VerSatilE plug-and-play platform enabling remote pREdictive mainteNAnce

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Summary: The purpose of this report is to describe the deployment of the SERENA solutions in the VDL WEW use case, testing the feasibility of the proposed concept in a real world industrial environment. In addition, a set of experiments has been conducted to test and validate the SERENA solutions in this use case and their contribution to its pre-defined in D1.1 business objectives.

Contents

List of Abbreviations

AR	Augmented Reality
CEN	European Committee for Standardisation
CPK	Process capability index
CWA	CEN Workshop Agreement
ICT	Information and Communications Technology
KPI	Key Performance Indicator
OEM	Original Equipment Manufacturer
PLC	Programmable Logic Controller
RUL	Remaining Useful Life
SME	Small and Medium Sized Enterprise
TRL	Technology Readiness Level
VPN	Virtual Private Network

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Executive Summary

This document aims to present the applicability and results of the SERENA system instantiation in the VDL WEW use case. It presents how the SERENA solutions were deployed, tested, and validated in the VDL WEW production line and in particular in its rolling milling machine. All aspects are presented and described from the end-user's perspective, including an overall SERENA project assessment.

The main aspects covered in the present report include the below items:

- Demonstrator overview: A description of the business case along with its specific business objectives regarding predictive maintenance, which guided the tests on the SERENA system.
- Experiments: A set of experiments testing the SERENA solutions as deployed and instantiated in the context of the VDLWEW business case.
- End-user evaluation: The results of the experiments are compared against the business objective to assess the SERENA system contribution to the business case and its applicability, along with an overall assessment of the SERENA system and lessons learned.

1 Demonstrator overview

1.1 Motivation and goals

The rolling process is an essential part of the production process of trailing arms at VDL WEW. The segments (tools mounted on the rolling mill) suffer from wear. Therefore, they are protected and hardened by a coating layer. If this coating layer wears too much, the underlying segment steel is damaged, and the segment is probably lost. So timely exchange for re-coating is essential. Exchange is currently performed based on product count.

In the following table (Table 1), the key performance indicators (metrics) identified in the context of the SERENA project are presented, and in line with the business objectives of the VDLWEW use case, including the baseline, the envisioned achievement and the motivation for each one of them from an end-user's point of view.

Table 1. The KPI's as stated

Metric	Baseline	Intended achievement	Motivation
Products produced by segments	18,000	36,000	Cost
Reduce maintenance costs	60000 euros/year for re-coating	30000 euros/year	Cost
Downtime	104 hours/year	52 hours/year	Time
Downtime in new product release	2-4 hours per change	1-2 hours per change	Time

The project is more focused on the first KPI: Products produced by segments. If this KPI improves, the other three are expected to follow. The project's goal is to achieve the segment exchange as late as possible, saving re-coating expenses and exchange time. To be achieved the above goal is needed to be identified the remaining layer thickness in the production line.

Apart from the above, the VDLWEW use case has a role of an extended demonstrator, focusing on investigating the applicability of the SERENA systems and their solution in its production environment. As part of it, the SERENA solutions have been customised, adapted and enhanced under the guidance of VDLWEW to fit its production environment and in line with the requirements mandated by the business case under consideration.

1.2 Testing environment and timeline

The testing environment is the actual production line, thus a real-world industrial environment. As the remaining layer thickness cannot be measured inline, and measurement during standstill is difficult because of the average segment temperature (200-250°C), the idea is to measure the product as it is produced. The layer thickness can be derived from the actual rolling mill data and the product dimension (thickness profile).

For this reason, two data sources are created:

1) Actual rolling mill data from the existing PLC
2) Actual product thickness profile from a new measurement machine

The aforementioned data is transferred to the Gateway (WP2). The Gateway sends the data to the SERENA Cloud (WP5). Data analytics are generated on the cloud (WP3). The resulting Remaining Useful Life (RUL) is then transferred to the Scheduler (WP3). The user is triggered by e-mail to check the manually schedule through the scheduler of the Segment Exchange action, after checking the analytics result. For validation of the calculated RUL, manual layer thickness measurements are performed, during the weekly maintenance production stop. The operator support services and in particular the workflows tool (WP4) is used for supporting production operators.

The timeline of the activities performed in the context of the present use case is resented hereafter.

