Flexible Remanufacturing using AI and Advanced Robotics for Circular Value Chains in EU Industry

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D6.1: Upskilling the workforce for remanufacturing

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Executive Summary

This document contains the development of a human-centric design framework for the RENÉE project, as well as the progress towards the integration of it in the design of technical and training activities. This framework forms the basis to monitoring and provide feedback towards the development of the technical solutions for the remanufacturing process in each of the four use-case organizations. First, we present a thorough literature review, combining different relevant scientific fields (work and organizational psychology, human-technology interaction, ergonomics) and analyzing current design guidelines to create the human-centric framework for designing systems that contribute to inclusive and effective human-AI collaboration in remanufacturing as well as designing upskilling strategies for the workforce to strengthen their capabilities. Second, we offer a thorough analysis of each of the four use-cases by observing the current work process and conducting interviews with both operators and managers to assess the skills gap that will be the consequence of implementing the RENÉE solutions. The outcome of this task will serve as input for the development of the content of the diverse upskilling trainings where we purposefully consider upskilling operators' technical skills as well as focus on so-called soft skills: job crafting (employees) and leadership development (managers), to better equip employees to their changing work environment. Finally, the progress that has been achieved in the design and prototyping of Operator Support Interfaces within the RENÉE project is being presented, including the outline of the education platform via which the RENÉE projects aim to support the development of the competencies necessary for the implementation of AI-supported robotic systems in remanufacturing processes. The activities presented in this deliverable will be subjected to a closed-loop feedback process ensuring a proper fit between end-users, technical solutions, and upskilling strategies.

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Abbreviations List

Abbreviation	Definition
AI	Artificial Intelligence
ALTAI	Assessment List for Trustworthy Artificial Intelligence
AR	Augmented Reality
CNC	Computer Numerical Control
COBOT	Collaborative Robot
DT	Digital Twin
EDU	Electric Drive Unit
EU	European Union
HAIC	Human-AI Collaboration
HMI	Human Machine Interface
HTI	Human-Technology Interaction
JD-R	Job-Demands-Resources (model)
KER	Key Exploitable Result
KSA	Knowledge, Skills and Abilities
LLM	Large Language Model
MSD	Musculoskeletal Disorder
NLP	Natural Language Processing
OSI	Operator Support Interface
UI	User Interface
VR	Virtual Reality
WP	Work Package
XAI	Explainable Artificial Intelligence

1 Introduction

1.1 Objective

The objective of RENÉE is to develop AI-driven solutions for Human-AI Collaboration (HAIC) in remanufacturing operations in such a way that it enhances the working conditions of operators. The project also aims to enhance workforce inclusion (e.g. the inclusion of more women) by designing human centred interfaces and strategies to upskill human workers operating in the remanufacturing process. Input and feedback from the stakeholders involved, including end-users, are pivotal in setting the design principles for the interfaces as well as the upskilling strategies.

In this document, we provide an in-depth analysis of the future interaction between human operators and system characteristics and its foreseen implications for interface design and on operators' needs for upskilling. In our analysis we focused on the end-users to create a human-centric design framework including design principles for interfaces design and upskilling strategies for operators that will facilitate effective implementation of the systems in the end-user remanufacturing processes.

In Figure 1, we present an overview of the methodology for the development of this human-centric framework within RENÉE. The yellow squares display the research activities that serve as an input to the different steps. In this Deliverable, we completed steps 2 to 4. Finalizing the design guidelines – including their validation – and step 5 will be carried out for Deliverable D6.2.

1.2 Structure

This deliverable is organized in 6 main sections. In the first, introductory section we shortly describe the objectives of the deliverable, including the relationships to other RENÉE deliverables. The second section contains a human-centric framework (based on reviewing the relevant literatures, please see Appendix) that guides the development of interfaces and systems. In the third section we analyse the impact of the introduction of the AI systems on end-users in the four use case organizations and distil the skills gap for human operators per use case. In the fourth section we develop human-centric strategies for upskilling the human operators in the four use-case organizations. Finally, in the fifth and the sixth section we provide an introduction to the RENÉE Chatbot and the educational platform.

It is important to note that the design guidelines are subject to change because end-users' and other stakeholders' feedback will be incorporated after each draft.

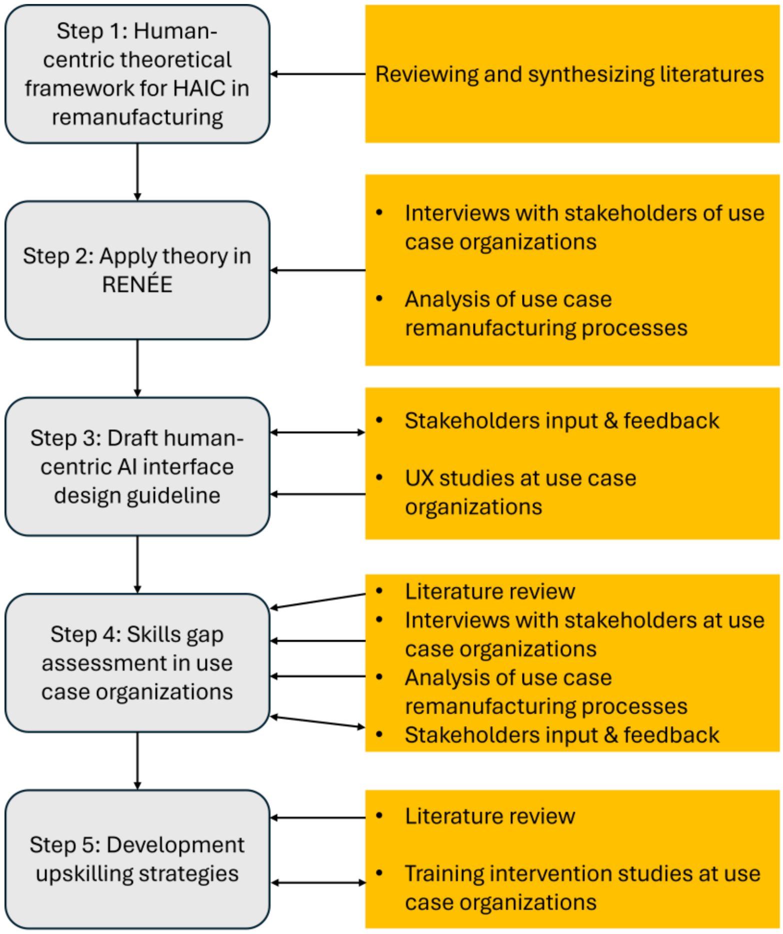


Figure 1: Steps to create human-centric approach in RENÉE

1.3 Connection to other RENÉE tasks/deliverables

This deliverable is an output of the activities described in Task 6.1, 6.2, and 6.3 of the RENÉE project. The design guidelines are related to the technical work packages, as feedback will be provided after each prototype release.

More specifically, the identification of job demands and current ergonomic risks, as well as the identification of current and future required skills (T6.1) lead to the human-centric design guidelines. T6.2 activities include the design of the operator support interfaces, based on T6.1 results, and are interconnected with WP4 and WP5 activities. The skills development strategy and the design of the RENÉE educational platform (T6.3) are also based on T6.1 results.

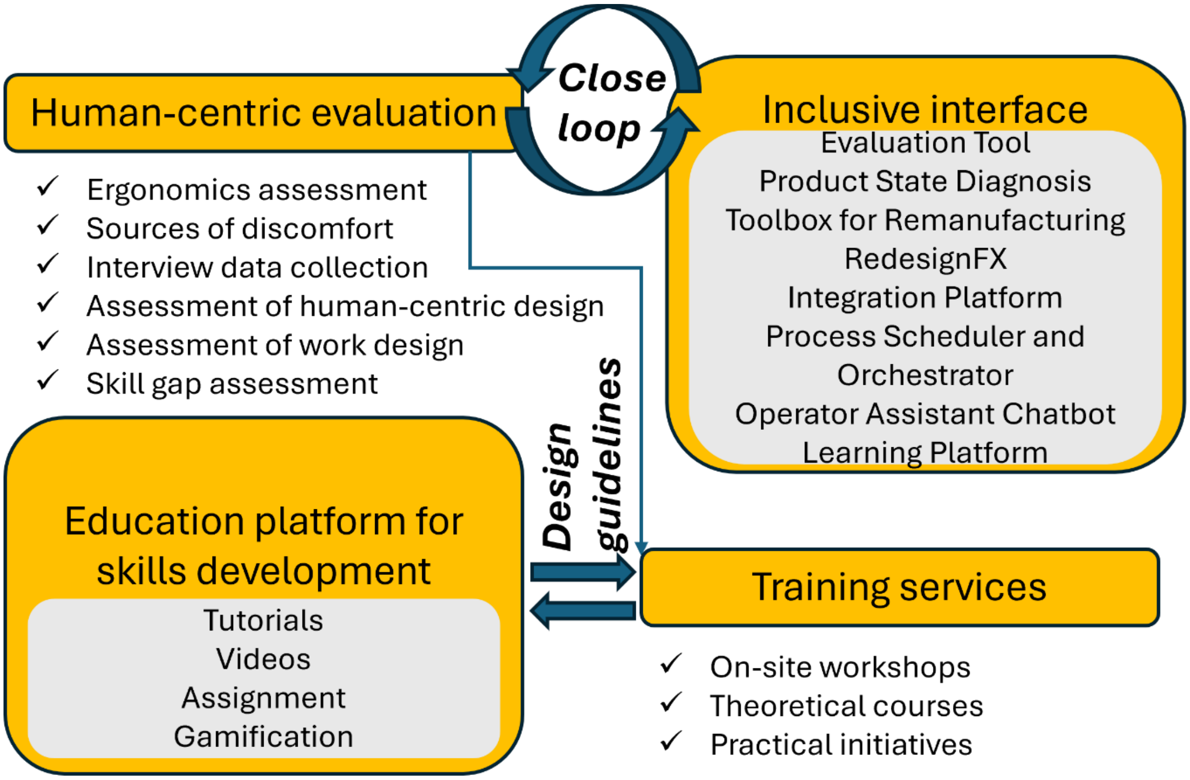


Figure 2: RENÉE WP6 Structure

2 Human-centric design guidelines for HAIC in remanufacturing

Various scientific fields have focused on how to design robotic and AI systems for human centricity. Even though many studies have been performed on this topic, companies still often face employee resistance when AI supported robotic systems are implemented and employees are required to collaborate with these systems (HAIC). Employees often experience a decline in the quality of their jobs and an increased fear and worrying about their job (Antón et al., 2022). In the RENÉE project, we aim to integrate prior literatures on this topic and to extend existing design guidelines by including perspectives from work and organizational psychology (WOP), human-technology interaction (HTI), and ergonomics. Based on the critical analysis of the current literature and design guidelines, we propose a human-centric approach in section 2.5. This approach will guide the RENÉE project further, resulting in creating a human-centric interfaces design guideline and human-centric upskilling strategies for remanufacturing, taking into consideration the different use case partners and end users' feedback.

2.1 Literature review

2.1.1 Literature review on HTI

2.1.1.1 Interfaces design

Human-centric robotics and AI interfaces aim to facilitate manufacturing and remanufacturing processes by fostering collaboration between humans and machines. These technologies, when well-designed, prioritize safety, adaptability, and user empowerment, aligning with the principles of Industry 5.0 (Martini et al., 2024).

The following types of technology will be applied to the RENÉE remanufacturing scenarios.

- *Collaborative robots (Cobots)*

Cobots are designed to work safely alongside humans, enhancing productivity and flexibility in manufacturing settings. They are based on a number of main features such as:

  - Intuitive programming through hand guidance or gesture control;
  - integration of force and proximity sensors to ensure safe interaction;
  - shared workspaces with real-time motion adaptation.

An example of such a robot was developed in the VALU3S European project (https://cordis.europa.eu/project/id/876852). Cobots are generally applied in assembly lines where humans and robots perform tasks in tandem or for tasks requiring precision and adaptability.

In remanufacturing, human-robot collaboration addresses the challenges of disassembling and refurbishing used products. Generally, in such contexts, robots assist humans in disassembly tasks that are repetitive or hazardous, while AI systems may assess the condition of components for reuse. Collaborative planning between humans and robots is necessary for efficient workflows. The industries in which such robots are the most often used are automotive component remanufacturing and electronics recycling and refurbishment (Xiao & Huang, 2024).

- *AI-Enhanced Human-Machine Interfaces (HMIs)*

AI-enhanced HMIs facilitate intuitive interaction between operators and machines, adapting to user needs and preferences. These may be interfaces, which adjust to the operator's skill level and cognitive load; integrate of natural language processing for voice commands and/or provide real-time feedback and guidance to assist decision-making. Examples of such interfaces are described in Alt et al. (2024).

These HMIs are often applied when humans have to work on complex machinery operation where user adaptability is crucial, and in training environments for new operators.

- *Augmented Reality (AR) and Virtual Reality (VR) Interfaces*

AR and VR technologies enhance the operator's perception and interaction with the manufacturing environment. In AR, important digital information is overlaid onto the physical workspace, while VR is used for simulating complex assembly or disassembly processes. VR is also used for providing immersive training experiences.

These interfaces are the most often used for maintenance and repair tasks requiring detailed guidance and in training scenarios for complex machinery operation (Chan et al., 2022).

2.1.1.2 Explainable AI (XAI)

To fulfil the different tasks from the RENÉE remanufacturing scenarios, operators need to trust and understand the AI-driven systems they are responsible for. Explanations must be given to ensure that the operators understand what is happening and what they need to do during the remanufacturing operations, as well as the results produced by the AI-driven processes. These explanations must be adapted according to the operator's profile (education, experience, gender, etc.).

Explainability is a well-defined property of trustworthy AI systems, and this section lists several open-source, and *post-hoc* software tools dedicated to implement explainability of AI systems. Some intermediate conclusions and perspectives are finally given at the end of this section.

Trust is at the center of the European approach regarding AI, putting human rights and democratic values at the heart of the European governance effort related to AI. Having trust in AI systems directly impacts the extent to which citizens adopt this technology, and how much businesses develop and deploy it. Thus, AI systems must be trustworthy, to ensure that they act in alignment with the expectations of their users and the society at large.

While "trust" has hundreds of definitions across different scientific disciplines (psychology, sociology, economics, computer sciences, etc.) but no standardized definition, "trustworthiness" is defined as "the ability to meet stakeholders' expectations in a verifiable way". It is the central subject of several standards related to AI[1,2,3] or applied in more sectoral contexts, such as within the sharing economy [4] or relative to the Internet of Things [5]. Nevertheless, the terminology related to trustworthiness is ambiguous, vague, and sometimes even contradictory, leading of course to some confusion between policymakers and the technical community, and to some obvious difficulties in ensuring the actual trustworthiness of AI systems. A common workaround is then to ensure trustworthiness by following specific underlying principles, generally linked to technical properties that AI systems must have.

XAI interfaces aim to make AI decision-making processes transparent and understandable to human operators. They may be based on visualizations which explain AI-driven decisions, interactive elements allowing users to query AI reasoning and/or adaptation to different user expertise levels

[1] ISO/IEC TS 5723:2022, Trustworthiness – Vocabulary
[2] ISO/IEC TR 24028:2020, Information technology – Artificial intelligence – Overview of trustworthiness in artificial intelligence
[3] CENELEC is working on one called "AI trustworthiness framework" (JT021008)
[4] ISO/TS 42501:2022, Sharing economy — General trustworthiness and safety requirements for digital platforms
[5] ISO/IEC TS 30149:2024, Internet of Things (IoT) — Trustworthiness principles

(Schoonderwoerd et al., 2021). These interfaces are often applied in quality control and inspection processes and/or predictive maintenance and anomaly detection.

In this context, AI explainability is generally an underlying principle of Trustworthy AI, among other principles related to ethics and human rights. Explainability is defined in the Assessment List for Trustworthy Artificial Intelligence (ALTAI) for self-assessment, produced by the EU Commission's AI HLEG, as "the ability to explain both the technical processes of the AI system and the reasoning behind the decisions or predictions that the AI system makes". Explainability is of course heavily linked to the transparency and the accountability of AI systems.

Below is a short overview of software tools implementing explainability in AI systems. These tools are open-source, applicable *post-hoc* once the model has been trained, and are still maintained.

Each software tool has been categorized according to the following taxonomy[6]:

Interpretability Tells how well the tool explains the model's predictions or decision-making process in a way that humans can understand		
Human-readable explanations	**Local interpretability**	**Global interpretability**
The tool should explain things in a way that makes sense, even if you're not an expert	Explain why the AI made a specific decision	A broad understanding of how the model generally works across all scenarios to provide an overview of its decision-making process

Table 1: Interpretability of software tools

Transparency Ability to provide clear insights into how the AI model operates. This includes details of how an AI model makes predictions or decisions		
Model transparency	**Feature importance**	**Decision rules**
Ability to show how the model makes decisions and specific predictions	Defines those input features or variables that can influence the model's predictions	Develops explicit conditions or guidelines that the model follows to make decisions—so we can comprehend the logic behind the AI's outcomes

Table 2: Transparency of software tools

Visualization Provides a greater understanding of the AI model by presenting its decision-making process in visual formats		
Graphical explanations	**Interactive dashboards**	**Model behavior analysis**
Uses visual tools like graphs, charts, or plots to explain how the model processes data and reaches decisions	Allows users to explore and interact with visualizations so they can look deeper into the model's behavior and explanations	Visualizes how changes in input data affect the model's predictions

Table 3: Visualization of software tools

6 https://data.world/resources/compare/explainable-ai-tools/

In Appendix 9.1 we list lists the different software tools according to these categories.

