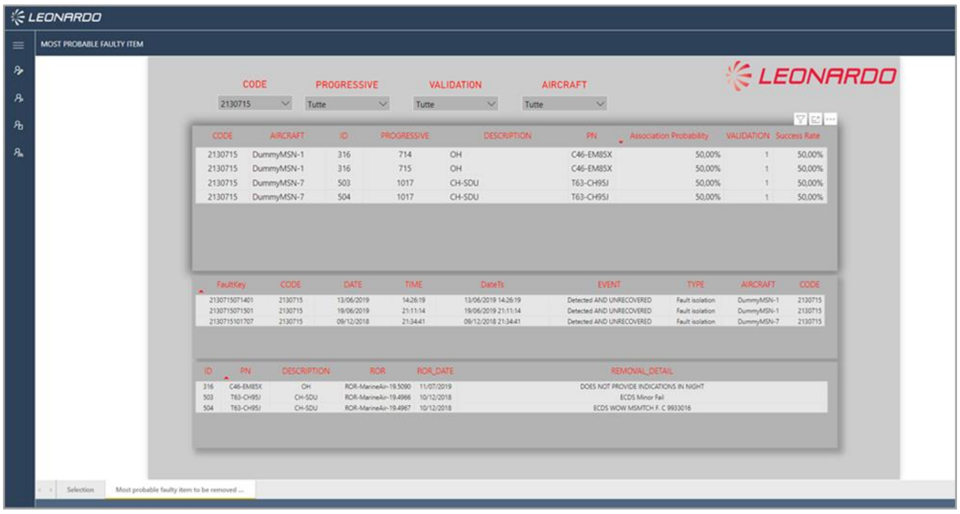
For the selected Fault Code the system produces and allows to download a report on .csv/.pdf file that contains:

- List of the item removed with: part number, success rates and Maintenance Time Deviation
- Validated correlations list between failures and flight parameters, failure cause statistics based on investigation data
- maintenance notes

Test result

An example of the test result is given below for Fault Code 2130715.

1. In the Airframer Operator troubleshooting section The Airframer Operator selects the Fault Code 2130715, and the system shows the list of automatically proposed associations with Success Rate, the list of faults events and the list of removed items.



The output can be exported. An example of export in excel format is shown below:

List of Faults with associated Removed items								
CODE	AIRCRA	ID	PROGR	DESCRIPTION	PN	Associa	VALIDA	Success
2130715	DummyM	316	714	OH	C46-EM85X	50,00%	1	50,00%
2130715	DummyM	316	715	OH	C46-EM85X	50,00%	1	50,00%
2130715	DummyM	503	1017	CH-SDU	T63-CH95J	50,00%	1	50,00%
2130715	DummyM	504	1017	CH-SDU	T63-CH95J	50,00%	1	50,00%

List of Removals					
ID	PN	DESCRI	ROR	ROR_DATE	REMOVAL_DETAIL
316	C46-EM85	OH	ROR-Marii	11/07/2019	DOES NOT PROVIDE INDICATIONS IN NIGHT
503	T63-CH95J	CH-SDU	ROR-Marii	10/12/2018	ECDS Minor Fail
504	T63-CH95J	CH-SDU	ROR-Marii	10/12/2018	ECDS WOW MSMTCH F. C 9933016

In the Investigation Data section the user can find the list of all the removals for the identified part number, with the actual Maintenance Time of each Removal as displayed below:

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Investigation Data

EXPORT LIST TO .CSV

Id	AC	PN	DESCRIPTION	SN	REMOVAL_DETAIL	QPA	ROR	ROR_DATE	REMOVAL_TYPE	MAINTENANCE_ELAPSED_TIME	Actions
	Enter AC...	Enter PN ...	ch-sdu	Enter SN...			Enter ROR...	Enter ROR_DATE...			
501	DummyMSN-1	T63-CH95J	CH-SDU	06014	Does not read magazines	14	ROR-MarineAir-18.4830	2018-12-06T00:00:00	Unscheduled	0.292	
502	DummyMSN-12	T63-CH95J	CH-SDU	05198	Does not read magazines	14	ROR-MarineAir-18.4831	2018-12-06T00:00:00	Unscheduled	0.675	
503	DummyMSN-7	T63-CH95J	CH-SDU	07037	ECDS Minor Fail	14	ROR-MarineAir-19.4966	2018-12-10T00:00:00	Unscheduled	0.754	
504	DummyMSN-7	T63-CH95J	CH-SDU	05150	ECDS WOW MSMTCH F. C 9933016	14	ROR-MarineAir-19.4967	2018-12-10T00:00:00	Unscheduled	0.491	
505	DummyMSN-8	T63-CH95J	CH-SDU	07026	SDU #3 does not read magazine	14	ROR-MarineAir-19.4840	2018-12-17T00:00:00	Unscheduled	0.721	
506	DummyMSN-10	T63-CH95J	CH-SDU	07028	SDU does not read magazines	14	ROR-MarineAir-19.4872	2019-01-16T00:00:00	Unscheduled	0.283	
507	DummyMSN-10	T63-CH95J	CH-SDU	05189	SDU n°14 does not read magazines	14	ROR-MarineAir-19.5025	2019-01-16T00:00:00	Unscheduled	0.052	
508	DummyMSN-2	T63-CH95J	CH-SDU	05132	Fixing nut does not remain in position	14	ROR-MarineAir-19.4923	2019-02-25T00:00:00	Unscheduled	0.588	
509	DummyMSN-10	T63-CH95J	CH-SDU	07023	ECDS Jetton degraded	14	ROR-MarineAir-19.5040	2019-03-18T00:00:00	Unscheduled	0.630	
510	DummyMSN-1	T63-CH95J	CH-SDU	08051	SDU with Magaizine reading pin dent	14	ROR-MarineAir-19.4993	2019-04-02T00:00:00	Unscheduled	0.589	

The output can be exported. An example of export in excel format is shown below

List of Removals with Maint Elapsed Time

ID	AC	PN	DESCRIPTIO	SN	REMOVAL_DETAIL	ROR	Date	Removal Type	Maint Elapsed Time
501	DummyMSN-1	T63-CH95J	CH-SDU	6014	Does not read magazines	ROR-MarineAir-18.4830	2018-12-06T00:00:00	Unscheduled	0,29
502	DummyMSN-12	T63-CH95J	CH-SDU	5198	Does not read magazines	ROR-MarineAir-18.4831	2018-12-06T00:00:00	Unscheduled	0,68
503	DummyMSN-7	T63-CH95J	CH-SDU	7037	ECDS Minor Fail	ROR-MarineAir-19.4966	2018-12-10T00:00:00	Unscheduled	0,75
504	DummyMSN-7	T63-CH95J	CH-SDU	5150	ECDS WOW MSMTCH F. C 9933016	ROR-MarineAir-19.4967	2018-12-10T00:00:00	Unscheduled	0,49
505	DummyMSN-8	T63-CH95J	CH-SDU	7026	SDU #3 does not read magazine	ROR-MarineAir-19.4840	2018-12-17T00:00:00	Unscheduled	0,72
506	DummyMSN-10	T63-CH95J	CH-SDU	7028	SDU does not read magazines	ROR-MarineAir-19.4872	2019-01-16T00:00:00	Unscheduled	0,28
507	DummyMSN-10	T63-CH95J	CH-SDU	5189	SDU n°14 does not read magazines	ROR-MarineAir-19.5025	2019-01-16T00:00:00	Unscheduled	0,05
508	DummyMSN-2	T63-CH95J	CH-SDU	5132	Fixing nut does not remain in position	ROR-MarineAir-19.4923	2019-02-25T00:00:00	Unscheduled	0,59
509	DummyMSN-10	T63-CH95J	CH-SDU	7023	ECDS Jetton degraded	ROR-MarineAir-19.5040	2019-03-18T00:00:00	Unscheduled	0,63
510	DummyMSN-1	T63-CH95J	CH-SDU	8051	SDU with Magaizine reading pin dent	ROR-MarineAir-19.4993	2019-04-02T00:00:00	Unscheduled	0,59
511	DummyMSN-10	T63-CH95J	CH-SDU	5199	FAIL	ROR-MarineAir-19.5228	2019-06-10T00:00:00	Unscheduled	0,53
512	DummyMSN-2	T63-CH95J	CH-SDU	7050	FAIL	ROR-MarineAir-19.5206	2019-09-25T00:00:00	Unscheduled	0,54
513	DummyMSN-12	T63-CH95J	CH-SDU	7029	FAULT	ROR-MarineAir-20.5291	2020-01-09T00:00:00	Unscheduled	0,73
514	DummyMSN-11	T63-CH95J	CH-SDU	7080	FAULT	ROR-MarineAir-20.5292	2020-01-13T00:00:00	Unscheduled	0,88

ID	AC	PN	DESCRIPTIO	SN	REMOVAL_DETAIL	ROR	Date	Removal Type	Maint Elapsed Time
8	DummyMSN-11	C46-EM85X	OH	17579	Fail	ROR-MarineAir-18.4732	2018-10-10T00:00:00	Unscheduled	0,81
10	DummyMSN-11	C46-EM85X	OH	21754	Fail	ROR-MarineAir-18.4734	2018-10-10T00:00:00	Unscheduled	0,12
12	DummyMSN-11	C46-EM85X	OH	20223	Functional test failed	ROR-MarineAir-18.4736	2018-10-12T00:00:00	Unscheduled	0,24

2. The user can look for if there are valid correlations between the selected Fault Code and Flight Parameters. The picture shows the correlations of fault code 2130715 (only a limited number of telemetries are displayed). For that fault no correlations have been identified.

Attribute	2130715
2130715	1,00
AC Bus 1/2 Lack Power	0,00
Any Cargo Lavatory Smoke Detector Fault	0,00
APU Battery Fault	0,00
Bleed 1 Selected	0,00
Cargo Duct Overheat Status	0,00
Cockpit Duct Overheat Status	0,00
DC Bus 1 Off	0,00
DC Bus 12 Lack Power	0,00
DC Bus 2 Off	0,00
EGI Inertial altit	0,00
EGI Pitch angle	-0,01
EGI Pres true head	0,00
EGI Roll angle	0,00
Emergency Battery Fault	0,00
Hydraulic System On Off 1	0,00
Left Elevator Position Monitor	0,00

The user can also export the failure cause statistics relevant to the identified removed items, obtaining the report below:

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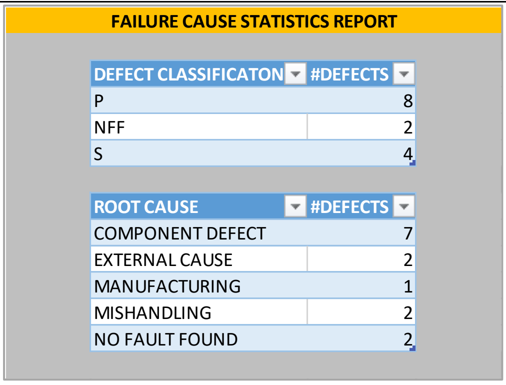

FAILURE CAUSE STATISTICS REPORT

DEFECT CLASSIFICATON	#DEFECTS
P	8
NFF	2
S	4

ROOT CAUSE	#DEFECTS
COMPONENT DEFECT	7
EXTERNAL CAUSE	2
MANUFACTURING	1
MISHANDLING	2
NO FAULT FOUND	2

Test Name	**Identification of Valid Correlations**
Test ID	8.3.22
Test Type	Acceptance
Test purpose	Verify that the Troubleshooting Component allows the Airframer Operator to perform data analysis on failure and flight parameters in order to identify known or new valid correlations through the analytics models
Test input	A set of Fault codes and items removals to be investigated
Test description	- Login as a user with Airframer Operator user profile - Go to Airframer Operator's analytics section - Select a Fault Code - Look at the results in the correlation matrix - Look at the automatic association between fault events and removals - Repeat the process for the fault codes and items removals to be investigated.
Expected output	The system calculates: • correlations coefficients between failures and failures vs flight parameters • association between fault events and removals that match the expected results deriving from reference engineering data, for known correlations, or that are confirmed with the support of engineering specialists and empirical data, in case of new correlations
Test Result	An example of the test result is given below. The Airframer Operator (user) logs in the Airframer Operator analytics section, specifically the Fault Codes Correlation Pearson Matrix. He selects two Fault Codes 2160000 and 2160705 to investigate:

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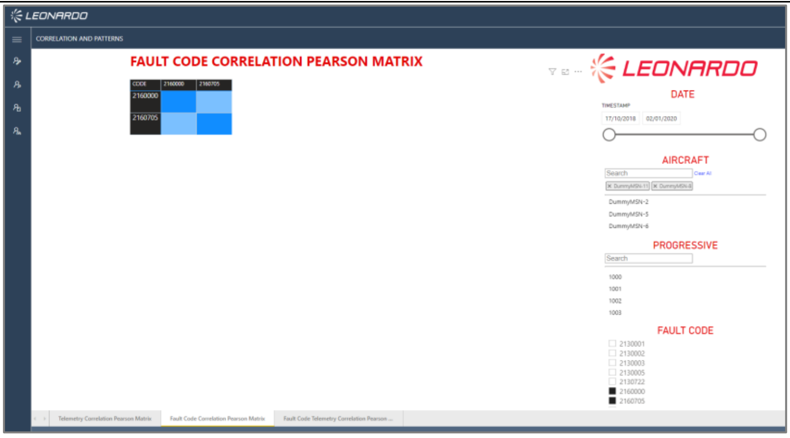
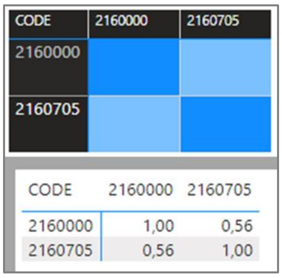
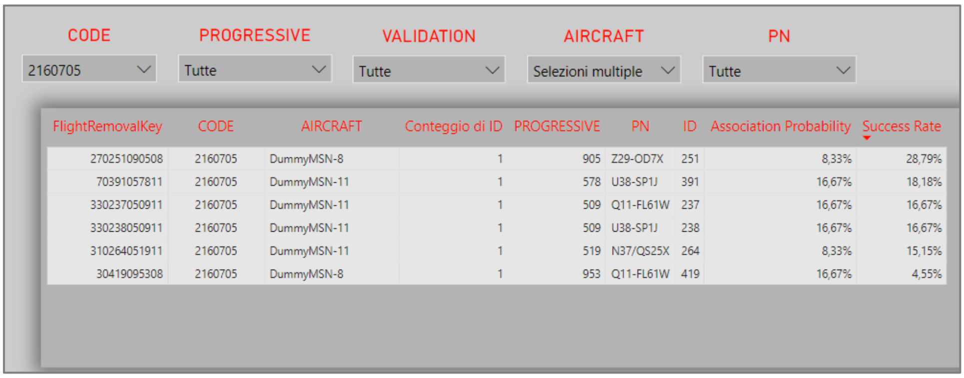


Then, he adds boundary conditions, in this case a specific subset of aircraft of the Fleet. The user looks at correlation matrix results, which in this case correctly identify a positive linear correlation between the two selected Fault Codes:



CODE	2160000	2160705
2160000	1,00	0,56
2160705	0,56	1,00

In the Most Probable Faulty Item section the user that shows the automatic association the system proposes between a Fault event and an Item Removal. Below Fault Code 2160705 is analysed:



CODE	PROGRESSIVE	VALIDATION	AIRCRAFT	PN
2160705	Tutte	Tutte	Selezioni multiple	Tutte

FlightRemovalKey	CODE	AIRCRAFT	Conteggio di ID	PROGRESSIVE	PN	ID	Association Probability	Success Rate
270251090508	2160705	DummyMSN-8	1	905	Z29-OD7X	251	8,33%	28,79%
70391057811	2160705	DummyMSN-11	1	578	U38-SP1J	391	16,67%	18,18%
330237050911	2160705	DummyMSN-11	1	509	Q11-FL61W	237	16,67%	16,67%
330238050911	2160705	DummyMSN-11	1	509	U38-SP1J	238	16,67%	16,67%
310264051911	2160705	DummyMSN-11	1	519	N37/QS25X	264	8,33%	15,15%
30419095308	2160705	DummyMSN-8	1	953	Q11-FL61W	419	16,67%	4,55%

When the user has checked the association probability values, he can decide to validate a proposed association of an item removal for that fault.