- M1-M12: Gathering requirements
- M7-M16: Testbed definition, first design of the measurement machine, rolling milling machine data acquisition to support analytics generation.
- M16-M30: First version of the measurement machine in operation. Accuracy and reliability issues. Data acquisition. Data format development in collaboration with technical teams. Investigation and consultation on the proposed AI approach for predictive analytics generation. Data issues identified and fixed.
- M18-M24: Gateway deployment and customisation. SERENA solutions gradual deployment, evaluation and customisation in collaboration with technical teams.
- M30-M33: Implementation of measurement machine v2.0.
- M33-M42: System evaluation.

1.3 SERENA system deployment

A high-level representation of the SERENA system instance deployment at the VDLWEW shopfloor is illustrated in the following figure (Figure 1).

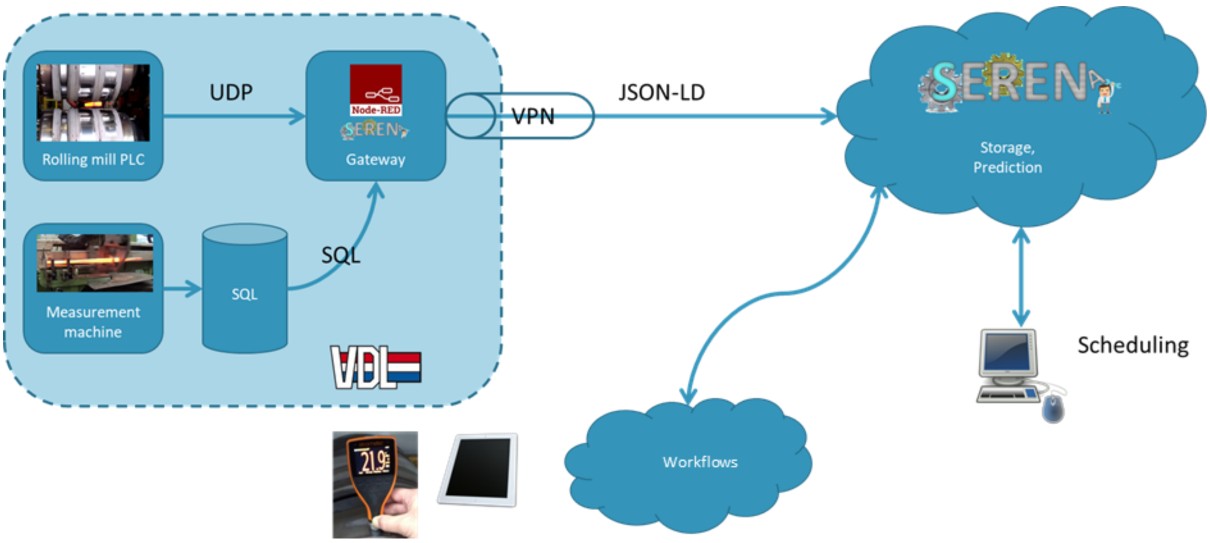

Figure 1. SERENA deployment

The components used to deploy SERENA within VDL WEW:

- Machine measurements from the Rolling Mill PLC are communicated to the Gateway
- The Measurement machine measures product dimensions. These are stored in a local SQL DB
- Gateway computer with NodeRed for preprocessing and forming JSON-LD (WP2)
- SERENA Cloud on Dell "Infinite" Testbed (WP5)
    - Mimosa data model
    - Data storage
    - Analytics
    - Scheduler
- Operator support system accessed through an iPad (WP4)
- Predictive analytics and scheduling services accessible through the SERENA cloud (WP3)

1.4 Roles & Responsibilities

The roles for the in-house testing of the VDLWEW deployment are described below:

- Technical testing is the responsibility of the Automation Engineers. They must take care of the measurements being made. They check if the gateway is running correctly as well as if the RUL value is presented.
- The implementation of the "workflows" AR tools is the responsibility of the Maintenance Engineer. The shopfloor operators test the "workflows" AR tool. The testing is done during production. The shopfloor operators have their normal responsibility to implement every operation related to the production.
- The evaluation of the layer thickness and the RUL values are the responsibility of the Tooling Engineer.

2 Experiments

2.1 Testing objectives

The testing was implemented on a technical, functional, and business level:

- Technical: The purpose of the technical level was to check if the system works as expected as well as if the data flow is operational along with the cloud deployment of the SERENA instantiation and its integrated services.
- Functional: The purpose of the functional testing was to identify if the SERENA's RUL values were valid.
- Business: The purpose of the business level was to test if the RUL values reach the VDL WEW's business objectives.

