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Methodology for managing maintenance strategy and remanufacturing projects of large industrial equipment

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European foreword

This CEN Workshop Agreement (CWA 18038:2023) has been developed in accordance with the CEN-CENELEC Guide 29 “CEN/CENELEC Workshop Agreements – A rapid prototyping to standardization” and with the relevant provisions of CEN/CENELEC Internal Regulations - Part 2. It was approved by a Workshop of representatives of interested parties on 2023-07-19, the constitution of which was supported by CEN following the public call for participation made on 2023-01-30. However, this CEN Workshop Agreement does not necessarily include all relevant stakeholders.

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Introduction

The work is based on the results of the RECLAIM European project (RE-manufaCturing and Refurbishment LArge Industrial equipMent) grant agreement No 869884.

The vision of RECLAIM is to demonstrate technologies and strategies in support of a new paradigm for the management of large industrial equipment that approaches the end of its design life. This paradigm will substantially reduce the opportunity cost of retaining strategies by allowing relatively old equipment that faces the prospect of decommissioning to reclaim its functionalities and role in the overall production system.

To achieve this, a methodology is proposed to use the accumulated knowledge of the health status of machinery together with innovative methods, tools or services for the systematic assessment of the most appropriate lifetime extension strategy.

Finally, in the annex some concrete cases from RECLAIM project will be also showcased in this CWA to have a direct connection between the theoretical part of the document and its concrete possible implementation.

1 Scope

This document defines a methodology that enables a new paradigm for the maintenance of large industrial equipment -specifically in the manufacturing sector- that approaches the end of its design life. The methodology is based on a systematic assessment of strategies comprised of one or more technical solutions (hardware, software, training, or a mix of those) related to the re-manufacturing or refurbishment of the equipment.

The target group of the CWA are industrial equipment maintenance practitioners concerned with re-manufacturing or refurbishment, public authorities concerned with circular economy models for large industrial equipment, as well as research and development departments in industry and research.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN ISO 12100:2010, *Safety of machinery - General principles for design - Risk assessment and risk reduction (ISO 12100:2010)*

CEN ISO/TR 22100-4:2020 *Safety of machinery - Relationship with ISO 12100 - Part 4: Guidance to machinery manufacturers for consideration of related IT-security (cyber security) aspects (ISO/TR 22100-4:2018)*

CEN ISO/TR 22100-5:2022, *Safety of machinery - Relationship with ISO 12100 - Part 5: Implications of artificial intelligence machine learning (ISO/TR 22100-5:2021)*

ISO 14025:2006, *Environmental labels and declarations — Type III environmental declarations — Principles and procedures*

ISO 14040:2006, *Environmental management — Life cycle assessment — Principles and framework*

ISO 14044:2006,[1] *Environmental management — Life cycle assessment — Requirements and guidelines*

ISO/TR 14121-2:2012, *Safety of machinery — Risk assessment — Part 2: Practical guidance and examples of methods*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in EN 13306 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp/

— IEC Electropedia: available at https://www.electropedia.org/

3.1
remanufacturing
remanufacture
industrial process which creates a new product, from used products, or components, which has to be placed on the market

[1] As impacted by ISO 14044:2006/Amd 1:2017 + ISO/14044:2006/Amd 2:2020

Note 1 to entry: Original manufacturers are not obliged to disclose technical documents to the remanufacturer for the reason of know-how protection.

[SOURCE ISO 8887-2:2023, 3.29]

3.2
refurbishing
refurbish
refurbishment
reconditioning
recondition
industrial process which returns a used product, or component to a satisfactory performance level when made available on the market as a used product

Note 1 to entry: The refurbisher by whom the product has been refurbished shall be indicated by a "refurbished by" or by the type plate of the refurbisher.

Note 2 to entry: With respect to refurbishing:

— manufacturing effort involves the replacement of worn or broken components but is generally more extensive than for repair;

— performance after refurbishing is expected to perform its intended role but the overall performance is likely to be inferior to that of the original model;

— any subsequent warranty is generally less than that for a new or remanufactured product but is likely to cover the whole product (unlike repair); refurbished products do not require a warranty equivalent to that of a newly manufactured equivalent.

[SOURCE ISO 8887-2:2023, 3.26]

3.3
retrofit
modification of an entity or system using parts developed or made available after the time of original manufacture or by other means with the objective of improving functionality.

[SOURCE:ISO 6707-4:2021, 3.5.27]

4 Abbreviations

The list of abbreviations used in this document is given in Table 1.

Table 1 — Abbreviations

2DCNN	Two Dimensional Convolutional Neural Network
AI	Artificial Intelligence
ALARP	As Low As Reasonably Practicable
API	Application Programming Interface
AR	Augmented Reality
ASN	Adaptive Sensorial Network
BIA	Business Impact Analysis

CBA	Cost Benefit Analysis
CCA	Cause-Consequence Analysis
CE	Circular Economy
CIM	Common Information Model
CLMS	ContactLess Motor Supervisor
CNN	Convolutional Neural Network
CSV	Comma-separated Values – file format
CVaR	Conditional Value at Risk
DB	Database
DBMS	Database Management System
DRyICE	Distributed data storage and analytics
DSF	Decision Support Framework
EC	Electrical Conductivity
ES	Expected Shortfall
ETA	Event Tree Analysis
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Modes Effects and Critical Analysis
FPGA	Field-Programmable-Gate-Array
FTA	Fault Tree Analysis
FWM	Friction Welding Machine
FTP	File Transfer Protocol
GUI	Graphical User Interface
GPIO	General Purpose Input Output
GPU	Graphic Processing Unit
GW	Cyber Security Gateway
HACCP	Hazard Analysis and Critical Control Points
HAZOP	Hazard and Operability studies
HMD	Head-Mounted Display
HMI	Human-machine Interface
HRA	Human Reliability Analysis
HTTP	HyperText Transfer Protocol
IMU	Internal Measurement Unit
IR	Infrared
IMS	Integrated Manufacturing System
IoT	Internet of Things

IP	Internet Protocol
IRR	Internal Rate of Return
JSON	JavaScript Object Notation – file format
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCES	Life Cycle Extension Strategies
LOPA	Layers Of Protection Analysis
LTE	Long-Term Evolution
MCA	Multi-Criteria Analysis
MD	Machinery Directive
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
MTBF	Mean Time Between Failures
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
NoSQL	Non-Structured Query Language
NPV	Net Present Value
OGC	Online Geospatial Consortium
OLAP	Online Analytical Process
OPC	Open Platform Communications
PBP	Payback Period
PHM	Prognostic and Health Management
PC	Personal Computer
PLC	Programmable Logic Controller
QR	Quick Response
RCM	Reliability Centered Maintenance
RTD	Resistance Temperature Detector
RTU	Remote Terminal Unit
SAFT	Scale Accelerated Failure Time
SCADA	Supervisory Control And Data Acquisition
SFARP	So Far As Reasonably Practicable
STPA	Systems-Theoretic Process Analysis
SWIFT	Structured What If Technique
TCP	Transmission Control Protocol
UI	User Interface

UL	Useful Life
KPI	Key Performance Indicator
VaR	Value at Risk
WIP	Work In Process

5 Overall methodology

The vision of RECLAIM is to demonstrate technologies and strategies to support a new paradigm for the refurbishment and re-manufacturing of large industrial equipment in factories, paving the way to a circular economy. Its ultimate goal is to save valuable resources by reusing equipment instead of discarding them.

RECLAIM's methodology and tools support legacy industrial infrastructures with advanced technological solutions with built-in capabilities for in-situ repair, self-assessment, and optimal reuse strategies.

The overall methodology encompasses four steps which include:

1. Assessing preliminary equipment conditions including digital retrofitting opportunities, fault diagnosis, maintenance methods, and the implementation of prognostic and health management.

2. Applicable options and selection of the best alternative including the analysis to maintain, upgrade, refurbish, remanufacture, or dispose of, the cost analysis and cost modelling, optimization and selection of the best option and the selection of key performance indicators and decision support models;

3. Design of the solution including the use of RECLAIM building blocks for in-situ repair and data analytics, refurbishment and re-manufacturing framework and KPIs and business models;

4. Sustainability assessment including the Social, Environmental and Economical dimensions, and risk assessment.

These steps of the methodology will be further detailed in the next clauses.

The technological core of RECLAIM is a novel Decision Support Framework (DSF) that guides the optimal refurbishment and re-manufacturing of electromechanical machines and robotics systems, coupled with technological building blocks that use an ensemble of methods for operational profiling trying to find the optimal time to carry out maintenance/refurbishment/ remanufacturing during the whole life cycle of the industrial equipment. This challenge is compounded by the fact that selecting the appropriate maintenance/refurbishment/remanufacturing will have a direct impact towards maximizing the Useful Life (UL) of equipment.

6 Step 1: Assessment of the preliminary equipment conditions

6.1 General

An assessment of the preliminary equipment conditions shall be performed:

a) To identify the potential machines and production lines in each industrial use cases for the implementation of RECLAIM high-tech solution following assessment of obsolescence, ageing and retrofitting potential criteria;

b) To define the requirements matrix, categorizations, and criteria;

c) To identify the potential technological solutions and corresponding maturity level for the technology matrix proposition;

d) To analyse the requirements matrix and technological matrix for the use case understanding;

e) To transform the requirements of the use cases into practical scenarios based on the RECLAIM technological solutions;

f) To propose the first approach for RECLAIM Pilot Scenarios for the project concept and technologies demonstration and validation.

6.2 Definition of KPI

Key Performance Indicators (KPIs) are essential measurable units that could be used as the control tool for any process evaluation and may consider aspects such as efficiency, quality, resources management, repair activities, production, and customer satisfaction. KPIs have also to be meaningful, coherent, objective driven, and standard for comparison purposes. The impact evaluation of the efficient coexistence of new highly digitalized machines with analogical ones at the same production line meant to enhance maintenance, remanufacturing and refurbishment practices of active machines can be performed by using KPIs listed in Table 2.

Table 2 — Performance indicators to assess efficient large equipment maintenance or end of life management

ID	Category	KPI	Potential target value
1	Productivity	Reduction in factory physical inspection costs through smart sensorial network for near real-time monitoring	50%
2	Planning	Improvement of electromechanical machines and productions' monitoring through Optimization Toolkit for Refurbishment and Re-manufacturing Planning	20%
3	Planning	Reduction of downtime due to unscheduled maintenance	20%
4	Planning	Reduction of maintenance effort required	50%
5	Productivity	Reduction of time it takes to resolve a failure, from the moment it was first noticed until the final wrap-up meeting or report	20%
6	Planning	Extension of lifetime (estimated) through improved machine adaptability and reliability	8-10 years
7	Productivity	Reduction in cost of annual machine maintenance	50%
8	General result	Operation of the re-manufactured/ refurbished machine shall comply with existing standards	Y

6.3 Sensors required

Sensors are essential for collecting and analysing the data that reflects the condition and performance of the equipment. Different types of sensors can measure different parameters, such as vibration, temperature, pressure, speed, fluid properties, position and sound, depending on the type and function of the equipment. These sensors can be attached to important parts of the equipment, such as motors, gears, pumps, valves, bearings and cables, and can send the data to a central unit through wired or wireless signals. The main challenge is to select the best sensor for each production process, which is not easy. Sensors vary in their accuracy, reliability, sensitivity, durability and cost. It can also be hard to integrate new sensors with existing equipment, especially in harsh environments or complex systems. The chosen sensor should be compatible with both the existing hardware (machine, PLC) and software (SCADA).

Some examples of sensors that can be used to upgrade existing machinery are:

- Temperature sensors, to measure the temperature of a part or fluid in the equipment. They can help detect faults such as overheating, cooling failure or contamination. They include thermocouples, resistance temperature detectors (RTDs), thermistors or infrared sensors;

- Electricity meters, to measure energy consumption and identifying load profiles. They can also help detecting anomalies in the equipment performance;

- Accelerometers, to measure the acceleration or vibration of a moving or rotating part of the equipment. They can be based on different principles, such as piezoelectric, piezoresistive or capacitive sensors;

- Pressure sensors, to measure the pressure of a fluid or gas in the equipment. They can help detect faults such as blockage, leakage, or wear;

- Fluid property sensors, to measure viscosity, density, or conductivity. They can help detect faults such as degradation, contamination, or dilution;

- Speed sensors, to measure the rotational speed of a part of the equipment. They can help detect faults such as slip, torque variation or load change;

- Position sensors, to measure the position or displacement of a part of the equipment. They can help detect faults such as misalignment, wear or backlash.

Additionally, there are some process variables from existing sensors, which may be “hidden” - in the sense that they may be used exclusively in a functional blocks/ladder diagrams of existing PLC’s, and could easily be exposed outside of the control program they are originally used in.

6.4 Preparation of the data

The data that are being published by the different sensors at the machines and at the factories shall be made available for the different RECLAIM algorithms, e.g., those of the Decision Support Framework. To cover this aspect a data ingestion mechanism shall be put in place so that the data are, firstly transformed, and secondly persisted. This mechanism is achieved via the execution of sequential activities:

1. The RECLAIM Data Handler is the entry point for the RECLAIM system and the point where the different sensors and machines will connect so that the data they generate and/or gather are made available to the rest of the infrastructure. In cases of data which cannot be recorded automatically, it is also possible for the end users of the RECLAIM platform to insert such data manually through the platform’s dashboards;

2. Once the data have been transformed, they reach the RECLAIM Repository database, where they will be persisted;

3. At this very moment, the data can be queried by any other of the RECLAIM components and then, through the Data Handler again, they will reach their destination in the format required by the demanding component. Output of algorithmic components is sent, usually through the Data Handler, to the respective Graphical Users Interfaces, and it is also sent to the database when its future reuse

is desired. In these cases, data from the database can be transferred also later to the Users Interfaces through the Data Handler;

The Data Handler shall include also standard cybersecurity encryption mechanisms (Transport Layer Security) that ensures the secure data communication among components.

