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VerSatilE plug-and-play platform enabling remote pREdictive mainteNAnce

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Summary:

This document reports the deployment of SERENA's services on Whirlpool's use case, including the outcomes of testing and validating the SERENA experiments from the end-user perspective

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List of Abbreviations

AI	Artificial Intelligence
API	Application Programming Interface
AR	Augmented Reality
CEN	European Committee for Standardisation
CMMS	Computerized Maintenance Management System
CWA	CEN Workshop Agreement
DB	Database
ENG	Engineering IT Solution spa
FMECA	Failure Mode Effect and Criticality Analysis
HMI	Human Machine Interface
ICT	Information and Communications Technology
KPI	Key Performance Indicator
MIMOSA	Machinery Information Management Open Systems Alliance
ML	Machine Learning
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
OEM	Original Equipment Manufacturer
OEE	Overall Equipment Effectiveness
P	Pressure
PaaS	Platform as a Service
PC	Personal Computer
PLC	Programmable Logic Controller
POLITO	Politecnico di Torino
POIL	Pressure of Oil
PM	Predictive Maintenance
PU	Polyurethane
RT	Realtime
RUL	Remaining Useful Life
SaaS	Software as a Service
SCADA	Supervisory Control And Data Acquisition
SME	Small and Medium Sized Enterprise
SMP	Standardized Maintenance Procedure
SQL	Structured Query Language
T	Temperature
TCM	Total Cost of Maintenance
TRL	Technology Readiness Level
VPN	Virtual Private Network
WHR	Whirlpool EMEA

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Executive Summary

In this document, it is reported the WHEMEA demonstrator's description and the results of the experiments done in strict correlation with its business impact. The main objective of the WHEMEA demonstrator was to improve the maintenance procedures on the most expensive and critical element of the foaming machine: the injection head.

Three different experiments have been set up: a first experiment was dedicated to evaluating the platform from the connectivity point of view to establish a reliable database; a second broad experiment, divided into three scenarios, was dedicated to evaluating the capability of the SERENA platform to extract relevant information from the data to influence in a positive way the maintenance of the head, i.e., to verify its health status (diagnostic) and to provide indications on the actions to be done (prognostic); a third and last experiment was addressed to evaluate SERENA platform on its function-oriented to maintenance operator. Each experiment has been linked with the KPIs impacted.

The document is finally describing the overall evaluation of the use case owner from a quantitative point of view, showing how KPIs can be impacted by SERENA and from a qualitative point of view, showing how SERENA provided a set of learnings that will be used in future adoption.

1 Demonstrator overview

1.1 Motivation and goals

Whirlpool demonstrator is focused on the prediction of the behaviour of the injection head of a polyurethane foaming machine as described in [1].

The demonstration focused on the intense analysis of the foaming machine's data, especially on the mechanical sensor applied in the injection head.

The main scope of the demonstrator is to identify and validate a mechanism of health prediction through the correlation of sensor data to alarms recorded at the machine level, which are good indicators of severe problems upcoming on the injection head.

The main target is to develop a RUL (Remaining Useful Life) estimator and thus allow the maintenance organization to schedule substitution of the injection head just before its irreversible damage.

This can positively impact the business: reducing unexpected breakdowns and impacting OEE; reducing maintenance cost, and improving main maintenance KPIs (MTTR and MTBF).

WHR expectation from the demonstrator:

1) Evaluate and validate analytical strategy to extract as much possible useful information from available data
2) Evaluate the robustness of the technical solution to ensure good trust in the system from the operators
3) Evaluate the effectiveness of data visualization platform
4) Evaluate the effectiveness of RUL estimation
5) Evaluate the AR support tool to maintenance operator

1.2 Testing environment and timeline

The demonstration has been carried out within the refrigeration factory in Biandronno, particularly on the cabinet foaming machine of the double door model production line. The complete description of the equipment is reported in [1] and below a simple schema is presented for the sake of reading clarity throughout the document.