Explainability of AI systems is nowadays a widely studied topic, and many open-source and post-hoc software tools as suggested in the previous section. But despite the diversity and the effectiveness of these tools, they still appear to be dedicated to AI experts, the explanations generated by these tools being very technical and complex. It is so doubtful that these tools are directly applicable to the different RENÉE scenarios and suitable for interacting properly with the operators involved in these scenarios. They need indeed to be combined with other techniques such as more standard and well-designed Human-Robot Interfaces and GenAI techniques. Experiments are going to be conducted in RENÉE following this direction.

2.1.1.3 Human factors / User characteristics

The effectiveness of HAIC relies on understanding the diverse characteristics of end-users - which are defined as the employees interacting with the AI systems in the context of remanufacturing operations. Key individual differences impacting HAIC are :

- User capabilities :a) technical knowledge
  b) operational skills,

c) physical abilities.

- User demographics. For example, physical limitations may come with age, such as reduced mobility, vision, or hearing, and thus it is important to design interfaces that are accessible and easy to use for all age groups. When end-users use a voice command system, different accents and/or languages need to be facilitated.
- Users' cognitive abilities and emotional states.
  - Cognitive abilities (educational level problem solving, decision making, logical reasoning).
  - Emotional states.
- Psychological factors:
  - self-efficacy: users having confidence in their ability to collaborate with an AI-supported robotic system is of vital importance for effective HAIC (Naiseh et al., 2025),
  - trust: the degree to which an end-user is willing to rely on an AI system affects HAIC effectiveness (Park et al., 2021).
  - adaptability: (quickly) learning new skills and easily adjusting to changes is essential for effective HAIC (Kumar & Mittal, 2024).proactivity: anticipating problems and taking initiative to tackle them is pivotal to manage the uncertainties and risks associated with AI technologies (Ding et al., 2025).

2.1.2 Literature review on WOP

2.1.2.1 Task characteristics

When designing AI systems for remanufacturing processes, it is important to identify current and future task characteristics to predict how the health, safety, performance and well-being of employees can be enhanced as much as possible by the implementation of the systems.

- Highly repetitive tasks are usually very suitable for automation, because AI-supported robotic systems tirelessly perform these tasks whereas human operators may suffer from physical strain, motivation loss and boredom (Bench & Lench, 2013).
- Highly complex tasks may increase work engagement (Parker, 2014) as well as stress-levels of employees. Regarding HAIC, highly complex tasks require close collaboration where human operators may provide guidance and supervision.
- Highly uncertain tasks may decrease employee motivation and performance (Parker, 2014) and such tasks require close HAIC to handle unforeseen challenges.
- Highly physical demanding tasks require sustained physical effort from employees, which, certainly in the long run, can be detrimental to their health (Deros et al., 2010). Such tasks seem very eligible for automation.
- Highly cognitive demanding tasks may also benefit from HAIC by leveraging the strengths of both the system and the employee.

2.1.2.2 Work design: the Job Demands and Resources model

How work is designed has an important effect on employees (Parker et al., 2017). The work design field is concerned about what distinguishes "good" from "bad" jobs. Well-designed jobs motivate employees, whereas poorly designed jobs can be intolerable and demotivating.

The Job-Demands-Resources (JD-R) model (Bakker & Demerouti, 2006) is applicable to all types of organizations and jobs. To explain how different aspects of a job can affect employee well-being and performance, the JD-R model highlights two main components of jobs, namely:

- Job demands: Those aspects that require sustained effort from employees in order to fulfill their job. The challenges or stressors that come with a job, for example, heavy workload, tight deadlines or social conflict.
- Job resources: Those are aspects of the job that help employees to fulfill the demands that are placed on them; that reduce job demands and their associated costs, and stimulate personal growth and development. Resources can include job autonomy, support from colleagues, feedback from managers, flexible working hours, but also opportunities for professional development.

Both job demands and resources affect employee outcomes, the JD-R model proposes two psychological pathways or processes. First, the health impairment process. When job demands are high and job resources are low, poor or missing, employees experience a steady decrease of mental energy which ultimately results in ill-health (Maslach et al., 2001). Second, the motivational process. Having sufficient job resources increases employees' work engagement, in turn leading to positive performance and well-being outcomes (Schaufeli, 2017).

Job characteristics may change significantly due to the implementation of AI-supported robotic systems (Bankins et al., 2023; Demerouti, 2022; Parker & Grote, 2022). AI can create a positive impact on work and the well-being of workers (Daheim et al., 2019) the puzzle is what is necessary to create positive impact.

Following Parker and Grote (2022) we suggest the following strategies –wen applied in combination- will increase the chance of creating a positive impact of implementing robotic systems in remanufacturing processes, namely:

- Human-centric development, design, and procurement of the technology: motivates to incorporate human operators' needs and capabilities in the design and development of the technology. This will likely increase the effectiveness of the HAIC and operator well-being compared to requesting operators to simply adapt to the designed system.
- Proactive design of work while implementing the technology: this strategy includes considering work characteristics (e.g. job autonomy, skill variety) in relation to the technology that is implemented. Usually, the implementation of robotic and AI systems affects multiple characteristics. This strategy recognizes that organizational characteristics such as employee behaviors and skills, managers' change communication and organizational culture affect the impact of technology on job characteristics.
- Education and training: Developing skills of human operators get a lot of attention in current research because it is instrumental in increasing their adaptivity to working with robotic systems. In addition, training employees to become more proactive (also in relation to the first strategy) is important to increase their agency in work (re)design, HAIC and upskilling. Furthermore, training of managers is not often considered while they are pivotal in providing resources for human operators.

In the four RENÉE use cases, the current remanufacturing process is done manually. That means that while implementing the RENÉE solutions, the job demands (i.e. aspects of the job that ask for sustained effort and are thus associated with certain costs such as high work pressure, cognitive demands, and irregular working hours) are subject to change (also see Section 3). When implementing AI solutions in their organizations, operators' job demands will - at least temporarily – increase. Operators need time and other job resources to successfully adapt to this change in their work process (Demerouti, 2022).

2.1.2.3 Organizational characteristics

The potential downsides of introducing HAIC for employees are well described in the literature and can decrease work meaningfulness (Goštautaitė et al., 2024), well-being (Turja et al., 2021), an increased fear of replacement, resistance, or stress (Sun & Deng, 2024). How remanufacturing organizatons communicate this change and support their employees in this process is crucial. In the RENÉE project we therefore focus on these aspects.

- *Change communication*

Implementing AI supported robotic systems into remanufacturing processes can be considered an organizational change (Ulfert et al., 2024; Salcedo Gil et al., 2024). Often change impacts employees in a negative manner and is met with resistance (Oreg, 2006). How employees react to change, depends among others on their interpretations of <u>why</u> the change is happening (Shapiro et al., 1994). The change literature has long identified the importance of a trustworthy change message that is spread by management (Rousseau & Tijoriwala, 1999; Rousseau & ten Have, 2022). Whereas managerial accounts are necessary to motivate change, they may not be sufficient to positively affect the attitudes and behaviors of employees. When employees see the reason for the change as trustworthy and perceive that the change will benefit them personally, the smoother the transition will be.

- *Providing resources*

In addition to understanding the reason for change, another important aspect to enhance the effective implementation of HAIC to remanufacturing processes is to provide employees with sufficient job resources to deal with the increased (change-related and HAIC-related) job demands (Demerouti, 2022; Tummers & Bakker, 2021). In addition to providing opportunities for development (e.g. training to upskill workers, also see 2.1.2.4 and section 4) stimulating employees to job craft the proposed change (namely HAIC) such that it fits their specific work situation and preferences is promising (Demerouti, et al., 2021Managers play a key role that process by creating and distributing job resources.

2.1.2.4 Upskilling

The implementation of AI-supported robotic systems into remanufacturing processes requires upskilling of employees. Training operators effectively will help them to adapt to use AI-supported robotic systems and is more cost effective than hiring new employees (Caterino et al., 2025). Upskilling can also help employees to develop the resilience and flexibility to adapt to the new work processes, job design and to deal with challenges (Leon, 2023).

Two types of skills are mentioned in the literature:

- Technical skills (e.g. programming, machine maintenance, data analysis)
- “Soft” skills (e.g. commitment to lifelong learning, problem solving, decision making)

In remanufacturing manual skills and abilities remain important, therefore using a human-centered approach to training in which technical knowledge and soft” skills are combined (increases effective HAIC (Salcedo Gil et al., 2024).

2.1.3 Major ergonomics issues in remanufacturing

Remanufacturing is a complex industrial process that involves recovering, restoring, and upgrading used or end-of-life products so that they meet the performance and quality standards of new items. Remanufacturing processes must accommodate a high degree of variability. This includes differences in the condition, geometry, and cleanliness of returned products, which introduces uncertainties at every stage of the workflow—from disassembly and inspection to refurbishment and reassembly (Bortolini et al., 2020).

These characteristics impose specific ergonomic challenges. For example, workers in remanufacturing must often perform physically demanding tasks such as manual disassembly of worn or corroded parts, handling heavy or awkwardly shaped components, or adapting their posture frequently to accommodate non-standard setups. The unpredictable task sequences—resulting from differing levels of wear and unexpected damage—can interrupt workflow and create cognitive and physical strain (Dimitrokalli, et al., 2024).

These challenges are detailed below.

2.1.3.1 Physical ergonomics challenges

Physical ergonomics challenges in remanufacturing are related to the interaction between workers and their physical environment. Key issues include:

- Task variability: In remanufacturing, workers may handle used, worn, or damaged components whose conditions can vary widely in terms of size, weight, contamination, and structural integrity. Disassembly, inspection, and reassembly processes are less predictable and less standardized than in new product manufacturing. As a result, employees must continuously adapt their movements and postures, increasing the risk of awkward positions, repetitive strain, and biomechanical overload (Odebiyi et al., 2023).
- Non-standardized workflows: Remanufacturing often require workers to perform tasks at variable locations, angles, and intensities. These unpredictable conditions may exacerbate exposure to musculoskeletal disorders (MSDs), particularly in the back, shoulders, wrists, and knees.
- Manual handling : Frequent lifting, shifting, and manipulation of irregularly shaped or heavy components without mechanical aids cause significant strain especially during complex disassembly.
- Workspace design : Many facilities are adapted from legacy industrial spaces, limiting ergonomic features such as, adjustable fixtures, or reconfigurable layouts which may impede efforts to reduce strain (Cardoso et al., 2021).
- Ergonomic assessments: Traditional risk assessment tools are less effective due to task complexity and variability, indicating a need for more flexible and dynamic evaluation methods tailored to remanufacturing contexts.

To address these issues, several adaptive and worker-supportive design strategies can be implemented such as:

- Adjustable- workstations: Allow customization of workstation heights to maintain or promote neutral postures.
- Modular and reconfigurable layouts: Enable quick workspace reconfiguration for varied tasks and products.
- Smart tools: Use tools with embedded sensors to monitor force application, motion patterns, and joint angles providing real-time feedback to prevent harmful movements.
- Collaborative robots: Deploy cobots in the disassembly phase to assist with repetitive tasks and heavy lifting, reducing physical loads on human operators and minimizing physical strain.

2.1.3.2 Cognitive ergonomics challenges

Remanufacturing tasks are often non-linear, adaptive, and information-intensive. Operators must constantly assess the condition of parts, decide on appropriate actions, and interact with interactive, AI or robotic systems that may work semi-autonomously or require supervision. This creates significant mental demands, especially in real-time decision making, robot monitoring, and exception handling. Although research on these cognitive challenges is limited, Guelle et al (2025) highlight assessment as a core process in remanufacturing.

Assessment involves multiple phases (pre-disassembly, post-disassembly, final inspection), each requiring diagnosis (current condition, reparability) and prognosis (lifespan, reliability).. Operators develop strategies to manage variability in component conditions, which are often unpredictable and not suited for automation.

These strategies can be both individual and collective. Individual strategies include detailed visual and tactile inspections, cleaning, and defect detection. Collective strategies involve team-based decisions on reusability, based on shared knowledge and consensus. Operators develop sensory expertise (e.g., visual, auditory, tactile), use feedback loops to communicate assessment data to engineering teams, supporting decision-making under uncertainty.

2.1.3.3 Research and technological gaps

Despite growing awareness of ergonomic issues in remanufacturing, there is a lack of rigorous, sector-specific quantitative assessments. Most existing research derives from traditional manufacturing, failing to address the distinctive challenges of remanufacturing such as the irregularity of incoming parts, non-standardized workflows, and the frequent need for manual interventions. This mismatch risks underestimating both physical and cognitive risks faced by operators.

Additionally, longitudinal studies on ergonomic impacts are scarce, making it difficult to understand how chronic biomechanical strain or cognitive overload contributes to cumulative injuries or mental fatigue. There is also a notable absence of standardized tools to assess cognitive risks, especially in human-robot collaboration and supervisory control scenarios where operators must multitask, make decisions under uncertainty, and interact with AI-based systems. Currently, these cognitive demands are often underestimated or assessed subjectively, limiting the ability to design targeted interventions.

Furthermore, ergonomic research often overlooks gender and inclusion dimensions. Differences in body size, strength, task perception, and interaction preferences based on gender or age are rarely considered in workstation or interface design. This oversight can result in inequitable working conditions or safety gaps, particularly for women or older workers. To develop truly human-centered, safe, and inclusive remanufacturing systems, future research and innovation must bridge these gaps by developing tailored ergonomic assessment frameworks, promoting inclusive design standards, and embedding diversity-aware methodologies into all stages of system development and evaluation.

2.2 Overview of existing guidelines

Existing guidelines for the design and evaluation of Human-Computer Interfaces are mainly proposed for manufacturing. These guidelines consistently underline the necessity to prioritize human capabilities, well-being, and agency when designing and implementing robotics, AI and VR and AR on the shop floor. However, they rarely integrate the specific features of remanufacturing.

We have analyzed a number of papers proposing such guidelines. The characteristics of the analyzed papers are summarized in table 4.

Study	Study Focus (AI/VR/AR/Robotics)	Application Context	Study Type
Gualtieri et al., 2023	Robotics, Cognitive Ergonomics	Industry 4.0	Systematic literature review
Chu and Liu, 2023	Augmented Reality (AR), Human-Robot Collaboration	Shared workspace for collaborative assembly	Experimental study
Gualtieri et al., 2022	Robotics, Cognitive Ergonomics	Collaborative workspace, lab assembly	Systematic literature review, Experimental study
Florescu et al., 2023	Augmented Reality (AR), Usability	Collaborative workspaces, manufacturing	Review and qualitative design study
Coronado et al., 2022	Augmented Reality (AR), Human-Robot Interaction (HRI)	Shipbuilding, collaborative workspace	Systematic literature review
Yang et al., 2023	Augmented Reality (AR), Human-Robot Interaction (HRI)	Collaborative workspaces	Experimental study
Tomidei et al., 2024	Augmented Reality (AR), Human-Robot Interaction (HRI	Aerospace, composite manufacturing	Qualitative study
Hietanen et al., 2020	Augmented Reality (AR), Human-Robot Collaboration (HRC)	Manufacturing	Experimental study
Kutz et al., 2023	Artificial Intelligence (AI), Human-Centered AI	Collaborative workspace	Conceptual review
Segura et al., 2021	Robotics, Human-Robot Collaboration (HRC) Systems	Automotive	Literature review
Pinheiro et al., 2021	Robotics, Ergonomics/Safety	Collaborative workspace	Literature review

Peruzzini and Pellicciari, 2017	Robotics, Ergonomics/Safety	Woodworking	Case study
Rosen and Wischniewski, "Task Design in HRI"	Robotics, Ergonomics, Task design	Manufacturing	Survey and scoping review
Harborth and Kümpers, 2021	Augmented Reality (AR)/Virtual Reality (VR), Intelligence Augmentation	Assembly, logistics, healthcare	Case study
Süsse et al., 2023	Artificial Intelligence (AI), Human-AI Interaction	Automotive, remanufacturing	Case study
Dimitropoulos et al., 2021	Artificial Intelligence (AI), Wearables, Robotics	Elevator manufacturing, assembly	Case study
Nakanishi, "Human Factor Guideline"	Augmented Reality (AR), Manuals	Assembly, maintenance	Experimental study
Wu et al., 2024	Robotics	Carpentry, construction	Case study
Passalacqua et al., 2022	Artificial Intelligence (AI)	Industry 4.0	Experimental study
Moghaddam et al., 2021	Augmented Reality (AR), Worker Assistance	Marine engine assembly	Case study
Egbengwu et al., 2025	Metaverse, Augmented Reality (AR)/Virtual Reality (VR)	Manufacturing	Literature review
Kaufeld and Nickel, 2019	Robotics, Virtual Reality (VR)	Manufacturing	Experimental study

Table 4: Overview of existing guidelines

The table shows that most of the papers and the associated guidelines are focused on robotics and Human-Robot interaction. There are also papers and studies focused on guidelines for Virtual and Augmented Reality. However, there is only a limited number of papers, studies and associated guidelines focused on AI. This is a clear research gap, which RENÉE will try to fill in.

The guidelines stemming from these papers could been found in Appendix 9.2, 9,3, and 9.4.

Critical analysis of existing guidelines

We identified the following shortcomings in the existing guidelines in the field of robotics:

- Task-specific ergonomic guidance is rarely provided, particularly for disassembly, inspection, or sorting tasks, which are frequent and variable in remanufacturing.
- Lacking design principles addressing how robots can adjust their behaviour in real time to support workers without increasing cognitive strain.
- Guidelines rarely focus on how to minimize the mental workload of human operators who monitor or collaborate with these robots, despite evidence showing that cognitive overload can affect both safety and performance.

For AI applications, we identified the following shortcomings:

- lacking guidelines on explainability features that help operators understand how the system arrives at decisions, such as defect detection or process optimization. The opacity of AI decision-making can undermine user trust and hinder adoption, especially in safety-critical environments.
- Limited user participation in the design and development of AI systems. Few projects involve operators early in the process to ensure that tools align with actual workflows, goals, and capabilities, and this is reflected in the proposed guidelines.
- Lacking guidelines on adaptive feedback loops that enable mutual learning between humans and AI systems—a critical feature for handling the dynamic and context-dependent nature of remanufacturing tasks.