8.3.2. Spare management: Acceptance test results

Test Name	**Stock demand**
Test Type	8.3.40
Test Type	Acceptance

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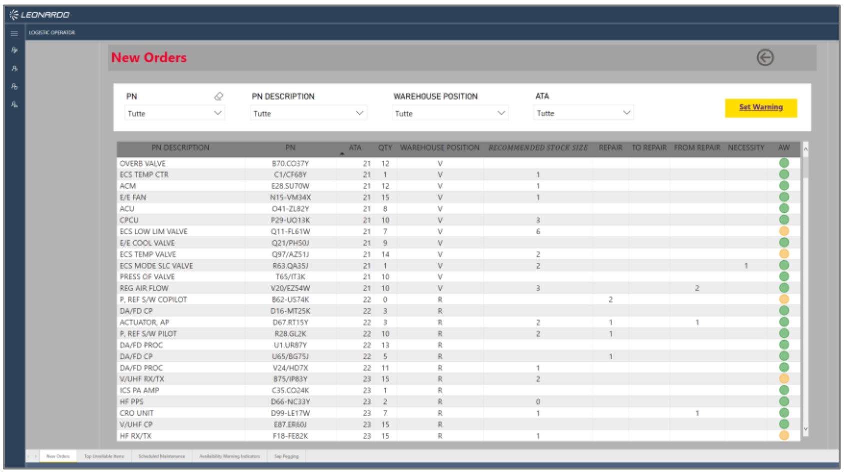
Test purpose	Verify that the Spare Management Component allows the Logistic Operator to monitor the items at stock and see if there is a demand to increase those items (now orders)
Test input	-
Test description	- Login as user with Logistic Operator profile - Go to Logistic Operator's section about new orders - Check the list of items at stock and the information displayed - Export the Parts availability report
Expected output	The system shows the list of items at stock and for each item the following information is displayed: • Part number • Relevant aircraft system • Quantity at stock • Recommended stock size • Demand (as the difference between recommended stock size and the quantity at stock) • Parts at repair or ordered • Availability Warning The system produces a Parts availability report on file in .xlsx / .csv / .pdf format that can be downloaded and saved.
Test result	Below is an example of the New Orders dashboard. The dashboard allows the user to check items at stock and information concerning position in the warehouse, quantity at stock, recommended stock size and demand (Necessity column), calculated as the difference between recommended stock size and available quantity:  The Necessity information, along with the Availability Warning (AW) and the parts in the supply chain for repair (columns Repair, To Repair, From Repair) supports the user decision on ordering new spare parts. The New Orders list can be exported. An example of the Parts Availability Report in excel format is shown below:

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	A	B	C	D	E	F	G	H	I	J	K
1	PN DESCRIPTION	PN	Somma	QTY	WAREH	RECO	REPAIR	TO REP	FROM I	NECESS	AW
2	OVERB VALVE	B70.CO37Y	21	12	V						11,6127
3	ECS TEMP CTR	C1/CF68Y	21	1	V	1					16,62276
4	ACM	E28.SU70W	21	12	V	1					14,75528
5	E/E FAN	N15-VM34X	21	15	V	1					5,988014
6	ACU	O41-ZL82Y	21	8	V						4,3989
7	CPCU	P29-UO13K	21	10	V	3					2,00057
8	ECS LOW LIM VALVE	Q11-FL61W	21	7	V	6					46,74487
9	E/E COOL VALVE	Q21/PH50J	21	9	V						8,8011
10	ECS TEMP VALVE	Q97/AZ51J	21	14	V	2					26,92117
11	ECS MODE SLC VALVE	R63.QA35J	21	1	V	2				1	17,84376
12	PRESS OF VALVE	T65/IT3K	21	10	V						15,279
13	REG AIR FLOW	V20/EZ54W	21	10	V	3			2		15,35506
14	P, REF S/W COPILOT	B62-US74K	22	0	R		2				26,40066
15	DA/FD CP	D16-MT25K	22	3	R						14,0547
16	ACTUATOR, AP	D67.RT15Y	22	3	R	2	1		1		24,16352
17	P, REF S/W PILOT	R28.GL2K	22	10	R	2	1				19,36559
18	DA/FD PROC	U1.UR87Y	22	13	R						17,1105
19	DA/FD CP	U65/BG75J	22	5	R		1				20,53458
20	DA/FD PROC	V24/HD7X	22	11	R	1					23,66707
21	V/UHF RX/TX	B75/IP83Y	23	15	R	2					28,29784
22	ICS PA AMP	C35.CO24K	23	1	R						15,8895
23	HF PPS	D66-NC33Y	23	2	R	0					2,097046
24	CRO UNIT	D99-LE17W	23	7	R	1			1		22,13533
25	V/UHF CP	E87.ER60J	23	15	R						14,0547
26	HF RX/TX	F18-FE82K	23	15	R	1					35,1913
27	V/UHF BLADE ANT	H20.TB93K	23	5	R	5					7,239892
28	LNA AMPL	H22-QQ76J	23	13	R						12,2232
29	CP HIU	H83.FB46J	23	11	R	1					18,16597
30	SAT HPA	N43-EE72J	23	15	R						10,9989
31	ATU-1	N6.TS86J	23	8	R	1					19,27535
32	MHIU	R46/EM25J	23	13	R						14,0547
33	PAU HF	R65-BN49Y	23	0	R						10,9989
34	CP HIU	S60.PM52J	23	6	R	0					13,15908
35	ICS MP	S84.PZ98K	23	1	R						17,1105

Test Name	**Top Unreliable Items monitoring**
Test ID	8.3.41
Test Type	Acceptance
Test purpose	Verify that the Spare Management Component allows the Logistic Operator to monitor the Top Unreliable Items and supports him showing reliability indicators and Availability Warnings
Test input	-
Test description	- Login as user with Logistic Operator profile - Go to the section about Top Unreliable Items - Select an observation interval and the number of items to be displayed - Check the items displayed and the Reliability KPIs that the system displays - order them by increasing URR - Go the section about stock status - Check the recommended stock size for those items - Export the Top Unreliable Items report
Expected output	The system shows a list of parts grouped by item Reference ID, and for each of them the following information is displayed: • Part description • Reference ID • MTBUR • URR • GRADIENT • STANDARD DEVIATION • Number of AOCP events • Availability Warning • Parts at repair or new orders

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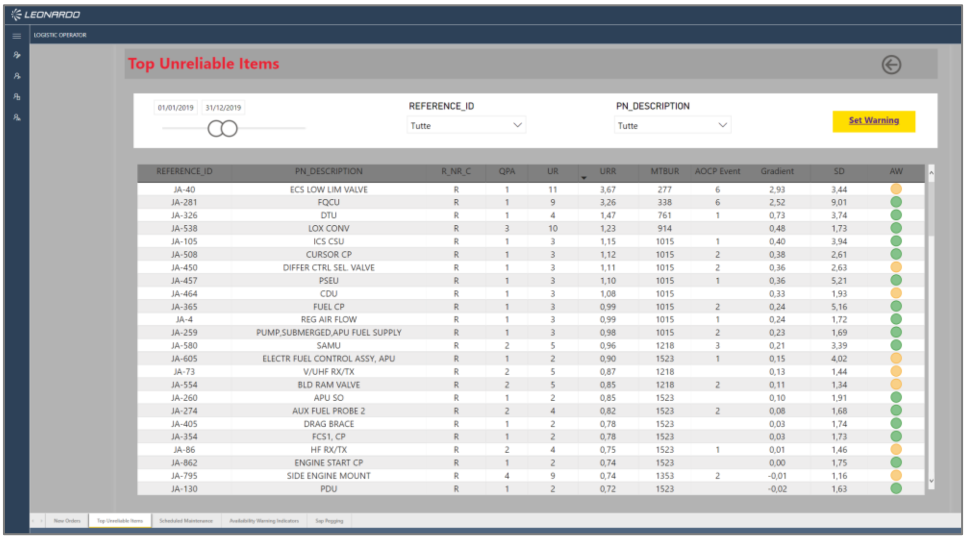
The system shows the recommended quantity in stock for the selected items

The system produces a report for Top Unreliable Items report on file in.csv/.xlsx/.pdf format that can be downloaded and saved.

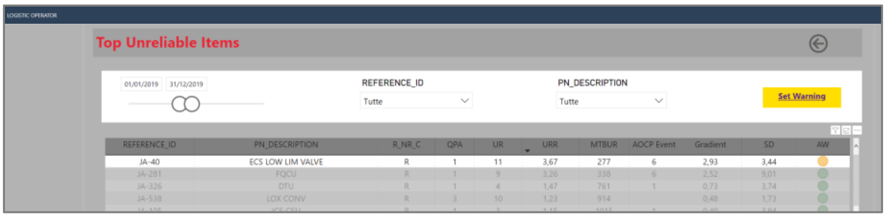
Test result

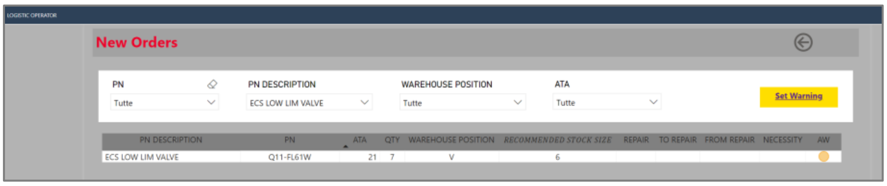
Below is an example of the test output.

In the Logistic Operator section the user can find the Top Unreliable Items dashboard, where he can select the observation interval, check the Reliability KPI and order the items by increasing URR:



For each item, in the list the user can check in the new orders dashboard the spares at stock and recommended stock size. The example below is for the ECS LOW LIM VALVE item:





The Top Unreliable Items report can be exported. Below is a picture of the export in excel format:

	A	B	C	D	E	F	G	H	I	J	K
1	'v_DIM_PI	PN_DESCRIPTION	R_NR_(	QPA	UR	URR	MTBUF	AOCP E	Gradie	SD	AW
2	JA-40	ECS LOW LIM VALVE	R	1	11	3,674909	277	6	2,929041	3,439662	46,74487
3	JA-281	FQCU	R	1	9	3,26233	338	6	2,516463	9,012953	13,1791
4	JA-326	DTU	R	1	4	1,474456	761	1	0,728589	3,739413	20,19847
5	JA-538	LOX CONV	R	3	10	1,225657	914		0,479789	1,730945	13,64971
6	JA-105	ICS CSU	R	1	3	1,147716	1015	1	0,401849	3,938405	17,32832
7	JA-508	CURSOR CP	R	1	3	1,124871	1015	2	0,379004	2,612447	16,33217
8	JA-450	DIFFER CTRL SEL. VALVE	R	1	3	1,105937	1015	2	0,36007	2,627752	25,29912
9	JA-457	PSEU	R	1	3	1,101176	1015	1	0,355308	5,211328	24,75
10	JA-464	CDU	R	1	3	1,077165	1015		0,331298	1,926448	26,00697
11	JA-365	FUEL CP	R	1	3	0,98664	1015	2	0,240772	5,159482	18,9453
12	JA-4	REG AIR FLOW	R	1	3	0,98664	1015	1	0,240772	1,719827	15,35506
13	JA-259	PUMP,SUBMERGED,APU FUEL SUPPLY	R	1	3	0,977421	1015	2	0,231554	1,68546	0,956769
14	JA-580	SAMU	R	2	5	0,960117	1218	3	0,21425	3,394133	14,0547
15	JA-605	ELECTR FUEL CONTROL ASSY, APU	R	1	2	0,899373	1523	1	0,153506	4,02085	34,00066
16	JA-73	V/UHF RX/TX	R	2	5	0,872674	1218		0,126807	1,441106	28,29784
17	JA-554	BLD RAM VALVE	R	2	5	0,854885	1218	2	0,109018	1,337047	29,45316
18	JA-260	APU SO	R	1	2	0,846634	1523		0,100767	1,911369	12,85592
19	JA-274	AUX FUEL PROBE 2	R	2	4	0,82206	1523	2	0,076192	1,683031	22,84929
20	JA-405	DRAG BRACE	R	1	2	0,780349	1523		0,034482	1,738936	22,02356
21	JA-354	FCS1, CP	R	1	2	0,777483	1523		0,031616	1,732984	17,0025

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	Note: requirement UC7-FNC-125 “The AHMS GF shall allow the user to change the number of Top Unreliable Items included in the list.” has not been implemented in the Troubleshooting Component. Therefore the user can export the entire Top Unreliable Items list or filter the data first by observation period, item reference identification number or description

Test Name	**Scheduled Maintenance monitoring**
Test ID	8.3.42
Test Type	Acceptance
Test purpose	Verify that the Spare Management Component allows the Logistic Operator to monitor the Scheduled Maintenances performances and supports him in the decision making process to guarantee the necessary logistic support for the scheduled maintenance activities
Test input	-
Test description	- Login as a user with the Logistic Operator profile - Go to section about scheduled maintenance activities - Check the listed items in the scheduled maintenance list. - Export Scheduled Maintenance report
Expected output	The system shows a list of Items subject to scheduled maintenance ordered by increasing Estimated Expiration Date, and for each of them the following information is displayed: • Part number • Serial number • Description • Aircraft • Aircraft system • Task to be achieved • Remaining flight hours to scheduled maintenance • Estimated Expiration Date • Availability warning The system produces a Scheduled Maintenance Report on file in.csv/.xlsx/.pdf format, that can be downloaded and saved.
Test result	Below is an example of the Scheduled Maintenance dashboard where for each item the user can check the Scheduled Maintenance tasks that are about to expire. The picture below shows the output when the ACM item is selected. For the aircraft involved, the remaining flight hours to scheduled maintenance and Estimated Expiration Date are displayed.