The following are examples of technologies that can be used to achieve the above exposed information. They should by no means be prescriptive:

a) *The core components of the RECLAIM Data Handler are mainly developed utilizing an Apache Camel instance, deployed inside an Apache Karaf container, which in turn is deployed as a Docker container. This setup provides flexibility with the integration of multiple communication protocols, data sources and data formats;*

b) *Regarding the RECLAIM Repository, its core components are mainly based on open-source technologies. In this sense, the database is based on ClickHouse technology, which is a high-performance, column-oriented SQL database management system (DBMS) for online analytical processing (OLAP). The part related to the data visualization is based on Apache Superset technology, which is fast, lightweight, intuitive, and loaded with options that make it easy for users of all skill sets to explore and visualize their data, from simple line charts to highly detailed geospatial charts. Like the Data Handler, it is deployed as Docker containers to benefit from the flexibility of integrating multiple technologies in an easy way;*

c) *As the RECLAIM system consists of many different data sources and components, it is crucial for the data coming from each one to be unique and easily discoverable. For this reason, the Common Information Model (CIM) is adopted, based on the OGC SensorThings standard of the Open Geospatial Consortium (OGC), which is one of the data modelling standards used generally in manufacturing. In order to match the required format accepted by the database and meet the RECLAIM needs, the CIM was slightly modified, before being applied to the transferred data. Generally, by applying the CIM to the data stored in the database, it is ensured that there will be a uniform way of discovering the data required by each component.*

6.5 Degradation models (general description)

6.5.1 Origin and Purpose of life-cycle extension strategies based on degradation modelling

The costs of Life cycle extension strategies (LCES) can be categorized in four different groups. The first group involves design of equipment/component or production line and includes e.g., the design for durability / reliability, design for ease of maintenance and repair or the design for easy disassembly and reassembly. Such design costs are already included in costs of new equipment and will therefore not be considered in the methodology. The same is true for the end-of-life strategies such as recycle and upcycling.

Most relevant are the LCES related to maintenance strategies and to the business models. LCES related to maintenance strategies during active production process targeting on:

1. Repair or Corrective Maintenance;

2. Preventive maintenance (time based);

3. Preventive maintenance (condition based);

4. Preventive maintenance (predictive).

LCES related to business models can be tailored to models for:

1. Pay per use;
2. Resell – Reuse;
3. Remanufacturing;
4. Reconditioning;
5. Refurbishing.

While the costs of LCES related to business models involve the various stakeholders of the supply chain, the costs of the LCES related to maintenance are mostly concentrated on production line owners.

6.5.2 General definitions of degradation modelling

In order to describe time evolution of machine components failure statistics we use a reliability function R(t). This function determines the probability for a component to survive within component usage time period t. At the beginning, at t = 0, the reliability of the equipment is obviously unitary, since it is not failed. In process time there is a chance that the equipment fails. At extremely large times, significantly larger than typical lifetime of equipment, it definitively fails and for that reason, for large times reliability reduces asymptotically to zero. For calculating the reliability, we suggest using the Weibull approximation, since it is simple to handle and has sufficient accuracy:

$$R\left(t\right) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad [1]$$

With t denoting usage time of component and β and η are the Weibull parameters. The larger η is, the longer the expectation lifetime of the component. β describes aging process of component in process of time. The larger β is, the stronger the degradation with time.

The reliability function allows to define further characteristic statistical functions and parameters, such as the reliable lifetime, the Mean time to failure (MTTF) or the Hazard rate that indicates the probability to fail within the next hour.

The degradation modelling using the Weibull approximation can further be improved by a stepwise parameter update in process of observations. The goal is to verify correctness of parameters η and β for a given time TF of failure happened.

6.5.3 SAFT model and equivalent time for varying load condition

For the calculation of the reliability of an equipment, various options are available. One of the most promising models is the Scale Accelerated Failure Time (SAFT) model. SAFT models are used for the computation of reliability when an equipment has varying load factors. Under a SAFT model, the time of failure of a component under high load is given by the time of failure under normal (use) load divided by load dependent acceleration factors. The model of varying load conditions is simply of having different load-related timescales, producing a faster aging of the device under higher loads.

As SAFT is a very common and successful model to derive Weibull parameters from accelerated failure tests, we apply it to time-dependent load conditions. Take as an example, a processing device in an industrial production line: for a specific product, the device shall perform a process with given process parameters producing some load on the device. The device wears-out and we assume that the wear is cumulative. At a given time the line is switched to production of a product variant which requires a different set of process parameters. The load has changed and the speed of additional wear-out has changed too. This can be modelled in failure statistics by a changed acceleration factor.

6.5.4 Support to Degradation model 1: Bayesian sensor-based failure diagnosis algorithm

Degradation modelling can be used for purposes other than the calculation of the reliability of a component or a system of components. An important feature of degradation modelling is to use degradation information for failure root-cause analysis based on Bayesian networks. To do so, a sensor-based failure detection systems shall be implemented. Sensor values and comparing these results with set values of sensors (expectation values). Details of such algorithm naturally depend on details of application. Strong deviation of sensor values is frequently a signature of that "something is going wrong" in a component. Frequently no definitive answer can be provided for correspondence between a sensor value deviation and failure of a certain component: it is rather a probabilistic guess. It should be noted that the sensor events Sk should be independent. The sensors should be uncorrelated and of different kind. They should be considered as different sources of information.

For Bayesian root cause analysis, the sensor deviation probability needs to be set for each sensor and for each component of the system. Probabilities close to the extremes (0 and 100%) should be avoided.

6.5.5 Support to Degradation model 3: Probabilistic anomaly classification based on Hidden Markov Model

Hidden Markov Models are a special case of Dynamic Bayesian Networks. In contrast to the Bayesian methods presented in the previous clauses, Dynamic Bayesian Networks also involve time in their architecture, i.e. the associated variables have particular time lag.

After starting with the log of machine failures and monitoring of the most relevant process parameters, it is possible to implement an automatic system which will predict failures before they cause damage and breakdown.

The end goal of this methodology is the early diagnosis of machine failures using a dynamic Bayesian probabilistic model. It may also be possible to identify the causes of each failure based on the behaviour of the sensor data. To apply a Hidden Markov Model, one needs to combine operational data and little expert knowledge for unsupervised learning. The hidden states correspond to the automatically distinguished reasons of anomalies/failures. The number of hidden states is user-defined. An algorithm was developed using the Gaussian Hidden Markov Model. A challenge is the human intervention in the production, which causes additional uncertainty in the data and difficulty in their interpretation.

Data anomalies can occur due to many different reasons; they can be due to a sensor reading error, or a communication error while data are being transmitted through a network, or they can simply be due to unexpected and rare system behaviour. The list is extensive but, in all cases data anomalies share the property of being a type of data that deviated away from normal data patterns. Anomaly detection is a very helpful instrument wherever it is applied.

Anomaly detection is useful in endless scenarios, and that is why it has been implemented and investigated in many ways, one of which is using probabilistic graphical models.

6.5.6 Stop types correlation

A discrete event association algorithm was developed to correlate stops of different types at the same or different machine components.

The most important data needed for this algorithm are stop data, i.e., timestamps of start, end, and reason for every stop instance. Stops with a reason related to the production line equipment are those considered as potentially correlated with each other, so these stops are those tested for correlation. An equipment stop may be involuntary (i.e., failure) or voluntary (i.e., a stop to perform a set of corrective actions on the equipment, e.g., related to lifetime extension strategies). The stop association algorithm aims at finding the types of involuntary stops with occurrence probability positively ("attracted stops") or negatively ("segregated stops") affected by previous voluntary stops or involuntary stops of different types.

Before feeding the main part of the algorithm, the stop data are calibrated by joining too close instances of stops of the same type, based on automatic, stop-type-dependent time difference thresholds. This is useful in cases where the stop data are not as clean as desired, in the sense that there are multiple registrations of stop intervals for instances of stops of the same type relatively close in time, but there is a single cause for all these registrations.

The association measures considered in order to statistically infer the cases where stop correlation is significant are the coefficient of segregation, and the mean and median inter-event time (forward and bidirectional). Based on simulations under the null hypothesis (no dependence), considering the initial Weibull distributions of Equivalent Time To Failure, which do not take into account stop dependencies, the p-values of the measures can be empirically estimated. An involuntary stop type F is considered as attracted or segregated by a stop type S w.r.t. a specific association measure if for the directed pair S-->F the p-value of the association measure value is too low or too high respectively, based on the assumed significance level.

When an involuntary stop type F is considered as dependent on other stop types, according to the stop type dependencies found, when some of the other stop types has occurred after the last instance of F, the Weibull parameters change according to different ones, which may be found by fitting the Weibull distribution to the historical data of the relevant stop types and relevant production and/or process data affecting the degradation speed (load).

7 Step 2: Applicable options and selection of the best alternative

7.1 General

Given that the process of globalization and tremendous industrialization are straining an already insufficient production system and leading to over-exploitation and resource extraction. A call for a revolutionary change was needed and has been brought forward by the concept of circular economy. Circular economy discipline tries to support the development of business models which aim to create performing products while maintaining at the same time the focus on the reduction of environmental impact. So, the scope is to reach objectives in terms of reduction of waste, reuse of materials, access to renewable sources; these measures are intended to increase resource availability and cost effectiveness, which are necessary to access new business models that are more successful than the traditional ones.

In addition, people are also becoming more aware of the necessity for a sustainable production and manufacturing method. Thereby, urging the companies to comply a timely transformation in the direction of a strategy as much as possible in line with the new value identity of the consumer.

7.2 Definition of the goals

Nowadays, many companies have been applying the remanufacturing strategies. The overall outcome represents a satisfactory and balanced outcome, and the majority of the choices made (to the question “I think that I have done the right choice when I decided to adopt the Remanufacturing approach”) are not fully satisfied.

It's crucial to emphasize that "technical upgrading" and "product quality" are the major opportunities organizations have been considering when selecting whether to use Remanufacturing methods.

Also, the companies agree that the push to invest in remanufacturing comes from the expectation of having a Life expectancy on par with a new product and improve its profitability.

As forementioned, when the machine reaches its lifespan, investor should at this point decide between either:

a) Selling the product as it is and might lose its opportunity cost value;

b) Remanufacture the machine, if advisable to do so.

Here comes the question; on which Economic model could investors support their decision to check if it is advisable to carry out the remanufacturing operation or not.

Is it based on the NPV-Traditional or classical Economic model to evaluate if we should do Remanufacturing or not by looking at the cost, revenue, and check the cash flows throughout the years to check if the NPV value is positive or negative so we can decide whether to accept or reject a project.

So, to best fit the needs for the Remanufacturing problems and be as much precise as we can. We have customized the Traditional Net present value economic model considering several indexes (such as Day payable outstanding, Supplier cost impact, Days sales outstanding, Real discount rate/Discount factor, Stock turnover rate, and Advanced payment incidence) but mainly considering the IRR (the Internal rate of return) and PBP (Pay back ratio) as an Output of the Simulation model that covers both Investment scenarios being With and Without Remanufacturing.

7.2.1 Key words

Payback period (PBP): It is the number of years needed to recover an investment (remanufacturing) that has been made. Therefore, it is the number of years needed to compensate for the investment through cash flows which, overall, shall be positive. It is the first deadline in which the cumulative cash flow becomes positive. It is a numerical value that represents a given number of years.

Internal rate return (IRR): It measures the percentage profitability of an investment. In general, an investment should be pursued if the IRR is higher than the IRR that the company is achieving or expects to achieve. It is a value expressed as a percentage.

7.3 Available choices

There are several circular economy solutions, which may often provide value over the short and long terms. However, it is challenging to identify a general principle pertaining to the use of a circular approach for products of various sorts. The 4 potential principles for the development of value adopting a CE approach that might eventually result in a competitive advantage and that could be applied to all situations are as follows:

1) **Inner Cycle:** Is the notion that a strategy is more successful the shorter its inner cycle. The integrity and intricacy of a product and energy are maintained more fully in short cycles. Additionally, there are less externalities produced, such as gas emissions or toxic compounds. When it comes to electromechanical machinery, a suitable example is an automobile, where maintenance or refurbishing rather than recycling allow for the preservation of the product's worth;

2) **Circling longer:** The fundamental idea behind the extended cycle is that by extending a machine's life, less material, energy, and labour are required to produce a new item. A further advantage of maintaining more goods, parts, and resources in the circular economy process is value generation. This idea may be put into practice by either prolonging a single cycle (such as the washing cycles in a washing machine) or by running numerous cycles back-to-back (for example, while refurbishing an engine). These extensive applications offset the dispersion of the material beyond the active economy and replace flows of virgin material;

3) **Cascading use:** It mostly refers to using the same kind of product or material in the original area of use, where cycles of various kinds are imagined in which there is a change in ownership with each subsequent iteration (example: buying old goods). A cascading usage, however, may also be used to describe the reuse of a product or material in fields of application that are distinct from the original one;

4) **Practical inputs and design:** Currently, waste is frequently gathered as a mixture of various materials, comprising contaminants that prevent them from being reused at a level of quality that is desirable. The major causes of this are two:

a) Different types of components are used to make the items;

b) The discards are gathered without segmentation or without considering the cleanliness and degree of the waste.

By creating formats that reduce the amount and type of materials used, making it easier to separate them, or by offering reverse logistic strategies, such as maintaining the products' integrity and preventing the entry of contaminants, it is possible to try to overcome these issues through product design. These treatments are crucial for the quick and most importantly cost-effective adoption of circular methods, resulting in increased material productivity.

7.3.1 Maintenance

Predictive maintenance is intended to base maintenance actions on a conditional preventive maintenance program based in turn on predictions made on mathematical models. In order to give some practical support, some implementation actions need to be defined. A general literature review is shown in the following paragraphs.

The maturity level of predictive maintenance 4.0 (PdM 4.0) and another type of inspection and presents a list of implementation actions.[1]. It also provides a framework for the step-by-step implementation of technical components in the PdM 4.0 model, in a manner that supports business strategy. [2] provides a roadmap towards an Industry 4.0-based CE business to provide a framework that gives basic guidance for companies that want to implement this strategy.

A fundamental implication of maintenance – valid both for predictive and corrective maintenance - is the implementation of repair actions. According to [3] repair actions can be performed by the customer or by third parts, at the customer's location, and through a repair company. Businesses may send recollected products to their own repair centres, to manufacturer controlled or to third party repair centers [4].

In summary, from the literature review of predictive maintenance strategy implementation what comes out is:

- The importance of data and related technologies for their collection, elaboration, and sharing;
- The need for new competences and a new digital culture;
- The need for repair actions management.

7.3.2 Remanufacturing

Remanufacturing by definition means Refabricating, unlike refurbishing, it potentially alters the nature of the object (e.g. the current plant is turned into a smart plant that no longer needs workers). It is, essentially, giving a second life to a product (e.g. industrial machinery). Moreover, it is a strategy that allows an already used product or component to be brought back to the market through using parts of discarded products in a new product with the same function maintaining the original equipment manufacturer performance specifications.