Regarding the use and evaluation of VR in remanufacturing, we identified the following shortcoming:

- Limited realism and practical utility because the complexity and variability of remanufacturing environments is not fully captured.
- Limited research on the ergonomic effectiveness of VR-based training, particularly in preventing musculoskeletal strain through safe motion guidance. Studies and guidelines help assessing long-term engagement, and acceptance of VR among operators are scarce, leaving open questions about the long-term value of immersive technologies in remanufacturing.

In order to fill in these gaps, in RENÉE we will:

- adapt the above-mentioned existing guidelines to the specific needs of remanufacturing environments expressed in the RENÉE use cases;
- provide a new list of adapted guidelines;
- organize 2 to 4 focus groups with operators, engineers, safety managers, and/or ergonomists to evaluate the relevance, feasibility, and completeness of guidelines;
- provide quantitative and qualitative results of these evaluations;
- propose a consensual refined set of context-specific, prioritized design guidelines tailored to real-world remanufacturing challenges;
- help operationalizing these guidelines into the RENÉE technological prototypes.

2.3 A human-centric framework for HAIC re-manufacturing

To overcome the limitations of prior design guidelines, in the RENÉE project we developed a human-centric framework to guide effective human-AI collaboration. We showed the importance of inclusive and transparent interface design, to be aware of the psychological and ergonomic factors that affect effective HAIC, and to put the employee central when designing upskilling strategies in remanufacturing. In this framework, we aim to align operator needs, organizational characteristics, and functionalities of the AI- systems, while taking into account the variability and uncertainty of the tasks in the remanufacturing context. The framework is intended to serve as a manual for how different combinations of human needs, organizational characteristics, and system functionalities can result in varying end-user outcomes.

The centricity of employees is underscored by focusing on their proactive behavior. Employees are not passive actors but they actively shape, change and customize their work situation to fit their needs and preferences and is functional in increasing motivation, well-being and task performance.

Our approach is based on the alignment of employee characteristics and needs (e.g. upskilling, resources), system characteristics (e.g. transparency) and organizational characteristics (e.g. change communication, provision of job resources and support). The better the alignment between these three elements, the more we expect human operators to show proactive behaviors to enhance the HAIC that results in higher levels of task performance, work meaningfulness and well-being.

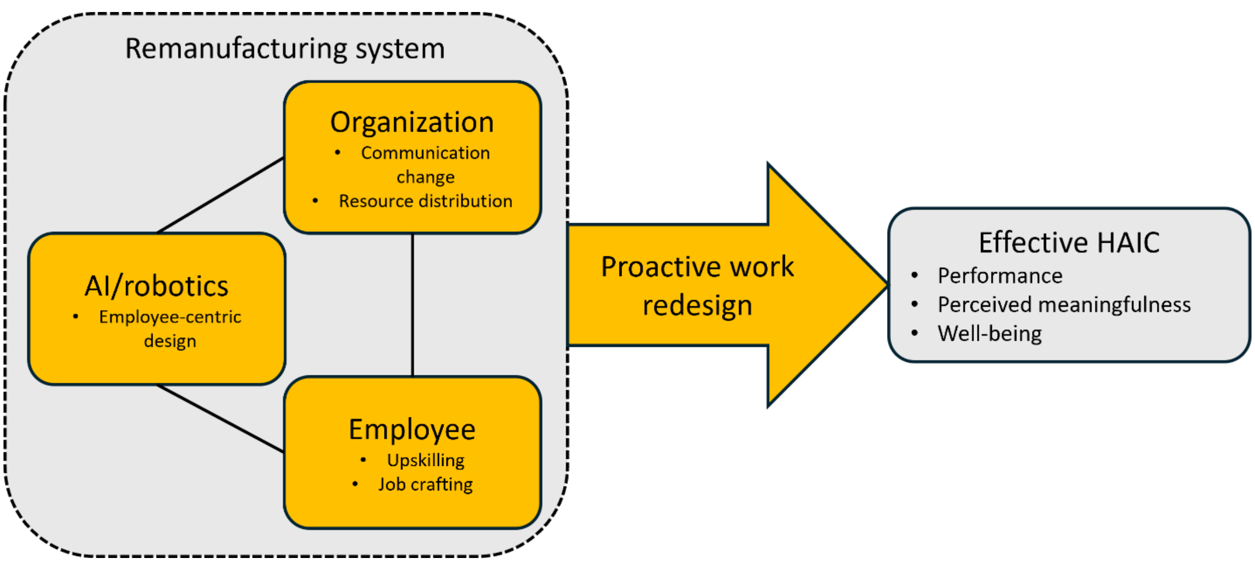


Figure 3: Framework of the approach

3 Assessing skill gaps within RENÉE use cases

Based on site visits and documents from RENÉE WP2 we observed the current work process of remanufacturing across the use case organizations regarding the key requirements that are required of employees to perform the tasks. To complement this assessment, we also compared the observed skill requirements of all the use cases with relevant occupations listed in the O*NET database[7] (e.g., bicycle repairers, robotics technician, electric motor repairers, home appliance repairers). Aligning the observed skills to standardized occupational profiles helped us to validate and contextualize the findings. We categorized this assessment using the Knowledge, Skills, and Abilities (KSA) framework, which provides a structured way to categorize the competencies needed to perform work tasks effectively. Knowledge refers to the theoretical or factual information required for the job, while skills refers to the learned proficiencies or techniques needed to perform tasks well, and abilities stands for enduring attributes or capacities that affect performance. Based on interviews with both employees and managers, we assessed the current work design with the focus on job demand. Comparing the current state with the envisioned future state, we were able to distill the skills gap for the human operators in the remanufacturing process of each use case. Figure 4 below summarizes the process:

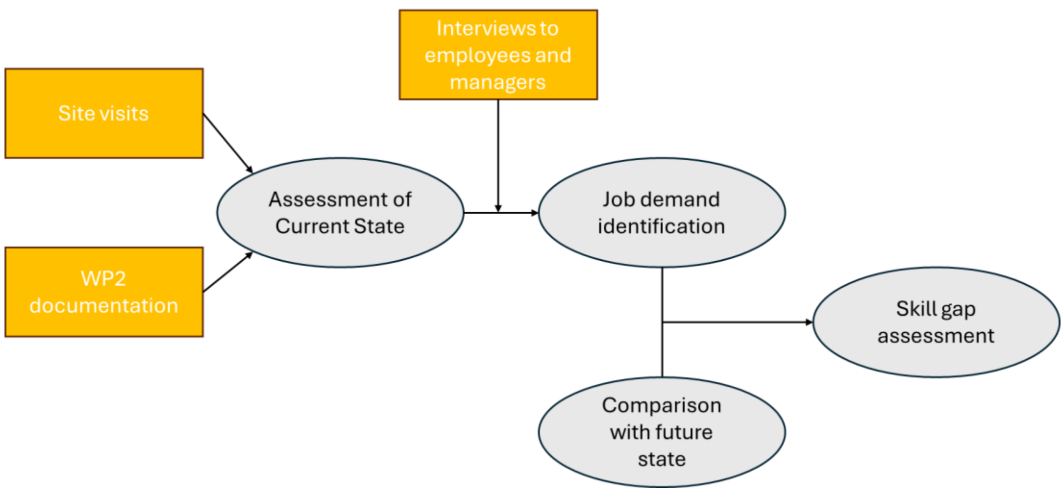


Figure 4: The process of skill gap assessment

3.1 RENÉE use cases

3.1.1 Remanufacturing of bicycles

3.1.1.1 Current process

The remanufacturing process of a bike at Decathlon involves the inspection, restoration, and testing of used or returned bicycles to ensure they meet safety, performance, and aesthetic standards before being returned to the market. The bike remanufacturing process combines diagnostic checks with simultaneous component adjustments and replacements. Operators evaluate the mechanics focusing on structural integrity, braking systems, drivetrain components, and the evaluate the

[7] https://www.onetonline.org/

electronic parts (such as the motor, battery, and sensors), and overall rideability. The inspection process is supported by an app that provides operators with the checklist of evaluations on various components of a bike (Figure 5).

Tasks related to the mechanical part of the bike remanufacturing process:

- Frame inspection: The bike is first checked for any cracks, bumps, or visible damage on the frame. This visual examination ensures the chassis is in good condition and forms the basis for determining whether further reconditioning is viable.
- Handlebar/fork inspection: Next, attention shifts to the handlebar, stem, and front fork. Operators begin by tightening the handlebar and stem. They then block the front wheel and attempt to rotate the handlebar perpendicularly to the stem, followed by testing for any rotation of the stem relative to the fork. Any unwanted movement indicates misalignment or loose components, requiring readjustment to ensure safe and stable steering.
- Wheels inspection: With the steering components approved, the operators proceed to inspect the wheels. They check the tightness of quick-release skewers or axle nuts, ensuring that the wheels are securely mounted. The wheel hubs are tested for proper alignment and for any play in the bearings. The wheels must run straight and remain stable under load. Finally, tire pressure is measured using a pressure gauge to confirm it meets the required minimum for safe operation.
- Brakes inspection: A thorough assessment of the braking system is performed in two parts. First, the brake levers, calipers, and cables of both front and rear brakes are visually inspected. There should be no signs of deterioration on the levers. Second, the operators focus on the calipers, pads, and brake discs, ensuring they are visually intact and that the wheels stop effectively when braking is applied.
- Drivetrain inspection: Following this, attention is given to the drivetrain, including the chain, sprockets, crankset, and pedals. A visual inspection and a manual pull of the chain assess its tension and wear. The pedal arms (pedagles) and pedals are tested for tightness, ensuring there is no movement or loosening. Components must be in good condition with secure fixation. The gear exchange and gear shift system is then evaluated through both visual and acoustic checks. The operators test the gear changes while the rear wheel is moving, ensuring that the shifts are smooth and properly aligned with the cable. A fully functional gear lever and gearbox are essential for this stage to be cleared.

Figure 5: Current APP interface

Besides visual inspection, the operators might use tools like bike stand, screwdrivers, allen keys, torx, and wrenches to help them with the bicycle handling, fixing and disassembly.

Tasks related to the electrical part of the bike remanufacturing process:

- Battery inspection: The electrical system check begins with the battery assessment, which varies depending on usage and time since sale. If the bike has less than 200 km and was sold less than a month ago, a visual and manual check is sufficient to confirm that the original battery is present. Otherwise, a full electric diagnosis is performed. The battery must show a health status above 80% using diagnostic tools (On laptop). The battery's waterproof condition is visually inspected for the presence of warranty stickers and absence of cracks, leaks, or signs of tampering. This ensures that the battery hasn’t been opened or damaged. The battery’s fixation is also tested, checking for secure placement and a functioning locking mechanism with no unwanted movement.
- Motor inspection: The operators then verify the engine performance through manual and visual inspection. The engine must start successfully, and there should be no error codes displayed. The motor mounting is physically checked to ensure it is properly tightened and securely fixed to the frame.
- Wheel sensor inspection: The wheel speed sensor is inspected next. It must be clean, intact, and firmly attached without any signs of disassembly. This step ensures accurate speed readings and system synchronization.

- Control unit inspection: The control unit undergoes a similar two-tier diagnostic approach: For bikes with <200 km and <1 month, a visual/manual control is sufficient. For those with >200 km and >1 month, an electric diagnosis is necessary to confirm the absence of errors and that the unit functions properly.
- Display inspection: The display is tested manually to ensure all buttons work, there are no error codes, and the screen remains in good aesthetic condition.
- Other sensors inspection: The sensor status (e.g., torque or cadence sensors) is also verified based on the same standard of usage and time since sale: For bikes with <200 km and <1 month, an LED confirmation suffices. For older bikes, diagnostic tools are used to check for proper operation and absence of error codes.
- Connection inspection: Finally, all connector connections across the electrical system are visually inspected to ensure they are properly secured and in place. This final check ensures full communication across components and supports the smooth operation of the bike's electrical features.

Operators use a diagnostic tool to help them with the inspection process (Figure 6).

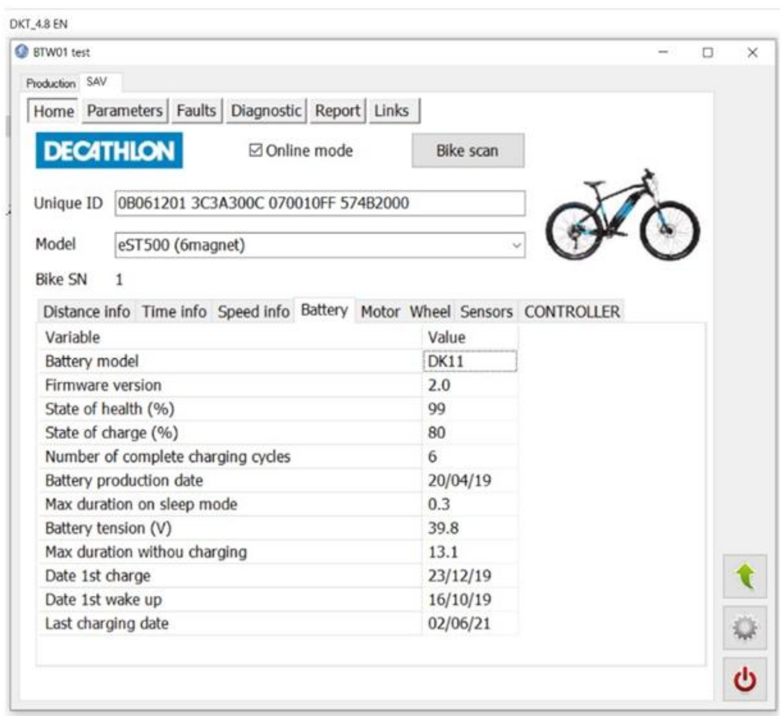


Figure 6: Interface of the diagnostic tool

Competency assessment

We summarized the following key requirements that are required by employees to perform the tasks:

- Knowledge:
  - Mechanical knowledge (understanding of mechanical systems and electronic components in both traditional and electric bikes; familiarity with the function and appropriate use of tools)

- Customer Service (customer needs assessment and evaluation of customer satisfaction)
- Product evolution (understanding ongoing developments in bike technology, especially in electric and smart bikes)

- Skills:
  - Repairing
  - Equipment maintenance
  - Equipment selection
  - Problem-solving
  - Troubleshooting
  - Critical thinking
  - Communication skills
- Abilities:
  - Near vision (the ability to notice small defects)
  - Manual dexterity (the ability to perform precise mechanical tasks)
  - Problem sensitivity (the ability to tell when something is wrong or is likely to go wrong)
  - Selective attention (the ability to concentrate on a task over a period of time without being distracted)

Interview study: Employee perspectives and Managers perspectives

Six interviews were conducted with three operators, 1 field manager, 1 operation manager, and 1 ergonomist working in Decathlon. Insights from the interviews were analyzed to identify the job demand and the major risks associated with the job in the current work process. Here are the main findings:

Job demands

- Workload: Heavy workload is the major demand the operators perceived in their jobs. Since current remanufacturing tasks need to be processed manually by the operators, they often feel stressed by the large number of orders during busy seasons.
  - Qualitative workload: The qualitative workload is characterized by significant cognitive demands, as workers must make real-time decisions during inspection, diagnosis, and selection of spare parts—often with limited access to clear or structured information. These tasks require high levels of attention, technical problem-solving, and tool-related judgment. Emotional and relational dimensions, such as maintaining good communication with clients or peers, also contribute to the overall complexity of the work.
  - Quantitative workload: Operators face a high quantitative workload due to the volume of bikes processed, especially during peak seasons that require additional shifts, including night shifts. The job involves repetitive tasks and extensive manual handling of heavy components, such as e-bikes, which contributes to physical strain and fatigue. Time pressure is a constant factor, as workers are expected to maintain productivity across inspection, adjustment, and repair tasks, often without sufficient recovery time between operations.

- Physical and cognitive demands: The current process of bike remanufacturing in Decathlon is highly manual and requires precision, experience, and physical effort. Operators follow a step-by-step procedure to inspect, repair, and prepare used bikes—especially e-bikes—for return to use. However, the process also presents physical and cognitive challenges as voiced by operators themselves.
    - Physical demands: Operators need to carry and move the heavy bikes by themselves with limited tools.
    - Cognitive demands: Operators often need to deal with a lot of information (regarding the products and spare parts) to make the most suitable selection during the replacement of bike components.

The findings are summarized and matched with each task (Table 5):

Task description	Physical demands	Cognitive demands	Qualitative workload	Quantitative workload
Frame inspection	✓	✓		✓
Handlebar inspection	✓			✓
Saddle inspection	✓	✓		✓
Brakes inspection	✓	✓		✓
Drivetrain inspection	✓	✓	✓	✓
Wheels inspection	✓	✓	✓	✓
Battery inspection	✓	✓	✓	✓
Motor inspection	✓	✓		✓
Wheel sensor inspection		✓		✓
Control unit inspection		✓	✓	✓
Display inspection		✓		✓
Other sensors inspection		✓	✓	✓
Connection inspection		✓		✓

Table 5: Job demands at Decathlon use case

3.1.1.2 Prospective process

In the future state of the bike remanufacturing process, the RENÉE project aims to enhance the process through human-AI collaboration in the following two ways:

- AI-Assisted Inspection
  Thermal cameras and computer vision systems scan the bike frame and components and identify possible defects on carbon parts, detect the frame shape of the bike. A platform measures the force needed to compress the forks. Sensors integrated measure the forks displacement. A software analyzes the force/displacement curves obtained from the compression test, to identify any possible defects on the forks. Operators review the results, confirm or override AI suggestions.
- Operator support AI-Chatbot
  The remanufacturing processes may be supported by AI-driven chatbot systems that act as intelligent digital assistants for frontline operators. During inspection and repair tasks, workers could interact with the chatbot through voice or text to access real-time guidance, technical specifications, or troubleshooting tips for specific bike models. The chatbot could also assist in identifying compatible spare parts based on scanned images or entered data, reducing time spent searching and improving decision accuracy. For new or less experienced employees, the chatbot could serve as a training companion—answering questions on procedures or safety protocols without interrupting the workflow.