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	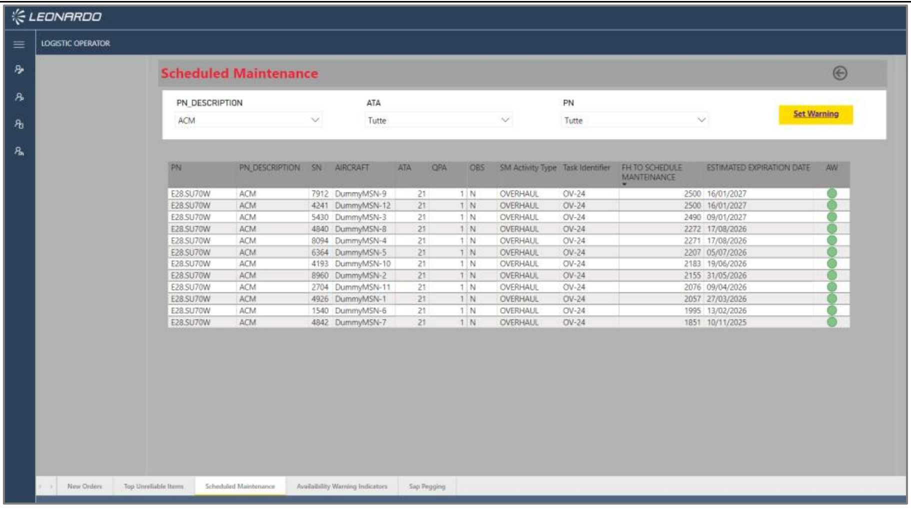 Below is a picture of the Scheduled maintenance report in excel format that can be exported:

	A	B	C	D	E	F	G	H	I	J	K	L
1	PN	PN_DES	SN	AIRCRA	Somma	Somma	OBS	SM Act	Task Id	Somma	ESTIMATED E	AW
2	E28.SU70V	ACM	7912	DummyM	21	1	N	OVERHAU	OV-24	2500	16/01/2027	14,75528
3	E28.SU70V	ACM	4241	DummyM	21	1	N	OVERHAU	OV-24	2500	16/01/2027	14,75528
4	E28.SU70V	ACM	5430	DummyM	21	1	N	OVERHAU	OV-24	2490	09/01/2027	14,75528
5	E28.SU70V	ACM	4840	DummyM	21	1	N	OVERHAU	OV-24	2272	17/08/2026	14,75528
6	E28.SU70V	ACM	8094	DummyM	21	1	N	OVERHAU	OV-24	2271	17/08/2026	14,75528
7	E28.SU70V	ACM	6364	DummyM	21	1	N	OVERHAU	OV-24	2207	05/07/2026	14,75528
8	E28.SU70V	ACM	4193	DummyM	21	1	N	OVERHAU	OV-24	2183	19/06/2026	14,75528
9	E28.SU70V	ACM	8960	DummyM	21	1	N	OVERHAU	OV-24	2155	31/05/2026	14,75528
10	E28.SU70V	ACM	2704	DummyM	21	1	N	OVERHAU	OV-24	2076	09/04/2026	14,75528
11	E28.SU70V	ACM	4926	DummyM	21	1	N	OVERHAU	OV-24	2057	27/03/2026	14,75528
12	E28.SU70V	ACM	1540	DummyM	21	1	N	OVERHAU	OV-24	1995	13/02/2026	14,75528
13	E28.SU70V	ACM	4842	DummyM	21	1	N	OVERHAU	OV-24	1851	10/11/2025	14,75528

Test Name	**Tuning of warnings**
Test ID	8.3.43
Test Type	Acceptance
Test purpose	Verify that the Spare Management Component allows the Logistic Operator to register new AOG events for missing parts (AOCP) and change the weights and threshold of the Availability Warning to better identify the items on which corrective and preventive logistic support actions are necessary.
Test input	-
Test description	- Login as a user with Logistic Operator profile - Go to Logistic Operator's administration section - Go to Logistic Operator's administrative section on item removals - filter removals according to specific selection criteria a) Check the AOCP column of a removal that caused an AOG event - Open the section to set weights and thresholds - select that part nr. that caused the AOG event

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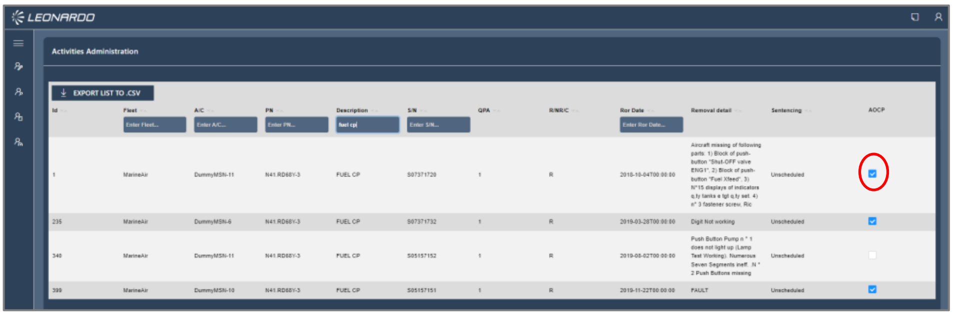
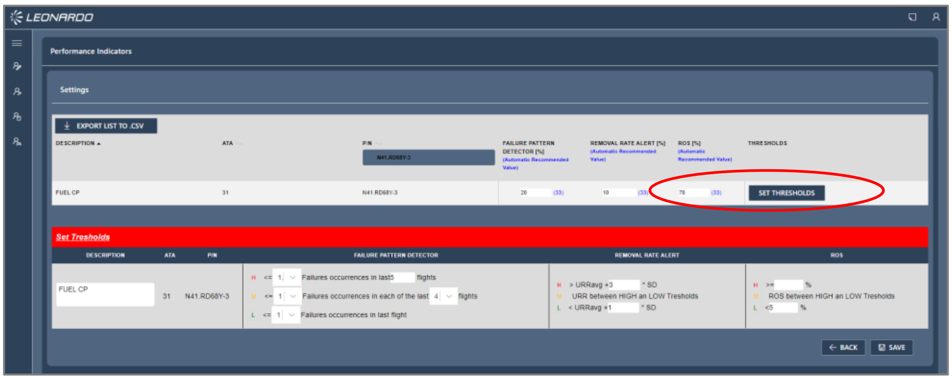
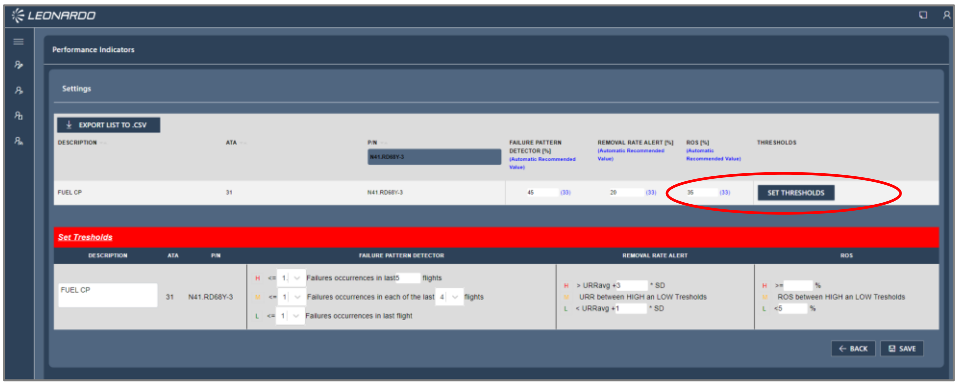
	- set the recommended values for weights of performance indicators in the availability warning on that part nr. - Open the section to set warnings thresholds - Set the recommended values for the thresholds of the performance indicators for that part nr. b) Check the availability warning and Performance Indicators for that part.
Expected output	a) the AOG column for the selected item displayed in section on top unreliable items counts also the new AOG event entered b) The availability warnings displayed in the stock status are updated according to the new values set and reflect the AOG event occurred registered for that item.
Test Result	An example of the test result is given below. In the section relevant to the administration of item removals, the Logistic Operator can enter if a specific removal caused an AOCP event. In the picture below the user filtered on the Fuel CP item, and checked one of the Removals as an AOCP event.  In the Performance Indicators Setting the user can set new values for weights and thresholds to update how the Availability Warning is calculated. The recommended settings the system suggest take into account the new AOCP event recorded by the user.  

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	By changing the weights of the performance indicators, the Availability Warning is consequently updated: 

Test Name	**Stock status monitoring for optimization**
Test Type	Acceptance
Test ID	8.3.44
Test purpose	Verify that the Spare Management Component allows the Airframer Operator to obtain information and indicators derived from field activities to support the optimization of the logistic support services offered to the end user.
Test input	-
Test description	- Login as a user with Airframer Operator profile - Go to the section about stock optimization - Check the items displayed and choose an item - Check the performance indicators for the selected item - Check the items at repair or new orders - check aircraft flight activity information
Expected output	The system shows a list of items and for each of them the following information is displayed: • part number, • description, • quantity at stock, • recommended stock size • AOG events. For the selected item the system displays both in graphical and in numerical forms these performance KPIs: • Failure Pattern Detector • Removal Rate Alert • Risk Of Shortage The system shows a the list of items at repair that can be fitered by part nr, serial nr, status of repair and shows tracking information on each item at repair.

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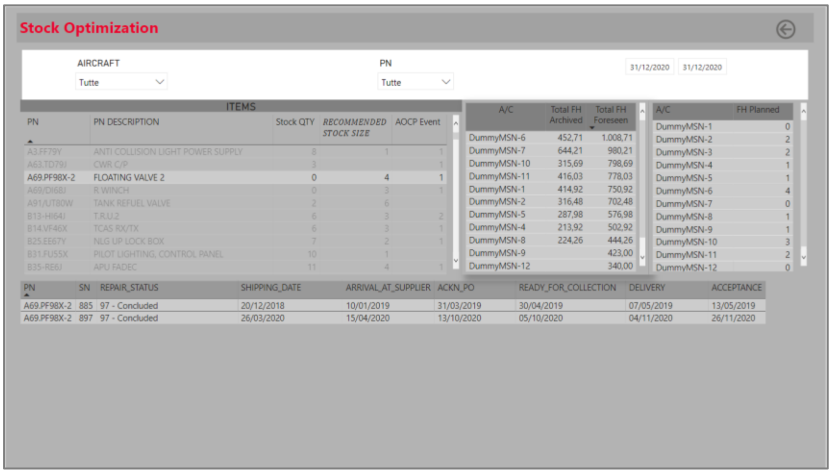
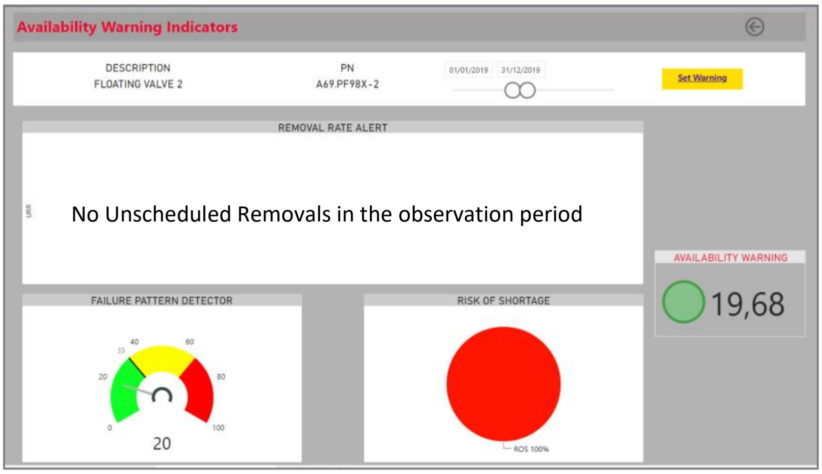
Test result	An example of the test result is given below. In the Stock Optimization section, the Airframer Operator can check the list of items with stock details and recommendations for stock improvements. In the picture below the user selected Floating Valve 2, where two parts are at repair (both concluded and delivered to the Customer).  The user can also check the Performance Indicators for the selected item along with the corresponding Availability Warning as depicted below: 

8.3.3. Data analysis in AHMS with quality statistics algorithms

This paragraph describes the analytics features the AHMS offers to support the AHMS users in their decisions.

- *Troubleshooting Component*
    - **Automatic association between Fault Codes and Item Removals**: an analytics algorithm in Python has been developed to automatically associate historical records between two databases, Aircraft Fault Code and Item Removals. This association is necessary for the calculation of the Success Rate KPI, that shows to the Maintenance Operator the most probable item to be replaced to solve a fault.
      Since no unique association key is available between a Fault Code and the relevant Item Removal, the algorithm search for elements in common within the records, like the aircraft causing the fault and the aircraft from which the faulty item has been removed, and identify a time-window to associate the most probable record couples in a decreasing probability order. Recommended "literature" solutions reported in Troubleshooting Manuals are used to support the process, but new associations can be identified.