As stated in 1.1, the project focuses on KPI "Products produced by segments." This is a KPI on the functional level. The remaining three KPI's are resulting KPI's on a business level, saving re-coating costs, saving downtime by doing fewer segment exchanges and saving downtime by faster product changeover because new segments cause extra setup time. The experiments focus on technical and functional testing and the business objectives follow from this.

2.2 SERENA features to be tested

As mentioned above, the purpose of the present use case is to test and validate the applicability of the SERENA solutions in the context of an industrial use case, support its update and improvement in the context of a steel industry production environment and in particular towards addressing the business objectives of VDLWEW. In particular, the focus on the technical aspects was put primarily on the data flow mechanism and the analytics. As a consequence, the features tested include the following:

1. IPR "RFCMC" Data acquisition and gateway:
   - Rolling Mill PLC:
     - Send machine data at a high rate (10ms) to the gateway during rolling of a part
   - Measurement machine:
     - Makes product measurements (thickness) for each produced part
   - Gateway:
     - Receives machine values from the PLC, converts them to JSON and send them to the SERENA cloud
     - Retrieves thickness measurement data from the SQL DB, converts it to JSON, and send it to the SERENA cloud
2. IPR "S_PLAT" SERENA cloud:
   - Stores the data received and makes it available for RUL calculation
3. IPR "DDPMP" RUL calculation:
   - RUL calculation
4. IPR "MPST"
   - Maintenance Scheduler based on RUL
5. IPR "AR" Oculavis operator support
   - Workflow for operator support when measuring the coating thickness

2.3 Experiments & Results

Technical Objective 1: Applicability of SERENA solution in the steel industry		
1. The reliability of the data that are provided from the Rolling mill's PLC 2. The reliability and the quality of the data that are collected from the measurement machine 3. The parsing of the data into JSON by the gateway The circulation of the JSON into the SERENA cloud		
Expected result		
Correct, matching specified JSON-LD format, data flowing in the SERENA cloud from the machine		
Scenario 1	**Scenario description**	
	Rolling mill is producing, sending data	
	Features to be tested	**Target result**
	Measurement machine performing the mechanical moves to do the measurements	No collisions, no unexpected wear
	Mechanical moves accurately measured by the encoders	accurate encoder readings
	Encoder values accurately converted to the product profile and stored in SQL DB	Profile stored in SQL DB
	Results	
	Cpk > 2 on the unrolled section of the product	
	Feedback/Comments	
	Creating mechanical stability was the first challenge. We needed to develop a version2.0, with more stability. Following that, we had EMC issues on the encoders, having a negative impact on accuracy/reliability. When all that was solved (September 2020), we had a reliable measurement machine.	
Scenario 2	**Scenario description**	
	Measurement machine producing reliable data in the SQL DB during production	
	Features to be tested	**Target result**
	PLC data processed to JSON	The collected data to be processed and parsed into a JSON file
	Mechanical moves accurately measured by the encoders	accurate encoder readings
	Encoder values accurately converted to the product profile and stored in SQL DB	Profile stored in SQL DB
	Reliable thickness data	Cpk > 1.67 on defined X positions
	Results	
	Cpk > 2 on the unrolled section of the product	
	Feedback/Comments	
	Creating mechanical stability was the first challenge. We needed to develop a version2.0, with more stability. Following that, we had EMC issues on the encoders, having a negative impact on accuracy/reliability. When all that was solved (September 2020), we had a reliable measurement machine.	
Scenario 3	**Scenario description**	
	Gateway processing into JSON	
	Features to be tested	**Features to be tested**
	PLC data processed to JSON	PLC data processed to JSON
	Measurement machine data processed to JSON	Measurement machine data processed to JSON
	Results	
	The data are collected from the Rolling Mill machine and parsed into a JSON file to be uploaded	

	in the SERENA cloud	
	Feedback/Comments	
	The data availability, as well as the retrieving of them, was an effort-needed part. However, the conversion was not so hard.	
Scenario 4	**Scenario description**	
	Send the JSON data to the cloud	
	Features to be tested	**Features to be tested**
	Connection link (VPN) available	Connection link (VPN) available
	Data available in the cloud	Data available in the cloud
	Results	
	The results seem good, for as long as the Dell Infinite testbed was available. After that, the data was sent to a server at Polito, for directly calculating the RUL	
	Feedback/Comments	
	The challenge here was: how to pass through the firewalls, surrounding the VDL WEW business environment.	
Achieved Metric/KPI value:	None directly. This technical objective was the base for the functional testing.	