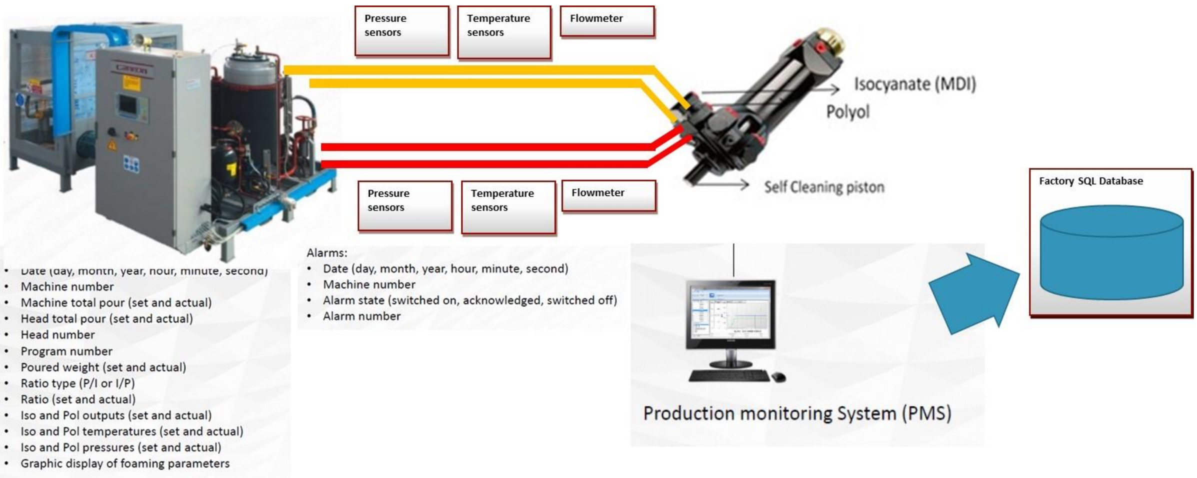


Figure 1. Equipment schematic description

A first data connection was available in March 2018. However, a second improved dataset with added sensors data is available since September 2019.

1.3 SERENA system deployment

Machine's sensors are available to the SERENA platform through an SQL database connected with the already available SCADA system. A gateway provides a robust and secure way to transfer the data in RT from the factory DB to the SERENA platform using a VPN provided by WHR. Data Visualization and Analytics were provided back to operators via the SERENA platform.

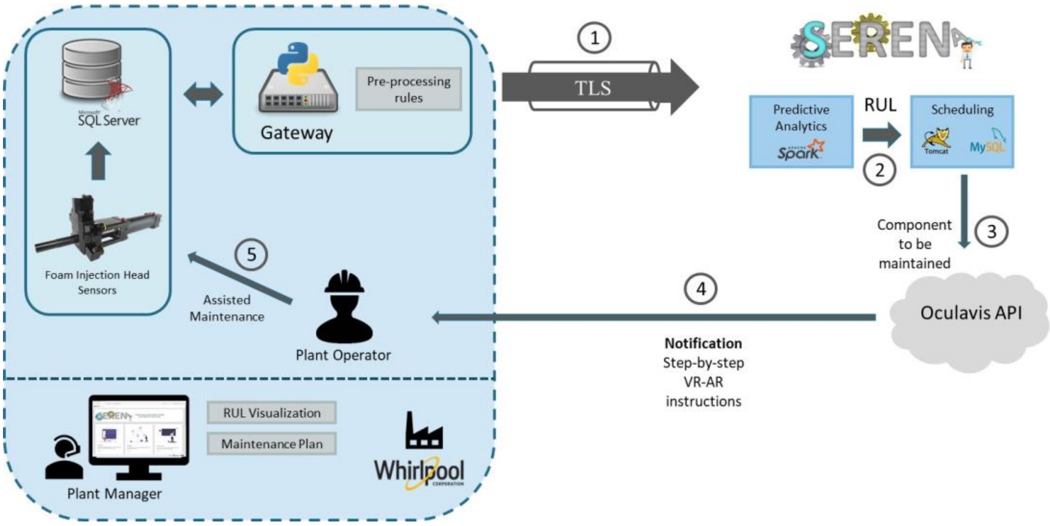


Figure 2. SERENA testbed configuration

2 Experiments

2.1 Testing objectives

The complexity of the matter of predictive maintenance for a foaming plant, lets WHR use case to identify and realize three major sets of experiments.
The potential failure component identified using FMECA is the "Mixing Head" of the foaming machine and it is the subject of predictive maintenance. Therefore, **SERENA** shall be aiding in predictive maintenance to meet the following objectives.

- To avoid the potential breakdown of predictive maintenance.
- To maximize the operating life of the component
- To improve maintenance operators in their effectiveness
- To reduce cost

The experiments are therefore oriented in the validation of the key technological enablers provided within the SERENA platform:

- ✓ **Remote condition monitoring & control:** Verify and validate those old and new sensors installed and the data format of their output are compatible and flexible to work with the factory's existing system. This will provide the necessary robustness of data flow and will serve as a foundation for trust achievement.
- ✓ **AI condition-based maintenance and planning techniques:** The edge computing techniques, based on artificial intelligence algorithm, applied to the data and the machine learning model to correlate data with failures mode and classify the level of technical intervention needed. (E.g.: Normal/Warning/Urgent)
- ✓ **RUL calculation:** the definitive approach to evaluate and communicate the health status of the mixing head is the RUL: this parameter, estimated at every cycle, is used primarily to schedule the related maintenance activity (head substitution).

The three experiments directly or indirectly impact the business and this impact is measured through basic and well known KPIs as presented in Table 1.

Table 1: Current scenario metrics

Metrics	Explanation	Current state	Notes
OEE	Overall Equipment Effectiveness	80%	(Approximated in %). Crucial to meet the production timelines
MTTR	Mean time to repair	3,5 h	To be reduced to maximize the availability of production.
MTBF	Mean time between Failures	180 days	The operating time of the component before the system fails
TCM	Total Cost of Maintenance	40.000 Euros/Year	This TCM accounts only for mixing head.

2.2 SERENA features to be tested

In WHR use case, due to the complexity of physical phenomena and considered the high level of integration of the expected solution with legacy systems are not achievable in the project itself, just a small number of features has been completely tested:

1) The secure connection between the source of data, represented by the SQL database installed in factory premises and the SERENA platform implemented in the ENGINEERING cloud.