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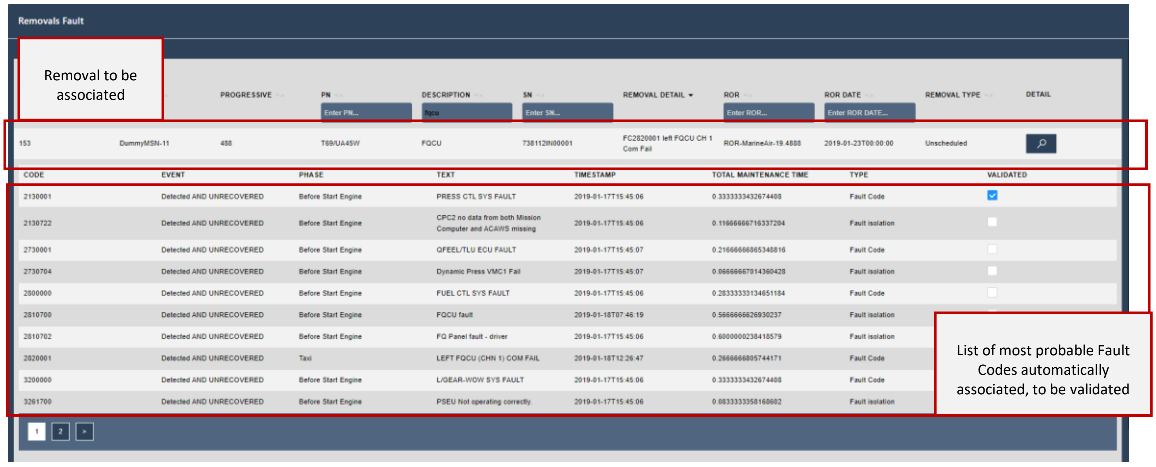
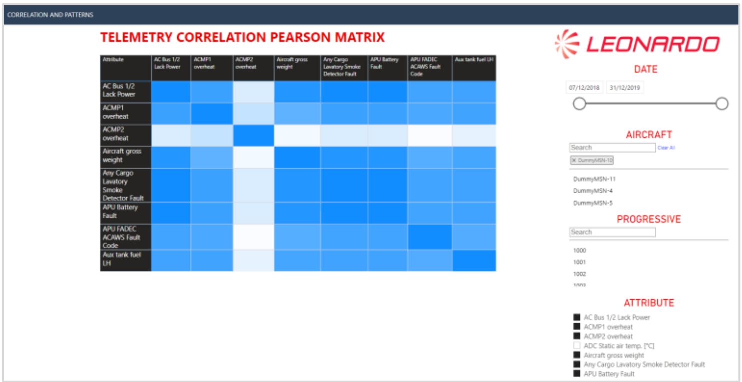
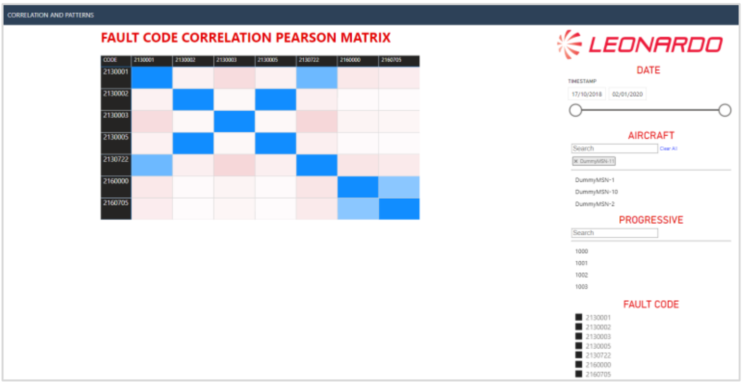
Then, the Airframer user can look at the results and validate only the proposed associations that he deems correct:



- **Correlation Matrix**: a Pearson Correlation Matrix has been developed to indicate, with a colour code, the grade of correlation between two variables (from -1 to 1) offering the possibility to investigate the correlation between flight parameters (Telemetry), Fault Codes and Telemetry-Fault Codes (see examples below). Investigating those correlations, the Airframer can identify new models that allows to predict possible failures of the equipment, to optimize the results shown in the *Troubleshooting* and *Spare Management Components*:





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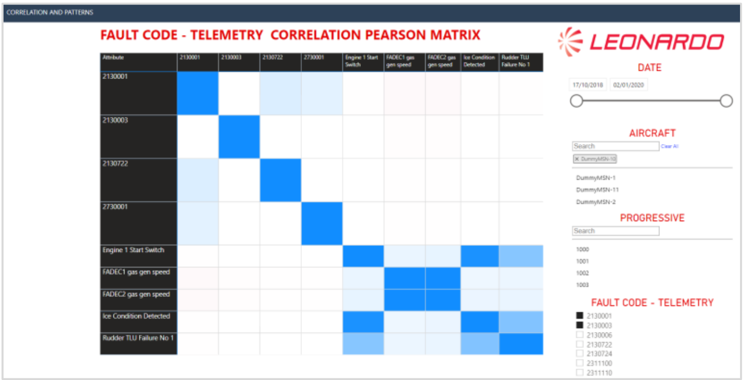
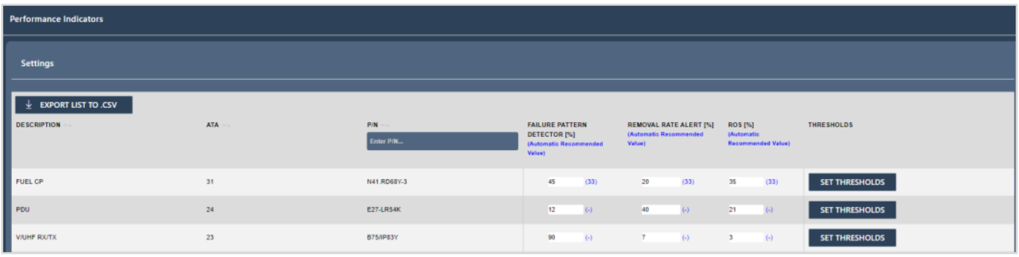


- *Spare Management Component*
  - **Recommended Weights and Thresholds**: the Spare Management Component provides to the Logistic Operator a predictive KPI, the Availability Warning, that measures the possibility of facing lack of spare parts to support maintenance operations.
    The KPI is based on the combination of three performance indicators: the Failure Pattern Detector, the Removal Rate Alert and the Risk Of Shortage, measured for each aircraft Item:

The combination of those performance indicators relies on weights and thresholds that can be tailored for each item by the Logistic Operator.
A dedicated algorithm has been developed to automatically recommend possible weights and thresholds value to be used (numbers in blue in the picture) considering the evolution of the three performance indicators and the actual Aircraft Out of Commission for Parts (AOCP) events reported:



The algorithm estimates future values of the performance indicators with forecast models, then compare the actual measured values with the estimated ones, to automatically recommend an increment, or decrement, in the thresholds and weights.
The accuracy of recommendations will depend on the amount of data feed to the system. The Logistic Operator can then choose to select custom values or to use the recommended ones.

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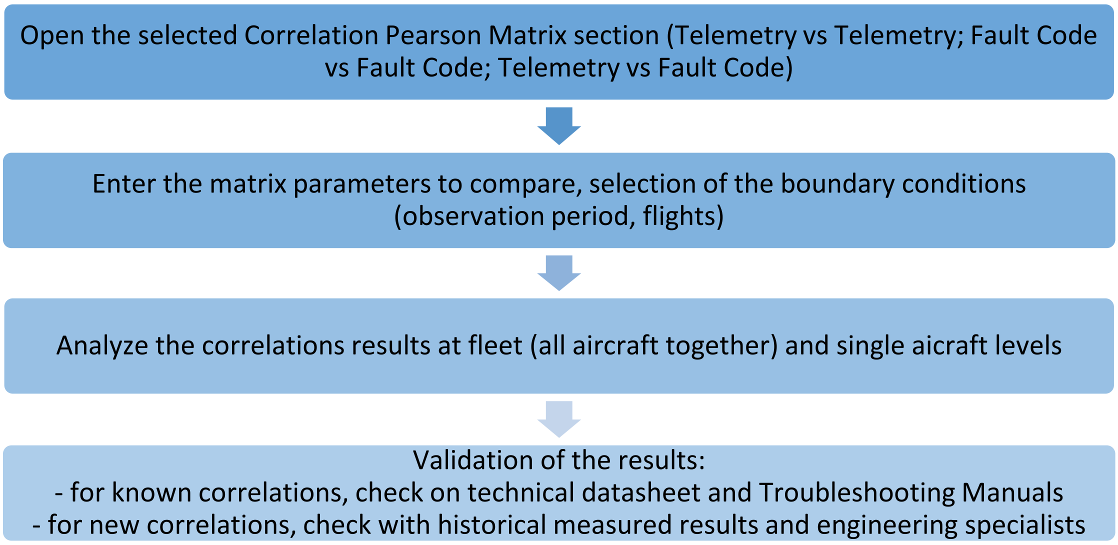
8.3.4. Identification of valid correlations of aircraft failures

Valid correlations have been identified in terms of Telemetry vs Telemetry, Fault Code vs Fault Code and Telemetry vs Fault Codes. Item Removals have been used to support or validate the analysis.

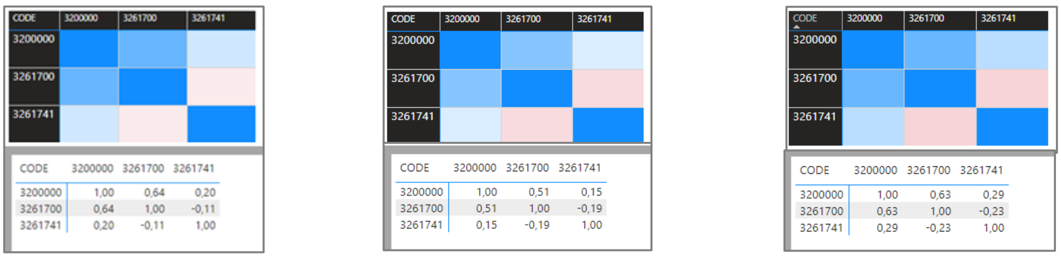
The process adopted to identify and validate the correlations is the following:



At first, the analysis focused on known correlations, to understand if the model is capable to correctly identify engineering proven relationships. Then, new correlations were explored.

Here are three examples of correlations: the numerical values represent the *Pearson correlation coefficient*, which is a measure of linear correlation between two set of data. Positive values correspond to positive linear correlation (1 is the maximum value), negatives correspond to negative linear correlation (-1 is the minimum value).

1. **KNOWN CORRELATION** – Aircraft System 32, Fault Code vs Fault Code: the "Fault Code Correlation Pearson Matrix" section has been used.
   This investigation has been performed on Fault Codes 3200000, 3261700 and 3261741, at Fleet and single aircraft level (as reference, only two aircraft with the highest amount of Flight Hours have been reported):



CODE	3200000	3261700	3261741
3200000	1,00	0,64	0,20
3261700	0,64	1,00	-0,11
3261741	0,20	-0,11	1,00

CODE	3200000	3261700	3261741
3200000	1,00	0,51	0,15
3261700	0,51	1,00	-0,19
3261741	0,15	-0,19	1,00

CODE	3200000	3261700	3261741
3200000	1,00	0,63	0,29
3261700	0,63	1,00	-0,23
3261741	0,29	-0,23	1,00

Figure 48: Fault Code vs Fault Code Investigation on System 32 for Fleet, aircraft DummyMSN-7, aircraft DummyMSN-11

From the relevant Troubleshooting Manual, the procedure to be followed during maintenance is:

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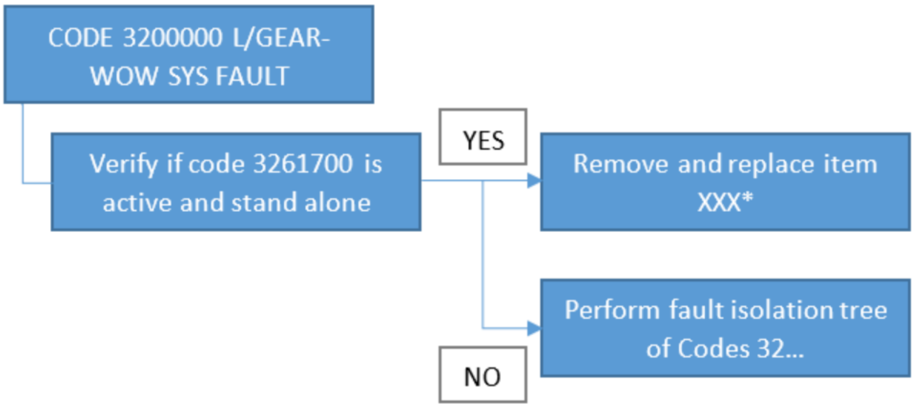

*Item details not reported since not significant for the investigation.

Code 3261700 allows to isolate from Code 3200000 the case in which a specific item XXX is causing the failure. Therefore, in these cases there is a linear positive correlation between the two Codes.

Code 3261741 is one of other alternative Codes that allows to isolate from Code 3200000 the case in which a different item is causing the failure. Therefore, there is a linear positive correlation with Code 3200000 and negative correlation with Code 3261700 (only one of the two can be active at the same time).
The solution is consistent at both Fleet and single aircraft levels.

2. **KNOWN CORRELATION** - Aircraft System 23, Fault Code vs Fault Code and crosscheck with Items Removals. Fault Codes 2350010 and 2331507 have been investigated:

Figure 49: Fault Code vs Fault Code Investigation on System 23 for DummyMSN-1, DummyMSN-2, DummyMSN-4, DummyMSN-5, DummyMSN-6, DummyMSN-7, DummyMSN-10 and DummyMSN-11

In this case, from Troubleshooting Manuals, Code 2350010 foreseen a series of Fault Codes to be tested, and therefore multiple possible items to be removed as in failure.

By investigating only one of these codes, 2331507, the test proved that on aircrafts that never experienced the failure, no relevant item removal has been experienced, while, whenever the Code 2331507 is present (with a positive correlation with Code 2350010), the removals of the relevant failed item have been reported by the Maintenance Operators.

3. **NEW CORRELATION** – Telemetry vs Items Removals. Starting from the historical removals of a specific valve of the Environmental Control System (ECS), the investigations aimed to identify a correlation with the Telemetries registered during flight.