Skills assessment

The introduction of the RENÉE technologies mentioned above—chatbots and AI-assisted inspection—in bike remanufacturing will lead to the emergence of new skill requirements beyond what is traditionally expected of operators. While traditional mechanical and manual skills will remain relevant, future operators in bike remanufacturing will increasingly be expected to possess hybrid capabilities—blending digital fluency, critical reasoning, and collaborative problem-solving with AI. Here is the assessment of the skills gap between the current process and prospective process:

Skills	Current process	Prospective process	Skills gap
Equipment maintenance	Performing routine maintenance on bikes and equipment. The ability of heavy lifting is required to carry and move the bikes manually.	Performing routine maintenance on AI systems. The requirement for heavy lifting ability is reduced.	Operators need basic knowledge to perform or support minor troubleshooting or recalibration of AI systems.
Equipment selection	Skilled tool handling and spare part selection based on experience; safety knowledge acquired over time.	AI may flag tool misuse or suggest safety steps; inspections enhanced by precision AI.	Need to interpret AI-generated suggestion or safety alerts and align them with manual practice.
Problem-solving	Hands-on, experience-based troubleshooting with occasional peer consultation.	Problem-solving is collaborative: AI vision systems assist in inspecting; chatbot can suggest common fixes.	Operators have to learn to operate and verify AI inspection outputs.

Communication skills	Internal team communication and some customer interaction.	Increased communication with digital systems; chatbot mediates some interactions.	Need for clear communication with both humans and AI systems.

Table 6: Skills gap assessment Decathlon

Interview study: Employee perspectives and Managers perspectives

Insights from the interviews were analyzed to identify both the operators and the managers' attitude and expectations towards the introduction of AI, and the possible risks in the future work process with human-AI collaboration in remanufacturing. Here are the main findings:

Attitude and expectations towards AI

Employees generally hold a positive and open-minded attitude toward the integration of AI and robotics into the remanufacturing process. There is little fear of job displacement; instead, operators see AI as a tool to support and ease their workload. Comparing the RENÉE foreseen solutions to the use-case stakeholders expectations, we see quite some differences which is important to keep in mind for creating change communication and the design of the upskilling training modules. **Error! Reference source not found.** summarizes these:

Impact of AI	RENÉE solution	Stakeholders' expectation
Cognitive demands	AI-supported sensors to assess the condition of bicycles and components, automated quality control systems for objective evaluation.	Besides inspection and diagnosis, operators expressed strong expectations on AI-assisted selection of spare parts which is considered as cognitive-demanding.
	AI-driven chatbot systems with the interface of the current app to provide real-time guidance or technical specifications.	Managers also expressed interest in how AI might improve communication with customers.
Physical demands	No relevant implementation.	Operators expressed strong expectations that AI implementation will help alleviate the physically demanding aspects of their work, such as lifting and moving heavy e-bikes which are currently labor-intensive and repetitive, leading to fatigue and potential injury.

Table 7: Comparison between RENÉE solution and stakeholders' expectation (Decathlon)

Risks

The integration of AI technologies into the bike remanufacturing process—such as chatbots and AI-assisted inspection—introduces new types of risks that shift from primarily physical to cognitive and organizational domains.

Risk type	Current risk	Future risk
Physical risk	• Manual handling of heavy bikes • Repetitive motions • Awkward postures • Improper use of hand tools • Muscle strain (upper limbs, back)	• Reduced physical demands due to automation • Some physical tasks remain (e.g., manual handling, adjustments)
Cognitive risk	• Cognitive overload from poor information systems • High decision-making demands	• Increased mental demands from interpreting AI feedback • Verifying AI decisions • Risk of mental fatigue • Overreliance on AI could erode critical thinking

Table 8: Risks observed in Decathlon use case

3.1.2 Remanufacturing of robotics

3.1.2.1 Current process

The remanufacturing process of an industrial robot at Campetella involves eight phases: inspection, first cleaning, component replacement, disassembly, electric part upgrading, reassembly, final testing, and final cleaning. The process combines deep technical expertise with careful planning, safety awareness, and a forward-looking view toward technological advancement. Below is a detailed look at the eight key stages of the current robot remanufacturing process:

- Inspection: The remanufacturing of an industrial robot begins with an initial status assessment, where the robot is inspected for visible damages, tested for basic functionality, and evaluated based on the technology it currently uses. This first step helps to get a general understanding of the robot's condition and technological generation. Subtasks include:
  - Cover removal: The operator first removes all covering parts to access the internal mechanical and electrical components for inspection.
  - Assessment of general state: At this stage, an operator conducts a non-functional inspection of key components, identifying any signs of wear, corrosion, or outdated elements. Grease and dirt make cleaning necessary to assess overall condition.
  - Evaluation of the functionality: To further evaluate operational capabilities, the operator powers on the robot via the robot's HMI (Human-Machine Interface) and power cables, and attempts a demo cycle, checking if the drives, motors, and other functions still work. This provides a practical sense of how much of the system remains functional. If the robot cannot be operated, the process becomes significantly more time-consuming, especially in terms of fault diagnostics.
- First cleaning: Once the initial inspection is complete, the robot undergoes a thorough cleaning process to ensure accurate evaluation and safe handling. The operator performs a general cleaning using tools such as a steam cleaner, vacuum cleaner, and degreasing

products. This cleaning not only improves visibility but also helps in assessing the true condition of various components more accurately. This step is critical, as grease and dirt often obscure vital components. The duration of this step can exceed two hours, depending on the robot's size and the level of contamination.

- Component replacement: Following this, a detailed evaluation is performed by the operator and a technical leader, focusing on whether each group and component should be replaced or retained. This involves a collaborative decision-making process takes place to identify damaged or obsolete parts and grouping them for replacement planning. Subtasks include:
    - Damaged parts identification: The operator, in consultation with the technical leader, identifies components that are visibly or functionally compromised.
        - Mechanical check: Specific mechanical elements (e.g., linear guides, slide blocks, belts, ball bearings, cable carriers, and cables) are examined. Some parts are only accessible or diagnosable once the robot is cleaned and partially disassembled, making operator experience and component knowledge crucial. Visual inspection sometimes is not enough, then a touch test or a sound check is required.
        - Electrical check: Electrical components are assessed, including CNC systems, drives, and input/output modules. If the robot cannot be operated, the identification of damaged components can be difficult. The old components are no longer available sometimes.
    - Upgrade check: After the analysis of mechanical and electrical parts, if an upgrade is deemed necessary, the team considers which modern technologies can be integrated into the robot—often guided by safety regulations and compatibility with current control systems. Based on this analysis, a decision is made whether to upgrade components such as CNCs and drives.
    - Production / purchase order: Once the upgrade path is clear, the availability of replacement materials and components is checked. Parts may be sourced from the warehouse, manufactured in-house, or ordered from external suppliers.
- Disassembly: After identifying which parts are damaged or at risk, the team begins robot disassembly. The process follows a specific sequence:
    - The vertical axis group is disassembled first. Electrical cabling and pneumatic utilities are removed, and if present, the rotative B axis is taken off. The group is then set aside.
    - Next is the extraction axis group. Depending on the transmission system—rack and pinion or belt—it is appropriately dismantled, along with associated cable carriers and tubing.
    - Finally, the trolley on the Z-axis is disassembled, involving the removal of the belt and trolley unit.

- Electric part upgrading: Once the mechanical structures are disassembled, electrical components are removed. This includes:
  - CNC replacement: Replacing the CNC unit with a newer model. Changing the type of CNC, requires to change also most part of electrical components, including HMI.
  - Servo drives replacement: Swapping out the servo drives and corresponding motor cables.
  - Cables replacement: The operator replace the old cables with new ones from the servo drives to the motors.
  - Upgrading I/O boards: If the same I/O board is no longer available, it is needed to use a compatible one.
  - Electrical system update: If necessary, modernizing parts of the electrical system to update it to the compatible version of the CNC and servo drives installed.
  - Pneumatic replacement: Upgrading pneumatic circuits, including balancing cylinders and valves.
- Reassembly: With all outdated components replaced or upgraded, the robot is reassembled, group by group:
  - The Z-axis group is reassembled with new linear guides, slide blocks, the trolley, and belts.
  - The X-axis groups follow, including cable carriers, motors, pulleys, and racks.
  - The technician then reassembly the vertical (Y) axis group.
  - Finally, the wrist axis group—whether pneumatic or electric—is reinstalled.
- Final testing: Once reassembled, the robot undergoes functional testing. It is first tested on the shop floor at limited speeds and strokes to ensure safe operation. Then, the robot is mounted on a support structure and tested at full speed and full axis stroke, confirming performance under operational conditions.
- Final cleaning: Before shipment, the robot receives a final deep cleaning. New labels are applied, and all cabinet covers and dedicated enclosures are securely closed.

Competency assessment

We summarized the following key requirements that are required by employees to perform the tasks:

- Knowledge:
  - Mechanical knowledge (understanding of mechanical systems in the robots; familiarity with the function and appropriate use of tools)
  - Electronics knowledge (understanding of electronic equipment in the robots including servo drives, I/O modules, and CNC systems)

  - Production and Processing (understanding production processes, quality control, costs, and other techniques for maximizing the effective manufacture of robotics)
- Skills:
  - Repairing
  - Equipment maintenance
  - Equipment selection
  - Problem-solving
  - Troubleshooting
  - Critical thinking
  - Quality Control Analysis
  - Installation
  - Judgment and Decision Making
  - Systems Analysis
- Abilities:
  - Near vision (the ability to notice small defects)
  - Manual dexterity (the ability to perform precise mechanical tasks)
  - Problem sensitivity (the ability to tell when something is wrong or is likely to go wrong)
  - Selective attention (the ability to concentrate on a task over a period of time without being distracted)

Interview study: Employee perspectives and Managers perspectives

Five interviews were conducted with 1 operator, 1 technical leader, 1 HR manager, 1 R&D manager, and 1 customer service manager working in Campetella. We analyzed the Insights from the interviews to identify the job demand and the major risks associated with the job in the current work process. The main findings are listed below:

Job demands

- Workload: One major demand perceived by operators is the heavy workload associated with the remanufacturing tasks. As the entire process is carried out manually, operators often experience stress, particularly due to the need to respond swiftly and adaptively to customer requests.
  - Qualitative workload: The qualitative workload in the robot remanufacturing process is driven by the cognitive, emotional, and technical demands of tasks such as inspecting, diagnosing faults, decision-making for component replacements, and ensuring the system's overall functionality. Operators must apply their expertise in mechanical and electrical systems, make critical decisions about upgrades, and work under emotional pressure during troubleshooting or testing phases. Attention to detail is essential,

particularly when identifying wear, corrosion, or the need for technological advancements.

- Quantitative workload: The quantitative workload in the remanufacturing process is high, with extensive time requirements across multiple phases, including cleaning, disassembly, reassembly, and testing. The number of components inspected, replaced, or upgraded is large, encompassing mechanical parts, electrical systems, and cables. The frequency of tasks, such as diagnostic tests, cleaning cycles, and component replacements, is also considerable. These tasks require continuous effort and coordination, making the physical and time demands substantial throughout the process. The high volume of repetitive activities, along with the complexity of ensuring every part meets functional and safety standards, contributes to the overall high quantitative workload.

- Physical and cognitive demands: The current remanufacturing process of industrial robots in Campetella is a complex, multi-step process that requires a high level of coordination, technical precision, and human labor. As pointed out by both operators and managers, the process involves layered demands across physical and cognitive dimensions.
  - Physical demand: The process requires manual handling of large and heavy robot components, especially during disassembly and reassembly. Repetitive manual tasks, particularly those performed by operators, lead to frustration and disengagement.
  - Cognitive demand: There is a strong reliance on undocumented, tacit knowledge held by experienced personnel. When employees leave the organization, valuable information is often lost, leading to disruptions in workflow and increased potential for errors due to missing or inaccessible knowledge.

The findings are summarized and matched with each phase of the remanufacturing process in **Error! Reference source not found.**:

Phase description	Physical demands	Cognitive demands	Qualitative workload	Quantitative workload
Inspection		✓		
First cleaning	✓			✓
Component replacement		✓	✓	
Disassembly	✓	✓	✓	✓
Electric part upgrading		✓	✓	
Reassembly	✓	✓	✓	✓
Final testing	✓		✓	✓
Final cleaning	✓			✓

Table 9: Job demands at Campetella

3.1.2.2 Prospective process

In the future state of the robot remanufacturing process, the work process will be enhanced through human-AI collaboration.

- Collaborative Workstation for Cleaning and Disassembly Processes
  The introduction of a collaborative workstation is aimed at supporting operators during the physically demanding cleaning and disassembly phases. This workstation will integrate robotic arms and AI-assisted tools to perform repetitive or ergonomically risky tasks, such as loosening bolts, handling heavy components, or removing accumulated dirt from returned robots. The AI system will be designed to detect operator actions in real time, enabling smooth coordination between human and machine without compromising safety. This collaborative setup not only reduces physical strain on workers but also improves precision, consistency, and throughput in the early stages of remanufacturing.
- Digital Twin for the Remanufacturing Cell
  A digital twin of the remanufacturing cell will serve as a real-time virtual representation of the physical workspace, simulating both current and future operations. This AI-driven system will collect and analyze data from sensors, machines, and manual inputs to provide actionable insights to operators and supervisors. For example, it can guide decision-making by suggesting optimal sequences for disassembly, flagging potential component failures, or forecasting material needs. By mirroring the physical process in a dynamic digital environment, the digital twin helps reduce uncertainty, enhance training, and enable continuous process optimization—ultimately boosting both efficiency and adaptability in the remanufacturing workflow.

Skills assessment

The introduction of human-AI collaboration in the remanufacturing process is expected to shift the skill demands from primarily manual and experience-based tasks to more cognitive and system-oriented competencies. While the need for hands-on equipment maintenance may decrease due to automation, there will be a growing requirement for operators to understand and interact with AI-driven tools and robotic systems. Equipment selection will demand more technical judgment as workers choose between various collaborative technologies. Critical thinking and decision-making will also evolve, with greater emphasis on interpreting AI outputs and integrating digital insights into workflow decisions. This transition highlights a clear skills gap in digital literacy, technical evaluation, and data-informed reasoning, necessitating targeted upskilling initiatives.

Skills	Current process	Prospective process	Skills gap
Equipment maintenance	Operators manually perform all cleaning and disassembly, requiring deep hands-on expertise and heavy lifting ability.	Basic maintenance still needed, but AI systems and cobots reduce manual involvement.	Operators need basic knowledge to perform or support minor troubleshooting or recalibration of AI systems.
Equipment selection	Equipment choice is limited and largely standardized across tasks.	Operators must understand and select from various AI tools and robotic configurations.	Need to understand technical options, tool compatibility, and configuration.
Critical thinking	Applied mostly in problem-solving during manual disassembly or troubleshooting.	Critical for interpreting AI outputs, responding to system suggestions, and strategy adaptation.	Increase in analytical thinking and system-level problem-solving capabilities.
Judgement and decision making	Reliance on manual inspection and experienced technicians for decisions.	Informed by AI/digital twin insights, but human input remains essential.	Shift from intuitive to data-informed decisions, requiring digital literacy and AI interpretation skills.

Table 10: Skills gap assessment Campetella

Interview study: Employee perspectives and Managers perspectives

Insights from the interviews were analyzed to identify both the operators and the managers' attitude and expectations towards the introduction of AI, and the possible risks in the future work process with human-AI collaboration in remanufacturing. Here are the main findings:

Attitude and expectations towards AI

The overall attitude toward AI among employees and managers in the remanufacturing company is largely positive and forward-looking. Interview participants expressed strong enthusiasm for integrating AI into their workflows, viewing it as a powerful and versatile tool capable of supporting a wide range of tasks. While they acknowledged AI's potential, they consistently emphasized that AI should serve as an assistant rather than a replacement. Operator experience and tacit knowledge are still seen as essential, especially for nuanced decision-making. From a managerial perspective, AI is viewed not only as a tool to enhance productivity but also as a catalyst for developing human skills—by enabling operators to train the AI and thus actively shape its learning and application in the workplace. Here is a comparison between the RENÉE solution and the stakeholders' expectation on AI technologies demonstrating that expectations are quite in line with the intended RENÉE solution:

Impact of AI	RENÉE solution	Stakeholders' expectation
Cognitive demands	The digital twin of the remanufacturing cell that helps reduce uncertainty, enhance training, and enable continuous process optimization by mirroring the physical processes.	Stakeholders expressed clear expectation that AI would store information and minimize the need to rely on memory. Operators expect AI to offer step-by-step instructions during complex tasks like disassembly.
Physical demands	Implement robotic arms and AI-assisted tools to perform repetitive and physically demanding cleaning and disassembly tasks.	Operators expected that AI-tools and collaborative robots could assist with labor-intensive tasks such as handling heavy components and performing repetitive actions like cleaning and disassembly.

Table 11: Comparison between RENÉE solution and stakeholders' expectation (Campetella)

Risks

The current remanufacturing process involves intense manual labor and time pressure, leading to both physical and mental strain for operators. As AI technologies are introduced, the nature of risks shifts toward cognitive challenges, including overreliance on automation, reduced autonomy, and diminished task meaningfulness.

