# Advanced technologies for the Repair, Reuse, and Recycling of industrial equipment

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**Abstract**

AIDEAS is a Horizon Europe project that aims to integrate Artificial Intelligence (AI) technologies for the improvement and extension of the service life of industrial machinery in Europe. The Project comprises 4 main parts: Design, Manufacturing, Use, Repair-Reuse-Recycle. Focusing on this last area, this article aims to show the synergy between all the solutions developed in WP6, which are involved in developing AI solutions for extending the useful life of a machine. The Smart Retrofit solution allows the connection of any machine by integrating a hardware side, including several devices, and a software side where all AI algorithms can work. In this way, the Prescriptive Maintenance and Disassembly algorithms contribute to a greater awareness of health status and remaining useful life. On the other hand, the Machine Passport constitutes the management element of all information concerning the machine, which, processed with Artificial Intelligence, allows a profile to be drawn up in the machine's life cycle.

**Keywords**: Advanced technologies, Interoperability, Smart Manufacturing, Data management

## 1. Introduction

The AIDEAS (AI Driven industrial Equipment product life cycle boosting Agility, Sustainability and resilience) [1] project is a European project that started on 1 October 2022 to develop a set of Artificial Intelligence (AI)-based strategies and technologies to improve various aspects of industrial machinery production in the EU over 3 years (end 30 September 2025). Focusing on the entire lifecycle of these machines, from design to production, to use and eventual repair/reuse/recycling, the project aims to strengthen the competitiveness, sustainability, and resilience of European machinery manufacturers/users. The project's approach involves developing four integrated suites: Design, Manufacturing, Use, Repair-Reuse-Recycle. The Design suite aims to optimize the design of industrial equipment components using AI technologies integrated with CAD/CAM/CAE systems. The focus lies on structural components, mechanisms, and control components. In manufacturing, AI technologies come into play for component selection, procurement, manufacturing process optimization, operations sequencing, quality control, and customization of industrial equipment. The Use section focuses on providing added value to industrial equipment users. It includes AI-driven support for installation, initial calibration, production, quality assurance, and predictive maintenance, ensuring optimal working conditions. Repair-Reuse-Recycle focuses on extending the useful life of machinery and includes AI technologies for prescriptive maintenance (repair), facilitating smart retrofitting for a second life (reuse), and identifying sustainable end-of-life options (recycling) [2]. The aim of the AIDEAS project is not only to improve the machinery production process but also to ensure sustainability, agility and resilience throughout the entire life cycle of industrial equipment, thus contributing to the competitiveness and strategic autonomy of the European machinery industry.

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In order to achieve all the objectives in the four areas mentioned above, the project is divided into several Work Packages (WP). This paper focus on the AIDEAS Work Package 6, "Industrial Equipment Repair-Reuse-Recycle". It is structured into several tasks, each addressing a different aspect of the Repair-Reuse-Recycle theme. In particular, Task 6.1 delves into Prescriptive Maintenance (PM), detailed in Section 3.2.1. Task 6.2 explores the Smart Retrofit solution (SR), with its description in Section 3.1. Task 6.3 covers the Sustainable End of Life solution, which encompasses the broader task, including the Disassembler (DIS), elaborated in Section 3.2.2. Finally, Task 6.4 focuses on the Machine Passport (MP), a tool for managing machine information, described in Section 3.3. A key point to highlight is the potential for integrating all these solutions within the work package, creating a cohesive tool that enhances various facets of an industrial machine lifecycle.