Remanufacturing process is developed in 5 steps:

1. Disassembly;
2. Cleaning;
3. Inspection, diagnosis and reorganization;
4. Refurbishing;

5. Reassembly.

This strategy brings considerable advantages to the producer as it:

a) Avoid buying a new product, and decrease the maintenance cost which, in turn, implies a lower cost for the final consumer;

b) Reduces the consumption of raw materials and energy;

c) Reduces the amount of waste released into the environment due to broken machines;

d) Saves space as well as reduces harmful chemicals that come from the disposal of electronic devices such as computer monitors;

e) For expensive parts, remanufacturing can be cost-effective, but sometimes the effort and manpower involved in recycling hardware costs more than replacing the hardware;

f) Increases the overall efficiency thanks to the technical upgrading done while remanufacturing.

The remanufacturing of one plant could be done as follows:

a) It can be done on one or more machines of the plant;

b) It can be done in different timelines for each machine (e.g. machine 1 with remanufacturing in 2023, machine 2 with remanufacturing in 2024);

c) For the same machine, it can be distributed over several years (e.g. machine 3 with remanufacturing in 2025 and 2026).

Below you may find a brief description of the business model:

To start with, the plant parameters, being the general base of the constructed model on which we will decide whether to Remanufacture or not. Where users enter the data relating to the plant on which they want to evaluate a remanufacturing operation. In our business model, we considered that the plant can consist of a minimum of 1 machine and a maximum of 5 machines. Regarding the NPV, we considered a value ranging between 4 to 10, where 4 is the minimum number of years that we considered on which it is possible to calculate the NPV and consider that the calculation of these years does not include the year ended. Depending on the number of machines inserted in the business model, it will be necessary to input all the data relating to consumption and costs for those machines.

Moving to the Business parameters, where we took into consideration the different indexes such as:

a) Days payable outstanding (in days), being the number of days its takes the company to pay for its supplies, noting that in the following years it will be a variation based on the first year;

b) Stock turnover rate, being the %, which reflect how many times the company is selling and replacing its inventory;

c) Advanced payment incidence, simplistically saying it is the early payments that are done by the company. Anticipating the Credit;

d) "Discount factor", we took into consideration that some Users do not have this data, so we provided them with a "7%" default value for the cash flow calculation.

Noting that the total displayed data is to decide if the company is willing or not to do manufacturing, and it's a base of the general data to construct the model to calculate IRR and PBP.

Also, we took into consideration within our business model the following:

a) The data relative to the price of sale of each product (of the plant in question) and the quantity of pieces sold, and the relative percentage variations. Noting that if Users are not considering to do Remanufacturing, the unit price is higher because they have more cost taking into account the consumables such as water and electricity are greater than the past. For example, the company can foresee that there is a price increase due to the reactivation of maintenance or electricity costs, because over the years the machine can lose performance and this can lead to a greater consumption, and more costs relating to consumption and maintenance, and therefore sells you at 22 euros per piece instead of 23 euros per piece;

b) The number of working hours, per person, on the plant and the relative percentage variations; the number of people on the plant and the relative percentage variations; the cost per person per hour and the relative percentage variations. Moreover, users have the possibility to insert the variation of number of working hours, per person, on the plant (based on the projected Market changes as we are evaluating future investment); this depends on if they do, or do not remanufacture. For example, users whom are not willing to do the Remanufacturing, the person working on the plant will work more since the plant at this stage has losses in its performance, so more manual work will be required from the usual work on that machine, and the same time this will be reflected on the variation of number of people working on the plant, taking into account that more people will be required to work… for instance if in 2022, 2 persons were enough to operate the machine, but then 2023, 3 persons will be required to work on that machine to operate it. Hence, the cost of labour will increase.

And finally, the Model results output that is detailed in clause 6.4 to help user precisely take their decision.

7.3.3 Refurbishing

Analysis of various possibilities at the end of production lifetime showed that there are three main scenarios, when refurbishment of an equipment is needed:

1. During production on an equipment, statistically there can occur a situation, when a large number of small components will get significantly degraded and they will need almost simultaneous maintenance. I.e., equipment needs deep maintenance actions. Such maintenance can be considered as refurbishment or can be replaced with economically preferable refurbishment (optionally with upgrade of additional components);

2. Second scenario may occur when equipment is used a long time and core components of equipment get degraded. In this case simple maintenance cannot improve situation, since significant part/mass of the equipment should be maintained, which is related with almost total disassembly, inspection, etc.;

3. Finally, third scenario may occur when equipment is still capable to do work, however there are changes in business model, or there are additional requirements to the business model, or need to satisfy more modern standards. This is very frequent scenario of equipment refurbishment in EU, since there is massive change to Industry 4.0 functionalities, implying implementation of networking and advanced data processing features. Modern development of Artificial Intelligence (AI) algorithms will only increase number of use case of such scenario.

While the first two scenarios listed above are related to degradation of equipment, which is very standard use case, third scenario is related to change of business model and related requirement standards. Since this latter scenario is very frequent the developed model should cover all above listed possibilities.

Main structure of business model financial flow is shown in Figure 1. Business owner(s) performs one time investment for e.g., buying or refurbishing a production line or equipment. This investment is coloured in orange. Next, production line owner has periodic expenses due to production. These costs are related to consumable materials which are needed for production of products, e.g., raw materials, electricity, oil, gas, water, etc… There are periodic costs related to maintenance of production line, which occur due to gradual degradation of equipment. Finally, there are periodic expenses related to regular salary to employees on the production line. These are three main category of expenses and all of them are coloured in red. In order to compensate all these expenses, successful business model should have income related to sale of the produced products. This income is denoted with green box in Figure 1.

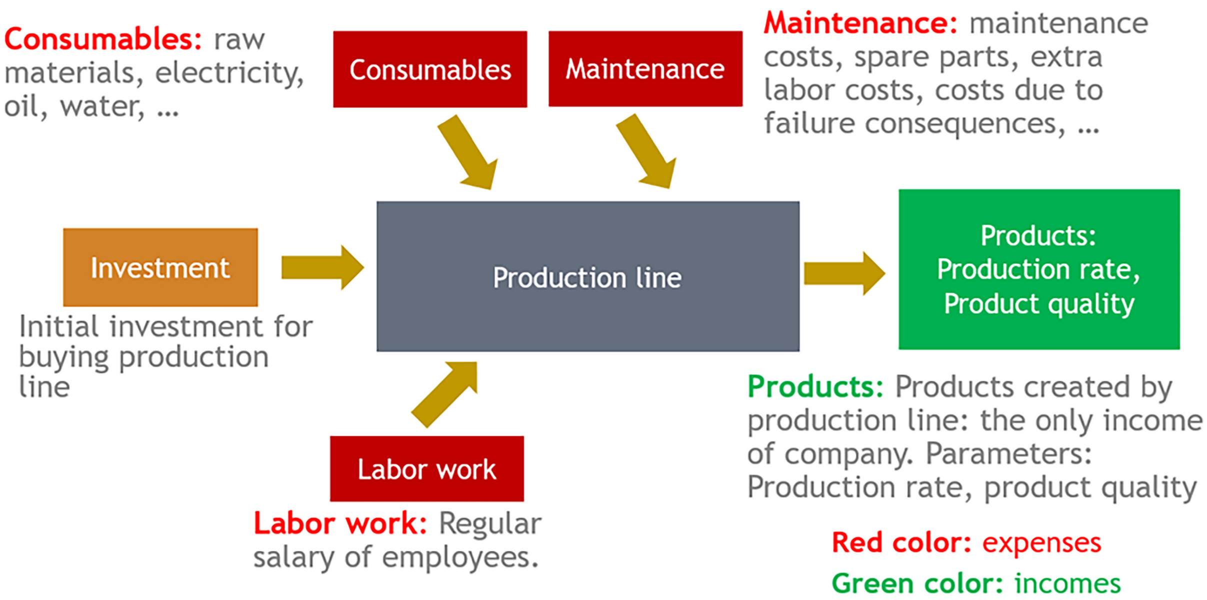

Figure 1 — General picture of financial flow of incomes and outcomes in a business model

7.4 Selection of the best option

Based on the result of the customised NPV-Economic model, the user will have the possibility to precisely decide if to do Remanufacturing or not to do Remanufacturing by looking at the 2 indexes being the PBP and IRR which are returned for each model.

Considering Scenario 1 - Without Remanufacturing, and Scenario 2 - With Remanufacturing; Investors will have the possibility to choose between the following possible 3 cases:

a) PBP of scenario 1(2) is less than PBP of scenario 2(1) and IRR of scenario 1(2) is more than IRR of scenario 2(1);

   Then scenario 1(2) should be chosen

b) PBP of scenario 1 is less than PBP of scenario 2 and IRR of scenario 1 is less than IRR of scenario 2;

   Then scenario 1 should be chosen if investor need to recover the investment in a short time and willing to sacrifice some return in the long run.

c) PBP of scenario 2 is more than PBP of scenario 1 and IRR of scenario 2 is more than IRR of scenario 1

   Then scenario 2 should be chosen if Investor is willing to wait a little longer to recover your investment and you want to maximise your return over the long term.

8 Step 3: Design (and implementation) of the solution

8.1 General

In this clause, the design of a lifetime extension strategy based on the RECLAIM methodology is described. First, the potential goals of a lifetime extension are illustrated, and pre-conditions are discussed. The major design elements are described later by showing the RECLAIM architecture, the building blocks and specific hardware- and software components.

8.2 Definition of goals

The first step of the design and implementation of a lifecycle extension strategy (LCES) is to define the specific goal(s). The RECLAIM methodology considers various lifetime extension strategies. For the:

a) Time-based maintenance;

b) Predictive maintenance (preventive);

c) Repair or Corrective maintenance;

d) Refurbish;

e) Remanufacture;

f) Preventive maintenance (non-predictive).

Depending on the strategy, a set of activities need to be performed. The RECLAIM methodology suggests considering actions in the following processes:

Design: The design of components, equipment or entire production lines should already consider (future) lifetime extension purposes. This could mean, e.g., designing for sensors that follow common standards and are easily swapped, almost in a “plug-and-play” format.

Manufacturing: The manufacturing process needs to be designed to support the envisaged lifetime extension strategy.

The **Logistic process** needs to support LCESs, especially when refurbishment and remanufacturing is envisaged.

The **equipment operation** needs to be assessed whether it supports the envisaged LCES and which actions need to be taken.

The actual **Maintenance** activities need to be reviewed and assessed.

Finally, the actions to be taken when the **End of “first” Life** of the equipment or component is reached.

As an example, an assessment of a component to be refurbished is provided in Table 3.

Table 3 — Assessment of a component to be refurbished (EXAMPLES)

Design
• Modular design that allows the upgrade of critical components or assemblies or the replacement of components subject to wear • Plan to make some components available for a long time
Manufacturing
• Flexible internal production process (to guarantee the spare parts production)

• Flexible purchasing process to guarantee the acquisition of the spare parts • Repair the damaged components and reuse them
Logistic process
• Organize reverse logistics of out of date or damaged components • Organize the distribution of the updated components or spare parts
Equipment operation
• Introduction of IoT devices to monitor the working conditions of critical components • Introduction of monitoring systems and decision support tools (automated) related to the IoT devices
Maintenance
• Introduction of maintenance services able to replace worn components and upgrade machineries • User of monitoring systems. It may decide to introduce IoT devices and create monitor systems. It may decide to change some pieces
End of "first" Life
• See reverse logistic in the Logistic process phase • Repairable / Reusable Component: Repair and reuse in different equipment • Waste components: send them for recycling • Dispose of damaged spare parts

8.3 Hardware and Software technical solutions

8.3.1 General

This clause illustrates the hardware and software solutions RECLAIM provides. The RECLAIM architecture is explained in detail by going through the various building blocks. Subsequently the technical solutions are described.

8.3.2 Gap analysis and necessary pre-conditions

In order to adopt the circular economy practices and improvements suggested in this document, it is important to assess the available products and production processes, the corresponding sensorial data - to determine which type of detections and predictions are possible – and, the available cost/revenue data - to determine which calculations can be conducted for deciding the optimal strategies to deploy (refurbishment, remanufacturing, or others).

8.3.2.1 Challenges/Gaps

The reality for many companies is such that most of the useful information is "hidden" in PLCs, siloed in several excel files from different teams (the kaizen team, the Production planning, the warehouse and maintenance team, etc.), or paper forms that aren't digitized at any point. The fact that this information is usually only gathered on a, after the fact, monthly basis, and the fact that the there are no "in-house" retrofitting/automation capabilities (e.g. usually relying directly on the machine manufacturers and/or third-party companies for some level of customisation to production processes) only compounds to this gap in data availability.

On the cost/revenue side, there is also, frequently, a lack of proper unit economics and "lumping together" of wrong data (e.g. having 2 distinct processes / products get added to the same KPI and/or counters simply because they are on the same machine.

These, and other commonly encountered realities, create a series of gaps that shall be closed.

For the aforementioned data challenge, one of the first steps to close this common gap, is to deploy a Building Block such as the BB1 - Adaptive Smart Sensorial Network and Digital Retrofitting Infrastructure (see 8.3.3). This is also one of the essential gaps to be closed in order to deploy higher level approaches (e.g. BB3 – Decision Support Framework), that we will defined next.

Companies usually measure some form of OEE/TEE (Overall/Total Equipment Effectiveness) which contain aspects of performance, quality and availability. Companies will also measure some form of equipment duration/wear and service/maintenance logs, both in incidences, times and costs to repair. This information is the most basic data necessary to allow for decisions on equipment interventions that can a) increase their performance and b) extended their useful lifespan. Of course, for this decision to be economic viable, the other necessary information is the cost of the alternatives (e.g. buying new), and the impact on procurement cycles and production load increase on other machines.

For this particular challenge, one most have higher level of data, specifically cost/revenue data (as previously mentioned). To close this gap one could deploy the Building Blocks BB4 – Cost Modelling and Financial Analysis Toolkit and the required BB3 – Decision Support Framework.

As we have presented, because of the existing challenges, one shall assess and then address any gaps that may exist in any of the 3 aforementioned data required: process/product data, sensorial data, costing/economic data[2].

8.3.2.2 Pre-conditions to be met

In order to successfully deploy the Building Blocks presented in 8.3.3, a number of pre-conditions shall be met:

Firstly, one shall gauge what information we have available, i.e. how easily is it reached, how readily it is available, how siloed/batched/clean it may be.

Secondly, an idea (or tentative value) of Theoretical Output, Quality and Availability for machinery/processes should be available.

With this information clearly defined and gathered, we can move towards the maintenance approaches best suited for the Circular Economy models proposed.

Although several categories of preventive maintenance exist (predetermined, condition-based, predictive, to name a few), for this section we accept the underlying assumptions and externalities that conducting preventive maintenance strategies are better alternatives to the reactive maintenance approaches, in particular towards extending the useful lifetime and performance of equipments.