Risk type	Current risk	Future risk
Physical risk	• Handling heavy robot components causing musculoskeletal strain • Exposure to industrial dust affecting respiratory health • Physically repetitive tasks	• Reduced physical workload due to automation • Some exposure risks may remain without updated safety protocols
Cognitive risk	• Cognitive fatigue from repetitive tasks • Emotional stress due to time pressure and customer demands • Risk of burnout	• Overreliance on AI leading to reduced autonomy • Erosion of critical thinking • Fear of diminished role meaning and engagement

Table 12: Risks observed in Campetella use case

3.1.3 Remanufacturing of electrical motors

3.1.3.1 Current process

The remanufacturing process of an EDU at Emotors follows a structured sequence of inspection, repair, and reassembly steps. The objective is to restore the EDU to optimal functionality, enabling cost-effective reuse and supporting sustainable manufacturing practices. The inspection and repair process combines are fully manual, while the reassembly process has already involved simple human-robot collaboration: a collaborative robotic arm brings components with a box to operators for further reassembly. Below is a detailed description of the current remanufacturing process of an electric drive unit in Emotors:

- Inspection & Disassembly: The process begins with a detailed diagnostic evaluation to determine the condition and remaining lifetime of the EDU and its core components. This includes:
    - Operational Testing: Assessing whether the combined motor and inverter are functional.
    - Lifetime Assessment: Estimating the remaining service life of key components such as the inverter, motor bearings, and windings.
    - Inspection of rotor magnetic properties and mechanical damage.
    - Inspection of stator electrical insulation and structural integrity.

  Following diagnostics, the EDU undergoes a systematic disassembly to allow for in-depth inspection and refurbishment:
    - Separation of the motor and inverter.
    - Disassembly of the Rotor ASS and main housing ASS, including removal of bearings.
    - Extraction of permanent magnets from the rotor stack laminations.
    - Removal of the stator from the main housing.
    - Detachment of gaskets from all housing components.

  This phase provides the necessary insights and access to prepare components for targeted repair and reuse.
- Repair: In this phase, all components are cleaned, restored, or refurbished as required to ensure reliability and performance:
    - Cleaning: Removal of contaminants from housings, bearings, and internal water-cooling channels.
    - Mechanical Refurbishment: Renewal or re-machining of shaft bearing seats and bearing housings to restore dimensional tolerances.
    - Electrical Restoration: Re-varnishing of the stator windings to enhance electrical insulation and durability.

  This ensures that all components meet the required standards for reassembly and performance.
- Reassembly & Quality Control: The final phase involves reassembling the remanufactured EDU and verifying its functional performance:
    - Rotor Assembly: New bearings are installed on the refurbished shaft. Rotor stacks (used or new) are mounted, and remanent magnetization is applied if necessary.
    - Stator Integration: The repaired stator is installed into the cleaned and refurbished housing.
    - Final Motor Assembly: The rotor is inserted into the stator, and the housing is reassembled.
    - Inverter Installation: A new or reconditioned inverter is mounted to complete the EDU.
    - Functional Testing: The remanufactured EDU undergoes quality control testing to verify operational integrity and ensure it meets performance specifications.

Competency assessment

We summarized the following key requirements that are required by employees to perform the tasks:

- Knowledge:
    - Mechanical knowledge (understanding of mechanical systems in the EDU; familiarity with the function and appropriate use of tools)
    - Production and Processing (understanding production processes, quality control, costs, and other techniques for maximizing the effective manufacture of EDU)
- Skills:
    - Repairing
    - Equipment maintenance
    - Equipment selection
    - Problem-solving
    - Troubleshooting
    - Critical thinking
    - Quality Control Analysis
    - Installation
    - Judgment and Decision Making
    - Systems Analysis
- Abilities:
    - Near vision (the ability to notice small defects)
    - Manual dexterity (the ability to perform precise mechanical tasks)
    - Problem sensitivity (the ability to tell when something is wrong or is likely to go wrong)
    - Selective attention (the ability to concentrate on a task over a period of time without being distracted)

Interview study: Employee perspectives and Managers perspectives

Three interviews are conducted to 1 operator, 1 field manager, 1 platform manager working in Emotors. Insights from the interviews are analyzed to identify the job demand and the major risks associated with the job in the current work process. Here are the main findings:

Job demands

According to the interviews conducted with operators, their perceptions of the current work process are generally positive. They described the workstations as well-optimized, flexible, and ergonomically supportive, with no particular tasks considered overwhelmingly difficult. Operators did not report experiencing an excessive workload, either in terms of the amount of work or the complexity of tasks. This suggests a good alignment between task demands and worker capabilities, as well as effective workstation design that supports efficient task execution. However, to gain a more comprehensive understanding of the actual demands placed on workers, we complemented the interview insights with direct observation of the remanufacturing process:

- Workload:
  - Qualitative workload: The qualitative workload involves moderate levels of complexity and cognitive demand. Operators perform tasks that require technical knowledge, precision, and attention to detail, especially during component inspection, rotor magnetization, and reassembly. Manual control of machines adds responsibility and requires continuous concentration.
  - Quantitative workload: The quantitative workload in the EDU remanufacturing process appears to be moderate. Operators are involved in a series of sequential tasks across diagnostics, disassembly, repair, and reassembly, which means that while the overall unit volume may not be high, each EDU demands considerable time and effort. The nature of the work includes manual handling of components, operation of tools, and process monitoring—activities that require physical involvement but are distributed in a way that does not overwhelm workers.
- Physical and cognitive demands:
  - Physical demand: The current process involves significant physical demands, primarily due to manual handling of heavy components such as rotors, stators, and housings. Tasks like lifting, aligning, disassembling, and cleaning parts require frequent movement, force application, and repetitive actions. Operators also work with hand tools and operate semi-automated machines, which can add to muscular strain. Although lifting aids are available, they are not fully automated, meaning workers still exert physical effort to control positioning and stability.
  - Cognitive demand: Cognitive demands in the process are moderate, shaped by the need for attention to detail, process adherence, and technical decision-making. Operators must assess the condition of components (e.g., bearing wear, insulation damage), carry out precision tasks like re-varnishing or rotor magnetization, and ensure proper alignment during assembly. Manual control of machinery requires ongoing concentration and procedural knowledge, particularly during diagnostic testing and quality control. The tasks require sustained focus, which is emphasized by both managers and the operator.

The findings are summarized and matched with each phase of the remanufacturing process:

Phase description	Physical demands	Cognitive demands	Qualitative workload	Quantitative workload
Inspection & Disassembly	✓	✓	✓	
Repair	✓			✓
Reassembly & Quality Control	✓	✓		

Table 13: Job demands at Emotors

3.1.3.2 Prospective process

In the future state of the EDU remanufacturing process, the work process will be enhanced through human-AI collaboration.

- Human-Robot Collaborative Cell for Assisted Disassembly
  Emotors plans to introduce a human-robot collaborative cell designed to support operators during the disassembly phase of the EDU remanufacturing process. This application aims to reduce physical strain by enabling robots to assist with the handling, positioning, and loosening of heavy or tightly assembled components. The robot will operate alongside workers in a shared workspace, performing repetitive or ergonomically challenging tasks, while human operators focus on more delicate or decision-based actions. This collaboration is expected to improve workplace ergonomics, reduce the risk of musculoskeletal injuries, and increase the overall efficiency and safety of the disassembly process.
- AI Tools for Product Diagnosis and Component Reusability
  Advanced AI tools will be deployed to enhance the diagnostic phase by analyzing sensor data, historical failure patterns, and visual inputs to assess the condition of electric drive units and their components. These tools will support workers by identifying which parts—such as bearings, windings, or magnets—are suitable for reuse and which require replacement. By automating the evaluation process, the system can reduce the cognitive load on operators, minimize diagnostic errors, and ensure more consistent decision-making. Moreover, this application will contribute to sustainability goals by improving material recovery, lowering waste generation, and supporting a more circular remanufacturing model.

Skills assessment

The introduction of human-AI collaboration in the remanufacturing process is expected to shift skill requirements toward more technical and digital competencies. While current tasks rely heavily on manual expertise in equipment maintenance, tool selection, and quality control, future roles will require operators to interact with robotic systems, interpret AI-generated diagnostics, and validate automated decisions. This transition highlights the need for upskilling in areas such as basic robotics maintenance, digital tool use, and data interpretation to ensure effective collaboration between human workers and AI systems.

Skills	Current process	Prospective process	Skills gap
Equipment maintenance	Operators perform routine manual checks and basic maintenance on mechanical tools and fixtures.	Performing basic maintenance on electromechanical systems and collaborative robotics.	Need for basic robot maintenance, understanding robot safety protocols, and minor robot troubleshooting.
Equipment selection	Workers rely on experience and process guidelines to choose appropriate	AI-supported systems recommend or automate tool selection based on	Need to interpret AI recommendations, develop digital literacy, and validate AI outputs.

	tools for disassembly and assembly.	component type and condition.	
Quality Control Analysis	Visual inspection and manual testing are used to assess component condition and final assembly functionality.	AI will assist in analyzing test data, component wear, and reusability through predictive diagnostics.	Need to work with AI-assisted analytics, understand sensor data outputs, and interpret AI-driven diagnostics.

Table 14: Skills gap assessment Emotors

Interview study: Employee perspectives and Managers perspectives

Insights from the interviews were analyzed to identify both the operators and the managers' attitude and expectations towards the introduction of AI, and the possible risks in the future work process with human-AI collaboration in remanufacturing. Here are the main findings:

Attitude and expectations towards AI

Both operators and managers expressed a generally positive attitude toward the implementation of AI in the remanufacturing process, viewing it as a necessary and strategic step to maintain the company's competitiveness in the evolving industry landscape. They emphasized that AI should serve as a tool to enhance operations rather than replace human workers. Importantly, they stressed that humans should remain in control of the process—positioning AI as a supportive assistant, not a decision-maker—ensuring that the operator continues to "pilot" the system while benefiting from AI-driven insights and automation. Here is a comparison between the RENÉE solution and the stakeholders' expectation on AI technologies:

Impact of AI	RENÉE solution	Stakeholders' expectation
Cognitive demands	Advanced AI tools will be deployed to enhance the diagnostic phase by assisting operators in decision-making processes.	Stakeholders expressed clear expectation that AI can help streamline diagnostic processes, identify reusable components, and ensure more consistent quality control.
Physical demands	Human-robot collaborative cell is designed to support operators during the disassembly phase of the EDU remanufacturing process.	Stakeholders anticipate that collaborative robots and automated tools will assist in handling heavy components, performing precise disassembly actions, and supporting awkward postures.

Table 15: Comparison between RENÉE solution and stakeholders' expectation (Emotors)

Risks

As EDU remanufacturing processes remain largely manual, workers face significant physical and ergonomic strain. The adoption of AI and collaborative robotics is expected to ease some of these burdens but introduces new physical coordination challenges and increased cognitive demands related to monitoring and adapting to intelligent systems.

Risk type	Current risk	Future risk
Physical risk	• Repetitive movements and awkward postures • Manual lifting of heavy parts • Strain from tool operation • Fatigue from partial mechanization	• Risk of accidents from shared human-robot workspaces • Potential hazards from falling or shifting components • New ergonomic challenges when interfacing with AI systems
Cognitive risk	• Physical strain may indirectly contribute to mental fatigue and reduced focus	• Increased vigilance required to monitor AI behavior • Need for situational awareness in dynamic environments • Cognitive load from adapting to new workflow

Table 16: Risks observed in Emotors use case

3.1.4 Remanufacturing of household appliances

3.1.4.1 Current process

The remanufacturing process of a refrigerator at Arcelik follows a structured sequence of sorting, refurbishment, spare part recovery, and scrap recycling. Each stage relies heavily on human judgment and physical effort—from checking shipment details and assessing product conditions to performing repairs, tests, and part extractions. The current refrigerator remanufacturing process in Arcelik is entirely manual and highly labor-intensive. Below is a detailed description:

- Sorting: The process begins by verifying incoming products and categorizing them based on their condition. This includes:
  - Shipment Bill Check: Confirm arrival of products against the shipment bill and enter product data into the central database.
  - Products Sorting: Sort units based on their condition, and then direct them to appropriate lines: scrap, refurbishment, or spare part recovery.
  - Refurbish Capability Check: Assess if the product is suitable for refurbishment by checking usage history (must be less than 90 days), then evaluate reliability and potential for resale.
- Refurbishment: Products deemed suitable for reuse undergo thorough cleaning, repair, and testing:
  - Paintshop: Refinish the exterior to improve appearance.
  - Hygiene Test: Ensure the interior and exterior are sanitized.
  - Performance Test: Test cooling and energy efficiency.
  - Safety Test: Verify compliance with safety standards.
  - Visual Test: Inspect for dents, scratches, or other cosmetic issues.
  - Minor Repairs: Fix minor mechanical or cosmetic issues.
- Spare Part Recovery: For units not suitable for refurbishment, usable parts are extracted and processed:

- Field Demands Evaluation: Analyse service needs to identify high-demand parts (e.g., PCB, fan motor, compressor, heater, display, doors).
- Demounting: Carefully dismantle and extract usable components.
- Visual Inspection: Check parts for physical damage or wear.
- Functional Tests: Test performance and reliability of recovered parts.
- Storage and Transportation: Label, store, and transport usable parts for reuse or resale.

- Scrap Recycling: Remaining components and materials are responsibly disposed of or recycled:
  - Non-reusable parts are processed according to environmental regulations.
  - Materials like plastics and metals are separated and sent to recycling facilities.

Competency assessment

We summarized the following key requirements that are required by employees to perform the tasks:

- Knowledge:
  - Mechanical knowledge (knowledge of refrigerators and tools, including their designs, uses, repair, and maintenance)
  - Electronics knowledge (understanding of electronic equipment in the refrigerator including PCB, display components)
- Skills:
  - Repairing
  - Equipment maintenance
  - Equipment selection
  - Problem-solving
  - Troubleshooting
  - Critical thinking
  - Quality Control Analysis
  - Installation
  - Judgment and Decision Making
  - Systems Analysis
- Abilities:
  - Near vision (the ability to notice small defects)
  - Manual dexterity (the ability to perform precise mechanical tasks)
  - Problem sensitivity (the ability to tell when something is wrong or is likely to go wrong)
  - Selective attention (the ability to concentrate on a task over a period of time without being distracted)

- Control Precision (the ability to quickly and repeatedly adjust the controls of a refrigerator to exact positions)

3.1.4.2 Prospective process

In the future state of the refrigerator remanufacturing process, the work process will be enhanced through human-AI collaboration.

- Collaborative Workstations with High-Payload Robots and Customized Mechatronic Devices
  Arcelik will implement collaborative workstations that combine high-payload industrial robots with customized mechatronic devices. These systems will assist in physically demanding tasks such as lifting and manipulating heavy components like compressors, fan motors, and doors. The robots will work alongside human operators to automate repetitive and force-intensive steps in demounting, repair, and assembly processes, aiming to reduce manual workload, increase process speed, and improve consistency in part handling.
- Smart AI and Probabilistic Models for Estimating Component Lifetime
  Arcelik will deploy AI-based systems and probabilistic modeling techniques to estimate the remaining lifetime of critical refrigerator components. These models will use operational data, usage history, and failure statistics to predict component reliability. The goal is to improve decision-making during sorting and refurbishment by identifying which units or parts are worth recovering, which can extend the lifespan of reused components, reduce unnecessary labor, and minimize material waste.

Skills assessment

The introduction of human-AI collaboration in the remanufacturing process is expected to shift skill requirements toward more technical and digital competencies. While current tasks rely heavily on manual expertise in equipment maintenance, tool selection, and quality control, future roles will require operators to interact with robotic systems, interpret AI-generated diagnostics, and validate automated decisions. This transition highlights the need for upskilling in areas such as basic robotics maintenance, digital tool use, and data interpretation to ensure effective collaboration between human workers and AI systems.

Skills	Current process	Prospective process	Skills gap
Equipment selection	High reliance on physical strength for lifting, demounting, and handling parts, required strong knowledge of mechanical tools and hands-on repairs	Significantly reduced due to robotic assistance; still relevant for oversight and complex repairs, but less hands-on work	Training on robot-assisted workflows and safety, supervising automated/mechatronic systems
Troubleshooting	Based on individual judgment and basic testing	Supported by AI predictions and probabilistic models	Training in using AI tools for decision support

Quality Control Analysis	Visual and manual inspection based on experience and judgment	AI will assist in analyzing test data, component wear, and reusability through predictive diagnostics.	Training in reading sensor data, AI output interpretation

Table 17: Skills gap assessment Arcelik

Risks

Manual remanufacturing of refrigerators places both physical and cognitive demands on workers due to heavy handling, safety-critical tasks, and repetitive decision-making. While AI and robotic systems promise to ease these burdens, they introduce new risks tied to system reliability, human-robot coordination, and the cognitive demands of adapting to a digitally transformed work environment.

Risk type	Current risk	Future risk
Physical risk	• Handling of heavy refrigerator components • Risk of injury during repairs and testing • Physical fatigue from manual labour	• Safety hazards in shared human-robot workspaces • Risks from technical failures (e.g., unexpected movement, system errors)
Cognitive risk	• Repetitive decision-making increasing mental fatigue • Variability and inefficiencies due to manual data handling	• Challenges in interpreting and trusting AI outputs • Adaptation stress without adequate training • Increased system monitoring demands

Table 18: Risks observed in Arcelik use case

3.2 Summary

Across the four remanufacturing companies—focused on bicycles, industrial robots, and EDU, and refrigerator—the integration of AI is driving a transformative shift in both operational efficiency and human work dynamics. Despite the differences in their technical context, all use-cases reveal a common set of job demands, with workers experiencing high physical workloads, repetitive manual tasks, and ergonomic strain, particularly during disassembly and reassembly. These physical and procedural demands currently form the core challenge of frontline remanufacturing work. Yet, across three use-cases settings, workers expressed a generally positive attitude toward AI, viewing it as a necessary step for staying competitive and as a powerful tool to reduce physical burdens and improve quality and decision-making. Importantly, operators believe that humans should remain central to the process, with AI acting as a supportive assistant, rather than a replacement.