## 2. The Industrial Equipment Repair-Reuse-Recycle background

The AIDEAS Repair-Reuse-Recycling practices in industries offer broad benefits such as reducing waste, preserving resources, and mitigating environmental impact. Repairing machinery extends its life, reusing components cut down new production needs, and recycling retrieves valuable materials, reducing resource demand. These practices aren't just sustainable; they're cost-effective, slashing expenses by favouring repair and reuse over constant new purchases. Saving materials also aids resource conservation, creating a more sustainable production cycle. Environmentally, they lower landfill waste and minimize energy needs for new production. Regulatory compliance is crucial, ensuring responsible waste management. Overall, these practices align with the circular economy, maximizing resource value and minimizing waste, crucial for sustainability, cost efficiency, regulatory compliance, and reduced environmental impact in manufacturing. To realise all these objectives of WP6, several tasks are developed, including Prescriptive Maintenance, Smart Retrofit, Disassembler and Machine Passport. All these solutions are developed by integrating Artificial Intelligence algorithms, which is also why they are innovative and different from what is available on the market. In fact, there are currently no companies providing a smart retrofit service on industrial machines that integrates both the hardware and software sides in such a way as to enable the connection and introduction of Industry 4.0 elements in a simple, cost-effective and rapid manner. There are several reported cases in the literature where specific attempts are made on certain machines or systems: in many cases, PLCs, Raspberry Pi, Industrinos, etc. are exploited to enable data acquisition via sensors connected to the machine; in others, it is preferred to directly integrate smart sensors that can directly acquire and send data. On the communication side, the most commonly used protocols are OPC UA and MQTT [3], and generally, the endpoints to which the data arrives are local or cloud databases. Since the definition of Smart Retrofit requires the implementation of a software side, it can be noted that in literature many cases are where the data obtained from the machine are used and re-processed to create Machine Learning [3], [4] or Artificial Intelligence [5]–[7] algorithms that go to extract information, creating added value. Among the AI algorithms that the smart retrofit solution could integrate we have that of Prescriptive Maintenance or that of the Disassembler. Among the AI algorithms that the smart retrofit solution could integrate we have that of Prescriptive Maintenance or that of the Disassembler. In fact, to determine the necessary maintenance to prolong the machine's lifespan or reduce maintenance costs, the Prescriptive Maintenance solution will employ AI algorithms to estimate the remaining life depending on the data available. Operating data (signal monitoring), maintenance records, or physical models will be the basis for estimating the Remaining Useful Life (RUL) of a piece of equipment (or some of its important components). This information will be crucial for the decision-making process of a maintenance or second-life modernisation strategy. The RUL calculated through the use of AI algorithms trained on real machine data, returns an accurate and specific measurement for each machine or element, allowing effective optimisation of maintenance interventions (in number and type) necessary for the correct operation of the machine.[8] In the case of the Disassembler, it requires the camera hardware part that can be easily integrated into the SR hardware part and the software part that utilizes AI to recognize and determine the wear state of a given component. The integration of this tool with SR simplifies and avoids the construction of a new hardware system to support the DIS algorithm. In addition, this tool is very simple and cheaper than the competitors already on the market (verified by comparing the prices of the major companies working with industrial cameras and computer vision) and better than the methods used so far in this field. Until a few decades ago, the disassembly phase of the product recycling process was not even taken into account because materials were often dumped [9]. Traditional manual disassembly has been a time-consuming process, so an automated or semi-automated disassembly can significantly reduce costs in terms of both time and operating resources. The first semi-automatic disassembly cell was created in 1994 [10] but due to high prices and technological constraints, automatic product disassembly was not widely used in existing production systems until recently [11]. The "change of course" was achieved thanks to the rapid development of CAM methods [12], AI technologies, ML algorithms and other computer vision software. Most automated disassembly systems currently available do not work entirely automatically and still require human involvement. Therefore, the fundamental objective of modern automated disassembly systems, like this DIS tool, is to efficient and efficient human-machine interaction during the entire disassembly process [13].In the case of the Disassembler, it requires the camera hardware part that can be easily integrated into the SR hardware part and the software part that utilizes AI to recognize and determine the wear state of a given component. Integrating this tool with SR simplifies and avoids constructing a new hardware system to support the DIS algorithm. In addition, this tool is very simple and cheaper than the competitors already on the market and better than the methods used so far in this field. Until a few decades ago, the product recycling process's disassembly phase was not even considered because materials were often dumped [9]. 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It is responsible for storing, retrieving, updating, and deleting production data. Furthermore, the MP will play the role of a “message bus” in this project. Depending on the circumstance, the message bus's job is to set up all communication between the various components. Every request must be directed to the relevant component, and based on the use case, it must manipulate the necessary knowledge in accordance with the specifications. This tool also enables AI capabilities and interoperable data management, allowing access to machine data and AIDEAS solutions knowledge. Managing data is the primary goal of Machine Passport. It is responsible for storing, retrieving, updating, and deleting production data. Furthermore, the MP will play the role of a “message bus” in this project. Depending on the circumstance, the message bus's job is to set up all communication between the various components. 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## 3. The Industrial Equipment Repair-Reuse-Recycle solution