Technical Objective 2: SERENA operator services		
Test the services as provided by the SERENA platform		
Expected result		
Good user interaction in terms of user-friendliness, reliability		
Scenario 1	**Scenario description**	
	The operator should manually measure the layer thickness of the segments, supported by the Oculavis workflow, implemented on an iPad.	
	Features to be tested	**Target result**
	User-friendliness	The operator can measure without further instruction
	Thickness results	A measured layer thickness
	Results	
	First tests were done with an experienced engineer: he knew the system and was able to do the measurements. After that, the iPad was handed over to the operator, coincidentally passing by. Without further instruction, he performed the measurement. The measurements are used in the RUL evaluation.	
	Feedback/Comments	
	The system has proved to be user-friendly. The trick is in the content. Steps can be forgotten because they are trivial to the engineer but not to the operator. For example, the measurements can only be done if the rolling mill is rotated to the correct position in advance. The engineers know, the operators must be told.	
Scenario 2	**Scenario description**	
	The maintenance engineer can see in the scheduling tool if and when the segment layer thickness will fail, based on the calculated RUL	
	Features to be tested	**Target result**
	User-friendliness	The maintenance engineer can use the platform and see when the segments must be exchanged
	Reliability	The maintenance engineer can rely on a good prediction of the RUL. The predicted RUL is correctly translated to a segment exchange date
	Results	
	The scheduling tool could only be tested with simulated RUL data: the actual RUL data was not available at that moment. So for the test, a RUL was entered manually.	

<table>
<tr><td rowspan="3"></td><td colspan="2">The web pages were easy to navigate, no extra instruction was needed.</td></tr>
<tr><td colspan="2">Feedback/Comments</td></tr>
<tr><td colspan="2">This scheduling tool is good. But it can only be used effectively if all related tasks are scheduled in the same tool. In the VDLWEW situation, the other tasks are scheduled in the asset management system “API-pro”</td></tr>
<tr><td colspan="2">Achieved Metric/KPI value:</td><td>None directly. This technical objective was the base for the functional testing.</td></tr>
</table>

<table>
<tr><td colspan="3">Technical Objective 3: predictive models</td></tr>
<tr><td colspan="3">The purpose of this objective is the testing and refinement of predictive maintenance models.</td></tr>
<tr><td colspan="3">Expected result</td></tr>
<tr><td colspan="3">Correctly pre-process raw data and use them to build a predictive model capable of predicting the remaining life of the machinery</td></tr>
<tr><td rowspan="8">Scenario 1</td><td colspan="2">Scenario description</td></tr>
<tr><td colspan="2">Feature Engineering computation</td></tr>
<tr><td>Features to be tested</td><td>Target result</td></tr>
<tr><td>Statistical features related to RUL</td><td>Find statistical features able to summarize raw data and capable to be good predictors for the remaining useful life of the machinery</td></tr>
<tr><td colspan="2">Results</td></tr>
<tr><td colspan="2">Each input signal is represented through 7 statistical features, capable of modelling the trend of slow degradation. Besides, the distance between the rolling mill and the measuring machine constitutes the eighth feature. Also, this last feature proved to be a good predictor</td></tr>
<tr><td colspan="2">Feedback/Comments</td></tr>
<tr><td colspan="2">The extracted features take into account both the measuring machines and the rolling mill. Working with these new features is more effective than working with raw data in the estimation of the remaining useful life</td></tr>
<tr><td rowspan="8">Scenario 2</td><td colspan="2">Scenario description</td></tr>
<tr><td colspan="2">Data Labelling</td></tr>
<tr><td>Features to be tested</td><td>Target result</td></tr>
<tr><td>RUL labels</td><td>Assign a label to each production cycle, estimating the categorical value of RUL</td></tr>
<tr><td colspan="2">Results</td></tr>
<tr><td colspan="2">Two different methodologies are implemented, able to automatically label the data collected by the machinery. Each label is a categorical representation of the remaining useful life of the machinery</td></tr>
<tr><td colspan="2">Feedback/Comments</td></tr>
<tr><td colspan="2">Since we had no certainty about the degradation trend in the analysed use case, we considered two different scenarios. The first in which the life of the machinery decreases linearly over time, the second in which it decreases exponentially.</td></tr>
<tr><td rowspan="8">Scenario 3</td><td colspan="2">Scenario description</td></tr>
<tr><td colspan="2">Predictive Modelling</td></tr>
<tr><td>Features to be tested</td><td>Target result</td></tr>
<tr><td>Have more predictions available</td><td>To be implemented more types of predictions related to the RUL for the VDL WEW</td></tr>
<tr><td colspan="2">Results</td></tr>
<tr><td colspan="2">By exploiting the leave one out cross-validation technique, we assess the performance of the predictive model. We test different approaches: with the worst, we obtained an accuracy of 69%, with the best accuracy of 99%.</td></tr>
<tr><td colspan="2">Feedback/Comments</td></tr>
<tr><td colspan="2">At each iteration, the technique used allows us to use a single production cycle as a test set, and</td></tr>
</table>