The shift towards HAIC also exposes a growing skill gap, as traditional mechanical expertise must now be complemented by new digital competencies. Workers will need to understand and interact with AI-driven diagnostics, robotic systems, and sensor-based quality analytics—skills that are not yet widely developed in these roles. Addressing this gap will require targeted upskilling initiatives to ensure that all employees can adapt to their evolving roles and interact confidently with new technologies.

Use case	Skills gap	Stakeholders' expectation
DECATHLON	• Operators need basic knowledge to perform or support minor troubleshooting or recalibration of AI systems. • Need to interpret AI-generated suggestion or safety alerts and align them with manual practice. • Operators have to learn to operate and verify AI inspection outputs. • Need for clear communication with both humans and AI systems.	• AI-assisted selection of spare parts which is considered as cognitive-demanding. • AI can improve communication with customers. • AI implementation will help alleviate the physically demanding aspects of their work, such as lifting and moving heavy e-bikes which are currently labour-intensive and repetitive, leading to fatigue and potential injury.
CAMPETELLA	• Operators need basic knowledge to perform or support minor troubleshooting or recalibration of AI systems. • Need to understand technical options, tool compatibility, and configuration. • Increase in analytical thinking and system-level problem-solving capabilities. • Shift from intuitive to data-informed decisions, requiring digital literacy and AI interpretation skills.	• AI would store information and minimize the need to rely on memory. Operators expect AI to offer step-by-step instructions during complex tasks like disassembly. • AI-tools and collaborative robots could assist with labor-intensive tasks such as handling heavy components and performing repetitive actions like cleaning and disassembly.
EMOTORS	• Need for basic robot maintenance, understanding robot safety protocols, and minor robot troubleshooting. • Need to interpret AI recommendations, develop digital literacy, and validate AI outputs. • Need to work with AI-assisted analytics, understand sensor	• AI can help streamline diagnostic processes, identify reusable components, and ensure more consistent quality control. • Collaborative robots and automated tools will assist in handling heavy components, performing precise disassembly actions, and supporting awkward postures.

Use case	Skills gap	Stakeholders' expectation
	data outputs, and interpret AI-driven diagnostics.	
ARCELIK	• Training on robot-assisted workflows and safety, supervising automated/mechatronic systems • Training in using AI tools for decision support • Training in reading sensor data, AI output interpretation	• *Analysis in progress*[8]

Table 19: Summary of skills gap and expectation per use case

As highlighted by Parker and Grote (2022), these changes underscore the importance of proactive work design, the deliberate structuring of tasks, responsibilities, relationships, and technology to optimize both performance and well-being. Work design provides a critical lens for understanding how AI systems can be introduced in ways that balance job demands, offer adequate resources, and support meaningful, engaging work. Operators who have the right skills and a positive attitude toward AI are more likely to experience enhanced work motivation and effectiveness, particularly when roles are consciously redesigned in advance. Drawing from Parker et al. (2017), a multi-level approach to work design—encompassing human-centered AI design, organizational communication and policy shifts, and individual strategies like job crafting—can help align technological innovation with human needs. In doing so, remanufacturing systems can move toward truly employee-centric HAIC, where the full benefits of AI are realized without compromising worker autonomy, safety, or engagement.

4 Skill development strategies

Due to the changes in skills, job demands and resources as well as changes in job characteristics that are accompanied with the introduction of AI supported robotic systems, it is pivotal to train employees so that they obtain the necessary new skills for their altered working situation (Charalambous et al., 2015). Furthermore, it is important that employees have sufficient job resources at their disposal during the implementation of the RENÉE solutions in order to adapt from a mostly manual to a remanufacturing process to one that requires HAIC. This in turn requires training of managers and supervisors. Finally, we propose tailored intervention trainings for employees to help them create a better fit with their changing job that results in increased worker well-being and performance.

[8] The interview process with ARCELIK end-users were still in progress as the deliverable was written. Final results will be included in the periodic report and next deliverables.

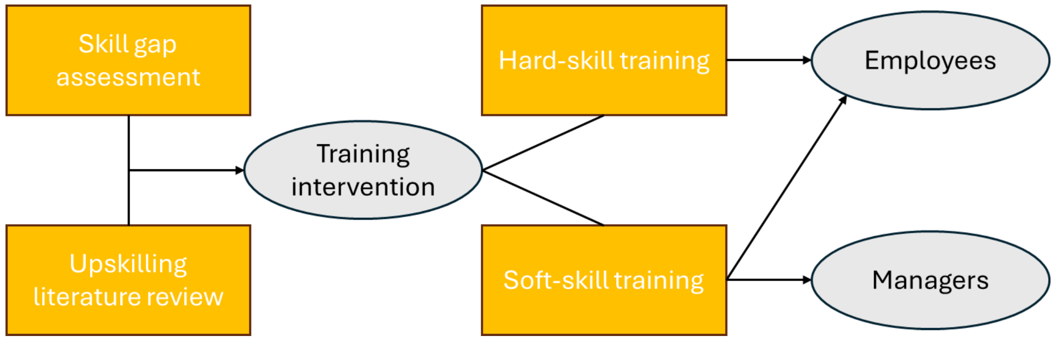


Figure 7: The process of designing training interventions

4.1 Effectiveness of upskilling strategies

We highlight below what the current literature identifies to be the most effective upskilling strategies and complement those with a tailored intervention training.

Effective upskilling programs:

- Realistic, immersive and context-specific: prepare operators to work with the new technologies; very relevant for remanufacturing where the transition will be significant (moving from mainly manual to integrating AI technologies; Leoste et al., 2021).
- Risk-free: environment in which operators can practice and experiment improves technical skills but also user confidence. Can be offered via VR (Matsas & Vosniakos, 2015).
- Are multifaceted: operators' soft skills are also promoted (Nikolova et al., 2024) to foster ownership and proactive engagement with the technology as well as their professional development (Charalambous et al., 2015; Chuang et al., 2024).

This participatory approach seems especially important in remanufacturing environments where team-based problem solving and adaptability are key. Furthermore, as training is a dynamic and ongoing process rather than a one-time intervention, the ongoing active engagement of employees is pivotal for its effectiveness (Chuang et al., 2024; Kopp et al., 2021; Zirar et al., 2023).

In summary, effective upskilling in the remanufacturing sector requires both updating technical competencies as well as supporting the psychological adaptation. In the RENÉE project we aim to create a comprehensive approach that aligns training methods with technological change so that employees in the remanufacturing processes learn the necessary new skills while at the same time being supported in their psychological adaptation to their new work situation. Furthermore, as indicated earlier (see section 2.1), in addition to training the employees to prepare them for the changes in the remanufacturing process, we also aim to train managers as they are the main providers of job resources during and after the implementation of the RENÉE solutions.

4.2 Hard-skill training strategies

Once the use-case partners have validated the skills gaps described in chapter 3, we are able to identify which technical or hard skills employees are required to develop. Based on that, the RENÉE project aims to develop tailored strategies for upskilling.

From the interviews we learned that:

- operators have a strong preference for in-person workshops over purely digital or self-guided formats.
- operators want hands-on training that directly relates to their daily tasks
- managers find only theoretical knowledge about the new technology insufficient
- managers expect operators learn via observing real demonstrations, by doing (experimenting) and by interacting with trainers and peers in a workshop setting

This feedback underscores the need to prioritize experiential, workplace-relevant learning approaches in the design of employee training interventions.

The table below outlines possible modules, content, and formats of the upskilling training:

Module	Key topics	Format
Introduction to AI & HAIC fundamentals	Introducing the basic principle of AI; overview of human–AI collaboration; builds trust through guided demos.	In-person workshop
Hands-on cobot skills	Operating and programming cobots in disassembly or cleaning tasks; safety and capabilities of cobots; safety protocols and teamwork.	In-person lab session
AI inspection tools	Using AI-assisted diagnosis and quality-inspection systems; interpreting AI outputs.	In-person demonstration and exercises
AI chatbot for support	Interacting with AI chatbot assistants for troubleshooting and on-the-job guidance.	In-person interactive session

Table 20: Upskilling training possibilities

4.3 Soft-skill training interventions

We aim to design two training intervention programs to both employees and managers for HAIC in remanufacturing.

For employees, we aim to design a job crafting training to optimally use their updated skills and knowledge regarding effective collaboration with the AI system in their workplace as well as to enhance their proactivity. The expected outcome of this training intervention is effective HAIC, in turn resulting in increased work engagement, work meaningfulness and wellbeing.

For managers, we aim to design a leadership training intervention to enhance effective implementation of AI-supported robotic systems into their remanufacturing process, with a specific focus on change communication and the supply of resources to employees during and after the implementation.

4.3.1 Employee job crafting training intervention

As the implementation of HAIC will change employees' jobs following a 'top-down' approach, it is important to realize that these approaches are not always effective. In fact, the change is more likely to become successful if employees can proactively engage in it. Job crafting is proactive behavior that enables employees to fit the job characteristics to their needs and preferences by seeking resources, seeking challenges, and optimizing demands (Demerouti et al., 2019). Training employees to craft their jobs is likely to enhance feelings of self-efficacy and control when introducing AI-supported robotic systems (Afiouni & Pinsonneault, 2022). Job crafting training interventions in various organizations have elicited positive outcomes such as increased employee well-being, meaningful work perceptions, and work engagement. The JD-R model (Bakker & Demerouti, 2006) and the experiential learning theory (Kolb et al., 2000) form the theoretical foundation of the training intervention.

Usually, the training starts with employees learning about the JD-R model via several exercises after which the theory of job crafting is explained, again using various exercises. After obtaining the relevant information and knowledge, employees engage in actual job crafting behavior in their own work situation, either by setting their own crafting goals or by engaging in specific assignments. So this means that job-crafting training interventions last several days to several weeks (with the most time spent on putting the new behavior into practice).

A job crafting training intervention is always tailor-made as the conditions (in terms of job demands and resources) will vary between organizations. Furthermore, both in-person as well as online self-training crafting interventions are effective in changing the targeted behaviors (Demerouti, 2023; Wang et al., 2024).

4.3.2 Training intervention for managers

Managers and supervisors can also be trained to enable the effective transition to HAIC implementation in the remanufacturing process. The design of such a leadership training may include sharing knowledge on how AI impacts the work design of employees and the importance of effective resource management for AI adoption – for instance, clear oversight, communication, and knowledge-sharing to coordinate people and AI systems (Xu & Cho, 2025). The training -similar to the employee job crafting training- would consist of both providing theoretical knowledge coupled with practical exercises in crafting change messages and providing resources to employees during and after implementation of the AI-supported robotic systems. The training intervention for managers combined with the job crafting training for employees will likely increase the effective implementation and use of HAIC in remanufacturing.

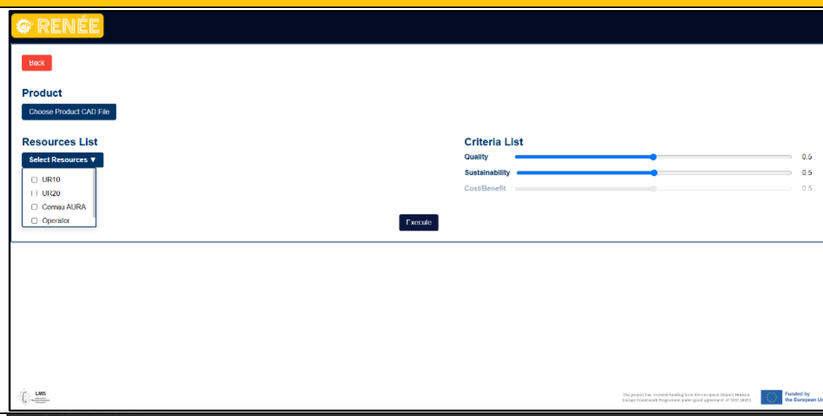
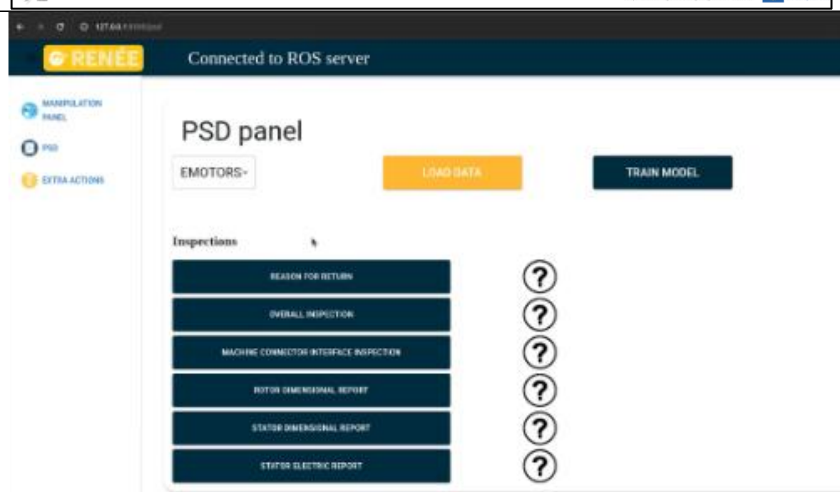
5 Human-Centric Operator Support Interfaces

Significant progress has been achieved in the design and prototyping of Operator Support Interfaces (OSIs) within the RENÉE project. These interfaces are developed with a strong human-centric focus, aiming to address the real and diverse needs of remanufacturing workers. The design process emphasizes intuitiveness, accessibility, and adaptability, ensuring that interfaces can effectively support operators with varying backgrounds, skills, and physical abilities. The RENÉE OSIs are not only intended to facilitate daily operations but also to enhance inclusion, well-being, and upskilling opportunities for the workforce

5.1 Overview of RENÉE User Interfaces

Several user interfaces have been developed across the RENÉE project to serve as the front-end for different technical modules and use cases. This section provides a summary of the main prototypes, offering readers an overview of the current state of interface development.

As the project progresses, a key objective is to harmonize the look, feel, and interaction patterns of all RENÉE interfaces. This effort aims to deliver a consistent and seamless user experience across modules, reducing cognitive load and training requirements for operators who interact with multiple systems