2) The data analytics features addressing the capability to discriminate, find and implement a robust and consistent correlation and predictive algorithm expressed eventually in an RUL estimation of the injection head
3) The visualization of the RUL and the data supporting the prediction in the platform
4) The implementation of the maintenance sequence through AR tool to an operator.

2.3 Experiments and results

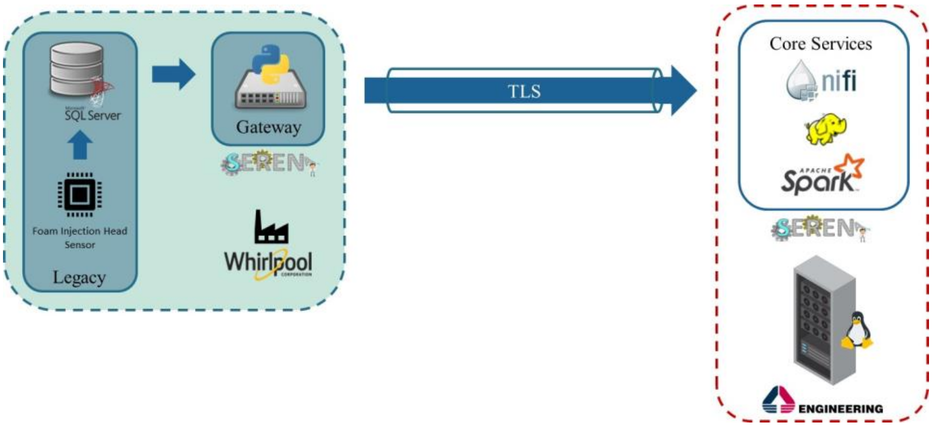
<table>
<tr><td colspan="3">Objective 1 – Sensor Data connection to Platform</td></tr>
<tr><td colspan="3">This experiment is meant to test the hardware connection between the machine and the SERENA cloud platform: the availability of SERENA as a PaaS or SaaS is of primary importance for WHR potential future consideration and the underlying mechanism to guarantee a consistent flow of data between from primary source (SQL DB associated with machine SCADA) to the services implemented in a cloud has to be validated.</td></tr>
<tr><td colspan="3">Expected result – Interconnection of dataflow from the equipment to SERENA platform</td></tr>
<tr><td colspan="3">99.999% of data availability</td></tr>
<tr><td rowspan="8">Scenario 1</td><td colspan="2">Scenario description</td></tr>
<tr><td colspan="2">The selected architecture to integrate the SERENA platform into the WHR shopfloor consists of a gateway installed in an Edge on WHR premises, connected with the SERENA platform in the cloud.


Figure 3. Data connection
The gateway is communicating to ENG cloud through a VPN maintained by WHR. This mechanism is not the best choice for a permanent installation, but it has been the only one authorized by WHR Cybersecurity department for the research project. The scope of the experimentation is to validate that the mechanism is robust enough to deliver all the data recorded in the local DB to the platform without any loss and in the proper time.</td></tr>
<tr><td>Features to be tested</td><td>Target result</td></tr>
<tr><td>Data Integrity, Consistency</td><td>No data loss</td></tr>
<tr><td colspan="2">Results</td></tr>
<tr><td colspan="2">The gateway installed in WHR premises allowed a consistent and robust data connection between the legacy systems represented by SQL server and SERENA platform with no data loss recorded and with demonstrated capacity to recover partial unavailability of the elements involved. The VPN demonstrated its limitation (very well known since the beginning) and will be of course not considered as a to go choice for a production (that will most probably rely on a firewall opening)</td></tr>
<tr><td colspan="2">Feedback/Comments</td></tr>
</table>

	The architecture tested positively is a significant achievement since it provides a solution to future implementation ranging from an on-premises solution to a mix of Edge + Cloud solution.
Achieved Metric/KPI value:	System Reliability (enabler for good trust)

Objective 2 – Injection Head health status recognition and RUL determination

This is the fundamental and most important objective experimented in SERENA: to find a good correlation between sensor data and the health status of the mixing head with the final result of being able to calculate a RUL and thus plan for the head substitution before a breakdown and only when strictly needed thus increasing its lifetime. Both these aspects are directly impacting two of the most important KPIs for maintenance: machine availability (reflected in OEE) and MTBF.

Expected result

The expected result is that it is possible to avoid one unexpected breakdown and to increase the lifetime of the head from 180 days to 360 days.

Scenario 1

Scenario description

Pressure and Temperature data inference.

In this first scenario, conducted from M6 to M18, the data coming from existing sensors has been analysed to verify whether some correlation with mixing head status was present. The rationale behind is due to the hypothesis that a compromised behaviour of the valves and the cleaning piston in the mixing head could reflect on the pressure and temperature of the two-component (e.g. for some leakages or some obstructions). A total of more than 65000 cycles where analyzed using different algorithm from POLITO,

Features to be tested	Target result
Algorithm for condition sensing	Head blockage prediction

Results

Data has been analysed using different AI algorithm but no evident correlation between data (P and T) and events head substitution were found.