In shifting from corrective maintenance approaches, especially those deployed based on a single data point for decision (i.e. Restoring a machine to functioning order regardless of economic factors, only after an issue is already noticeable[3]), toward preventive maintenance approaches based on multiple data-points, including economic factors, the set of pre-conditions that shall be met are the following:

1. Data exists (i.e. it is being “sensed” and exported);

2. Data is available in a timely manner both for detection as well as decision making;

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[2] We deliberately didn’t define a category called “maintenance data” as this has aspects of all of the three presented data: has an economic impact - downtime, materials/parts, labour; has a process/product impact – efficiency, quality, idleness; has sensing impact – machine in maintenance, machine restored.

[3] Noticeable, in this context, is roughly defined as having a significant negative impact in time (delay/stoppage) and/or cost (material waste, reduced yield, more scraps).

3. The costs of maintenance and other repair/refurbish strategies are understood (unit costs or similar);

4. The data allows for analysis of trends (e.g. There is an historic perspective, especially regarding failures and maintenance events);

5. There is some level of process/functional analysis that can be leveraged (e.g. FMEA, FTA, HAZOP) to assess criticality of machine deviations from normal operation.

8.3.2.3 Closing the gaps

Independently of the level of digitalisation or IIoT solutions available, most manufacturing plants will usually track performance, maintenance man-hours, serviceable parts inventory, and, machine and part wear in some form. Below we enumerate a series of data sources that can be leveraged to source the data necessary for each of the Key Areas (suggested in this standard and presented in Table 4):

- PLCs and IIoT enabled sensors;
- SPC (Statistical Process Chart - aka Shewhart chart, control chart) and other Quality data;
- Production reports;
- Production/Work Orders;
- Products and Part inventory;
- Machine and Part inventory;
- FMEA, FTA, HAZOP or other functional safety assessments;
- Economic and Cost center data (unit economics or otherwise).

With all this data in hand, we can deploy the strategies of the Key areas presented in Table 4:

Table 4 — Key areas for decision making

SENSOR INTEGRATOR
DIGITAL TWIN MODEL
SECURITY
DEGRADATION MODEL, FAULT DIAGNOSTICS
MACHINE PROFILE INDEX
MAINTENANCE PLAN
REFURBISHMENT AND REMANUFACTURING PLAN, PROCESS REFURBISHMENT
LCC/LCA
PREDICTIVE MAINTENANCE
DECISION SUPPORT FRAMEWORK
PROCESS PLAN, MACHINE CALIBRATION
PHM
CIRCULAR ECONOMY STRATEGY
DASHBOARD ANALYTICS
COST MODELLING
AUGMENTED REALITY

All the key areas presented in Table 4 will assist us in extending the useful lifecycle of a machine as well as making the best economic decision of what type of maintenance strategies to deploy. All of this, ideally in a preventive, before the fact, manner.

As a few quick examples, if a company already has camera vision systems, 3d rendered catalogue of products (and any intermediate parts) the gaps to deploying an Augmented Reality solution would be greatly reduced.

As a bit longer example, if we are working with old machinery, and want to deploy a Degradation Model, Maintenance Plan and Predictive Maintenance Strategy, we would have to assess the gaps in the following order:

1. Refurbishing (bringing a machine to proper working condition to start gathering "normal" data);

2. Digitalisation (add sensors that are crucial to measure output/performance, quality of output, number of cycles/output, categorical failure scenarios, etc);

3. Integration of data (with other sources - matching e.g. Production orders to actual output and machine uptime);

4. Analysis / modelling (process univariate or multivariate);

5. Tie in to outcomes for anomaly detection;

6. Confirm models/findings. Prevent future occurrences;

7. Define cost effectiveness of repairing strategy (when, how long offline, etc) when to intervene (what other data points? - cost of doing nothing – cost of run to failure - cost of performing maintenance prematurely).

8.3.3 RECLAIM Architecture

The requirement analysis, the prioritization of the building block, and the mapping of the stakeholder's needs to the objectives and KPI's provide a profound basis for deriving an architecture of the solution. The architecture shall fulfil the requirements of the end user. Additionally, the architecture shall be open, allowing the easy adoption of additional needs not known or not in focus.

The architecture, in Figure 2, basically consists of two levels:

1) The Pilot level in which the machines, individual databases, and third-party products and services are located. The solution contributes to the Pilot level by adding technology such as machine wrappers, sensors, or local data analysis services;

2) The RECLAIM level which adds various services and frameworks for supporting the lifetime extension of machines and equipment on Pilot level.

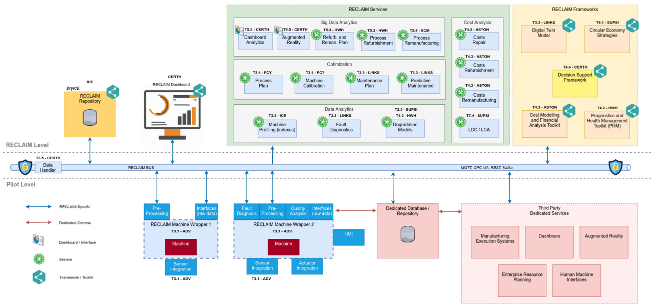

Figure 2 — RECLAIM architecture

The RECLAIM architecture organizes the RECLAIM building blocks (BB1 – BB9) – see Table 5, associating them to the various components in the architecture. The flexible architecture allows the selection for each end-user of the more appropriate and fruitful technologies permitting customizable solutions. The common interfaces between the components allow for a fast and individual customisation of the architecture to specific needs.

Table 5 — RECLAIM building blocks

RECLAIM Building Block (BB)	Short Description
BB1 - Adaptive Smart Sensorial Network and Digital Retrofitting Infrastructure	A distributed and adaptive smart sensor service to collect and process data for industrial environments, including IoT controllers to be attached at existing devices and machines to

	retrieve data and enabling predictive maintenance tasks.
BB2 - Embedded Cybersecurity for IoT devices	Embed cybersecurity endpoint protection into the design and development processes of Digital Retrofitting Infrastructure but also in the post market phase.
BB3 - Decision Support Framework (DSF) for Optimal Lifetime-Extension Strategies	The DSF component is designed to support and improve the effectiveness of decisions concerning the refurbishment and re-manufacturing of production infrastructure.
BB4 - Cost Modelling and Financial Analysis Toolkit	The cost modelling will carry out cost estimation and analysis by using the combination of parametric costing and activity-based costing methods. The cost model will consider all type of life extension strategies and activities for carrying out refurbishment and re-manufacturing of the industrial equipment, as well as the resources needed for each activity.
BB5 - Prognostic and Health Management Toolkit	The prognostics and health management (PHM) provides a peer-to-peer health evaluation as well as component prediction methods to increase equipment (machine) lifetime, productivity, and service quality
BB6 - Fault Diagnosis and Predictive Maintenance Simulation Engine using Digital Twin	Fault Diagnosis and Predictive Maintenance Engine aim to monitor and predict the performance and status of factory assets, providing information to schedule the maintenance works on the machines, optimizing the production throughput, reducing the production lines stoppages, and avoiding failures.
BB7 - Optimization Toolkit for Refurbishment & Re-manufacturing Planning	This Optimization Toolkit supports the planning optimization through multi-variable monitoring of the machine’s operational parameters where the effects of variable changes will determine the best practices/methodologies for model-based plat-site/shop-floor control.
BB8 - In-Situ Repair Data Analytics for Situational Awareness	Used to identify and recognize machine operational and behavioural patterns, make fast and accurate predictions and act with confidence at the points of decision.
BB9 - Novel shop floor AR-enabled Multimodal Interaction Mechanisms	This component aims to provide a novel way to visualize and localize information on equipment refurbishment and re-manufacturing operations directly situated on top of the physical equipment.

The initial architecture provides a profound basis for further specification and development within RECLAIM. It will further be detailed and adapted based on the experiences of integration into the pilots. The pilots' needs are associated with different RECLAIM solutions. Each pilot will have an architecture diagram (pilot consolidated view) allowing the selection and definition of each end user's most relevant components and solutions.

The components selected to handle the pilot issues provide different solutions, such as:

1. new sensors or other components (e.g., cameras, PLCs) to collect more information about the process;

2. predictive algorithms like fault diagnostics or degradation modelling to infer the machine health, or

3. prescriptive methods like predictive maintenance or process parameter optimization.

8.3.4 Technical solutions

This clause describes the functionality of the software and hardware architectural components. The information flow of the architecture, which shows what kinds of data are exchanged between all main software components, is shown in Figure 3.

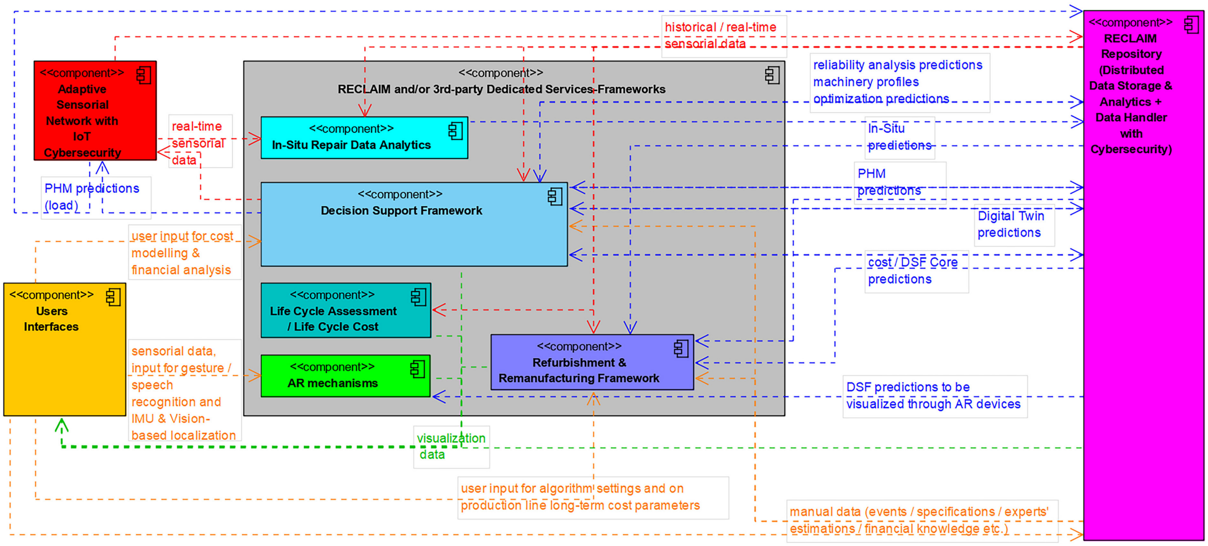

Figure 3 — Information flow

8.3.4.1 Software components

In general, software components are generic and applicable to multiple industries.

8.3.4.1.1 Adaptive Sensorial Network (ASN) with Internet of Things (IoT) Cybersecurity

8.3.4.1.1.1 IoT Gateway software stack

The software stack is comprised of the communication and protocol adaptation services for the IoT device communication and provides the necessary tools, libraries and middleware for using the TensorFlow framework on IoT gateways based on the NVIDIA Jetson platform.

8.3.4.1.1.2 Field-Programmable-Gate-Array (FPGA)-accelerated cyber security module

The modules comprising this software a) facilitate the use of acceleration (FPGA) for detecting and analysing cybersecurity threats; b) provide the monitor and management modules of the Cyber security gateway (GW); c) provide the cyber threat detection and analysis modules; d) provide the threat mitigation/control modules, that block the threats; and e) provide the communication/interfacing modules, that enable the interaction with other external components (central logging server, software agents, etc.).

8.3.4.1.1.3 ASN Sensor Protocol Adaptation

This component is responsible for the protocol adaptation of the deployed sensor devices in the shop floors which communicate through the IoT Gateways. It translates this data to the relevant JavaScript Object Notation (JSON) format and publishes it using Message Queuing Telemetry Transport (MQTT) to the IoT Gateway's internal MQTT broker. It employs a time ordered volatile queue mechanism ensuring that no data are lost in case of brief communication failures with the DRyICE and timestamps sensor data coming from sensors that do not inherently provide time information.

8.3.4.1.1.4 ASN Actuator Protocol Adaptation

This component is responsible for the protocol adaptation of the deployed actuator devices which communicate through the IoT Gateways. It registers these devices through the RECLAIM Repository and exposes a unified communication interface, irrespective of the underlying communication protocol of each device.

8.3.4.1.2 RECLAIM Repository

8.3.4.1.2.1 Distributed data storage and analytics (DRyICE)

This is the RECLAIM Repository database described in clause 6.4.

The Distributed Data Storage and Analytics component is a storage and a set of data aggregators tailored according to the requirements from RECLAIM. The storage covers data from the machines connected to the RECLAIM environment as well as the data calculated by the different algorithms. Internally, the component accounts with two data buses: Kafka data bus to serve the data stored in the storage to the rest of the RECLAIM system and an MQTT data bus to store the data coming from the sensors. In addition, two extra modules are present: one to generate the necessary metadata for the calculation of the three indexes and another one (based on Spark) to analyse the data and extract patterns from the underlying data.

The DRyICE is based on Apache Druid, a column-store distributed database. Since Joins are not supported and the storage model is based on columnar decomposition, it's based on Non-Structured Query Language (NoSQL) technology.

This software is part of the RECLAIM Repository together with the Data Handler with Cybersecurity.

The corresponding visualization [User Interface (UI)] of the data stored in the repository is going to be based on Superset. These UIs are already integrated with the DRyICE and they shall be called from the RECLAIM platform dashboards menu.

8.3.4.1.2.2 Data Handler with Cybersecurity

This component, which was also described in clause 6.4, transforms the format of data exchanged between components deployed in different machines. In most cases, the RECLAIM Repository database (DRyICE) is one of the communicating components. A holistic data model (common information model) is used for storing data in the database of the RECLAIM Repository. Thus, the Data Handler transforms the format when necessary in the cases of communication where the DRyICE is involved:

a) Input from machinery data collectors to the DRyICE;

b) Input from end users to the DRyICE;

c) Input from the DRyICE to algorithmic components (DSF, In-Situ Repair Data Analytics, Refurbishment & Remanufacturing Framework, AR mechanisms, Life Cycle Assessment);

d) Output from algorithmic components to the DRyICE;

e) Output from the DRyICE to Users Interfaces. The Data Handler includes also cybersecurity mechanisms that ensure the secure data communication with the Distributed data storage and analytics component.