Module	WP	UI
Evaluation Tool	WP3	
Product State Diagnosis	WP3	

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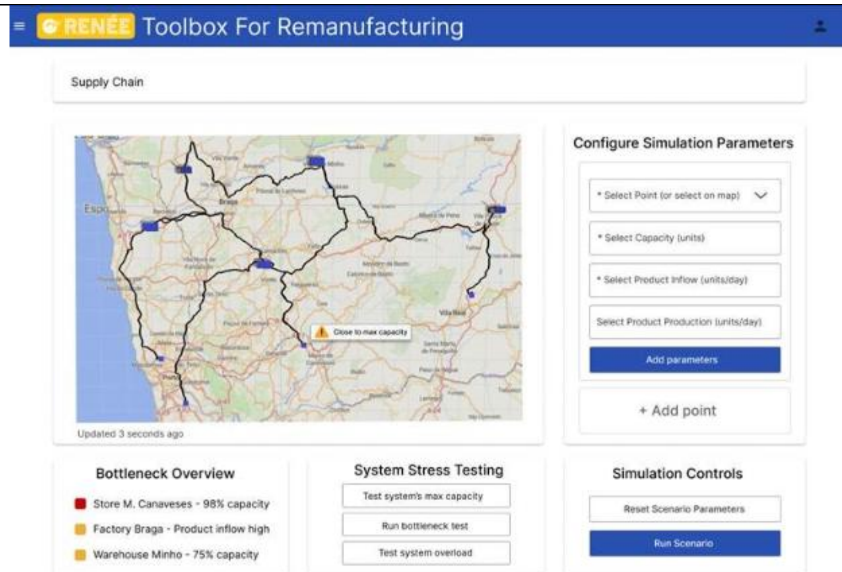
<td>
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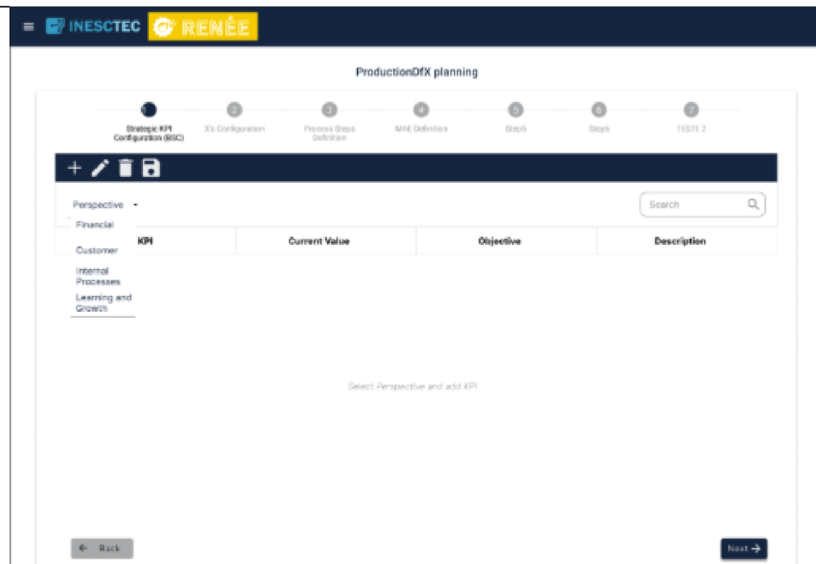
<td>RedesignFX</td>
<td>WP3</td>
<td>
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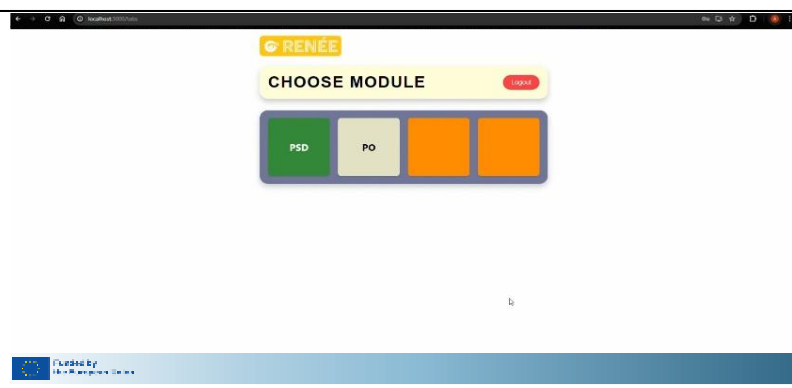
<td>Integration Platform</td>
<td>WP4</td>
<td>
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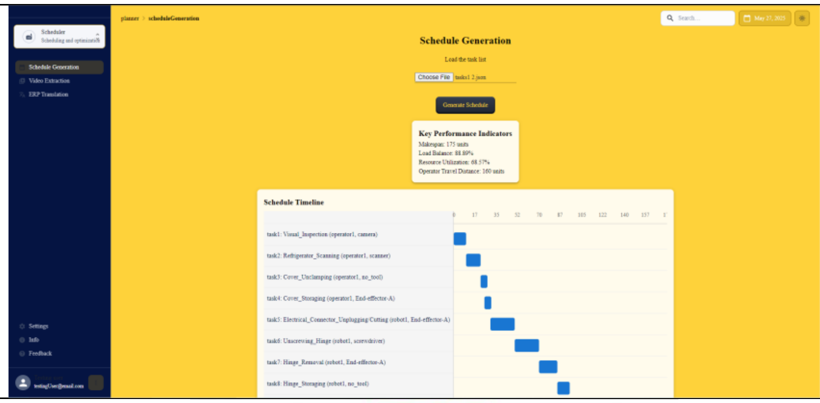
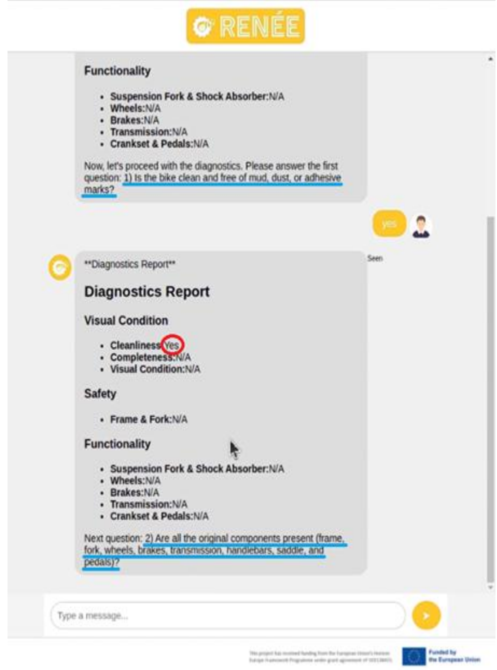
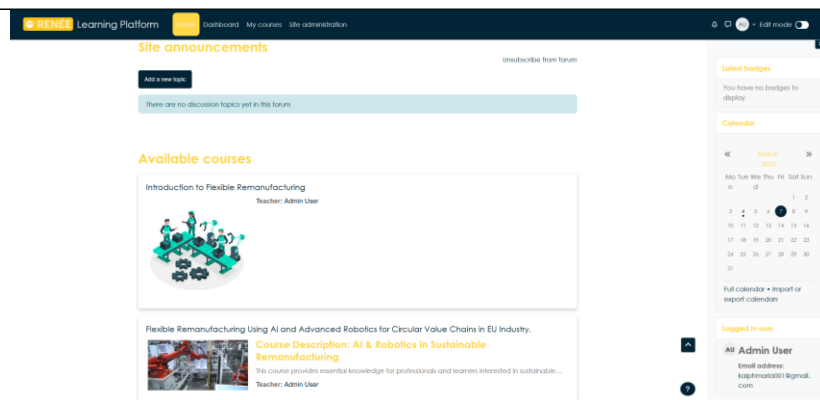
Process Scheduler and Orchestrator	WP4	
Operator Assistant Chatbot	WP6	
Learning Platform	WP6	

Table 21: RENÉE User Interfaces

5.2 RENÉE Operator Assistant Chatbot interface

The **RENÉE Operator Assistant Chatbot** application has been developed as the main **OSI** application, to achieve natural and easy to use interaction. This AI-enhanced interface uses the power of Multi Modal LMs for natural language processing in audio and textual modalities and acts as an interactive assistant designed to support the RENÉE remanufacturing processes.

The implementation of this interface is following the work of Gkournelos et. al. (2024) on how to develop efficient LLM agents for increasing the collaboration of human workers with robots in manufacturing cases. This approach provides the following features:

1. **System knowledge**: Access to manufacturing proprietary knowledge bases and data sources. OSI has direct access to the RENÉE Knowledge Database (see D4.1), which includes the all the data of the process and the system.
2. **Online information:** Integration with the Digital Twin (DT) (see D4.1) of the system allowing the access of dynamically updated data.

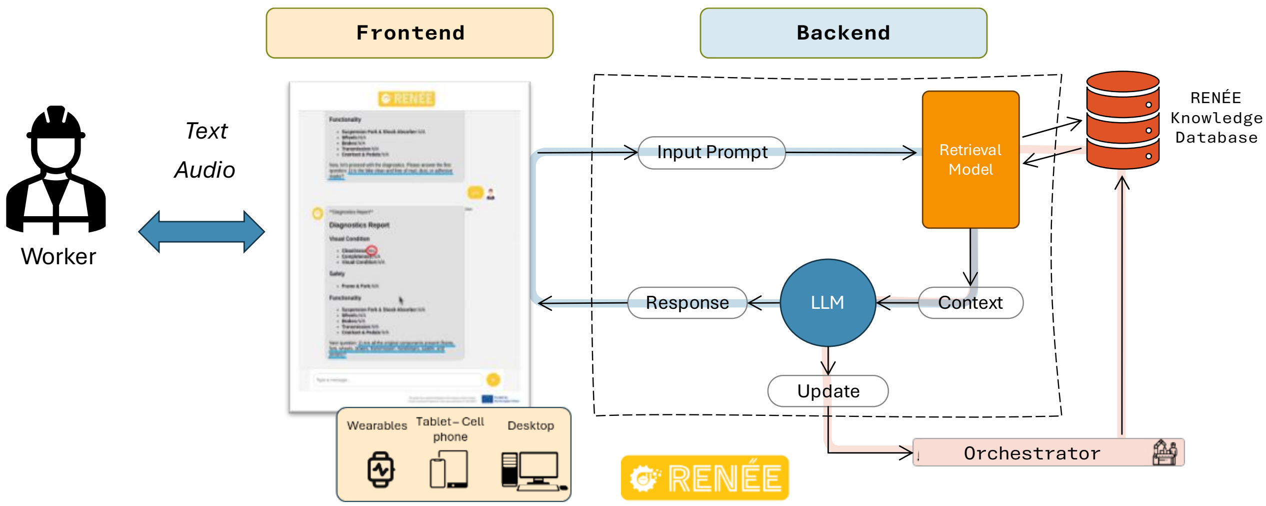


Figure 8: RENÉE Chatbot Architecture

The system architecture is structured around three main components:

- **User Interaction Layer:** This layer manages all operator inputs and outputs, supporting both voice and text communication. It ensures that operators can interact with the system in the most convenient and accessible way, regardless of their technical background or physical abilities.
- **AI Reasoning and Orchestration Layer:** Here, the Multi-Modal LMs interpret user queries, access relevant system knowledge, and generate context-aware responses. This layer is responsible for integrating information from the RENÉE Knowledge Database and orchestrating real-time data retrieval from the Digital Twin (DT), ensuring that the chatbot's guidance is always up-to-date and reflective of the current shopfloor status.
- **Data Integration Layer:** This component provides secure and efficient connections to proprietary manufacturing knowledge bases and the Digital Twin infrastructure. It enables

the chatbot to retrieve detailed process data, system status, and historical records, supporting advanced features such as explainable AI, traceability, and decision support.

This modular architecture allows the RENÉE Operator Assistant Chatbot to deliver personalized, context-sensitive support to operators, while ensuring interoperability with other RENÉE modules and scalability for future extensions.

The key features of the current chatbot application shown on the Figure 9:

1. Bot's Dynamic Message Stating.
2. Text Input Field (for the user).
3. Arrow Icon for submitting user's input.
4. Diagnostics Report Board.
5. Bot's Question .

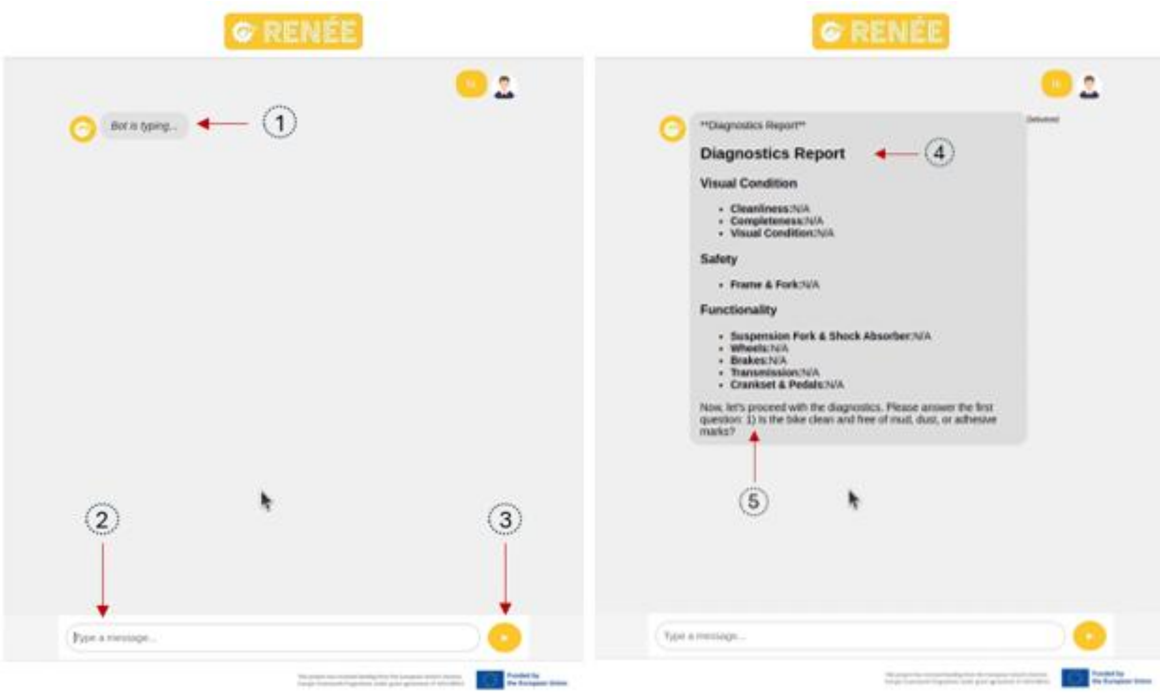


Figure 9: Frontend Key Features

The RENÉE Chatbot has been prototyped to support operators in Decathlon's bike inspection process, where workers currently perform manual tests and checklist documentation. By fine-tuning the chatbot using Decathlon's inspection data and workflows (Figure 5, **Error! Reference source not found.**), we validated its ability to guide operators through standardized diagnostic procedures while maintaining alignment with existing quality protocols.

Key Achievements to Date

- **Data-Driven Customization:** Successfully adapted the chatbot to Decathlon's specific inspection requirements, ensuring accurate guidance for mechanical, electrical, and safety checks.

- **Workflow Integration:** Demonstrated seamless integration with the existing diagnostic tool interface (Figure 6), minimizing disruption to operator routines.

The chatbot will evolve into a proactive assistant with three key upgrades:

1. Context-Aware Guidance
    - Real-time troubleshooting suggestions based on outcomes
    - Dynamic adaptation to operator expertise levels (e.g., novice vs. experienced)
    - Integration with the RENÉE Digital Twin for retrieving real-time information for the status of the robotic resources.
2. Streamlined Interaction Design
    - Predefined response buttons for yes/no, ratings, and status updates
    - Structured input formats to reduce errors and accelerate documentation
    - Integration with Action recognition modules developed in WP5
3. Multimodal Interaction
    - Speech-to-text functionality for hands-free operation during physical tasks
    - Audio-visual alerts for critical safety feedback

6 RENÉE Educational Platform and initial plan for training activities

6.1 Introduction

Task 6.3 focuses on supporting the manufacturing community by designing and delivering a comprehensive educational strategy that targets both skilled and unskilled operators. RENÉE will develop a modular educational platform that promotes upskilling, reskilling, and awareness-raising, using several digital tools.

To achieve this, the training plan includes a series of webinars, self-paced online courses, and hands-on workshops tailored to different levels of expertise. The webinars will introduce key remanufacturing concepts and technologies, while online courses will provide in-depth knowledge and microlearning modules. Workshops will offer practical, in-person training connected to pilot use cases, focusing on soft skills, safety, and flexible remanufacturing practices.

The materials will follow a learner-centred approach, using interactive content, video demonstrations, quizzes, and Bloom's taxonomy to guide knowledge development. The content will be made available both online and onsite, ensuring wide accessibility.

Special attention will be given to gender inclusivity and stakeholder-specific learning needs. TU/E will also support soft skill identification through interviews and field feedback, feeding into the training design. All learning activities will be aligned with Key Exploitable Results (KERs) (WP7, D7.4) and supported by dissemination materials (newsletters, flyers, and videos) at different stages of the project.

Webinar Phase

The webinar phase is designed to introduce key concepts and raise awareness about the core technologies and methodologies of remanufacturing. These 45-minute sessions will follow a structured agenda including a brief presentation, conceptual examples, and a moderate Q&A session. Topics include AI and robotics for flexible remanufacturing, digital twin technologies, and human-centric design. The goal is to provide high-level knowledge and engage potential partners or clients through interactive discussions and demo videos. This phase will be delivered fully online and requires no special equipment.

Online Course Phase

The online course phase offers a deeper and more structured learning experience. These self-paced courses will span 2 to 4 weeks and include microlearning modules built around Bloom's taxonomy. The material will be delivered through short educational videos, interactive content, quizzes, articles, and video demonstrations. This phase aims to build technical and soft skills across different learner levels and is suitable for both upskilling and reskilling activities. All content will be made available online and free of charge, ensuring accessibility and scalability.

Workshop Phase

The workshop phase provides practical, hands-on training aligned with the project's pilot technologies. Conducted in physical locations of partners, these sessions will last 1–2 days and offer direct interaction with equipment and technologies used in the pilots. Workshops will include demo setups, role-based assessment scenarios, and guided training modules that reinforce the theoretical content of the online courses. Special attention will be given to engaging female workforce participants and other stakeholders identified in the project. This phase supports experiential learning and enhances practical understanding of remanufacturing systems.

6.1.1 Overview of Technical Setup

Designed for a diverse audience, the platform offers modular, interactive courses that accommodate different expertise and style learners, through a microlearning approach. Leveraging Moodle's open-source flexibility, the platform provides a scalable and customizable learning environment enriched with forums, quizzes, and multimedia resources to enhance engagement and learning outcomes.

Moodle, an open-source learning management system, was selected as the foundation for the RENÉE Educational Platform for several strategic reasons:

- **Flexibility and Customization:**
  Moodle allows for the development of a highly modular and customizable learning environment. It supports various course structures, content types, and interaction models, which align with RENÉE's goal to offer a rich and adaptive learning experience.
- **Scalability:**
  Whether serving a small group of pilot learners or a wider audience across academia and industry, Moodle's scalability ensures that the platform can grow with user demand.
- **Interactivity and Engagement:**
  Moodle's native features - including quizzes, forums, assignments, messaging, and certification - promote active learner engagement and knowledge retention.

- **Integration Potential:**
  Moodle offers integration with other tools, plugins, and third-party systems, allowing RENÉE to enhance the platform with AI-driven analytics, gamification elements, or external resource links if needed.
- **Accessibility and Inclusiveness:**
  Committed to universal access, Moodle complies with international accessibility standards, ensuring that users with diverse needs can fully participate.

By using Moodle, RENÉE ensures that its educational platform remains adaptable, user-friendly, and capable of supporting a wide range of current and future learning needs.

6.1.2 User Roles

In terms of user roles and permissions, the platform supports a structured access control system with three primary user categories:

- **Administrators:**
  Responsible for the overall management of the platform, including user management, course creation, configuration of system settings, plugin maintenance, and monitoring of platform performance.
- **Instructors/Teachers:**
  Course creators and content managers who develop, organize, and deliver course materials. They also manage learner activities, assessments, and provide feedback.
- **Learners/Participants:**
  Registered users who enroll in and complete courses. Participants can access learning materials, submit assignments, engage in forums, take quizzes, and earn certifications upon successful completion.

Each role comes with a predefined set of permissions, which can be fine-tuned to match specific operational needs or accommodate evolving course structures.

6.2 Platform Architecture and User Interface

6.2.1 Platform's Overview

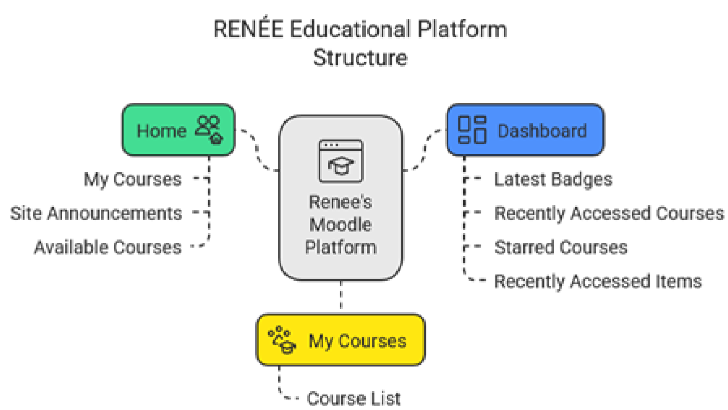


Figure 10: RENÉE Educational Platform Structure

The figure above illustrates the structure of the RENÉE Educational Platform as implemented in Moodle. At the centre is RENÉE's Moodle Platform, which connects users to three main sections: Home, Dashboard, and My Courses.