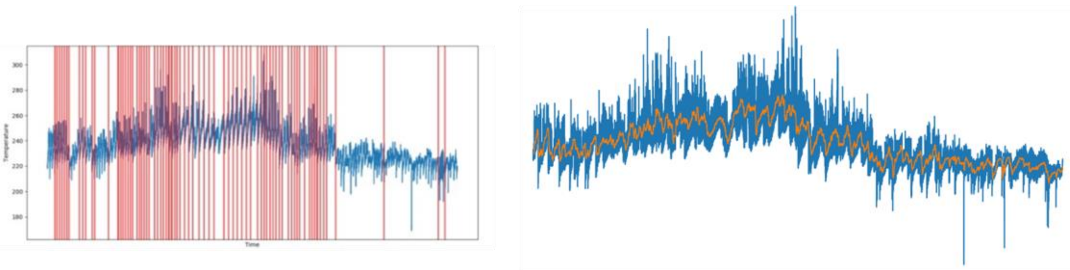


Figure 4. Data analysis via AI

Feedback/Comments

The hypothesis that P and T data could help to infer the injection head health status was unfortunately not confirmed. The reason why we were looking for it is that these data are straightforward to obtain and are commonly monitored in every foaming machine: a potential correlation would have meant a very cheap and quick solution to provide a reliable reduction and thus to enable fast adoption of PM.

Scenario 2

Scenario description

Vibration data inference.

The second scenario was dedicated to a more focused approach: a new mixing head, supplied by a machine supplier (Afros Cannon), equipped with a set of embedded sensors representing mechanical stresses measured on the cleaning pistons.

<table>
<tr><td rowspan="7"></td><td colspan="2">

Figure 5. The analysed machine

After a first analysis of the data, a potential robust correlation mechanism was hypothesized, in the fact that two specific flows coming from the head could bring information on injection head status as represented by the generation of alarms (Self Cleaning Piston Blocked).</td></tr>
<tr><td>Features to be tested</td><td>Target result</td></tr>
<tr><td>Algorithm for condition sensing</td><td>Head blockage prediction (RUL)</td></tr>
<tr><td colspan="2">Results</td></tr>
<tr><td colspan="2">Data from sensors installed on the new head has been correlated with pre-alarm recorded in SCADA system: a good correlation has been found between prediction and real event (F1(0) score = 0.98)</td></tr>
<tr><td colspan="2">Feedback/Comments</td></tr>
<tr><td colspan="2">The experiment in this scenario brought significant results: 1) the preliminary analysis conducted in scenario 1 allowed to restrict the field of correlation between few signals (POIL1,POIL2) with a restricted number of hardware alarms (piston blocked); 2) the algorithm applied to verify the potential correlation between signals and events recorded in the equipment during a long period of time (> 6 months of data) resulted in a high capacity of prediction represented by a F1 score of 0.98</td></tr>
<tr><td rowspan="2">Scenario 3</td><td colspan="2">Scenario Description</td></tr>
<tr><td colspan="2">RUL determination
Once verified the correlation between sensor data and events, the scope of the third part of the experiment was oriented in developing the algorithm for RUL estimation applying a double phase, a ML phase on a known cause and effect dataset and a verification phase on other parts of the dataset (parts of the dataset represent period of time, usually many months each).
The ML algorithm has been trained on a set of data recorded before the physical events of a breakdown. The algorithm has then tested on other period of data to test it robustness. The results of it has been transferred to a RUL algorithm implemented in the platform.</td></tr>
</table>

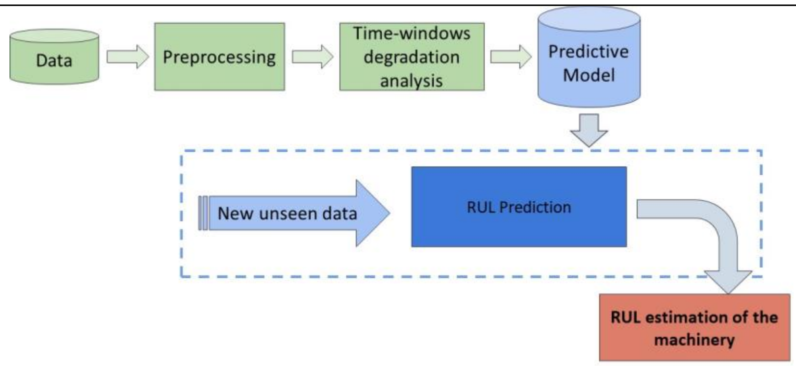


Figure 6. Analytics architecture

The dataset used for this experiment was all the sensor data recorded from December 2019 to May 2020; the cycles used for the ML was those from October 2019 to December 2019: end of previous life cycle.