8.3.4.1.3 Decision Support Framework

8.3.4.1.3.1 Reliability Analysis Tool

The Reliability Analysis Tool implements statistical analysis to calculate machines reliability and average residual useful life. Starting from historical data (e.g. failure occurrences) of machine's components and/or sub-systems, the Reliability Analysis Tool is able to build the related failures probability functions (2-parameter Weibull, 3-parameter Weibull etc.) and to calculate failure probability of the single components and of the overall machine.

This tool shall be used to develop simple analysis in order to have a first overview of machines' reliability and status. It includes a simple interface supporting companies in providing the required data and in performing the analysis.

The tool is composed by the following sub-components:

1) **PluginManagement:** Since it may be required to have custom distribution fitting functions, a plugin approach has been chosen. The component handles all the aspects of managing the various plugins installed and to be installed on the modelling platform;

2) **UserGUI**: This component represents the whole Graphical User Interface (GUI) that the user is presented with. Not only the graphic aspect but also the retrieval of information to be displayed on the latter;

3) **AnalysisExecutor**: Component in charge of executing the analysis upon user request. The executor initializes the required function from the PluginManagement component and saves the results in database, where they can be consulted by the user or stored into the RECLAIM repository;

4) **ComponentsDesigner:** This component handles the design of the system structure, allowing the user to design a flow diagram that represents the components in the system;

5) **Security:** This component is in charge of authenticating the users and allowing them to operate only on their systems;

6) **Persistency:** The persistency component is in charge of handling all the aspects of the data storage of the platform. An embedded database like H2 or a server database like PostgreSQL may be used.

Most of the data are saved within the tool database, while the data necessary for the calculation of the health index (Machinery Operational Profiling) are made available in the RECLAIM Repository.

8.3.4.1.3.2 Machinery Operational Profiling

The Machinery Operational Profiling algorithm calculates the three indexes (Health, Performance, Production) to generate the profile of the machine based on the data and parameters provided by the machines of the user partners. These data can either be manual (based on manually entered maintenance data or estimated changes), static (based on specification and functionalities from the machines) or dynamic (based on capacity, usage, history etc.).

In terms of dependency, the Machinery Operational Profiling is part of the Decision Support Framework and the calculated indexes are stored in the RECLAIM Repository.

The corresponding visualization (UI) for the profiles is built on top of Superset. This UI is already integrated with the DRyICE and it shall be called from the RECLAIM platform dashboards menu.

8.3.4.1.3.3 Fault Diagnosis and Predictive Maintenance Simulation Engine using Digital Twin

The main goal of this component is to create a Digital Twin of the factory environment and to use it to monitor and predict the performance and status of factory assets. This allows providing to the user all the features needed to schedule the maintenance works on the machines to avoid failures being predicted by the "Prognostic and Health Management" algorithms (see later), as well as to perform proper maintenance planning, optimizing the production throughput and reducing the production lines stoppages.

This component includes the algorithmic sub-components about Digital Twin for Simulation, Predictive Maintenance and Anomaly Detection, which are described later in more detail.

Furthermore, this component includes the following components:

1) **Artificial Intelligence (AI) environment**: It is the engine leveraged to host and run the Fault Diagnosis and Predictive Maintenance algorithms;

2) **AI engine:** It is hosted in the AI environment and it is used to abstract the heterogeneous algorithms of Fault Diagnosis and Predictive Maintenance and to control their interactions;

3) **Orchestrator:** It is used to orchestrate all tasks of the component, coordinating the interactions between the AI Engine and the distributed Simulation Environment. Furthermore, it receives the historical and real-time data from the IoT Gateway software stack, stores them and processes them with data quality mechanisms;

4) **Simulation Environment:** It is a distributed environment composed by a set of distributed Digital Twins for simulation running on different machines, each one wrapped by a Simulation Manager that exposes its features through common Application Programming Interface (API);

5) **Front-end including two graphical user interfaces (internal sub-components):** The Output/monitor GUI, allowing the user to monitor the output in real time (developed using Thingsboard), and the Configuration GUI to configure the component;

6) The functionality of the aforementioned algorithmic sub-components follows below:

a) Digital Twin for Simulation:

The ultimate goal of this sub-component is to evaluate different maintenance scenarios and production strategies by means of discrete simulation to reduce the impact of maintenance activities on the performances of a production system. It is composed by 2 main modules:

1) Production data Input / Output (I/O) manager that imports the production sequence over a period of time from a legacy system (Production scheduler) and converts it into a readable input for the DDD (libraries for the digital twin development and process plant simulation of complex environments) simulation model component.

2) DDD simulation model that allows to create the simulation model of a manufacturing shop floor. It receives as input:

- the defined maintenance plan over a period of time;

- the machine profile of each production resources to be simulated (from the Machinery Operational Profiling component);
- the machine failure probabilistic model as defined in the Predictive Maintenance sub-component;
- the current shop floor status mainly in terms of Work In Process (WIP), machine/tool utilization time from the last failure, machine/resource availability, etc.

It is composed by 2 sub-component types:

- Process modules: to describe the production processes to be simulated along with control logics, priority, Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), etc.;
- Transport modules: to describe the material flow in the shop floor along with the control logic, the routing rules.

The digital twin for simulation provides, as output, a list of Key Performance Indicators (KPIs), such as: average throughput of the shop floor, average utilization of each resource, average lead time, average WIP. Furthermore it can provide detailed simulation results such as the utilization time of each resource over a period of time, the duration of every failure happened during a simulation run, the number of failures of each resources, etc.

b) **Anomaly Detection:** Techniques to find abnormal behaviors that deviate from normal process conditions to raise warnings and find root causes for the problem. This algorithm is feedback directly with sensor data (when possible and pertinent) or transformed data from the pilots in order to be more interpretable. Based on the analysis of data streaming, the algorithm should indicate if a warning should be sent to the key personnel to check the system. This algorithm is the first frontline of analysis from shop-floor components in order to understand machine's health.

c) **Predictive maintenance:** The predictive maintenance approach is composed of:

   1) a component failure prediction in the future (e.g. 48h);

   2) an optimization module for scheduling future maintenance actions based on the existing scheduling. The main idea of this method is to predict what kind of maintenance is required based on the failing component in the machine. With this, it is possible to understand what changes need to be done in order to compensate the downtime of the failing machine.

8.3.4.1.3.4 Optimization Toolkit for Refurbishment and Remanufacturing Planning

The Optimization Toolkit for Refurbishment and Remanufacturing Planning aims to support planning optimization through multi-variable monitoring of the machines' operational parameters where the effects of variable changes are possible to determine and combine learning methodologies for model-based plant-site/shop-floor control. Based on the multimodal data provided by the IoT infrastructure, new approaches of real-time production planning optimization algorithms have been developed to apply proven optimization methodologies to deliver measurable performance improvements. Also, this monitoring takes into consideration the data collected from the sensors network, the machine profiles, production processes, and previous predictive maintenance simulations.

This toolkit is composed of three different blocks: State and Failure Identification, Decision Making, and Process Plan Optimization.

The first block intends to identify the current state of the machine and characterize it according to its state and impact on the machine. This block receives the trigger of a predicted failure from Digital Twin and interprets according to it within the Machine Identification module.

The Decision-Making block receives the Severity Range from the previous block and evaluates its impact on the machine operation and performance. With the addition of the machinery profile, this block proposes and characterizes different operations to the machine. Four different operations can be returned: "Machine OK" if the machine doesn't need any optimization, "Refurbishment", "Remanufacturing" or "Production Line Modification" according to the more efficient solution for the machine optimization.

The final block associates the proposed solution to the machine process plan and life cycle cost (received from Cost Framework) and generates the Process Planning according to it. It is expected that this plan considers all the different options and chooses the optimized solution according to machine performance and production. The proposed plan can be validated with simulation engines. Besides, a machine calibration proposal should be reported as a suggestion to parameter change.

This component has a GUI developed in the VueJS language. The output of the Optimization Toolkit is going to be transferred to this UI via repository. The other specifications of the UI are the common ones for most UIs, which are described later.

This component includes the following algorithmic subcomponent:

- Algorithms for quality prediction and process parameter optimization: Algorithms to predict the final product quality in a specific machine based on the parameters used for the process. These methods are based in data, where both parameters and final quality should exist in order to train machine learning models, both regression and classification. Ultimately, based on the quality predictive model it is possible to estimate future machine parameters if a new product needs to be yielded.

8.3.4.1.3.5 Prognostic and Health Management (PHM) Toolkit

This consists of the following subcomponents:

Degradation models.

The aim of this toolkit is the development of a comprehensive framework for predictive and preventive control and management. The framework contains a number of physical and virtual tools integrated for diagnostics and prognostics in manufacturing in order to provide a significant contribution on enhancing operations and maintenance intelligence.

Exposed Services:

- Degradation model service;
- Machine Component Description Modeller.

Private Services:

- Friction Welding Machine (FWM) Load Calculator;
- Web-UI;
- Web Service Data Provider;
- RECLAIM Orchestrator.

More details can be found in clause 6.5.

Integrated equipment degradation & quality Bayesian probabilistic models.

This component corresponds to an algorithm for probabilistic anomaly/failure diagnosis on the system level. It uses Dynamic Bayesian Networks (particularly, Hidden Markov Models) combining operational data and little expert knowledge for unsupervised learning. The hidden states correspond to the automatically distinguished reasons of anomalies/failures. The number of hidden states is user-defined. More details can be found in clause 6.5.5.

8.3.4.1.3.6 Cost Modelling and Financial Analysis Toolkit

The cost modelling carries out cost estimation and analysis by using the combination of parametric costing and activity-based costing methods. Cost breakdown structure has been established to represent all the cost elements associated with the selected lifetime-extension strategy. Analogy-based costing may also be used to estimate certain cost elements that lack sufficient data.

The cost model considers all types of lifetime-extension strategies and activities for implementing them, as well as the resources needed for each activity.

The model provides cost estimates to be used by the Decision Support Framework (DSF, particularly the DSF Core component described below) to provide decision support to end-users in RECLAIM concerning which the most suitable and cost-effective lifetime-extension strategy is for a given condition of equipment/component.

8.3.4.1.3.7 Integrated Decision Support Framework (DSF) for Refurbishment & Remanufacturing Optimization - core component (DSF Core)

Based on defined evaluation metrics, raw data from the Adaptive Sensorial Network, the output of data analysis components, as well as defined lifetime extension strategies, this ultimate component of the DSF infers:

1) the most suitable remanufacturing/refurbishment strategy;

2) the preferable timeframe for the implementation of the strategy;

3) the right components to be remanufactured/refurbished;

4) the optimal design alternative.

In contrast with the Optimization Toolkit, which performs only operational optimization of specific KPIs in single machines w.r.t. process parameters, the DSF Core performs operational optimization globally, i.e. in whole production lines or set of machines of each pilot use case, for all KPIs together, and provides recommendations for all possible lifetime extension strategies considered in the respective use case.

8.3.4.1.4 In-Situ Repair Data Analytics

This is an image processing tool based on (deep) machine learning techniques, like two-dimensional (2D) convolutional neural network (2DCNN) and boosting methods. It is being adaptable to the needs of each industry. The main considered scenario is that a camera takes 2D or 3D data from the product, and a supervised (deep) machine learning algorithm compares it with the ideal form of the product and based on that infers its quality. This scenario is applicable to most industries. Two other relevant use cases are part identification and part alignment verification.

8.3.4.1.5 Refurbishment & Remanufacturing Framework

This is a decision-making strategy tool that allows for an economic assessment of refurbishment and remanufacturing. It is focused on finding optimally refurbished equipment design, which corresponds to optimal economic KPIs.

As an input this tool uses user input described in rough/global business model parameters (general incomes and outcomes related to design of equipment). It uses methods of the DSF for computation of optimal (minimal) maintenance costs. The algorithm and its UI have been constructed with flexible input connection possibility, such that the more input information is provided, the more detailed the output result is.

As an output it generates optimized refurbishment/remanufacturing decisions (design alternatives etc.) and corresponding economic KPIs in form of array of objects.

8.3.4.1.6 Augmented Reality (AR) mechanisms

The main objective of the AR mechanisms is to display the DSF recommendations for lifetime extension strategies and the particular steps to refurbish/remanufacture specific machines and/or their components to end users on top of the physical equipment through AR glasses or tablets / mobile phones. The initial position of the user is identified by a marker, and then it is tracked by the device's Inertial Measurement Unit (accelerometer, gyroscope) and camera sensors, providing to the user directions to the equipment of interest. The equipment is recognized based on another marker when the user arrives there, and the 3D models of the machine and its components are displayed on top of the physical machine. Then, the user can view annotated recommendations for lifetime extension strategies and other potential DSF predictions, and navigate over the steps to perform refurbishment or remanufacturing when recommended by the DSF.

The above are achieved thanks to the following activities:

1. Develop novel Localization Mechanism:

- Research Inside-out 3D registration [based on Inertial Measurement Unit (IMU) and Vision hybrid methods];
- Implement indoor localization using above methodologies.

2. Develop novel AR Visualization Mechanism:

- Implement head-mounted display (HMD) and Mobile device-based AR Visualization pipeline;
- Integrate Indoors localization to AR 3D visualization;
- Implement real-time Localised 3D Annotation module;
- Research multimodal (gesture + voice) interaction techniques.

3. Integrate with AR devices to receive user input for interaction, input from device sensors for IMU and vision-based localization, and camera data for marker-based feature recognition, as well as to send visualization data.

4. Integrate with the DSF to receive notifications and display relevant instructions.

The special benefits of using AR glasses over tablets and mobile phones for augmented reality are that the users do not need to use hands while acting on the equipment, the 3D visualization is more realistic, and gesture recognition is also supported apart from speech recognition for interaction.

8.3.4.1.7 Life Cycle Assessment

The main functionalities of the Life Cycle Assessment (LCA) Tool and its dashboard are the following:

1) real-time assessment of the sustainability performances;

2) generation of machine use/refurbishment scenarios;

3) comparison of the identified scenarios;

4) visualization of assessment results.

The tool is composed by the following subcomponents, divided in three layers: repository, LCA platform, user interface.

8.3.4.1.7.1 Repository layer

Users database (DB): the component stores the data related to users accessing the platform and makes them available to the User Manager whenever necessary.

Models DB: the component is deputed to store the models of processes, production systems or supply chains designed inside the platform. The Models DB exchanges data by means of the Models input/output (IO) to the related Model Managers within the LCA platform.

Sustainability indicators DB: this component is dedicated to the storage of the KPIs and/or methodologies that are used by the Sustainability Engine to calculate the environmental, social and economic LCA impacts;

Sustainability DB: this component is dedicated to the integration and storage of external databases necessary for LCA impacts computation.

8.3.4.1.7.2 LCA service platform

User Manager: it manages the profiles of the users of the platform.