All tasks in WP6 are aimed at favouring an extension of a machine's useful life, acting according to the 3 basic principles characterising the WP: Repair, Reuse, and Recycle. As previously said, the PM estimates the next intervention to be carried out on the arm, the SR solution wants to enable the connection of the machine by bringing it closer to the paradigm of Industry 4.0 or enabling the acquisition of new parameters of interest, the DIS allows to understand the state of wear of a certain element of the machinery allowing its disassembly only when necessary. All these aspects can be integrated into a single solution that utilizes the hardware part of the SR and the software and management parts of the PM, DIS and MP. As shown in Figure 1, the connection of any industrial machine can be enabled by the SR-Box, the analysis is carried out thanks to the DIS and the PM, while the management of this information is ensured by the MP, which also enables the connection between the WP of the entire AIDEAS project.

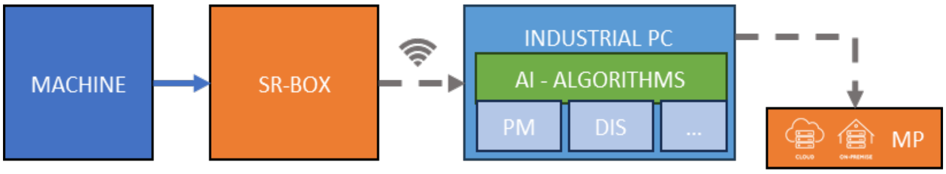


**Figure 1.** Integration of AIDEAS WP6 solutions

## 3.1. Smart Retrofitting for the second life

The Smart Retrofit solution in the project AIDEAS has, as its main goals, the possibility to enable the connection of all types of machines, the acquisition of the information necessary from these machines, and elaborate data with AI algorithms to create added value [14]. The main contribution of the Smart Retrofit solution, in this case of cooperation with the other tools, lies in providing a hardware element, the Smart Retrofit box, which enables the connection of any industrial machine (old or new machine). From a preliminary analysis of the current state of the machine, it is possible to understand which sensors are necessary to install to collect data with which to develop the algorithms integrated into the software part. The Box, made with a polycarbonate box, will contain a PLC with various analog and digital input and output modules, a power supply, a router for Wi-Fi communication and another for communication via LoRaWAN. Communication via intranet/internet enabled via the Wi-Fi connection provided by the Router (in green in Figure 2) allows us to obtain a large number of data quickly and to process them in a very short time, giving the possibility to develop solutions in real-time or near real-time.