Features to be tested	Target result
Estimate RUL	Head remaining life prediction in # cycles

Results

From all the previous analysis done a specific connection between two input signals (*Force, Self cleaning Piston, closing*' and '*Force, Self cleaning Piston, opening*' has been correlated with a known adverse event (*Alarm Head Blocked*). This data has been used to train the system and applied to other period of dataset for validation, The experiment provided very good results:

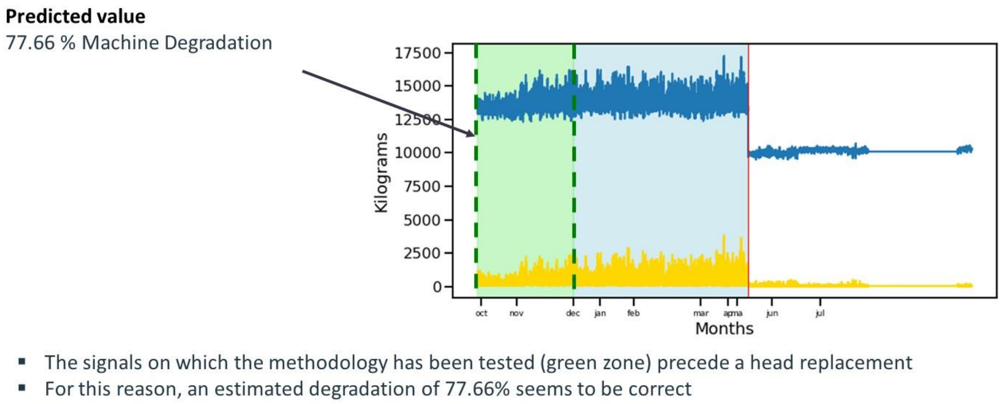


Figure 7. SERENA results

This approach has then been used to determine RUL and as such, implemented in the SERENA platform:

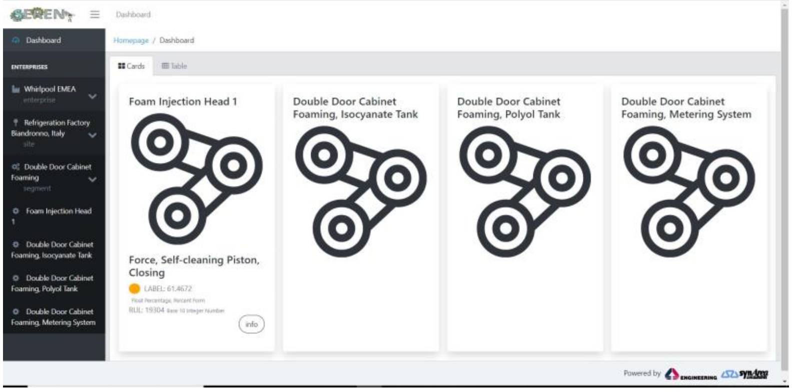


Figure 8. SERENA's dashboard

The RUL for injection head is expressed in numbers of cycles, since this is the physical entity most representative for expressing the RUL and it is commonly used in WHR maintenance department. It can be translated in number of shifts or days by dividing it by the number of pieces produced during a shift or a day (1 cycle 0 1 product) which is a very well known quantity by each operator.

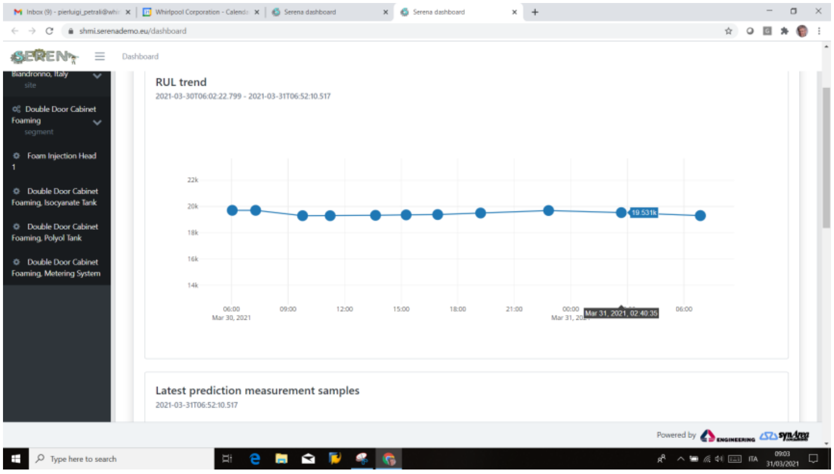


Figure 9. Predictive analytics service

The graph is showing the trend of RUL estimation and the raw data used for its last projection is also displayed to reinforce the connection between the RUL and the source data used.

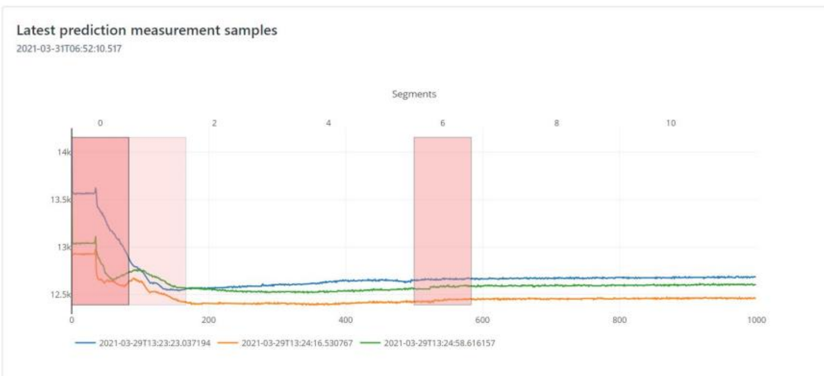


Figure 10. Connection between RUL and source data

The RUL is then being used by the maintenance organization to arrange the head substitution in the proper time: whether in advance in respect of Preventive Maintenance plan to avoid unforeseen breakdown, or in delay to improve the head lifetime. In any case, the ability to plan the substitution some day before the event allows for a saving cost and have impact on OEE (thanks to an increased machine availability) and MTBF, TCM (breakdown avoidance).