Process Model Manager, Production Model Manager: these two components are dedicated to the design and editing of respectively production processes (e.g. milling) or group of processes linked to produce a component (e.g. production line).

User IO, Models IO, Indicators IO, Importers: all these component are dedicated to the dispatching to the other internal components of the LCA platform of data coming from external sources or DBs.

Sustainability engine: it is the core of the platform and stores the algorithms required to calculate the LCA impacts.

Sustainability executor: it uses the defined process/production models and the calculation logics embedded in the sustainability engine to provide as output the impacts of each analysed production/process.

8.3.4.1.7.3 User interface layer

Process Editor: this is the interface that allows the user to edit a new process.

Production editor: this is the interface that allows the user to interlink a set of processes in a production system.

Sustainability executor GUI: this is the main user interface that provides the visualization means of the calculations performed by the platform. It is composed by two subcomponents: production data entry and Sustainability ind. Monitor. The first is dedicated to the data entry of process/production specific data, required to feed the LCA platform engine. The latter visualizes the sustainability related performances of the system and allows the user to work on the provided data.

8.3.4.1.8 Users Interfaces

This component consists of the visualization panels of the RECLAIM platform corresponding to the output of the Decision Support Framework, the In-situ Repair Data Analytics Toolkit, the Refurbishment & Remanufacturing Framework and the AR mechanisms, and appears on relevant hardware (AR devices for AR mechanisms, and usually personal computers for the rest). The component also allows the end users to provide manual input for the algorithms of the DSF and the In-situ Repair Data Analytics using the Common uploader UI, under the holistic data model supported by the Data Handler.

The visualization provided by these UIs is based on Angular 8, which appears to have more capabilities than Grafana.

These UIs support Websocket or also MQTT protocol, depending on the interfaces of the interacting components.

8.3.4.2 Hardware components

The hardware components discussed here are divided into sensors, gateways, devices and controllers. In contrast to software components, most of these hardware components are industry-specific.

8.3.4.2.1 Sensors

8.3.4.2.1.1 Machine Vision System

This includes hardware components (cameras along with IoT gateway including Jetson Nano module and carrier) providing input to the image processing algorithm of the In-Situ Repair Data Analytics component.

8.3.4.2.1.2 Water flow meter: ENERKON 204855314 impulz modul+m 1L/imp

8.3.4.2.1.3 Energy meters: Siemens 7KM2200-2EA30-1EA1

8.3.4.2.1.4 Hydraulic oil level sensors: NS 2-N0/300/105 Level switch HBE

8.3.4.2.1.5 Hydraulic oil temperature sensor: 923457 ETS 4545-A-100-000 HYDAC

8.3.4.2.1.6 Filter control sensor: PE3 PRESSURE SWITCH WITH CHANGEOVER CONTACTS OMT

8.3.4.2.1.7 Welding current sensor: rogowski sensor with integrator connected through analog input 4…20mA to PLC

8.3.4.2.1.8 Rotary Shaft incremental encoder for robot and welding reel speed: connected to PLC through fast inputs - optoPulse - EIL580P-T

8.3.4.2.1.9 Welding voltage sensor.

8.3.4.2.1.10 Resistance temperature detector (RTD, resistance thermometer) for cooling water temperature: RTD with converter with head in process end (4...20mA)

8.3.4.2.1.11 Robot sensors: Robots have integrated sensors for the position of axes and other process variables got from motor data (e.g. operation time).

8.3.4.2.1.12 White enamelling line wireless sensors: Sensors for diagnostic of surrounding environment (temperature, humidity and pressure) for enamelling process. Real-time wireless monitoring for optimizing white enamelling process at white enamelling line. Their measurement is a radio module that allows temperature, humidity and environment air pressure wireless monitoring. Their signals are digital (temperature, relative humidity, pressure, battery level).

8.3.4.2.1.13 Outdoor weather station: It measures outdoor environmental parameters (temperature, relative humidity, precipitation).

8.3.4.2.1.14 AR Smart Glasses (Microsoft Hololens) with red-green-blue-depth (RGB-D) camera and IMU sensors

The first fully self-contained holographic computer to run Windows 10. Now, with HoloLens 2, each device provides commercial ready management capabilities enhanced by the reliability, security and scalability of cloud and AI services from Microsoft.

Device capabilities:

1. Human understanding:

a) hand tracking,

b) eye tracking,

c) voice.

2. Environment understanding:

a) 6 Degrees of Freedom tracking;

b) spatial mapping,

c) mixed reality capture.

The signals are digital.

These are devices where the AR mechanisms run to guide end users in performing lifetime extension strategies. They include the following sensors:

   a) Head tracking: 4 visible light cameras

   b) Eye tracking: 2 Infrared (IR) cameras

   c) Depth: 1-MP Time-of-Flight depth sensor

   d) Inertial measurement unit (IMU): Accelerometer, gyroscope, magnetometer

   e) Camera: 8-MP stills, 1080p30 video

8.3.4.2.1.2 Temperature sensors - thermocouples: Measure the temperature of the machine every time that it works.

8.3.4.2.1.3 Piezoelectric sensors: These flexible piezoelectric sensors for deformation monitoring measure susceptance. Variations in structural behaviour and geometry were measured, and the load and μ strains during operational conditions were quantified in the time domain. The lead zirconium titanate (PZT) sensors were able to distinguish between material types and thicknesses. The influence of the PZT voltage applied was assessed to reduce power consumption without signal loss, and calibration to μ strains and loads was performed.

8.3.4.2.1.4 IoT ContactLess Motor Supervisor (CLMS): power & voltage sensors, environmental sensors, self-powered electronics to gather data from smart sensors: Non-contact motor monitoring sensor. It adheres to the body of the motor in order to obtain the necessary variables for monitoring the condition of the motor without the need to insert intrusive elements in the system. A network analyser is used to measure all the electrical parameters (current, voltage, face angles,...) in a front part forming machine of a shoemaking industry.

8.3.4.2.1.5 Membrane change sensor: Used for a rear-part forming machine of a shoemaking industry.

8.3.4.2.1.6 Mobile phones with camera and TIME sensors: Images and video signals are captured by standard Android smartphone. The smartphone video camera detects Quick Response (QR) Code, which serves as a component tag [unique identity (ID)]. Based on this tag detailed information on this component state is delivered in user-friendly form in smartphone app.

8.3.4.2.1.7 Sensors for variables useful for load (degradation speed) computation and anomaly detection - predictive maintenance: Sensors used for degradation monitoring of a friction welding machine, measuring temperature, rotation speed, force, displacement, sample detection sensor and vibration.

8.3.4.2.1.8 Thermal cameras: Used for welding process monitoring.

8.3.4.2.1.9 Sensemore vibration sensor: Used for predictive maintenance by motor and roller failure forecasting in a bleaching machine of a textile manufacturer.

8.3.4.2.1.10 Global Shutter Industrial Camera at exit of bleaching machine: The camera system ensures that a certain area of the fabric is photographed periodically and stored in the desired folder by naming it. It records white fabric images from fast moving fabric with digital signals.

8.3.4.2.1.11 Shade Bar sensors for whiteness and middle-side colour difference in textile.

8.3.4.2.1.12 Chemical sensors for recipe: Smart IoT multiparametric sensor to gather process parameters such as pH, electrical conductivity (EC), caustic concentration and bath temperature.

8.3.4.2.2 Gateways

8.3.4.2.2.1 IoT Gateway with AI acceleration: Operates as a border router for wireless sensors, caches and processes sensor data using machine learning (ML) algorithms when needed (optional machine vision camera interface).

8.3.4.2.2.2 Industrial IoT Gateways with data logger: 4th-Generation (4G) Long-Term Evolution (LTE) remote data logger / controller created for measuring and logging data from Meter-Bus (M-Bus) meters, Modbus remote terminal unit (RTU) devices, analog inputs [current, voltage, resistance or Pt100 (platinum resistance thermometer with nominal resistance 100Ω) temperature sensors] and discrete inputs (pulses, alarms or events). It also performs control capabilities over discrete outputs. Able to push data through File Transfer Protocol (FTP) and MQTT protocols.

8.3.4.2.2.3 Flexible FPGA platform to be adapted to specific requirements: Edge Industrial gateway: flexible gateway that can connect different machines, sensors, cameras, etc., and hosts different type of algorithms using an Advanced Reduced instruction set computer (RISC) Machine (ARM) + FPGA or ARM + Graphics Processing Unit (GPU) approach. AI algorithms can be optimized to work on FPGA/GPU to be faster and consume less power.

8.3.4.2.3 Devices

8.3.4.2.3.1 FPGA-accelerated cyber security device: This cybersecurity gateway monitors and analyses network traffic destined to or stemming from the assets for detecting threats and anomalous patterns, blocks the network connections that are evaluated as threats, logs security-related events (e.g. to be used later from an auditing mechanism) and provides acceleration to the sophisticated cyber threat detection and analysis algorithms.

8.3.4.2.3.2 Wireless M-Bus to Modbus Bridge: Once properly configured, the wireless Modbus bridge becomes transparent inside the RS485 network, not only maintaining the electric requirements of the bus, but also the integrity of Modbus RTU packet frames transmitted. It is used to communicate wireless M-Bus temperature, humidity and pressure sensors installed.

8.3.4.2.3.3 IBH Link S5++ bridge device: This interface S5 PLC - data logger measures all data from the PLC registers map. The IBH link S5++ is a cost-efficient alternative solution for conventional PLC - Personal Computer (PC) connections via Ethernet. The used protocol is the standard Transmission Control Protocol (TCP) / Internet Protocol (IP) protocol. Using this protocol all data from the PLC are extracted and serve to the data logger by Modbus TCP.

8.3.4.2.3.4 Servo-based drive: This servo-based drive for servo-motor control includes digitally controlled equipment for motor control in order to control the welding process. Merits of this equipment is that it allows to control acceleration and deceleration speeds, stability of rotation frequency, and stopping angle precision.

8.3.4.2.4 Controllers

8.3.4.2.4.1 PLCs

1. Siemens PLC

a) 3 x SIMATIC S7-1500, Central Processing Unit (CPU) 1511-1 PN 6ES7511-1AK02-0AB0

b) 4 x SIMATIC S7-1500, CPU 1516-3 PN/DP 6ES7516-3AN02-0AB0

2. S5 PLC measuring binary data about states of the production process

8.3.4.2.4.2 Siemens CP 1545-1 communications processor: 6GK7545-1GX00-0XE0

8.3.4.2.4.3 Temperature controllers: OMRON E5CC controllers. They take the temperature in analogic signal and they convert the values into digital, which is sent by Modbus to the industrial IoT Gateways with data logger.

8.3.4.2.4.4 XGenius: XGenius is main control unit for welding process. It generates all start/stop/control signals for operating all actuators (moving components). As a feedback it receives and records all sensor signals. It evaluates quality, and transfers data to connected main PC with GUI. XGenius is integrated to the rest of the system with PLC input outputs. In minimal configuration it supports several digital bus systems [SERIAL RS232, Controller Area Network (CAN), Ethernet], 16 PLC-inputs and 16 PLC outputs, general-purpose input/output (GPIO) and 4 analogue inputs 0-10V. HyperText Transfer Protocol (HTTP) protocol has been implemented. Digital and analogue IO interfaces can be extended with additional hardware cards (extended configuration) like in a desktop PC.

9 Step 4: Sustainability assessment

9.1 General

The sustainability assessment is implemented by environmental Life Cycle Assessment activities that address two main purposes:

1. Measure the current sustainability performances of a machine in order to:

a) Increase users' awareness on their machines' sustainability performances.

b) Create benchmarks, i.e., a set measures of the facilities sustainability performances to be used as a reference during new machine design.

2. Support the definition of recommendable sustainability-driven lifetime-extension methods to be adopted (e.g., Repair, Reuse; Remanufacturing, Recycling) through providing:

a) Assessment of the actual sustainability performances allowing benchmark, comparison and ranking to analyse machines portfolio and define intervention priorities

b) Forecast of the sustainability performances and comparison of the different scenarios which differ on the lifetime extension methods.

The current sustainability performances of the equipment are measured through the application of the Life Cycle Assessment (LCA) methodology. The LCA is an analytical and systematic methodology that assesses the environmental sustainability of a product or service and is internationally regulated by the ISO 14040/44 series of standards (ISO 14025, 2006; ISO 14040, 2006; ISO 14044, 2006) that provides a basic framework for the steps necessary to carry out the assessment. LCA quantifies potential environmental impacts associated with emissions, waste generation and resource consumption of products along the entire life cycle, i.e., from the extraction of raw materials through production and use to final disposal, including recycling, reuse, and energy recovery.

LCA can be performed according to different target objectives; however, usually, the final aim is to drive decision-making towards higher sustainability application/implementation levels. In view of this future-oriented goal, the LCA can be performed according to two different perspectives.

The ex-ante LCA is a prospective approach, which is typically used during the design phase of a product or service to identify and evaluate potential environmental impacts before the product or service is produced [5].

The ex-post LCA, on the other hand, is a retrospective approach, typically used after a product or service has been produced to evaluate the actual environmental sustainability of the product or service. Indeed, the main difference between the two is that ex-ante LCA is used to inform design decisions, while ex-post LCA is used to evaluate the performance of a product or service [6].

9.2 Definition of the assessment dimensions to be addressed (based on RECLAIM vision)

The Cost Benefit Analysis (CBA) assesses the solutions to determine whether the value/benefit gained from the implemented solution is worth the cost required for deploying the innovative solutions.

The CBA model will output the cost-benefit ratio, payback period and the monetary cash flows of both costs and benefits associated with implementing the RECLAIM solutions in order to gauge the economic viability.

The Cost-Benefit Analysis requires to identify all conceivable costs and benefits associated with the RECLAIM solution throughout its life cycle. Expected costs associated with implementing the solution are classified into two main categories:

- **One-Time Costs**: these types of costs are expected to be provided by the main developer/owner of the KERs:

  — Development of the solution (e.g., costs for developers, equipment, training, software tools, etc);

  — Hardware needed (e.g., costs for servers, workstations/PC, peripherals, networks/telecommunication equipment);

  — Deployment of the solution (e.g., costs for preparation, testing and deployment).

- **Recurrent Costs**: these types of costs are expected to be provided by the pilot users of the KERs:
  - — Operational and maintenance of the solution (e.g., costs for upgrades, technical support, supplies, licenses, security, etc) are estimated over a short-, medium- and longer-term basis.

Benefits associated with implementing the solution are estimated based on the improvements in the identified KPIs. Two main categories of Benefits can be identified:

- KPIs improvements gained from implementing the solution are quantified into monetary values over a short-, medium- and longer-term basis;
- Benefits gained outside of the KPIs are quantified into monetary values over a short-, medium- and longer-term basis.