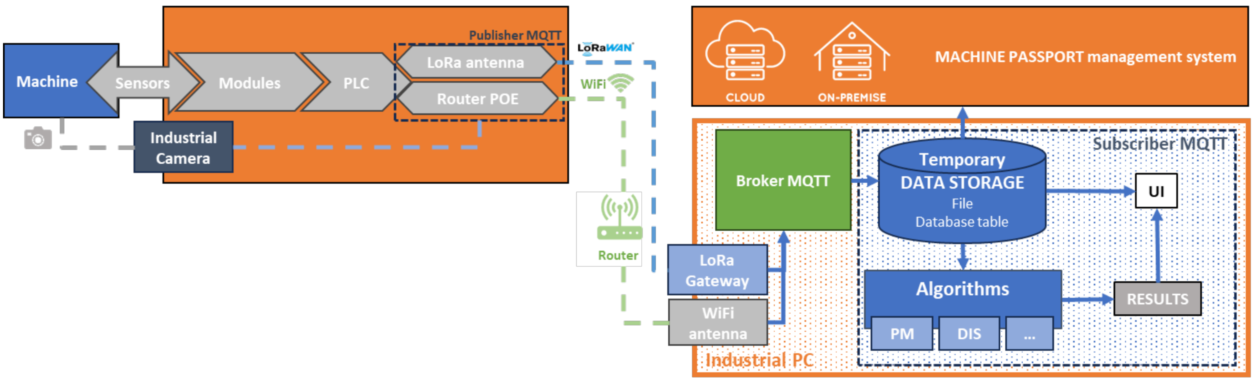


**Figure 2.** Smart Retrofit Solution: devices for WP6 solutions

This type of communication will take advantage of the MQTT protocol. MQTT (Message Queuing Telemetry Transport) is a lightweight messaging protocol designed for IoT applications; it follows a publish-subscribe model, and the key components of this protocol are the broker, subscribers and publishers, categorized by topics of interest. In this situation, the PLC serves as the publisher (client), whereas the industrial PC functions as both the broker and the subscriber. This configuration allows the PC to act as a server and enables it to receive and read all the messages transmitted by the PLC. All the data are then saved in a local database and then sent to the Machine Passport and AI algorithms (Prescriptive Maintenance, Disassembler, and also other integrable algorithms) for their re-processing. Also the communication protocol LoRaWAN enables the connection via wireless, but by exploiting the frequency bands 863-870 MHz: this, on the one hand, guarantees the possibility of sending data even at long distances but, on the other hand, limits the number of transmissions per minute. This means that the data is not sent in real time but in almost real time. It has also been decided to integrate this communication channel as it is widely used in industrial contexts, the signal can be transmitted over long distances and constitutes an excellent system of control of the parameters sent via the internet/intranet. In LoRa transmission, the antenna reads the data from the PLC and sends it to the gateway, which will then connect to the MQTT broker for sending to the local database. From the Local database, data can be extracted and processed by AI algorithms, such as Prescriptive Maintenance, to obtain information about the state of the machine's health. Similarly for the AI algorithm of the DIS, the images required for the algorithm are taken from the local database of the PC. The images are acquired via an 'add-on part' to the box consisting of the POE (Power over Ethernet) router (also required for PLC communication) and the industrial camera. The camera will be connected to and supplied with power by the POE router, which will send the data to the PC for collection in the local database as mentioned before.

## 3.2. AI for Extending the Useful Life

The implementation of Artificial Intelligence to extend the life of machinery is a growing field that offers numerous benefits, including many related to maintenance, performance optimisation and waste reduction. The following are the AI solutions that the AIDEAS project is implementing and that can be integrated with the SR solution to create a single life management tool.

### 3.2.1. Through Prescriptive Maintenance

Predicting component remaining life allows early detection of component degradation on industrial processes. This allows to schedule maintenance to avoid system failure when it is necessary and to define the specific set of actions for that specific potential failure instead of preventive maintenance, which is scheduled regularly entailing greater costs. The primary main goal of this PM solution is to provide as accurate information as possible regarding the degradation of a system or component, along with the remaining useful lifetime, in order to support the decision-making process aimed at extending the overall machine lifespan. Utilizing signal monitoring (physical or data models) or maintenance records constitutes the foundation for estimating the Remaining Useful Life (RUL) of equipment or its critical components. Leveraging this input data, the Prescriptive Maintenance solution will deploy various techniques and algorithms—such as regression, artificial intelligence, and statistical methods—to develop an accurate degradation model tailored to the available data type. Each algorithmic approach offers a distinct insight: one provides a more specific estimation value of the remaining lifetime, while another one offers a more generalized assessment of the risk of failure. Both measures take into account a range of uncertainty. The SR box makes it possible to collect all the signals monitored by the equipment, necessary requirement for assessing the RUL. Moreover, both algorithms can be inserted into the dedicated environment of the SR solution's industrial PC in order to obtain useful information on the state of health of the machine. This information will be crucial for the decision-making process of a prescriptive maintenance or second life modernisation strategy. Prescriptive maintenance strategies will repair or replace damaged components in an optimal period of time, avoiding unplanned downtime, minimising preventive costs and ensuring optimal performance levels of our equipment during usage phases. With significant degradation impacting an entire assembly or piece of equipment, decision-making will pivot towards strategies involving modernization or end-of-life considerations, including options for reuse or recycling to optimize the residual value of materials.