<table>
<tr><td></td><td>all other cycles as a training set. A more meaningful sample of data should be collected to evaluate the performance of the two proposed approach and choose the one that more accurately models the application context under analysis</td></tr>
<tr><td>Achieved Metric/KPI value:</td><td>In terms of accuracy, precision, and recall, we performed well with the available data. However, it is necessary to use a larger and more accurate sample of data to generate a model for RUL estimation that is accurate, generalizable, and more robust.
During the model training phase, we used measurements collected over one month, corresponding to two machine life cycles. The period considered may not be sufficient enough to generalize the trend of machinery degradation adequately.
By considering multiple life cycles, perhaps ending with different failures or different maintenance, the predictive model would undoubtedly be more robust and able to provide more accurate predictions.</td></tr>
</table>

<table>
<tr><td colspan="3">Functional Objective: Products produced by segments</td></tr>
<tr><td colspan="3">Measure the number of products produced by a segment pair, and compare that to the calculated Remaining Useful life from the acquired data</td></tr>
<tr><td colspan="3">Expected result</td></tr>
<tr><td colspan="3">Increased number of products produced by a pair of segments</td></tr>
<tr><td rowspan="7">Scenario 1</td><td colspan="2">Scenario description</td></tr>
<tr><td colspan="2">Automatic RUL calculation</td></tr>
<tr><td>Features to be tested</td><td>Target result</td></tr>
<tr><td>Calculated RUL compared with manual layer thickness measurement</td><td>To calculate and predict the RUL of the segment coat of the Rolling Mill machine</td></tr>
<tr><td colspan="2">Results</td></tr>
<tr><td colspan="2">On February 2, 2021, newly coated segments were mounted.
For the period February 2-23, 2021 the RUL is consequently calculated and compared to the weekly manual measurement of the layer thickness.</td></tr>
</table>