9.2.1 Social dimension

When evaluating the implemented solution, it is crucial to consider the social dimension, which includes aspects related to the well-being and safety of the operators.

An important aspect to consider is noise. Refurbished machines may produce higher levels of noise than new machines, which can have a negative impact on the health and well-being of the operators. Companies need to evaluate the noise levels of refurbished machines and take steps to reduce noise pollution.

Physical work is also a significant factor to evaluate in the social dimension. Refurbished machines may require different physical tasks than the previous models, which can put extra strain on the operators. Companies should assess the physical demands of the refurbished machines and provide appropriate training and support to operators.

Finally, the training of the operators is another key area to evaluate. Refurbished machines may require new skills and knowledge that operators may not possess. It is essential to provide appropriate training to operators so that they can work with the refurbished machines safely and effectively.

9.2.2 Economic dimension

To determine the potential of the new implemented solutions in contributing to the company objectives, it is crucial to evaluate their impact on the economic dimension, which includes aspects such as production capacity, cost reduction, cycle time, changeover time, and equipment reliability.

One of the key aspects to evaluate within the economic dimension is the reliability of the refurbished equipment. A reliable machine ensures uninterrupted production, reduces downtime, and lowers the risk of defects, resulting in increased productivity and cost savings.

Another crucial factor to consider is the production capacity of refurbished machines. Companies shall evaluate the production capacity of the machines and ensure that they can meet the demand while maintaining a high level of quality. This includes optimizing the equipment layout, implementing automation, and leveraging real-time data to improve production efficiency. Cost reduction is also an essential aspect of the economic dimension, and it can be achieved in various ways when refurbishing machines.

Companies shall assess the cost reduction opportunities in inventory management, maintenance practices, and defect prevention, which can all contribute to cost savings.

Moreover, cycle and changeover time are critical factors to evaluate within the economic dimension. Refurbished machines should be optimized to reduce cycle and changeover times to increase production efficiency and flexibility.

9.2.3 Environmental dimension

To ensure that RECLAIM solutions are environmentally sustainable, it is essential to evaluate their impact on the environmental dimension, which encompasses aspects related to water consumption, energy consumption, raw materials and generated waste.

One of the key factors to evaluate within the environmental dimension is water consumption, which may vary depending on the refurbishment process and the design and technology of the machine. Therefore, it is crucial to assess the water usage of the refurbished machines and implement measures to reduce water consumption, such as installing water-efficient technologies and reusing water whenever possible.

Similarly, energy consumption may also differ depending on the machine's refurbishment process, technology, and other factors. As such, it is important to evaluate the energy consumption of the refurbished machines and implement energy-efficient practices, such as using renewable energy sources, optimizing machine settings, and improving insulation.

Moreover, the amount and type of waste generated by refurbished machines may vary depending on the refurbishment process and the materials used. Companies should assess the waste generated by the machines and implement measures to reduce waste, such as using eco-friendly materials, recycling waste, and adopting circular economy principles.

9.3 "Risk assessment" methodologies

The European standard EN ISO 12100:2010 "Safety of machinery — General principles for design — Risk assessment and risk reduction", is the reference harmonized standard that establishes the principles for risk assessment and risk reduction in the field of safety of machinery. This standard specifies basic terminology, principles and a methodology for achieving safety in the design of machinery. *The primary purpose of this standard is to provide designers with an overall framework and guidance for decisions during the development of machinery to enable them to design machines that are safe for their intended use.* EN ISO 12100 describes procedures for identifying hazards and estimating and evaluating risks during the relevant phases of the machine's life cycle (including the different modes of machine operation), and for the elimination of hazards or the provision of sufficient risk reduction.

There are different methods and tools available for machinery risk assessment. The selection of a particular method will depend on different factors, such as e.g., the type of machinery, the complexity of the assessment, or even personal preference. *The choice of a specific method or tool is less important than the process itself* (ISO/TR 14121-2).

ISO/TR 14121-2:2012 "Safety of machinery — Risk assessment — Part 2: Practical guidance and examples of methods" is an International Technical Report giving *practical guidance on conducting risk assessment for machinery in accordance with ISO 12100 and* describing *various methods and tools for each step in the process (e.g., risk matrix, risk graph, numerical scoring, hybrid method). It gives examples of different measures that can be used to reduce risk and is intended to be used for risk assessment on a wide variety of machinery in terms of complexity and potential for harm. Annex A further provides a specific example for a risk assessment and a risk reduction process.*

The International Standard IEC 31010:2019 "Risk management — Risk assessment techniques", *provides guidance on the selection and application of techniques to assess risk in a wide range of contexts.* The document procures an extensive range of techniques for risk assessment (non-exhaustive), giving guidance for their selection and application, as well as references to other documents where these techniques are described in more detail. Annex A categorizes the application of techniques in the risk management process, and the extensive Annex B, classifies and describes RA techniques as follows:

- <u>Techniques for eliciting view from stakeholders and experts</u>: Brainstorming, Delphi technique, Nominal group technique, Structured or semi-structured interviews, Surveys.

- Identification techniques: Checklists, classifications and taxonomies, Failure modes and effects analysis (FMEA) and Failure modes, effects, 60 and criticality analysis (FMECA), Hazard and operability (HAZOP) studies, Scenario Analysis, Structured what if technique (SWIFT).

- Analyzing sources and drivers of risk: Cindynic approach, Ishikawa (fishbone) method

- Techniques for analyzing controls: Bow tie analysis, Hazard analysis and critical control points (HACCP), Layers of protection analysis (LOPA).

- Techniques for understanding consequences, likelihood and risk: Bayesian analysis, Bayesian networks, Business impact analysis (BIA), Event tree analysis (ETA), Fault tree analysis (FTA), Cause-Consequence Analysis (CCA), Human reliability analysis (HRA), Markov analysis, Monte Carlo simulation, Toxicological risk assessment, Value at Risk (VaR), Conditional value at risk (CVaR) or expected shortfall (ES).

- Techniques for analyzing dependencies and interactions: Causal mapping, Cross impact analysis.

- Techniques for selecting between options: Cost benefit analysis (CBA), Decision tree analysis, Game theory, Multi-criteria analysis (MCA).

- Techniques for evaluating the significance of risk: ALARP/SFARP, Frequency-number (F-N) diagrams, Pareto charts, Reliability centered maintenance (RCM), isk indices.

- Techniques for reporting and recording risks: Risk registers, Consequence/likelihood matrix (risk matrix or heat map), S curves.

9.3.1 Risk assessment and digitalization

The introduction of digital technologies in machinery and integrated manufacturing systems (IMS), introduces new risks in the safety design of machines that shall be considered to ensure a safe and compliant product. Two new aspects derived from machinery digitalization shall be considered in the risk assessment of the machine:

a) Incorporation of Artificial Intelligence (AI), because safety of machinery can be compromised due to the significant complexity of introducing AI to machines.

b) Cybersecurity and protection of machinery against cyberattacks because smart manufacturing increases the vulnerabilities of machinery against security threats that can jeopardize the safety of the machine and put workers and others at risk of harm.

Table 6 lists two EU-safety of machinery standards that can be used as a guide by machinery manufacturers to guide the consideration of these new risks. Both standards describe how to apply the risk assessment process according to ISO 12100 to cybersecurity aspects and AI machine learning applications respectively.

Table 6 European machinery safety standards to guide the risk assessment process according to ISO 12100 in the aspects of cybersecurity and AI machine learning applications respectively.

Table 6 — EU-safety of machinery standards that can be used as a guide by machinery manufacturers to guide the consideration of these new risks

Safety aspect/risk	Standard for practical guidance	Standard´s scope
Cybersecurity and protection of machinery against cyberattacks	CEN ISO/TR 22100-4:2020 Safety of machinery — Relationship with ISO 12100 — Part 4: Guidance to machinery manufacturers for consideration of related IT-security (cyber security) aspect	The primary purpose of this document is to address aspects on safety of machinery that can be affected by IT-security attacks related to the direct or remote access to, and manipulation of, a safety-related control system(s) by persons for intentional abuse (unintended uses). This document gives machine manufacturers guidance on potential security aspects in relation to safety of machinery when putting a machine into service or placing on the market for the first time. It provides essential information to identify and address IT-security threats which can influence safety of machinery. ISO/TR 22100-4 gives guidance but does not provide detailed specifications on how to address IT-security aspects which can influence safety of machinery.
Artificial Intelligence (AI) and safety	CEN ISO/TR 22100-5:2022 Safety of machinery — Relationship with ISO 12100 — Part 5: Implications of artificial intelligence machine learning	The document addresses how artificial intelligence machine learning can impact the safety of machinery and machinery systems. The primary purpose of ISO/TR 22100-5 is to provide guidance for the development of artificial intelligence (AI) machine learning applications and assists machinery designers to develop solutions appropriate for their particular applications. The document describes how hazards being associated with artificial intelligence (AI) applications machine learning in machinery or machinery systems, and designed to act within specific limits, can be considered in the risk assessment process. ISO/TR 22100-5 is not applicable to machinery or machinery systems with AI applications machine learning designed to act beyond specified limits that can result in unpredictable effects. The document does not address safety systems with AI, for example, safety-related sensors and other safety-related parts of control systems.

9.3.2 Example used in RECLAIM, HAZOP

There are many safety and risk assessment techniques like Hazard and Operability Study (HAZOP), Systems-Theoretic Process Analysis (STPA) method or Fault Tree Analysis (FTA) that can be used to determine the safety and sustainability of any remanufactured machine. Safety and risk assessment needs to be a continuous exercise to ensure workers' safety and optimal performance of the machines.

Under this scope, RECLAIM is making use of HAZOP to cater for both aspects to ensure that the delivered solution promotes a safe and secure environment for all stakeholders.

Hazard and Operability (HAZOP) Studies is a structured and systematic technique for examining a defined system, with the objective of identifying potential hazards in the system and identifying potential operability problems with the system identifying causes of operational disturbances and production deviations likely to lead to nonconforming products.

HAZOP studies consist of four basic sequential steps (see Figure 4).

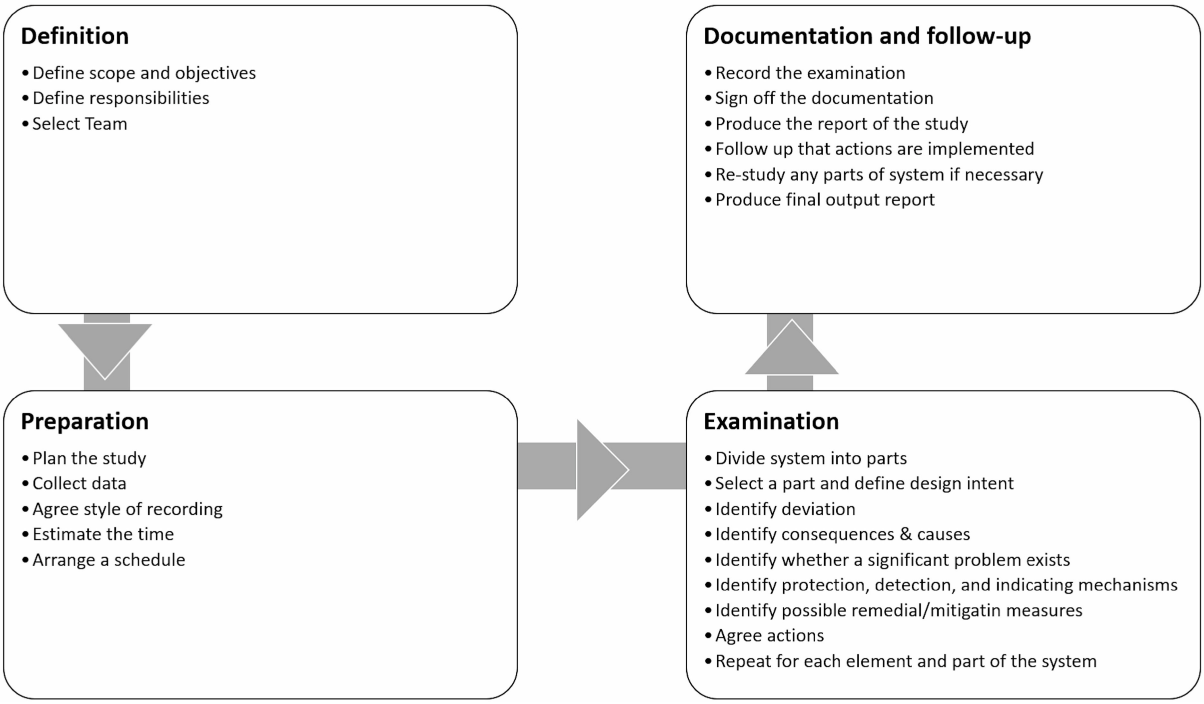

Figure 4 — The Hazop study procedure

HAZOP is beneficial for risk and safety assessment for several reasons:

1. **Comprehensive identification of hazards**: HAZOP systematically examines a process or system to identify potential deviations from normal operations that could lead to hazards or safety concerns. It helps in identifying a wide range of possible hazards, including those that may not be immediately apparent.

2. **Focus on operability**: HAZOP not only considers hazards but also evaluates the operability aspects of a system. It looks at how the system could potentially deviate from its intended design and identifies any issues that may affect its efficient and safe operation.

3. **Team-based approach**: HAZOP involves a multidisciplinary team comprising individuals with different areas of expertise, such as process engineers, operators, and safety professionals. This collaborative approach enhances the identification and understanding of risks and safety concerns from various perspectives, leading to a more thorough assessment.

4. **Systematic analysis**: HAZOP follows a structured methodology guided by a set of predefined guidewords to systematically examine each part of the system. This methodical approach ensures that potential hazards and risks are systematically reviewed, reducing the likelihood of overlooking important safety considerations.

5. **Early detection of issues**: HAZOP is typically performed during the design or modification phase of a process or system. By conducting it early in the project lifecycle, potential hazards and risks can be

identified and addressed before they become costly and difficult to rectify in later stages of the project.

6. **Risk reduction and mitigation**: HAZOP helps in prioritizing risks and identifying appropriate risk reduction measures. By understanding the causes and consequences of potential deviations, the study enables the development of effective mitigation strategies to minimize or eliminate risks, improving overall safety.

Overall, HAZOP provides a structured and systematic approach to identify and assess risks and safety concerns, facilitating effective risk management and enhancing the safety of processes and systems. As such, it is perfectly suited for its use within RECLAIM. Any structured process can be transformed into a sequence of steps to produce a result. One of the bases of HAZOP is a “guide word examination” that helps and guides on how to perform the analysis in a very standardized way. These process and guided steps that can easily be followed and automated.