### 3.2.2. Through the identification of the most Sustainable End-of-life

The AIDEAS Disassembler (DIS) is developed to make the manual disassembly of equipment more efficient, which is traditionally a time-consuming and resource-intensive process. Its primary goal is to minimize waste and enhance the recovery of valuable materials and components, thereby reducing environmental impact. This smart tool offers several benefits, including higher recovery rates, waste reduction, cost-effectiveness, and environmental impact mitigation. By adopting automated disassembly technologies, there is a significant improvement in the efficiency of disassembly processes, leading to increased productivity and sustainability [2]. Using Artificial Intelligence, the AIDEAS DIS can elaborate the images acquired by an industrial camera, allowing you to monitor the product's condition and assess when it is approaching the end of its life cycle. In the proposed configuration, where there is strong integration between the various tasks of WP6, the industrial camera is placed in the SR box area, onboard the machine, and physically connected to the box POE router. In this way, the camera can be placed close to the part to be controlled, photos can be taken and sent directly to the router, which in turn, via the router-enabled Internet/intranet, can send these images to the WiFi antenna and save data in the local memory (MQTT communication protocol). From the local memory, the algorithm will take the image as input and analyse it as a matrix to understand the element's degree of wear and tear. From this, it will then be possible to understand whether the part needs to be changed or not and, thus, whether it needs to be disassembled. In the proposed configuration, the industrial camera is placed in the SR box area, onboard the machine. In this way, the camera can be placed close to the part to be controlled, photos can be taken and sent directly to the router, which in turn, via the router-enabled Internet/intranet, can send these images to the WiFi antenna and save data in the local memory (MQTT communication protocol). The algorithm will take the image as input from the local memory and analyse it as a matrix to understand the element's state. From this, it will then be possible to understand whether the part needs to be changed or not and, thus, whether it needs to be disassembled. Once the algorithm has processed the image, the results will be saved in the local database and displayed on the graphical interface, allowing the operator to make a more informed decision regarding the analysed part.

### 3.3. Machine Passport: Repair-Reuse-Recycle Data

The transition to a circular economy necessitates a robust data exchange system to navigate the end-of-life processes: Repair, Reuse, and Recycle. These stages involve various actors, including consumers, repair shops, and waste management companies. The Machine Passport emerges as a dynamic platform to manage multi-source, large-scale data acquisition, ensuring data compatibility and interoperability across product life phases. The Machine Passport utilises unified standard service modelling techniques to emphasise data compatibility, interoperability, consistency, and quality. These standards ensure that data remains coherent throughout its lifecycle, from manufacturing to disposal. The Machine Passport provides a scalable and trust-enhancing solution for managing end-of-life data within the circular economy. By ensuring data quality and leveraging explainable AI, it significantly improves the decision-making processes across the supply chain, reinforcing the sustainability of manufacturing practices. In the proposed solution, which integrates the tasks of WP6 of the AIDEAS project, the MP represents the synthesis element that collects all the WP6 data, integrates them with those from the solutions of other WPs and helps in the decision-making process of the operators.

## 4. Discussion and conclusions

The AIDEAS project, funded under Horizon Europe, aims to enhance and prolong the lifespan of industrial machinery in Europe by integrating AI technologies. In particular, AIDEAS WP6 involves Repair-Reuse-Recycle aspects by trying to develop AI-based strategies for extending a machine's useful life. The synergy between all the Tasks of WP6 makes it possible to build a unique solution, comprising a hardware side and a software side: the software side involves communication, analysis through AI algorithms such as those developed by PM and DIS, and an information management side, represented by MP. The integration of all these solutions makes it possible to develop a compact, cooperative tool suitable for studying the useful life of machinery and its elements, capable of sharing this information also with other systems and other tools (thanks to MP) and able to help operators and managers in the management of the industrial system.

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## Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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