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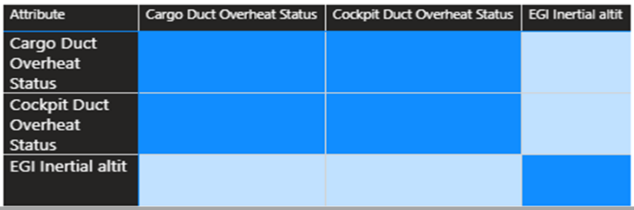
No specific Fault Codes are related to this issue, since the reasons for removal usually reports hot air in cockpit or cargo areas felt by the personnel. Therefore, the investigations focused on correlation between Cockpit/Cargo Ducts Overheat status and flight parameters. A relation was found with the aircraft altitude (EGI Intertial altit):



Attribute	Cargo Duct Overheat Status	Cockpit Duct Overheat Status	EGI Inertial altit
Cargo Duct Overheat Status	1,00	1,00	0,26
Cockpit Duct Overheat Status	1,00	1,00	0,26
EGI Inertial altit	0,26	0,26	1,00

Figure 50 – Monitoring Overheat status vs Flight EGI altitude Parameter to identify possible failure cause

Laboratory test confirmed that a relation between the actuation of the ECS valve and the variation of the altitude exists, which causes the hot air to be supplied to the ducts with consequent overheating.

8.3.5. Validated Troubleshooting requirements

The table below shows for each requirement set in D8.9 with high priority if the requirement was satisfied in the use case prototype, and provides a reference to the test case where it was tested and validated.

For each requirement you can see if is counted (1= requirement fulfilled; 0 = requirement not satisfied) to answer the question "AHMS Troubleshooting component is functional and fulfils its requirements.

Requirement ID D8.9	Description	Counted (for the metric)	Test ref. as from D8.7	Test and validation notes
UC7-OPR-11	The AHMS GF shall allow the Maintenance Operarator to access Throubleshooting service	1	8.3.5	Req. fulfilled
UC7-OPR-12	The AHMS GF shall allow the Airframer Operarator to access to Throubleshooting service	1	8.3.6	Req. fulfilled
UC7-FNC-73	The AHMS GF shall be able to store and manage the following data collected by the On-Board CPS of each aircraft of the Fleet: - alerts and warnings; - failures; - maintenance messages; - event date and time; - flight parameters.	1	8.3.1 8.3.2	Req. fulfilled

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UC7-FNC-74	The AHMS GF shall be able to store and manage the following data collected by the Maintainer CPS during Troubleshooting: - Aircraft ID (unique key for each aircraft in the AHMS GF); - Item ID (unique key for each item part number and serial number combination in the AHMS GF); - Maintenance Elapsed Time; - Maintenance Date and Time; - Activity typology: Item removed from aircraft or installed on aircraft; - Maintenance Operator User ID.	1	8.3.3	Req. fulfilled
UC7-FNC-77	The AHMS GF shall be able to calculate the success rate of each option included in a Fault Isolation procedure, as the percentage of the times in which an option solved the issue vs. the total times of the Fault Isolation procedure execution.	1	8.3.9	Req. fulfilled
UC7-FNC-78	The AHMS GF shall be able to determine the most probable faulty items to be removed for each Fault Isolation procedure using the success rate and relationship with fligth parameters patterns, if any	1	8.3.9	Req. fulfilled
UC7-FNC-80	The AHMS GF shall be able to show to the Maintenance Operator the Fault Codes that require a maintenance activity.	1	8.3.7	Req. fulfilled
UC7-FNC-81	The AHMS GF shall allow the Maintenance Operator to select a single, a subset or all the Fault Codes on which he will directly perform the activities.	1	8.3.7	Req. fulfilled
UC7-FNC-82	The AHMS GF shall be able to automatically show the Fault Isolation procedure, succes rate and possible items to be removed for each Fault Code selected by the Operator.	1	8.3.9	Req. fulfilled
UC7-FNC-86	The AHMS GF shall be able to access to the Warehouse CPS stock data and external Supply Chain management software (e.g. SAP) to show the Operator if a spare part is available for replacement.	1	8.3.9	Req. fulfilled
UC7-FNC-87	The AHMS GF shall be able to show the Maintenance Operator the designed Maintenance Time reported in the manuals and the average actual Maintenance Elapsed Time.	1	8.3.9	Req. fulfilled
UC7-FNC-89	The AHMS GF shall be able to associate to each removal and installation record the item additional information retrieved from a dedicated DB through the Item ID (e.g. item part number and serial number, description, Supplier, ...)	1	8.3.11	Req. fulfilled
UC7-FNC-90	The AHMS GF shall allow the Maintenance Operator to insert notes relevant to the Maintenance performed for each Fault Code: - Troubleshooting option that solved the issue; - Troubleshooting solutions different from Item removal (e.g. on-aircraft tests, minor components replacement, ...); - Textual description of the activity performed; - Summary of the Item removal reason, if any.	1	8.3.10	Req. fulfilled

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UC7-FNC-93	The AHMS GF shall be able to link to each Fault Code the removed Item ID, if any, along with the Maintenance and Airframer Operators note.	1	8.3.12	Req. fulfilled
UC7-FNC-94	The AHMS GF shall be able to analyse the flight parameters and the registered failures to identify possible parameters patterns that may cause a failure.	1	8.3.13	Req. fulfilled
UC7-FNC-95	The AHMS GF shall be able to link the failures, alerts and warnings messages to their relevant description retrieved from a dedicated DB.	1	8.3.7	Req. fulfilled
UC7-FNC-97	The AHMS GF shall allow the user to perform a search of failures, alerts and warnings showing relevant failure causes statistics.	1	8.3.9	Req. fulfilled
UC7-FNC-98	The AHMS GF shall allow the user to generate grouping queries on Fault Codes based on aircraft, date, removed item, Failure causes statistics.	1	8.3.9	Req. fulfilled
UC7-DSG-15	The AHMS GF shall be able to represent all the statistics using both charts and tables.	1	8.3.9	Req. fulfilled
UC7-DSG-16	The AHMS GF shall be able to support and manage Maintenance Procedures Manuals in xml or PDF.	1	N/A	Req. fulfilled by Microsoft Azure environment
UC7-FNC-102	The AHMS GF shall allow the Airframer Operator to look at the options success rate and the removed items in order to improve the Fault Isolation procedures.	1	8.3.15	Req. fulfilled
UC7-FNC-103	The AHMS GF shall allow the Airframer Operator to look at actual Maintenance Elapsed Times, automatically highlighting deviations between designed and actual values.	0,5	8.3.15	Actual Maintenance Elapsed Time reported. Not automatically reported the deviations between design and actual values
UC7-FNC-106	The AHMS GF shall allow the user to manage the list of removed items by: - looking at the list; - filtering the list; - generating grouping queries; - generating charts.	1	8.3.15	Req. fulfilled
UC7-FNC-108	The AHMS GF shall allow the user to export reports containing for a selected flight or a time period the following: - list of Fault Codes analysed; - list of Troubleshooting solutions; - list of removed items with details.	1	8.3.16	Req. Fulfilled
		23,5	**Out of 24**	**98%**

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8.3.6. Validated Spare Management requirements

The table below shows for each requirement set in D8.9 with high priority if the requirement was satisfied in the use case prototype, and provides a reference to the test case where it was tested and validated.

For each requirement you can see if is counted (1= requirement fulfilled; 0 = requirement not satisfied) to answer the question “AHMS Spare management component is functional and fulfils its requirements.

Requirement ID D8.9	Description	Counted (for the metric)	Test ref. as from D8.7	Test and validation notes
UC7-OPR-13	The AHMS GF shall allow the Logistic Operarator to access Spare Management service	1	8.3.26	Req. fulfilled
UC7-OPR-14	The AHMS GF shall allow the Airframer Operarator to access Spare Management service	1	8.3.27	Req. fulfilled
UC7-FNC-113	The AHMS GF shall be able to store and manage the following data collected by the Warehouse CPS: - Item ID and relevant quantities available at stock; - Item position inside the warehouse; - Warehouse environmental conditions; - Environmental conditions warnings; - Item moved from/to Suppliers;	1	8.3.23	Req. Fulfilled
UC7-FNC-114	The AHMS GF shall be able store and manage the following data for Scheduled activities retreived from a dedicated DB: - Item ID subject to Scheduled Maintenance (SM); - SM activity type (overhaul, discard, inspection, servicing, ...); - SM Task identifier; - Task interval; - Shelf life, if any; - Aircraft ID subject to SM.	1	8.3.28	Req. Fulfilled
UC7-FNC-115	The AHMS GF shall be able to manage the Customer flight activity, stored in a dedicated DB, in particular: - actual achieved Flight Hours (FH) per aircraft per day; - planned FH per aircraft per day.	1	8.3.25	Req. fulfilled
UC7-FNC-116	The AHMS GF shall be able to manage external parts Track & Trace software (e.g. SAP) data, like: - Items to be shipped to Supplier and relevant data; - Items shipped to Supplier and relevant data; - Items coming back from Supplier and relevant data; - New purchased spares.	1	8.3.24	Req. fulfilled

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UC7-FNC-119	The AHMS GF shall be able to automatically retrieve from a dedicate DB for each item its unique Reference Number used to group different part numbers, the relevant Quantity installed on aircraft (QPA) and the number of Unscheduled Removals (UR).	1	8.3.29	Req. fulfilled
UC7-FNC-121	The AHMS GF shall allow the Logistic Operator to look at all the Items ID subject to SM in a table, ordered by increasing Estimated Expiration Date, that reports: - Item description; - SM Activity Type; - SM Task Identifier; - Aircraft ID; - Estimated Expiration Date; - Availability Warning.	1	8.3.28	Req. fulfilled
UC7-FNC-122	The AHMS GF shall be able to calculate Items Reliability Key Performance Indicators (KPI) relevant to a specific Observation Period: - Unscheduled Removals Rate (URR) [1/1000 FH]= #UR / (QPA x Sum(aircraft FH)) x 1000 - Mean Time Between Unscheduled Removals (MTBUR) [FH] = 1 / URR x 1000 - Gradient = angular coefficient of the Linear Regression Trend line of URR - Standard Deviation (SD) = standard deviation of the URR	1	8.3.29	Req. fulfilled
UC7-FNC-123	The AHMS GF shall allow the user to change the observation period interval and typology (weeks, quarters, years).	0,5	8.3.29	Is it possible to change the observation period, not the period typology
UC7-FNC-124	The AHMS GF shall allow the Logistic Operator to look at a list of Top Unreliable Items, orderd by increasing URR, that reports: - Item description; - Item repairability type (Repairable/Not Repairable/Consumable); - Number of UR; - Reliability KPI; - Availability Warning. The Last Reliability Analysis Date shall be shown with the list.	1	8.3.29	Req. fulfilled Note: Last Reliability Analysis Date equal to the date of the dashboard opening
UC7-FNC-126	The AHMS GF shall update the Reliability KPI at defined time intervals, based on the actual hours flown. The relevant Last Reliability Analysis Date shall be updated consequently.	1	8.3.30	Req. fulfilled
UC7-FNC-127	The AHMS GF shall be able to calculate an Availability Warning for each Item subject to Scheduled or Unscheduled removals using a Weighted Average Method that combines three Performance Indicators: - Failure Patterns Detector; - Removal Rate Alert; - Risk of Shortage (ROS).	1	8.3.31	Req. fulfilled

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	The Availability Warning numerical results shall be scaled to 100.			
UC7-FNC-128	The AHMS GF shall be able to calculate a Failure Patterns Detector as a mathematical value between 0 and 100 that indicates a low, medium or high severity of the indicator, based on the failures occurrences number of each item. For each item the thresholds are: - LOW: x failures occurrences in the last flight - MEDIUM: x failures occurrences in the last n flight - HIGH: y failures occurrences in the last n flight where x, y and n are values customizable by the user and tailored to each item.	1	8.3.31	Req. fulfilled
UC7-FNC-129	The AHMS GF shall be able to calculate a Removal Rate Alert as a mathematical value between 0 and 100 that indicates a low, medium or high severity of the indicator, based on a comparison between the actual URR and three alert levels. For each item the thresholds are: - Low: Actual URR lower than the URR_{Avg} - Medium: Actual URR between URRAvg and (URRAvg +2*Standard Deviation) -High: Actual URR higher than (URRAvg +2*Standard Deviation)	1	8.3.31	Req. fulfilled
UC7-FNC-130	The AHMS GF shall be able to calculate for each item a ROS as a mathematical value between 0 and 100 that indicates a low, medium or high severity of the indicator, based on a Poisson distribution that considers the Customer demand rate, the parts Supply Chain status, the foreseen Scheduled Removals and Customer flight activity. In details the ROS formula can be expressed as: ROS = 1 - SUM(λ^k*e^-λ/k!) where: - k goes from 0 to ST. SIZE-1 - λ = (T*Daily FH*QPA)/MTBUR is the Demand Rate - T = forecast days for the analysis or Turn Around Time (TAT) - ST.SIZE = number of items available at stock minus the number of items required for scheduled activities. For each item the customizable thresholds are initially set to: - Low: ROS lower or equal to 5% - Medium: ROS between 5% and 25% - High: ROS equal or higher than 25%	1	8.3.31	Req. fulfilled
UC7-FNC-131	The AHMS GF shall allow the Logistic Operator to modify the weights and thresholds assigned to each Performance Indicator and the Availability Warning thresholds.	1	8.3.32	Req. fulfilled

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UC7-FNC-132	The AHMS GF shall allow the Logistic Operator to document if a removal has caused an Aircraft On Ground (AOG) condition due to missing of parts.	1	8.3.33	Req. fulfilled
UC7-FNC-133	The AHMS GF shall be able to suggest modification to the weights and thresholds assigned to each Performance Indicator, using the actual AOG recorded.	1	8.3.34	Req. fulfilled
UC7-FNC-134	The AHMS GF shall be able to show the Logistic Operator the Availability Warning using a pre-defined set of colour scheme based on user customizable low, medium and high level thesholds: - Green: parts available, Availability Warning value lower or equal to 25; - Yellow: possible parts unavailability foreseen, Availability Warning value between 25 and 60; - Red: parts unavailability foreseen, Availability Warning value equal or higher than 60.	1	8.3.31	Req. fulfilled
UC7-FNC-135	The AHMS GF shall allow the Logistic Operator to look at the calculated Performance Indicator for each SM or Top Unreliable Item selected from the lists.	1	8.3.35	Req. fulfilled
UC7-FNC-138	The AHMS GF shall allow the user to export a report with: - parts available at stock; - parts in the Supply Chain; indicating for each part the relevant Availability Warning, if calculated.	1	8.3.37	Req. fulfilled
UC7-FNC-139	The AHMS GF shall allow the user to export a report with the foreseen Scheduled Maintenances, including the Availability Warning, if calculated.	1	8.3.38	Req. fulfilled
UC7-FNC-140	The AHMS GF shall allow the user to export a report with a selected number of Top Unreliable Items, including the Availability Warning, if calculated.	0,8	8.3.39	Req. fulfilled Note: it is not possible to select a number of Top Unreliable Items, it is possible to insert filters to identify subset of items
UC7-FNC-141	The AHMS GF shall allow the user to filter and generate queries on items subject to SM and Top Unreliable Items list.	1	8.3.28	Req. fulfilled
		24,3	**Out of 25**	**97%**

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8.4. UC8 Test case results details [TRUMPF]

The following paragraphs provide details on the output of the tests executed according to the test plan (see D8.7.