SERENA platform is also providing a basic scheduler that can be used alone or in conjunction with an existing CMMS to schedule the task associated with the specific failure in the timeline indicated by RUL estimation.

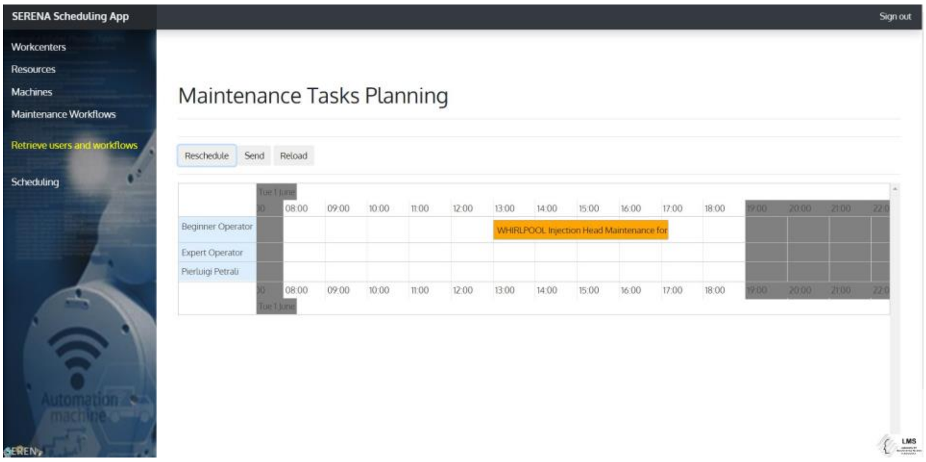


Figure 11. Scheduling service

In this specific case two typologies of maintenance operator has been defined (Beginner and Expert operator), both enabled to the task associated with a specific time (it can be different depending on each single experience or proven skill): the task can be then rescheduled by Manager to choose the best timeframe to optimize cost.

Feedback/Comments

This new experimentation actually identified the easiest and more effective way to use data sensor and managed to achieve the objective of selecting few signals to be analysed instead of many. This lesson can be used in the future allowing to reduce the number of sensor and speeding up the machine leaning phase. Moreover the correlation found between data (Force Closing and Head Blocked) provided a condition that can be used to determine RUL and thus provide a quantitative information to maintenance to organize their work to replace the injection head when its health status is deteriorated but avoiding breakdowns.

Achieved Metric/KPI value:	Reduction of OEE, TCM, Improvement of MTBF

Objective 3 – AR operator support	
Implementation of AR support to guide operators during Standard Maintenance Procedures	
Expected result	
Maintenance Worker improve the effectiveness	
Scenario 1	**Scenario description**
	Whirlpool current procedure for maintenance scheduled activities is represented by SMP (Standardized Maintenance Procedure), a simple document (usually an Excel file) describing the steps to perform a specified activity.

Whirlpool PROCEDURA STANDARD DI MANUTENZIONE 3

SAP CODE:

Fabbrica	Area	Macchina	Sottogruppo	Componenti		Responsabile
REF	LINEA 3	TAMBURO	TESTE DI INIEZIONE	Testa iniezione afros FLP 14	JMEZZH0377	MANUTENZIONE

Time Based Maintenance

☐ Elettrico ☒ Meccanico ☐ Fluidodinamica

☐ Pulizia ☐ Lubrificazione ☐ Ispezione

Stato macchina	Attività	Ricambi:
OFF	SOSTITUZIONE TESTE INIEZIONE	Testa iniezione afros FLP 14
N° Operatori		Durata [min]:
0		140
N° Manutentori		Frequenza mesi:
2		6
PPEs		Attrezzatura:
		chiavi fissa del 22 e 27 chiavi a brugola del 6 e 8

Attenzione: Prima di intervenire verificare le parti elettriche, e che non ci siano energie attive
- Utilizza la procedura (LOTO)
- Non toccare le parti in movimento e rotazione
- Utilizzare guanti per le parti metalliche

Figure 12. WHR SMP document

The steps have been inserted in SERENA OCULAVIS platform using the Workflows editor:

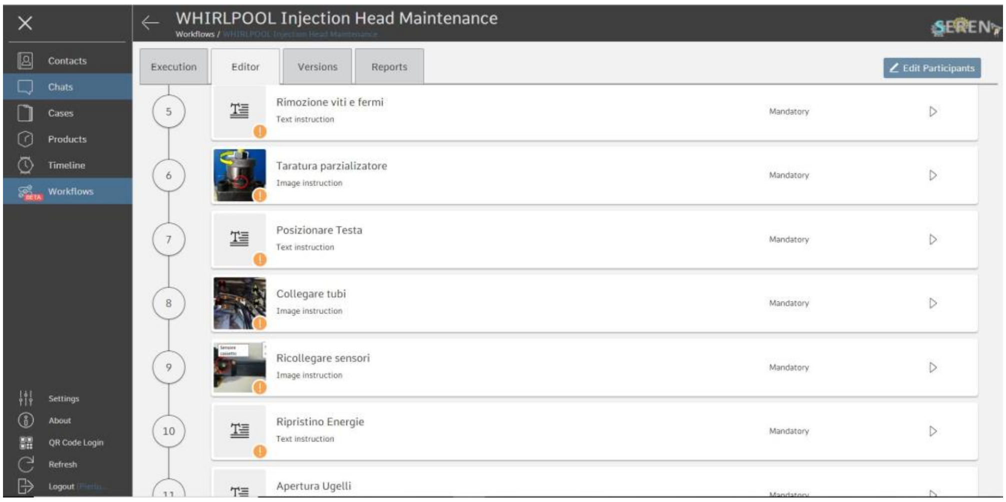


Figure 13. Operator support tool

and the execution of it tested using Realwear™ glasses.

Features to be tested	Target result
AR Support tool and Platform	Improve Operators effectiveness
Results	
The workflows editor represent a quite straightforward mechanism to translate a static but structured mechanism such as standard maintenance procedure into a multimedia, content	

	rich and dynamic system. The advantages are the extremely easiness of use that allows to create new workflows in few minutes; the possibility to add picture, video, drawings etc.; the capability of capturing the feedback from the operator in terms of confirmation of the work done and documentation of it. All these aspects represent a very important way to improve the maintenance operator work and also they are enabling a more interactive and controlled operation. The Workflow automation has been tested using Realwear™ glasses using vocal command: steps are shown on the screen and operator can follow them while keeping hands free. The feedback mechanism has not directly tested since so far there is not a business preparedness to manage in a structured way this kind of feedback.	
	Feedback/Comments	
	The platform allows for a fast and intuitive way to convert Excel based SMP into sequences of steps. Each step is the effectively communicated to operator with Realwear™ device. This feature allow for a better management of SMP which are currently kept simple due to the physical support (Excel file to store and paper to communicate).	
Achieved Metric/KPI value:		Reduction of MTTR

3 End user evaluation

3.1 KPIs/Metrics

All the experiments conducted have been interpreted within their business implication: a reliable system (i.e. robust SERENA platform and robust data connection) and an effective Prediction System (i.e. data analytics algorithm able to identify mixing head health status in advance) will have an impact on main KPI related to the foaming machine performances.

The KPIs have been extrapolated by the analysis performed on the period of data in which the selected sensors (as in Scenario 2) were available and are presented in the following table:

Table 2. KPIs table

WHIRLPOOL	BASELINE	INTENDED ACHIEVEMENT	EXPERIMENTS	SERENA
Overall Equipment Effectiveness (OEE)	80%	+15%	2	80,4%
Mean Time to Repair (MTTR)	3,5h	-20%	3	3h
Mean Time Between Failures (MTBF)	180d	+20%	2	>360d
Total cost of maintenance (TCM)	17400€	-60% to -70%	2,3	8000€

3.1.1 OEE – Overall Equipment Efficiency

SERENA impacts on a specific component of OEE, the Availability. Statistically, 2 events/year of the broken head are recorded in our historical files. The prediction system's capability to anticipate the failure will allow to schedule in anticipation the substitution of the head and move it into a non-production period (e.g. weekends, reduced production, etc.). Since each substitution is requiring an average of 3,5 hours of works, this saving has an impact of 0.4% of total OEE, able to increase it to 80,4%.

3.1.2 MTTR

The Mean Time To Repair is the average time used to restore a condition after a failure. Since we expect non more failures due to the block of the mixing head, the MTTR is reduced to zero.

3.1.3 MTBF

The Mean Time Between Failure indicates the frequency of a specific failure. As said, the average number of events of the blocked head is 2/year, and thus, the MTBF is 180 days. With a prediction system in place, we can expect this to increase at least double.

3.1.4 TCM

The Total Cost of Maintenance of the blocked head consists of the labour cost substitution and the cost of restoration of the head, which the component supplier must do. We expect this value to halve because an anticipated substitution (i.e. before the failure) requires fewer works of restoration, consisting mainly of very accurate machining.

3.2 Overall assessment of the SERENA system and its features

Table 3. Pros and Cons table

Pros	Cons
The overall platform is providing a lightweight and portable solution not very demanding in terms of computing power	Platform HMI still too complex to be used in a shopfloor environment
Robustness of the gateway solution	Real wear glasses require some adaptation period which can vary from person to person (also depending on visual impairment)
The modular approach allows for easy integration with shopfloor legacy system	
Adoption of MIMOSA standard	
AR platform easy to use and very effective	

3.3 Lessons learned

Besides practical results, SERENA provided some important lesson to be transferred into its operative departments:

Data Quality
Finding the relevant piece of information hidden in large amounts of data, turned to be more difficult than initially thought. One of the main learnings is that Data Quality needs to be ensured since the beginning and this implies spending some more time, effort and money to carefully select sensor type, data format, tags, and correlating information. This turns particularly true when dealing with human-generated data: if the activity of input data from operators is felt as not useful, time-consuming, boring and out of scope, this will inevitably bring bad data.