9.3.3 Systems-Theoretic Process Analysis (STPA)

STPA is designed to identify not only direct, linear event sequences leading to accidents, but also indirect or time-delayed causal chains. For example, the influence of management or organizational culture, unexpected automation behavior, and gradual system changes over time may enable accidents that would otherwise be prevented.

An analysis using STPA is intended to be traceable and updatable. The hazards, unsafe control actions, and safety constraints identified in STPA’s top-down analysis are numbered so that the results can be updated with reasonable effort if the system under analysis changes or evolves. The analysis does not necessarily need to be completely redone after system changes.

The STPA process starts with a description of the system to be analyzed, including relevant system components and agents, their available actions, and how these actions affect other components and agents. This description could be provided by documents or other input from experts on the system; it is used to build a control structure diagram depicting the control relationships within the system. STPA shall also start with a definition of unacceptable accidents or losses and a list of situations likely to lead to them; these unsafe, pre-accident situations are defined as hazards in STPA.

The next step is to identify the unsafe actions or inactions that can lead to hazards. This step identifies not only the action itself, but also the agent performing it and the relevant context—including timing, system state, and the information available to the agent.

A set of four general categories of unsafe control actions helps to guide this step:

1. Not Provided when required for safety;

2. Providing Causes Hazard;

3. Too soon, too late, or out of sequence;

4. Stopped too soon, applied too long.

Note that these categories include both actions and inactions.

Given a list of unsafe control actions, the process next determines their potential causes and associated contextual factors (causal scenarios). This step considers potential causes at any point in the control structure, including flaws in the agent’s situational awareness and inadequate operation of control mechanisms or actuators. The unsafe control action, cause, and contextual factor define an unsafe scenario.

The final step determines what constraints are needed to prevent the identified unsafe actions from occurring for each unsafe scenario; these constraints can also be interpreted as requirements on system behavior. The safety constraints and requirements identified by STPA assist with safety-guided design of the system. The safety constraints and requirements can be cast as inversions of each unsafe scenario. That is to say, the requirement provides a solution to prevent a cause from ever occurring or a contextual factor from manifesting.

Theoretically, STPA is a more complete analysis for hazards or unsafe actions, than traditional methods like HAZOP or Fault-Tree Analysis (FTA), however, this analysis is harder to automate. It lacks well-defined steps to generate the analysis. These are guidelines that, followed by experts, lead to successful analysis.

9.4 Machinery regulation and remanufacturing/refurbishment

The Machinery Directive 2006/42/EC (MD) was adopted in the context of establishing the internal market, in order to harmonize health and safety requirements for machinery and remove barriers to trade in machinery between Member States.

Recently, the European Parliament and the Council have formally adopted and published (29 June 2023) the new Regulation (EU) 2023/1230 on Machinery (MR), which entered into force 20-day after its publication in the Official Journal of the European Union and will be applied from 14 January 2027. The new MR repeals the MD and transforms it into a Regulation, which will be mandatory in its entirety and directly applicable in all Member States. During the transitional period, until 14 January 2027, Member States shall not impede the making available on the market of machinery which were placed on the market in conformity with the MD.

One of the main objectives of the new MR is to ensure that digital technologies applicable to machinery are covered by this Regulation. The MR establishes requirements regarding cybersecurity of safety control systems and software, for the use of artificial intelligence (AI) in safety functions or with collaborative robots (Cobots). It also establishes digital instructions as the default option for providing information about the machine.

A physical or digital retrofitting/refurbishment can provide significant added value to a machine or assembly of machinery, as well as increase its useful life. However, this change can also have a significant impact on machine safety or data protection among other factors. In this context, the new RMP introduces the concept of "substantial modification", which *means a modification of machinery or a related product, by physical or digital means after that machinery or related product has been placed on the market or put into service, which is not foreseen or planned by the manufacturer, and which affects the safety of that machinery or related product, <u>by creating a new hazard, or by increasing an existing risk</u>, which requires:*

(a) the addition of guards or protective devices to that machinery or related product the processing of which necessitates the modification of the existing safety control system; or

(b) the adoption of additional protective measures to ensure the stability or mechanical strength of that machinery or related product.

Thus, MR will apply to those “substantially modified” machines, including software updates.

Annex IV of Directive 2006/42/CE, which exhaustively listed the machines considered high risk, has become Annex I of the new Regulation. The products included in the original Annex have remained unchanged, but the inclusion in Part A of Annex I of the following digital product categories is relevant for RECLAIM:

a) Safety components with fully or partially self-evolving behavior using machine learning approaches ensuring safety functions;

b) Machinery that has embedded systems fully or partially self-evolving behavior using machine learning approaches ensuring safety functions that have not been placed independently on the market, in respect only of those systems.

The requirements of the European regulation on machinery shall be considered to ensure the conformity of refurbishing/retrofitting/remanufacturing designs, especially if such designs constitute substantial modifications and/or the digital solutions designed include aspects of artificial intelligence (machine learning) and cybersecurity.

Annex A
(informative)
RECLAIM use case

A.1 Lifetime extension of friction welding machines

A.1.1 Introduction and context

Harms & Wende is a medium-sized German company grounded in 1946 in Hamburg, which is specialized in joining technologies. An important part of joining technologies is various kinds of welding. Harms & Wende is mainly focused on spot welding and friction welding techniques. While the spot-welding technique is widely used in various industrial fields, the friction welding technique is still in the process of development, and its application is rapidly growing in last years. The reason for it is its flexibility in joining various metallic and nonmetallic materials. e.g., it allows one joining of complex materials with significantly different melting points and/or resistivities, such as copper with steel or carbon material with steel sheet, which is not possible with e.g., standard resistive welding technique.

The typical lifetime of our welding system is of the order of 10 years. However, there are also systems operating significantly more than a decade. For that reason, reuse, upgrade, refurbishment, and in general, lifetime extension strategies are challenges that our customers and we meet. In addition, new Industry 4.0 requirements concerning networking, security, and a high degree of flexibility and automatization, together with new European-Union regulations regarding usage of green technologies and reduction of waste is additional challenge to our customers and company.

Here we describe the lifetime extension strategy for a RSM401 friction welding machine, current reuse and lifetime extension strategy-related challenges, which we and our customers encounter in industrial production.

The HWH Pilot represents a friction welding machine which was built back in 2008 by HWH and delivered to Lufthansa Technik and now it is back at HWH again. The machine was used by Lufthansa Technik to weld components of the aircraft's turbine engine and was in operation within a period of 10 years.

This machine does not meet today's requirements e.g., on adaptability to different welding tasks, increased cycle times, operator guidance by HMI, safety, quality control, degree of automatization, etc. In order to get the machine operational again and to enable it for predictive maintenance it requires remanufacturing and upgrading as well as equipment state and condition monitoring. The next section illustrates the need for lifetime extension more in detail.

A.1.2 Purpose of lifetime extension

According to the RECLAIM methodology, the first step is to generate a clear vision on the purpose and the goals of the lifetime extension strategy. For that, the current state of legacy equipment handling, and the vision need to be defined.

A.1.2.1 Existing Limitations

The following Table A.1 provides an overview of the limitations and barriers we faced related to our friction welding machines.

Table A.1 — Overview of the limitations

Topic	Description of Challenges
Operability/HMI	An old and small touch display is used and typically integrated into the control cabinet door. The visualization on the HMI is based on an excel tool that is no longer supported. The operation is not always intuitive and therefore not user-friendly. The clarity of the user interface and the shown information are limited, and the setting options are not very flexible. The operator needs to be familiar with the machine for smooth work. Skills and competence for human machine interaction as well as a codified framework to train people is needed.
Repair and Maintenance	Today a repair and corrective strategy as well as a time-based maintenance strategy for selected parts are driven. There is for example no prediction on wear out and users cannot identify problems quickly as little information about the status of the machine is known. This leads to unexpected and expensive machine stops. Sometimes entire assemblies shall be sent to HWH for maintenance and repair purposes which means long down times if this is not planned.
Construction and Mechanics	Different machines having the same functionality are implemented and constructed different. Some main mechanical parts are outdated. Especially the drive technology is not state of the art anymore and converters are no longer available in some cases.
Interfaces	Communication between the PLC of the friction welding machine and high-level interfaces is currently done via the old standard CAN Open or PROFIBUS or with additional effort by using a converter to PROFINET. This is no longer state of the art. New standard communication protocols are required.
Quality Monitoring	Quality monitoring is mainly carried out by analysing the data from the displacement measuring system and the pressure sensor. From this for example, the part contact and part reduction are calculated. Other quality parameters are described by indexes such as “brake index” and “pressure index” which are values that have been integrated over a certain area of a curve as a function of the process phase. These indexes are not self-explanatory and often lead to questions from the customer.
Remote Access	Remote access to the machines is not yet a standard and needs to be implemented individually and tested for each machine. Old machines usually do not have a modem included and in order to get access in case of an error or a planned update a special remote maintenance unit shall be send out to the customer and shall be connected to the machine. This is not practical and time-consuming.
Data Archiving	There is currently no automatic archiving of process data implemented. The export of process curves can be done via OPC in .csv format or by using the external Software MScope on a Windows-PC. The necessary hardware and activities for implementation needs to be done by the customer/user of the machine. This is not very user-friendly and often criticized.

Safety	Older systems were built and delivered according to guidelines that are now out of date. The safety of electrical cabinets needs to be improved from a standard point of view.
Software Updates	In the event of errors or new functionalities due to customer requests, updates of the existing software are necessary. This often shows that this works with new systems, but with older systems it often leads to problems, especially with older safety technology.
Reliability	The reliability of friction welding machines for future tasks and jobs needs to be predicted

A.1.2.2 Targets of lifetime extension strategy

As described in the chapter above, the HWH friction welding equipment is facing several challenges today. Various approaches to the optimization of existing and new machines are derived from this. All belong to the goal of *Lifetime Extension of Friction Welding Machines*.

Further to that, the intention is to update and to significantly enhance the welding equipment by predictive maintenance features. The scope is the remanufacturing and upgrading of friction welding machine RSM401, including the use of advanced sensors and on data analysis of the gathered data. Within the remanufacturing and upgrading processes the focus is on the following aspects given in Table A.2 below.

Table A.2 — Focus on refurbishment and remanufacturing

Sustainable system design to produce future-proof welding systems.
Use of identical parts to reduce production costs and improve service as well as maintenance of the welding systems.
Proactive and tailored service through predictive maintenance.
Ensuring holistic resource efficiency.
Fast, user-friendly, energy-efficient system design.
Smart management and operation.

A.1.2.3 Identified tasks for lifetime extension

Following the aspects listed above the fields of improvement for the HWH friction welding equipment as well as the solutions to be implemented are described more detailed in Table A.3 below.

Table A.3 — Identified tasks for lifetime extension

Topic	Description of Improvements/Solutions
Lifetime Extension of Friction Welding Machines	Bringing new technology to old machines by refurbishing and upgrading them. This should be done by the reuse of as many parts as possible.
Hardware	The outdated hardware components will be changed under the aspect of modularity and standardization as well as upgradability.

PLC	The old PLC will be replaced by a modern control which is also a HWH standard.
HMI	A more user-friendly and changeable HMI e.g. PC/Laptop, tablet or smartphone is planned.
Software	A standard software will be available for the various friction welding systems.
Sensors	Adding more sensors (physical and non-physical) in order to receive more information of the process and status of the machine.
Monitoring	Monitoring in terms of machine data analysis and visualisation. Quality and safety check of friction welding process based on data collected.
Predictive Maintenance	Next to time-based maintenance the collected data will be analysed to make condition-based maintenance as well as predictive maintenance possible.
Remote Access	The machines and components will be equipped with remote access as standard to make remote diagnostics and further to enable data processing and access to the web or cloud level.
Data Approach	There will be two levels of data. Data at machine/shop floor level and Data at high level cloud for further monitoring, display and networking options. There will also be data archiving.

A.1.3 Implementation of lifetime extension

For the implementation of the lifetime extension solution, the general RECLAIM architecture has been used as a basis. This architecture is designed in a flexible way to allow for specific, customer-tailored shape and deployment. As the major purpose is to enable predictive maintenance features, only those building block have been implemented which are needed for fulfilling the respective requirements. In particular these are:

- Big data analysis on refurbishment and remanufacturing planning as well as on data analytics;
- LCC analysis;
- Fault diagnosis, preprocessing, quality analysis, sensor- and actuator integration, interfacing, and HMI implementation on machine level.

To enable the interaction of those components, the following framework building blocks have been used: Data repository, Digital Twon Model, and the Prediction and Health Management Toolkit

To enable advanced data analysis, the friction welding machine's PLC has been wrapped by using a Harms&Wende control unit ("*Genius*"). This allows to implement, high-sophistic and intelligent features without hampering the original friction process execution. This is of particular importance as the process execution needs time-consuming qualification and validation procedures. By implementing the RECLAIM approach, machine upgrade was possible without performing major re-validation.

Bibliography

[1] Mulders M., Haarman M. (2017). Predictive Maintenance 4.0, Predict the unpredictable (PwC Publication). PwC Documents, June, 32. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwj3tvD415CBAxXI0wIHHQKYCowQFnoECBkQAQ&url=https%3A%2F%2Fwww.pwc.be%2Fen%2Fdocuments%2F20171016-predictive-maintenance-4-0.pdf&usg=AOvVaw34gIR7pGgxWdmUfiqLyE2i&opi=89978449

[2] Ghoreishi M., Happonen A. (2020). New promises AI brings into circular economy accelerated product design: A review on supporting literature. E3S Web of Conferences, 158, 1–10. https://doi.org/10.1051/e3sconf/202015806002

[3] Reike D., Vermeulen W.J.V., Witjes S. (2018). The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. Resources, Conservation and Recycling, 135(February 2017), 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027

[4] Thierry M., Salomon M., van Nunen J., van Wassenhove L. Strategic Issues in Product Recovery Management. Calif. Manage. Rev. 1995, 37 (2) pp. 114–135 https://doi.org/10.2307/41165792

[5] Thonemann N., Schulte A., Maga D. How to Conduct Prospective Life Cycle Assessment for Emerging Technologies? A Systematic Review and Methodological Guidance. Sustainability. 2020, 12 (3) p. 1192 https://doi.org/10.3390/su12031192

[6] van der Giesen C., Cucurachi S., Guinée J., Kramer G.J., Tukker A. A critical view on the current application of LCA for new technologies and recommendations for improved practice. J. Clean. Prod. 2020, 259 p. 120904. Available at: https://www.sciencedirect.com/science/article/pii/S0959652620309513