8.4.1. Semantic Enrichment Module Test

<table>
<tr><td>Test Name</td><td>Semantic Enrichment Module Test</td></tr>
<tr><td>Test ID</td><td>8.4.1</td></tr>
<tr><td>Test Type</td><td>component</td></tr>
<tr><td>Test purpose</td><td>Testing whether the detection and recognition rate of TRUMPF and third-party machines from 2D images and a 3D shopfloor scan is sufficiently high. The test success metrics are defined in D3.3.</td></tr>
<tr><td>Test input</td><td>A shopfloor scan from TRUMPF Customer Center containing:
A colorized point cloud (see Figure 51) and
360-degree images (see Figure 52)</td></tr>
<tr><td>Test description</td><td>The semantic enrichment module is tested using the 3D scan. Since the required 360-degree images were provided for a subsection only this area was labelled and evaluated.

The models applied in this test scenario were trained on two-dimensional images from the web. Therefore, the data included in the 3D scan was not used during training.

A prototypic implementation combines the results of individual models. Since the models operate on 2D images, the 360-degree images are firstly transformed to multiple planar images. The models then can predict the type of a machine, the producer, and the machine series. Partially, the models provide positional information. Those positional information and classification results are subsequently transformed back to three-dimensional space. A fusion combines the information provided over time and space.

The performance is measured two-fold:
top-k accuracy: Measured is the correctness of the top k predictions of the type of a machine, the producer, and the machine series.
intersection-over-union (IOU): Measured is the correctness of position and orientation of predictions. IOU describes the overlap of the prediction and label.</td></tr>
<tr><td>Expected output</td><td>Top-1 accuracy should exceed 80%.
IOU should exceed 80%.</td></tr>
<tr><td>Test output</td><td>The output contains multiple components:
A semantic map containing environmental information regarding:
Free space
A height-map
Walls
Doors
And markings on the floor
Information regarding the equipment containing
Producer, type, and series of a machine</td></tr>
</table>

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	o Position and orientation The schematic output is displayed in Figure 53. The user interface (see Figure 54) allows the correction of labels, position and borders, but also allows to add connections between equipment. An IOU of 97.42% and a top-1 accuracy of 98% were measured.

Figure 51: 3D hallscan of the TRUMPF Customer Center in Ditzingen.

Figure 52: A 360-degree image of the TRUMPF Customer Center in Ditzingen.

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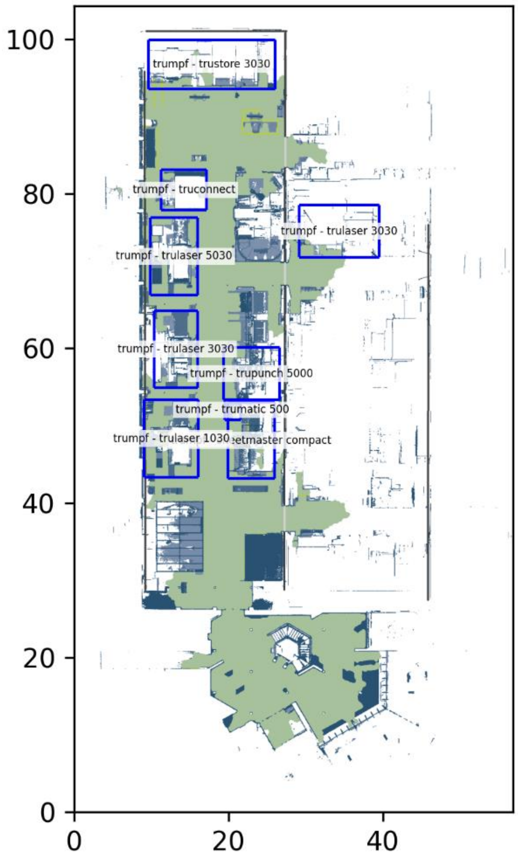

Figure 53: Results of the semantic enrichment of the TRUMPF Customer Center in Ditzingen. Scale in meters.

Figure 54: User interface for making final adjustments to equipments. A connection to another device is created.

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8.4.2. UWB Infrastructure Test

Test Name	UWB Infrastructure Test
Test ID	8.4.2
Test Type	Component
Test purpose	Test if the UWB Infrastructure works as expected and in the defined operation limits
Test input	Installed Track and Trace system in a shop floor. Instrumentation of system according to test plan. Including: simultaneous movement of larger number of tags, benchmarking, association of product and order information, upload of position to cloud.
Test description	UWB infrastructure is deployed and evaluated based on the Track and Track release qualification tests. This includes a localization quality assessment and cloud connectivity testing, among others. The tests of the UWB infrastructure were conducted in conjunction with WP3. In D3.4 the detailed tests and test results are presented.
Expected output	Localization accuracy is within specified boundaries. Position and order information successfully communicated to cloud for further processing. UI and Hardware E2E all work as expected and defined.
Test output	**Localization accuracy:** The test results are shown in Figure *55*. We found that for all points and all marker heights the system fulfilled our accuracy requirements of: • at least 50% of the positions fall within an accuracy of 0.80m • at least 80% of the positions fall within an accuracy of 1.50m **Localization latency** when moving 80 markers at the same time as depicted in Figure 56: • The localization frequency of all markers was stable at 1Hz as defined by the specification. **Transfer of position information to the Track and Trace cloud server:** • local connectivity client reporting the successful upload of positions and the by observing the incoming messages on our cloud based Kibana instance as shown in • The uplink worked as specified **Testing of association of product and order information:** • In this e2e test a specific order information was entered into the Track and Trace UI and it was verified under various that the assignment was both digitally (mapping in database, UI visualization) and physically (EINK on marker showing correct entry) correct. • The mapping worked as specified. A screenshot can be found in Figure 58.

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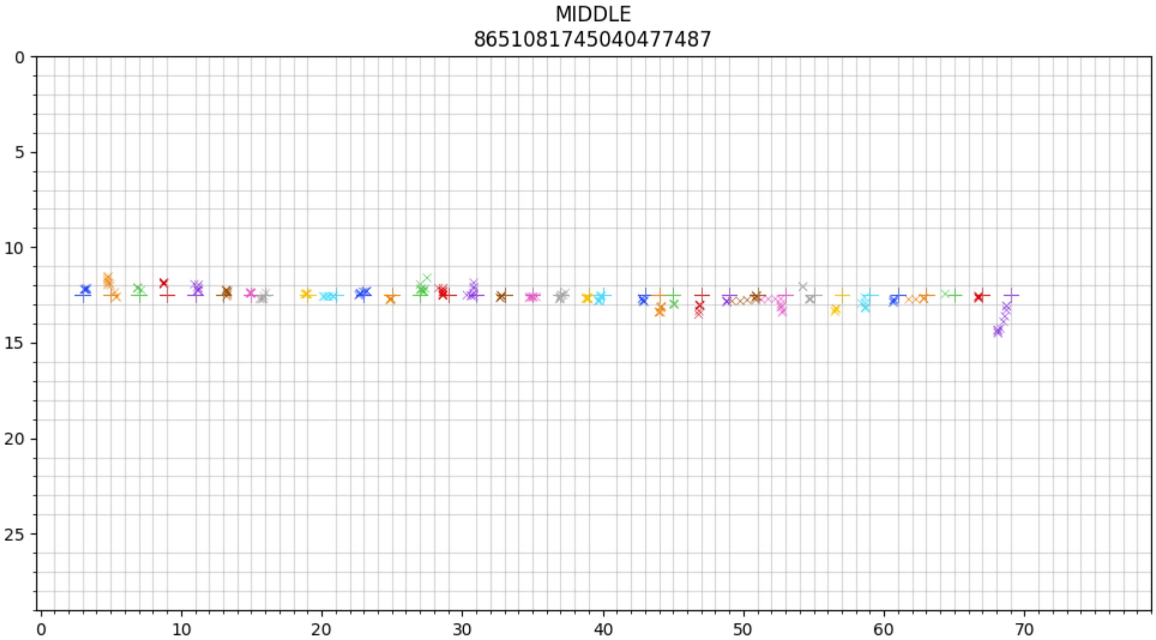

Figure 55: Example of benchmark for a single marker moving along the main axis of the instrumented shop floor: "+" symbols indicate the true position; "x" symbols indicate the position estimated by the UWB infrastructure.

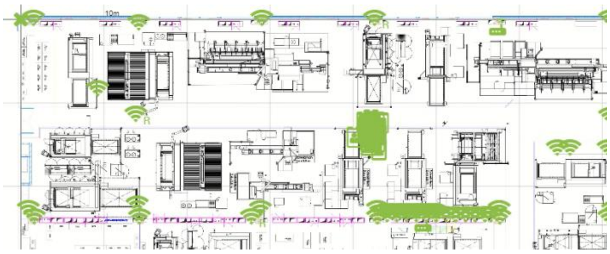


Figure 56: Left: Test of the joint movement of 80 markers (green group of markers in the middle of the UI screenshot). Right: To simulate the production case where 80 markers move simultaneously we placed them side by side on a production table and rolled them through the shop floor.

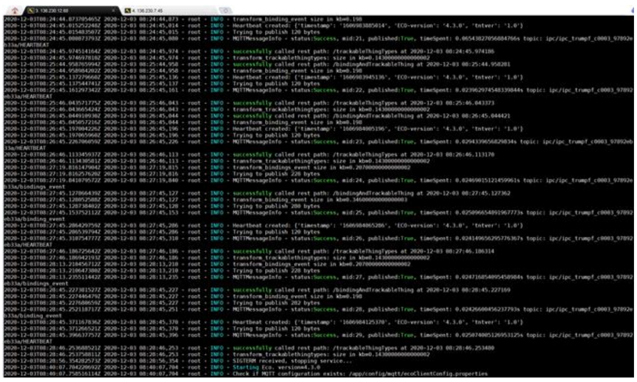
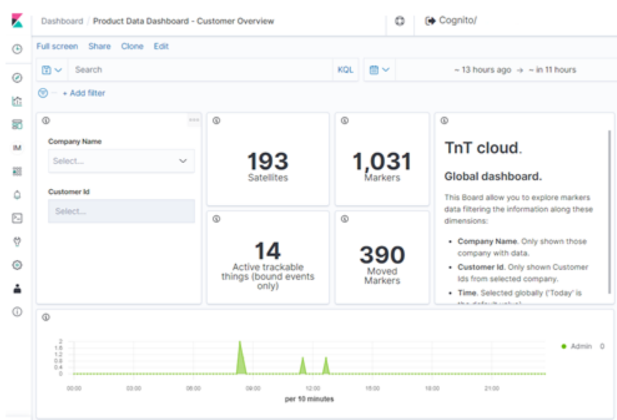

Figure 57: Left: Cloud connector running on TNT edge device reports successful upload of heartbeat and postion data. Right: Receipt of position data in Kibana allows for analysis of UWB infrastructure

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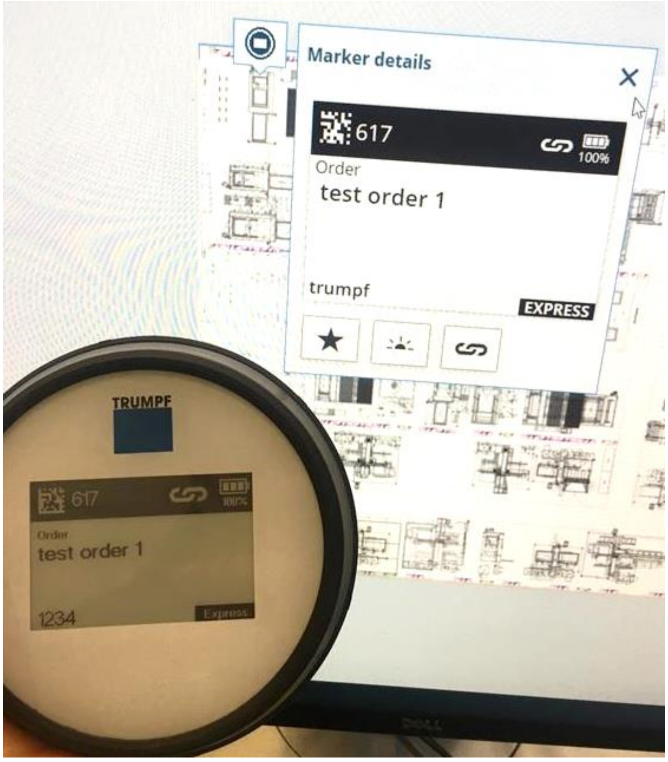

Figure 58: Consistency between physical marker and digital twin of marker in Track and Trace UI.

8.4.3. Interface Test

Test Name	Interface Test
Test ID	8.4.3
Test Type	integration
Test purpose	Validation whether the results from the semantic enrichment module are exported correctly in the defined data exchange format. The results should then be importable to the simulation model framework.
Test input	machine types and respective positions from 8.4.1
Test description	The results from 8.4.1 are exported in the defined exchange format. The exchange file is checked for compliance with the .xml standard and the defined structure. It this then checked, if the results can be imported into the simulation model.
Expected output	The export from the semantic enrichment module results into the defined json exchange format works properly and the results can be imported into the simulation model framework.
Test output	The generation of simulation models according to shopfloor descriptions works as expected.