Some examples of poor quality are represented by:
a. Missing data
b. Poor data description or no metadata availability
c. Data not or scarcely relevant for the specific need
d. Poor data reliability

The solutions are two: 1) train people on the shop floor to increase their skills on Digitalization in general and a Data-Based decision process specifically; 2) design more ergonomic human-machine interfaces, involving experts in the HMI field with the scope of reducing time to insert data and uncertainty during data input.
These two recommendations can bring in having a better design of dataset since the beginning (which ensure machine-generated data quality) and reduce the possibility of errors, omissions and scarce accuracy in human-generated data.

Data Quantity
PU foaming is a stable, controlled process and it turned to have less variation: thus, machine learning requires large sets of data to yield accurate results. Also, this aspect of data collection needs to de designed in advance, months, even years before the real need will emerge. This turns into some simple, even counterintuitive guidelines:
1. Anticipate the installation of sensors and data gathering. The best is doing it at the equipment first installation or its first revamp activity. Don't underestimate the amount of data you need to improve good machine learning. This, of course, also needs to provide economic justification since the investment in new sensors and data storing will find payback after some years.
2. Gather more data than needed. Common practice advice is to design a data-gathering campaign starting from the current need. This could lead, though to missing the right data history when a future need emerges. In an ideal state of infinite capacity, the data gathering activities should be able to capture

all the ontological descriptions of the system under design. Of course, this could not be feasible in real-life situations, but a good strategy could be to populate the machine with as many sensors as possible.

3. Start initiatives to preserve and improve the current datasets, even if not immediately needed. For example, start migrating excel files spread in individuals' PC into commonly shared databases, making good data cleaning and normalization (for example, converting local languages descriptions in data and metadata to English).

Skills

Data Scientists and Process Experts are not yet talking the same language and it takes significant time and effort from mediators to make them communicate properly. This is also an aspect that needs to be taken into account and carefully planned: companies need definitely to close the "skills" gaps and there are different strategies applicable: train Process Experts on data science, train data scientists on the Subject matter; develop a new role of Mediators, which stays in between and shares a minimum common ground to enable the extreme cases to communicate.

4 Conclusion

The overall evaluation of the SERENA project is very positive from the end-user perspective, and we can consider that almost all of the initial requirements have been achieved.
But while the specific results obtained on the injection head have a limited exploitability, the general learnings about data management, skills and predictive maintenance project management have a much broader impact and are those that will be consolidated in a short time and a structured form.
Whirlpool is following World Class Manufacturing as a continuous improvement methodology and one specific pillar, Professional Maintenance, is providing the rules and the prescribing path to achieve excellence in equipment maintenance.

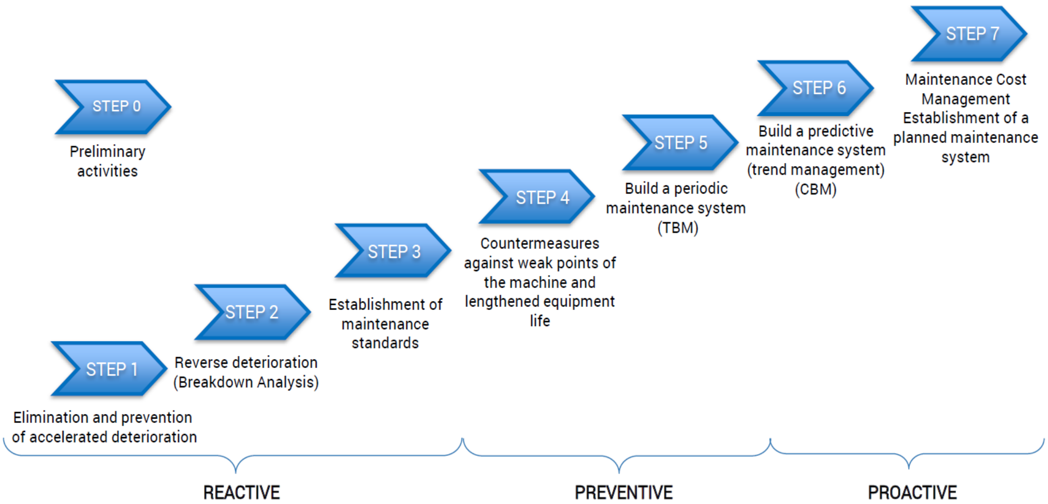


Figure 14. Seven (7) steps of Professional Maintenance Pillar

Proactivity, hence predictive maintenance, is required only at Step 6, meaning that it is not useful to apply it in situations where basic conditions and a robust preventive are not in place.
SERENA results provided Whirlpool all the indications to describe in detail, and thus prescribe, the ways to move equipment from Step 5 to Step 6, avoiding further trials, errors and set the basis for accurate planning of investment in technology and training at the right time.

References

[1] SERENA D1.1 deliverable, title: 'Report on use-case definition, evaluation metrics and end-users requirements'