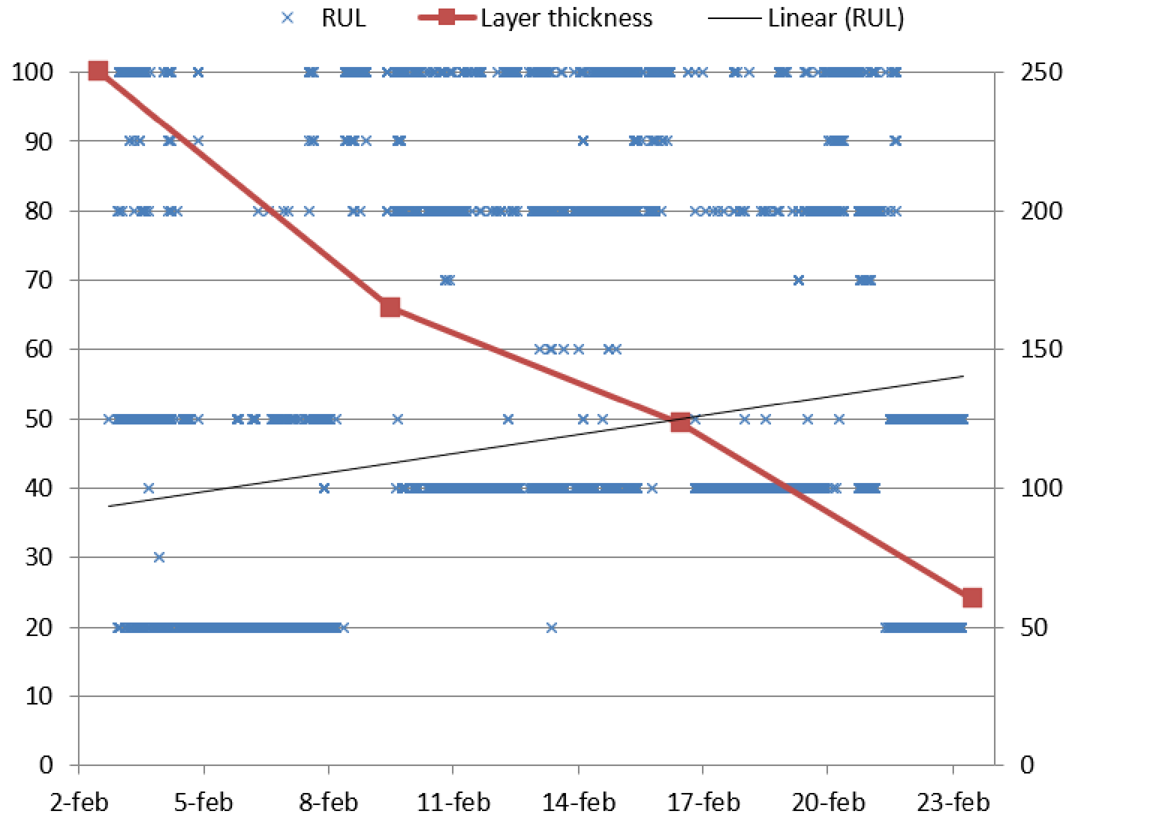

Figure 2. RUL graph

The 24656 calculated RULs seem random over time. Excel tried to draw a linear line through the RULs: the layer thickness seems to increase. The red line shows the actually measured layer thickness.
The result: this RUL calculation does not predict with great accuracy the actual layer thickness.

Feedback/Comments

This is a difficult use case. The late availability of the reliable data flow did not help. It surprised me that the RUL could be calculated from a single measurement from the measurement machine, not using any history, and not using the PLC data.

Achieved Metric/KPI value:	The calculated RUL did not contribute as expected to improve the KPI "Products produced by segments" because the RUL was not predicted with big enough accuracy

3 End user evaluation

3.1 KPIs/Metrics

The main KPI to be improved was the “Products produced by segments”. However, an essential rise of this KPI was not observed as expected. Reasons for this:

- The accuracy of the calculated RUL is not satisfactory from an end-user’s perspective, as shown in the experiments and the operator cannot confidently base his decision for segment exchange on the calculated RUL.
- Since the start of the SERENA project, several new products are introduced on the rolling mill, having a greater impact on the actual RUL. After recognizing this fact, the production method for some products is changed, affecting the RUL.
- A new layer application method was introduced, giving a much longer useful life (about double). This changes the business case assumptions, from the end-user’s point of view.

Due to the fact the main KPI “Products produced by segments” is not significantly affected by the SERENA project, it can be safely supported that the other three KPI’s are also not affected: Reduce maintenance costs, Reduce Downtime, Reduce Downtime in new product release.

3.2 Overall assessment of the SERENA system and its features

Table 2. Overall assessment table

Pros	Cons
The Data acquisition using the Gateway together with Node-Red gives great flexibility, even in special situations like at VDL WEW	The RUL calculation did not bring a reliable base for late exchange of segments
SERENA has shown versatility by accommodating such very different use cases	The KPI “Products produced by segments” is not essentially improved by the SERENA system
The Oculavis operator support brings great value in deploying untrained operators on jobs that require expertise. A prerequisite for this being successful is good content.	

3.3 Lessons learned

Building a reliable measurement machine was more challenging than expected. Nevertheless, it provided the means to safely evaluate the generated predictive analytics and the methodology developed in the SERENA project. Furthermore, creating a reasonable RUL calculation for the VDL WEW situation was expected to be complicated. This expectation became true as the accuracy of the calculated RUL was not satisfactory. Node-Red is a very versatile tool, well-chosen for the implementation of the gateway.

During the 3 years of a project like SERENA, the circumstances of the project can change and be done so essentially, both businesswise and technically. In the 3 years, we introduced new products on the production line, with a large impact on the segmented wear. The COVID-19 pandemic first caused a significant dip in our turnover. Luckily, we had an enormous surge in our turnover later because of legislation change in China, driving our products' great demand. Both turnover changes caused a focus on new short-term projects, competing for resources with the SERENA project. Thus, VDL WEW was not organized well enough to handle both the short-term and long-term projects.

4 Conclusion

In conclusion, SERENA represents a versatile plug-and-play platform regarding industrial machines and its maintenance approach, AI-based analytics, maintenance activities scheduling, and support to the operator in those activities' performance. The above items are integrated into a flexible and resilient platform. Regarding the VDL WEW use case, the contribution of the SERENA project was challenging, and the impact of the project, in this case, was not as expected. Furthermore, the COVID-19 pandemic provides several restrictions which prevented the physical meetings. However, the SERENA project remains a promising concept in all ways.