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8.4.5. Simulation Model Unit Tests

Test Name	Simulation Model Unit Test
Test ID	8.4.4
Test Type	component
Test purpose	Verification whether the simulation model units interact correctly with each other.
Test input	Updated simulation model library Test production orders
Test description	Multiple test cases are created for each simulation model unit. In each test case different combinations of machines, automation units and intralogistics agents like AGVs or workers are performed. An example can be seen in Figure 59. For each release of the simulation model library all test are automatically executed by a batch script which is depicted in Figure 60. Their results are exported as an Excel file shown in Figure 61.
Expected output	Findings on errors that occurred due to an update of the simulation model logic.
Test output	All tests were executed successfully for the final status of the simulation model library as depicted in Figure 61.

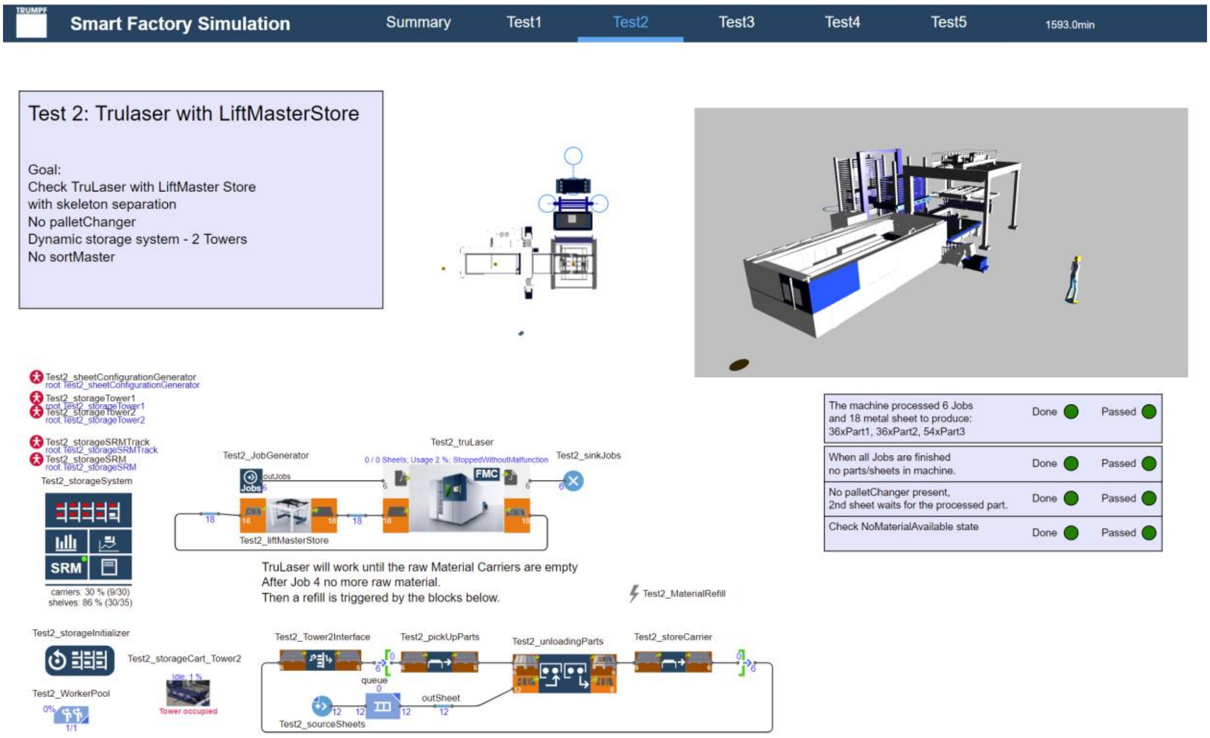

Figure 59: Example simulation model unit test

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```
@ECHO OFF
rem
rem Copy Excel File Template
copy "%cd%\ModelTestLibrary\*.xlsx" "%cd%\ExportedTests"
rem
rem
rem Copy xml files needed for OrderSchedulerTests
rem
copy "%cd%\OrderSchedulerTests\*.xml" "%cd%\ExportedTests\OrderSchedulerTests_RunOrderSchedulerTest"
copy "%cd%\OrderSchedulerTests\*.xml" "%cd%\ExportedTests\OrderSchedulerTests_RunWorkOrderSourceTest"
cls
rem
rem  RunAnylogicTest.bat        TestFolderName     TestCaseName          PackageName          TestModelleDir.
rem  -----------------------    -----------       ---------------------  -------------------  --------------
call RunAnylogicTest.bat        EdgeBreakerTest    RunEdgeBreakerTest     edgebreakertest      %cd%
call RunAnylogicTest.bat        FlatMasterTest     RunFlatMasterTest      flatmastertest       %cd%
call RunAnylogicTest.bat        LiftMasterTest     RunLiftMasterTest      liftmastertest       %cd%
call RunAnylogicTest.bat        LiftMasterTest     RunLiftMasterStoreTest liftmastertest       %cd%
call RunAnylogicTest.bat        LoadMasterAK10Test RunLoadMasterAK10Test  loadmasterAK10test   %cd%
```

Figure 60 Batch file that executes the automatic unit tests

	Test Model	Experiment	TestCase	TestCase Description	Check Description	CheckResult
4						
5	EdgeBreakerTest	RunEdgeBreakerTest				
6						
7			Test1_testCase	Testet die korrekte Verarbeitungvon Jobs und Parts.Prüfung der Visualisierung in geänderter Orientierung.		
8				Test_automaticCheck1	Nach 18 Minuten muss der erste Job und 10 Parts verarbeitet sein.	pass
9				Test_automaticCheck2	Wenn der Job beendet ist müssen 10 Parts verarbeitet sein.	pass
10				Test_automaticCheck3	Check if height, width, length and weight are set correctly	pass
11				Test_automaticCheck4	Check if operationID is set correctly	pass
12						
13			Test2_testCase	Testet die korrekte Verarbeitungvon Jobs und Partsbei automatisiertem Beladen und geänderter Orientierung.		
14				Test2_automaticCheck1	Nach 18 Minuten muss der erste Job und 10 Parts verarbeitet sein.	pass
15				Test2_automaticCheck2	Wenn der Job beendet ist müssen 10 Parts verarbeitet sein.	pass
16						
17			Test3_testCase	Testet das korrekte Zusammenspielmit einem Lagerbaustein bezüglich Materialanforderung. Unter Anderemob Folgepaletten für einen Auftragangefordert werden.		
18				Test3_automaticCheck1	Nach 40 Minuten muss der erste Job und 18 Parts verarbeitet sein.	pass
19				Test3_automaticCheck2	Wenn der Job beendet ist muss die zweite Palette weg sein.	pass
20						
21			Test4_testCase	Testet den Bürstenwechselmechanismusmit unterschiedlichen Materialien und nach Zeit.		
22				Test4_automaticCheck1	Zwischen Job 1 und Job 2 findet ein Bürstenwechsel wegen Material- wechsel statt.	pass
23				Test4_automaticCheck2	Zwischen Job 2 und 3 findet ein zeitbedingter Bürstenwechsel statt.	pass
24	FlatMasterTest	RunFlatMasterTest				
25						
26			Test1_testCase	Testet die korrekte Verarbeitungvon Jobs und Parts.Prüfung der Visualisierung in geänderter Orientierung.		
27				Test1_automaticCheck1	Nach 18 Minuten muss der erste Job und 10 Parts verarbeitet sein.	pass
28				Test1_automaticCheck2	Wenn der Job beendet ist müssen 10 Parts verarbeitet sein.	pass
29				Test1_automaticCheck3	Check if height is set correctly	pass
30				Test1_automaticCheck4	Check if operationID is set correctly	pass
31						

Figure 61 Export of the unit test results as Excel file

8.4.6. Simulation Model Performance Test

Test Name	Simulation Model Performance Test
Test ID	8.4.5
Test Type	component
Test purpose	Verification whether the simulation model units cycle times meet the required precision
Test input	• Defined validation cycles for simulation model units (e.g. picking up, moving and dropping a part in a certain way) • Time measurement with the same parameters as the simulation model
Test description	Test scenarios are defined for each simulation model unit. Real experiments are conducted under the same circumstances as in the simulation. The deviation regarding cycle times is measured. A validation experiment example can be found in Figure 62. The values of the axes of an automation unit are displayed.
Expected output	The simulation model cycle times have a maximum deviation of 5%.

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Test output	After some adjustments in the model parameters, all simulation model units met the precision requirements under defined circumstances. However, stochastic effects such as machine downtimes or human interaction that occur in reality are not included in the simulation models and require further investigation.

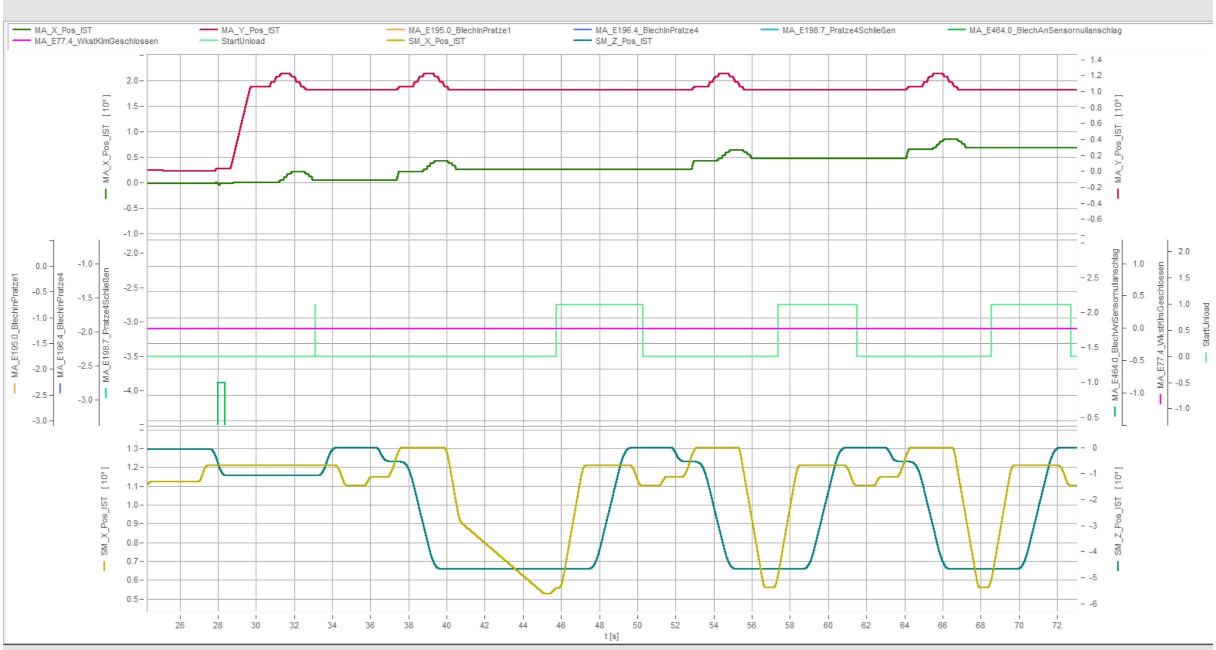

Figure 62: Screenshot of axis values of an automation unit visualized in IMC Famous

8.4.7. Simulation Model Generation Test

Test Name	Simulation Model Generation Test
Test ID	8.4.6
Test Type	system
Test purpose	This test shows if a) data from the simulation configurator can be received and interpreted by the Simulation Model Framework and b) if this data can be used to produce an initial Simulation Model. Remark: This test also covers the test purpose of the Interface Test (for details see D8.7 Test 7.4.3)
Test input	- 8 synthetic machine position datasets for additional test cases - Production data configured by the simulation configurator using the results from the UWB localization data
Test description	- A shop floor scan is performed and processed by the Semantic Enrichment Module. The extracted data is provided to the Simulation Model Framework - Locations and location-bound order information is provided to the Simulation Model Framework - Simulation Model Framework consumes this data

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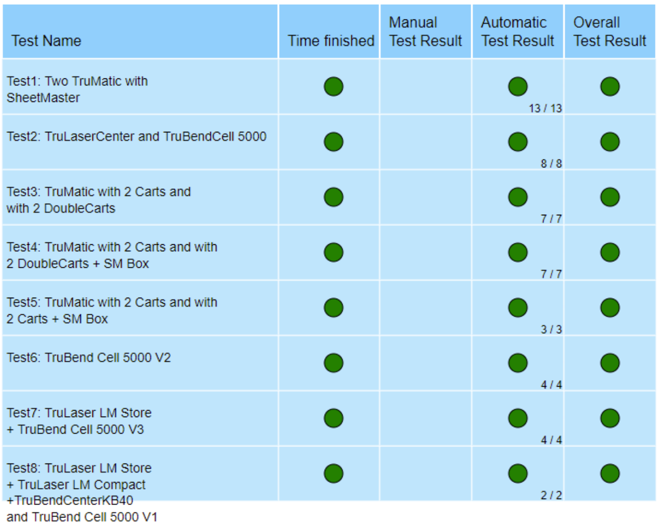
	- Simulation Model Framework creates an initial model based on this data - The created model is evaluated by an expert
Expected output	The created model meets the requirements for an initial simulation model.
Test output	All 8 test cases were executed successfully for the final status of the simulation model library as depicted in the dashboard in Figure 63. An example screenshot of a test case can be found in Figure 64.



Test Name	Time finished	Manual Test Result	Automatic Test Result	Overall Test Result
Test1: Two TruMatic with SheetMaster	●		● 13 / 13	●
Test2: TruLaserCenter and TruBendCell 5000	●		● 8 / 8	●
Test3: TruMatic with 2 Carts and with 2 DoubleCarts	●		● 7 / 7	●
Test4: TruMatic with 2 Carts and with 2 DoubleCarts + SM Box	●		● 7 / 7	●
Test5: TruMatic with 2 Carts and with 2 Carts + SM Box	●		● 3 / 3	●
Test6: TruBend Cell 5000 V2	●		● 4 / 4	●
Test7: TruLaser LM Store + TruBend Cell 5000 V3	●		● 4 / 4	●
Test8: TruLaser LM Store + TruLaser LM Compact +TruBendCenterKB40 and TruBend Cell 5000 V1	●		● 2 / 2	●

Figure 63: Simulation model generation test dashboard

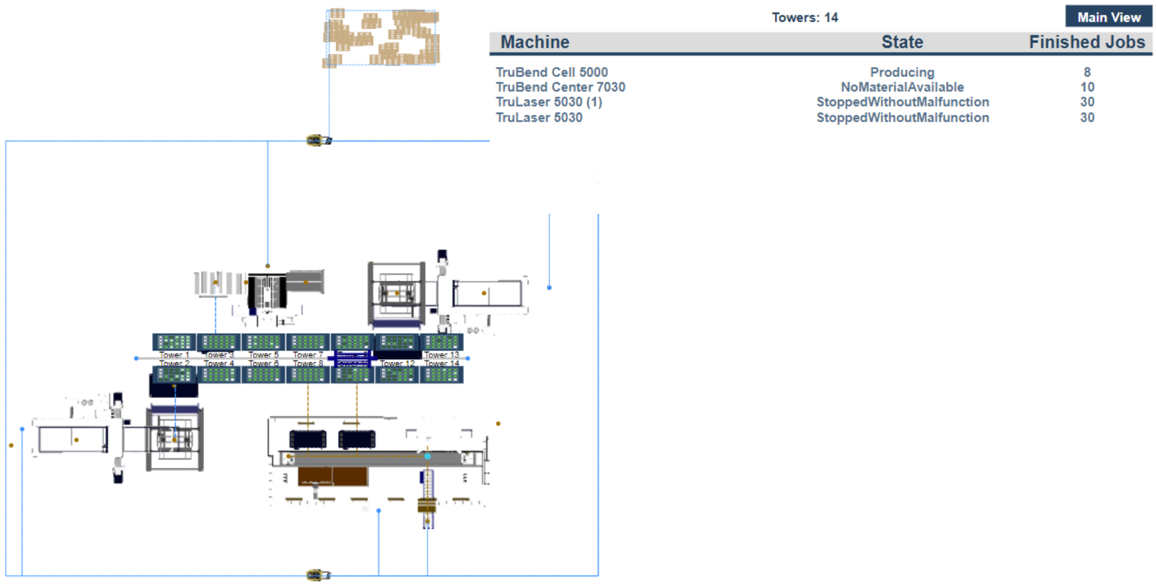


Figure 64: Example simulation model generation test

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8.4.8. Overall Use Case Test

Test Name	Overall Use Case Test
Test ID	8.4.7
Test Type	acceptance
Test purpose	System validation
Test input	3D shopfloor scan and 2D images from TRUMPF customer center
Test description	The semantic enrichment module detects and recognizes the machines and their respective positions from the 3D shopfloor scan and 2D images. This information is exported in the defined exchange format which is fed into the simulation model generator. The resulting simulation model is compared to a reference model that has been created manually according to the existing floor plan.
Expected output	executable material flow simulation model of the TRUMPF customer center
Test output	The material flow simulation model of the TRUMPF customer center works as expected and delivers KPIs for future production scenarios. An example dashboard that visualizes the KPIs for a TruLaser machine can be found in Figure 65.

Figure 65: Example KPI Dashboard

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8.5. UC9 Test case results details

The following paragraphs provide details on the results of the tests executed.

8.5.1. MATLAB Simulation

Test Name	MATLAB Simulation
Test Type	System
Test purpose	To show that the control values can be transmitted to a MATLAB Simulation of a crane and result in an simulated Movement. The resulting orientation and positions shall be transmitted back to the cloud for further calculations.
Test input	• Recorded control signals from a physical model are send to the Relayr cloud.
Test description	The cranes in the MATLAB simulation will move according to the sent signals resulting in a new orientation and position of the main boom. Its values are then transmitted to the Relayr cloud.
Expected output	New geometric data of the crane representation is received by the cloud and be used for further calculations.

8.5.2. Anomaly detection

Test Name	Anomaly detection
Test Type	System
Test purpose	Detect abnormal behaviour in the movement of the crane. For example the change in inclination of the the main boom, shall not be too high in a defined timeslot (Derivation dAngle/dt <= threshold)
Test input	• Dataset with received geometry data and timestamps
Test description	The anomaly detection will apply DBSCAN and OPTICS algorithms on the data and will report found errors
Expected output	When a dataset with erroneous values is sent to the anomaly detection it shall report an error.

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8.5.3. Measure delay

Test Name	Measure delay
Test Type	System
Test purpose	Detect the time between the sending and receiving of data from the cloud to the MATLAB simulation and back. This time shows how close the real world application and the simulation would fit each other.
Test input	Timestamp of sending and timestamp of receiving
Test description	Save the timestamp when the input data is sent and save the timestamp when the result is received. Log the delay in a file and calculation the average delay time.
Expected output	The expected time is less than 0.8s.

8.5.4. Navigation Algorithm

Test Name	Navigation Algorithm
Test Type	Component
Test purpose	To show that the drone can successfully navigate to specific location and with required orientation while avoiding obstacles
Test input	• Drone Take-off • Drone navigate (x,y,z,roll.pitch.yaw)
Test description	The drone will prepare itself and take-off. It will then run the algorithm and navigate to a specified location and orientation.
Expected output	The status of the simulation and the internal sensors of the drone did not report aa single crash for all the test cases. The navigation was accurate with an average error of 0.03m for any required coordinate.

8.5.5. Object Detection and Position Estimation

Test Name	Object Detection and Position Estimation
Test Type	Component
Test purpose	To show the drone camera can successfully detect the object and estimate the right position with respect to itself
Test input	Detect the object Calculate the Position
Test description	The drone will detect the object using a real-time object detection algorithm and will run its position estimation algorithm, generate the detected position and compare it with the actual position.

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Expected output	The deviation between the detected position and the actual position ranged from 0.2 m to 0.7 m with an average of 0.45m

8.5.6. Exploitability analysis of the receiver module of the crane

To ensure code quality, UnA's tool MoCoAnalyzer was adopted and used on parts of the use case. The MoCoAnalyzer was developed during WP5 activities including a modelling editor and multiple analyses on architecture and code level. The tool is detailed in D5.6. UnA supported WIKA with this tool during their modelling of the use case and following analysis activities. The test was executed in several steps. Firstly, the structural view of the use case was created using the MoCoAnalyzer (Figure 66). Then, the bevioral model of the receiver module was derived from program code describing the behavior of the receiver module (Figure 67). Followed by connecting the behavioral and structural models. Lastly, UnA's three code-based analyses were applied on the use case.

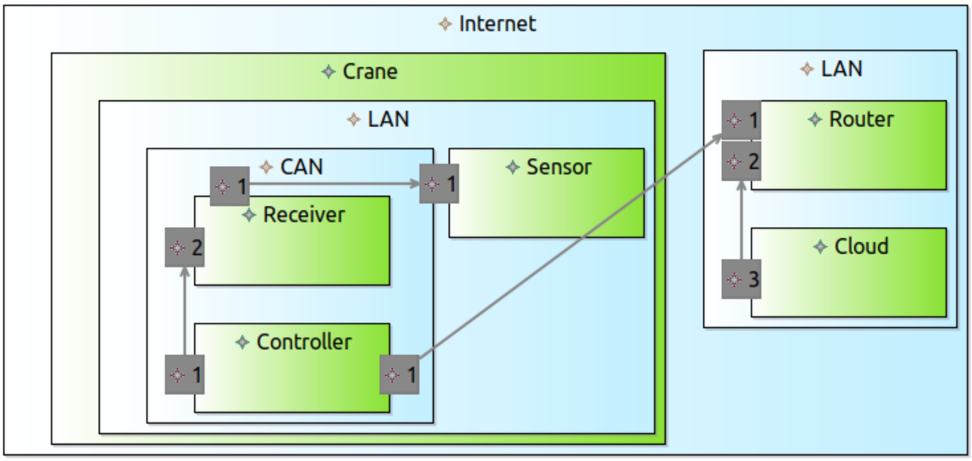

Figure 66: System model of use case 2

The results of the first step are detailed in Figure 66 showing the structural view of parts of the use case created with the Model Editor as part of the MoCoAnalyzer. The Model Editor and the underlying meta model was created during WP1 activities and initially detailed in D1.1 and updated in D1.9 and D1.2. A detailed description of the available classes can be found in these deliverables. The modelling process was conducted based on information from WIKA. The resulting system model represents the structural view of parts of the use case focussing on the orchestration of networks. There, a sensor sends data to a receiver through a LAN. The receiver is connected to a controller via CAN. The controller can communicate with cloud services over the internet by utilising a router. The sensor, the receiver and the controller are mounted on a crane. The behaviour of the receiver was further described by program code. The MoCoAnalyzer supports the automatic transformation of program code into code models by invoking the LLVM framework. The framework is used to compile and optimize input data into LLVM-related compilation artefacts. These artefacts are abstractly linked and lossless transformed into a code model. This procedure represents the second test step. The result of this step is shown in Figure 67 picturing a snipped of the resulting code model:

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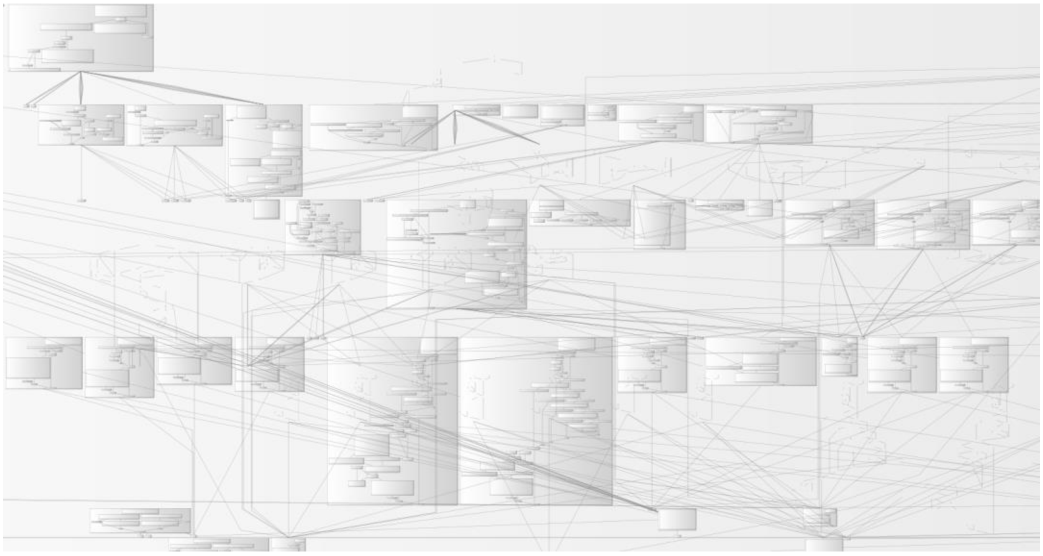

Figure 67: Code model describing the behavior of the receiver

The meta model of this model type was created during WP1 activities and initially detailed in D1.9 and updated in D1.2. In summary, the code meta model enables the merging of source code with machine code and compilation artefacts. In our case, the LLVM framework was used resulting in the generation of artefacts written in the LLVM Intermediate Representation. An example extracted from Figure 67 can be found in Figure 68 showcasing a function, its basic blocks and their instructions.

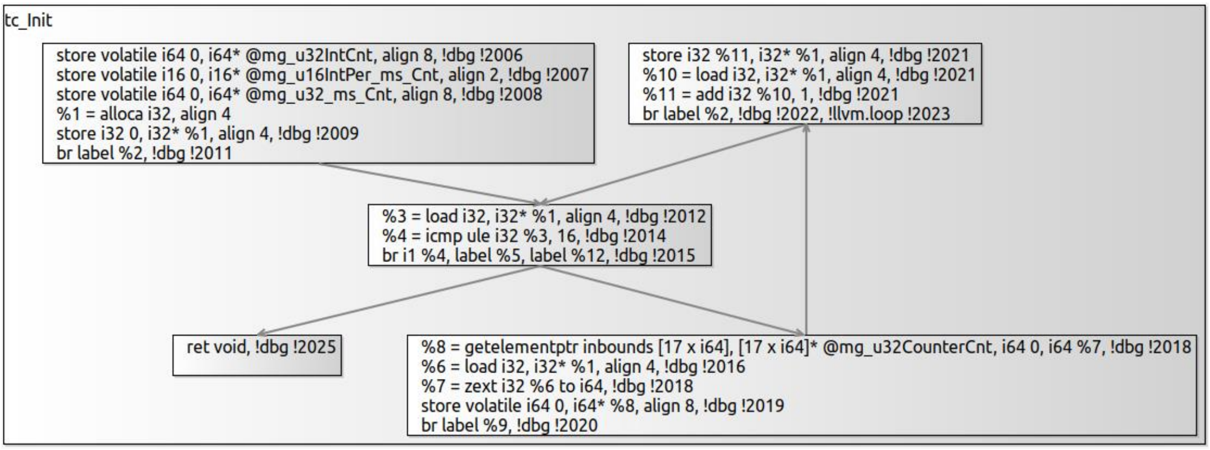

Figure 68: Function contained in the code model

The third step consists of linking the system model with the code model. This is achieved by associating functions of the code model to services or machine-related entities of the system model. In more detail, the ability for system components to communicate with each other is usually provided by precompiled libraries. Thus, functions that transfer data from or to such libraries are marked and manually associated with services and machine entities of the system model. Based on this information, connections are derived that connect the components of the system on the code layer. Since the code model describes the behavior of the receiver, certain functions of the code model were linked to the *Receiver* entity of the system model shown in Figure 66.

The last step involves executing UnA's three code-based analyses. The analyses follow an iterative process. Firstly, the code model is scanned for code weaknesses. Then, the discovered weaknesses are elevated to vulnerabilities and their severity is assessed. Lastly, the impact of these vulnerabilities on the entire system is analyzed.

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CWE	MoCoAnalyzer	
	Warnings	Reachable
Out-of-bounds Read	0	0
Use After Free	0	0
NULL Pointer Dereference	0	0
Out-of-bounds Write	0	0

Table 17 - Results of code-based analysis

The results of the first code-based analysis are detailed in Table 17. We expected to not find any code weaknesses as WIKA is forced to check their code on certain code weaknesses by law. However, one problem with static code analysis tools is the large number of false positives. Thus, if we had found any number of code weaknesses, we could have assumed that false positives were present, but as expected, the code model did not contain any of the code weaknesses. Therefore, no false positives were found. A validation of the results is contained in chapter 0. As no weaknesses were found, the second and third code analyses were not applicable to the use case.

8.6. References

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