- **Home** provides access to general platform features, including "My Courses," site announcements, and a list of available courses.
- **Dashboard** offers personalized insights such as latest badges earned, recently accessed courses and items, and starred courses for easy access.
- **My Courses** leads directly to the user's course list, allowing quick navigation to active learning modules.

This structure ensures a user-friendly and organized experience, enabling industrial employees and other learners to easily access relevant training content and track their progress. Following the website visual identification features, the platform is being designed with respect to RENÉE color palette and style.

6.2.2 Homepage

The homepage of the RENÉE Educational Platform is designed to offer a consistent experience to both guests and logged-in users, serving as the main point of entry into the platform's educational resources.

- Enrolled Courses: A section lists the courses the user is actively participating in, including their progress status.
- Site Announcements: Platform or course specific announcements are displayed in home page, ensuring a centralized information point.
- Available Courses: In addition to enrolled courses, logged-in users can see and enrol in other open courses.

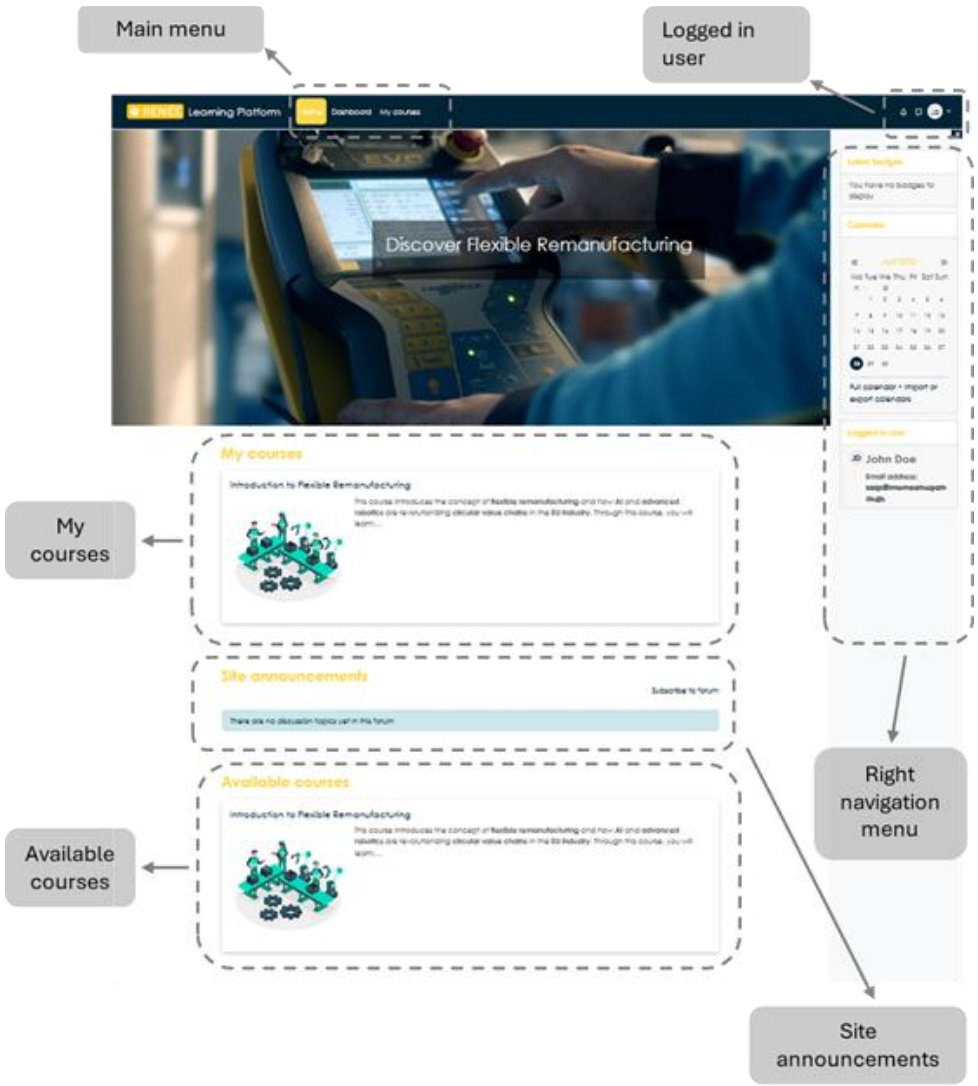


Figure 11: Homepage for logged in users

The platform's footer includes the project logo and EU funding acknowledgment, contact details, and links to social media platforms as shown in **Error! Reference source not found.**, and in alignment w ith project's website related section.

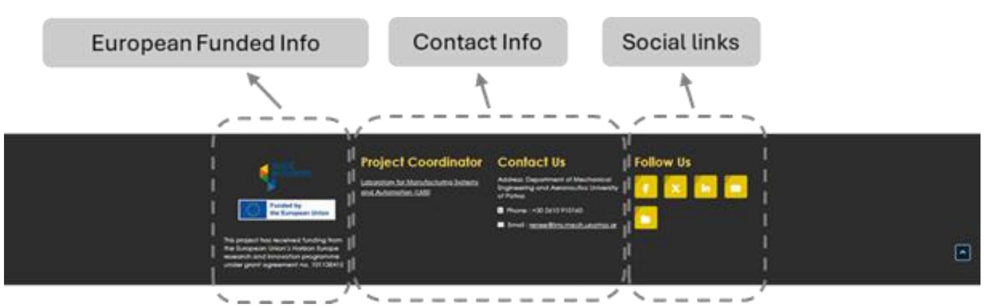


Figure 12: Footer with platform information

6.2.3 Dashboard

The Dashboard is a personalized area accessible only to authenticated users, designed to help them manage their learning activities.

Key sections on the Dashboard include:

- **Latest Badges:** Displays recently earned badges and achievements (replaced by the Timeline for detailed tracking).
- **Timeline:** A chronological view of upcoming activities.
- **Recently Accessed Courses:** Quick links to courses the user has recently viewed.
- **Starred Courses:** Courses marked as favourites by the user for easier access.
- **Recently Accessed Items:** Direct links to recently opened modules, activities, or resources.

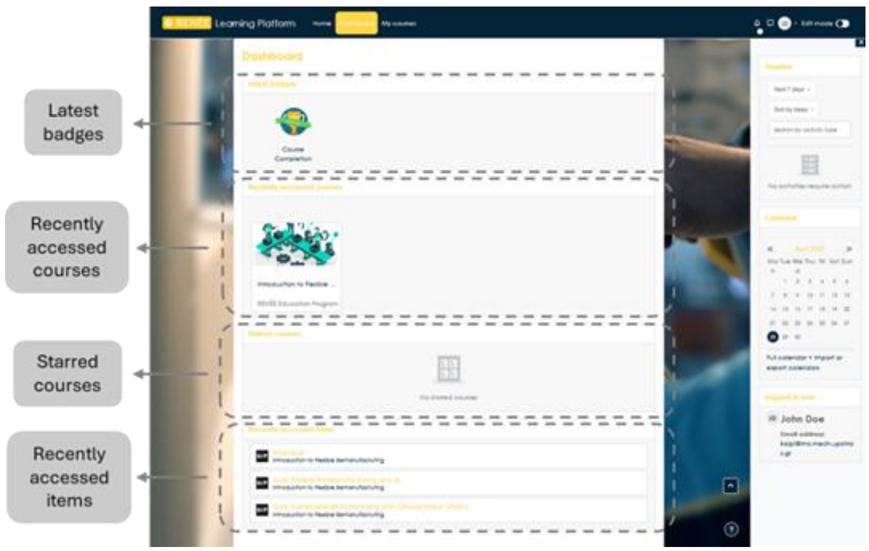


Figure 13: Dashboard for logged in users

6.2.4 "My Courses" Page

The My Courses page, accessible only to logged-in users, presents an overview of the user's course enrolments.

- **Course Overview:**
  A visual list or grid of all courses the user is currently enrolled in, with progress indicators and access links.
- **Search and Filter Options:**
  Tools for sorting or searching through the user's enrolled courses (where applicable).

This page centralizes the learner's course-related activities in a structured, easily navigable format.

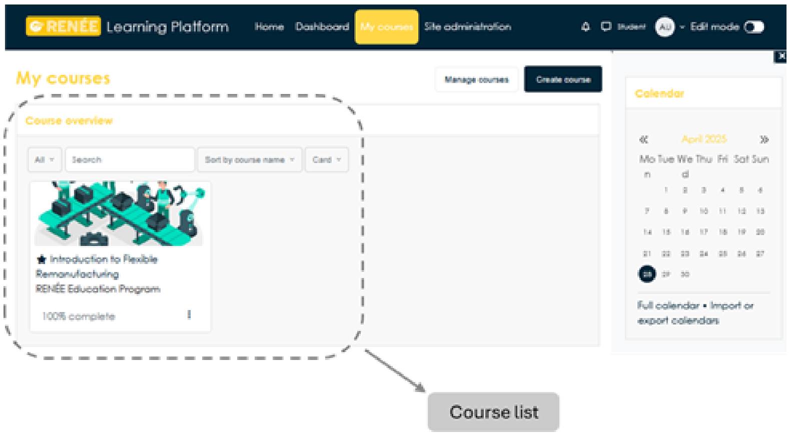


Figure 14: "My courses" page with course list in cards format

6.2.5 Course Structure and Content

The RENÉE Educational Platform's courses are structured to provide an organized, engaging, and user-friendly learning experience. The courses may be divided into sections, each designed to help learners progress through the material systematically. In that way, the structure is focused on ensuring that users not only access content but are also motivated to complete activities and assessments that reinforce their learning.

The course format is designed to be user-friendly and visually appealing, ensuring that each section is easy to navigate. Learners can easily resume the course from where they left off, providing a seamless learning experience without losing track of their progress.

Each course is divided into sections, which may be presented as cards on the main course overview page. This card-based layout allows learners to easily navigate through the course content and see at a glance the key topics or themes covered in each section.

Each course section has specific activity completion criteria to ensure learners engage with the material and are ready to progress. These typically include:

- **Quizzes:** Learners must complete quizzes to unlock the next section, reinforcing key concepts and knowledge.
- **Assignments/Activities:** Some sections require assignments to deepen understanding.
- **Completion Markers:** Activities are tracked with progress indicators. There is the option where once all tasks are complete, learners can move on to the next section.

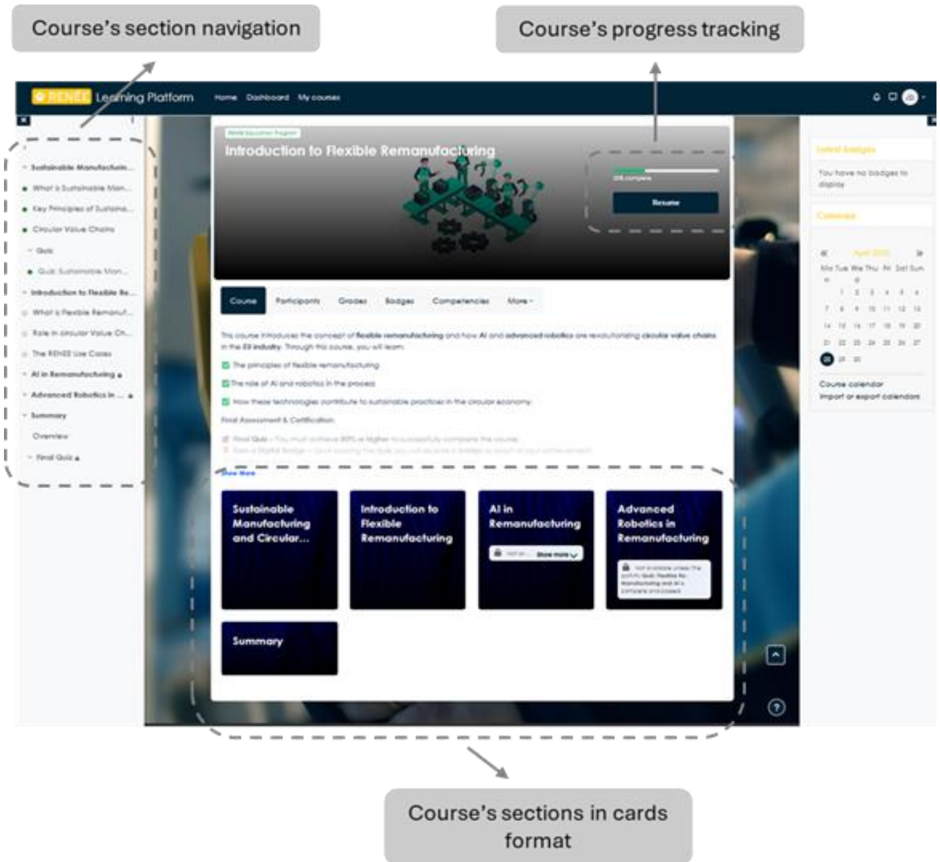


Figure 15: Course with cards format, progress tracking and resume option

6.2.6 Gamification

Users can earn multiple digital badges by meeting various criteria throughout the course. These badges recognize specific achievements such as completing the entire course, finishing individual modules or activities, or engaging in forums. Each badge is automatically rewarded when the associated conditions are met, serving as a motivational tool and a visual record of progress.

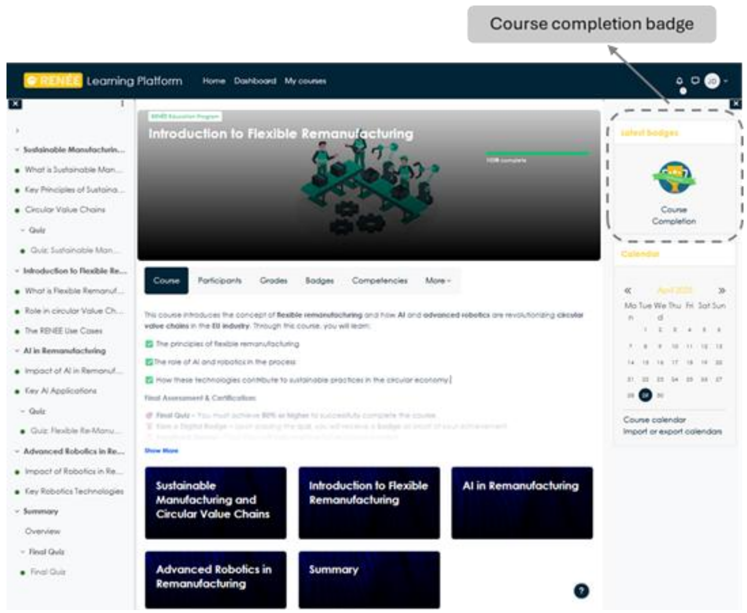


Figure 16: Course completion badge

H5P interactive content helps users learn faster and more easily by transforming traditional course materials into engaging, hands-on learning experiences. Through interactive videos, quizzes, presentations, and other dynamic formats, learners can actively participate in the learning process rather than passively consuming information. This interactivity reinforces understanding, provides instant feedback, and keeps users motivated. By breaking complex topics into visually rich, bite-sized activities, H5P makes the platform's content more accessible, memorable, and enjoyable to explore.

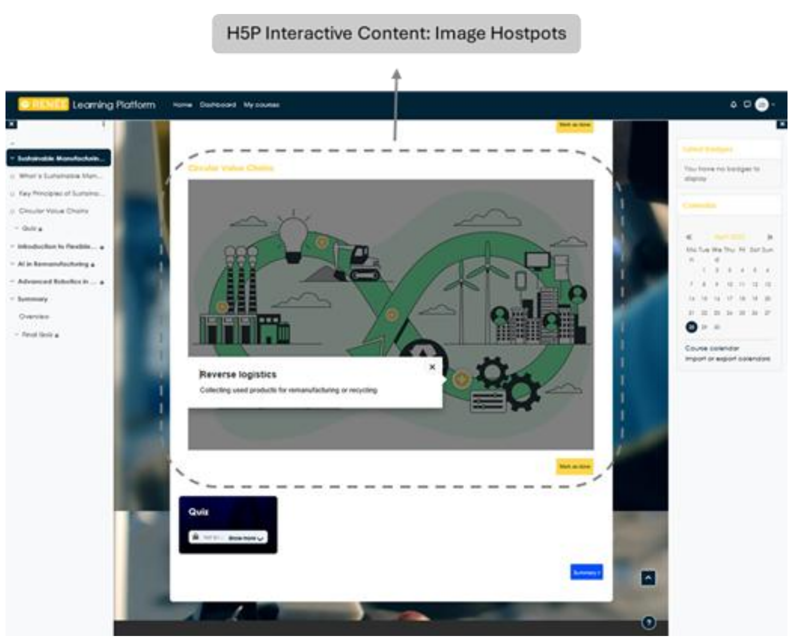


Figure 17: Image Hotspots H5P Interactive Content

6.3 Future Developments

The future development of the RENÉE Educational Platform is focused on enhancing the user experience by introducing more personalized and engaging features. One key improvement is the integration of statistics directly into the user dashboard, allowing learners to easily track their progress, course completions, time spent on activities, and earned achievements all in one place. This data-driven approach empowers users to take control of their learning journey.

Additionally, the platform aims to expand the use of H5P interactive content, offering richer, more engaging learning experiences. With more interactive elements such as adaptive quizzes, and scenario-based learning, users will benefit from a more immersive and effective educational environment. These advancements are designed to make learning not only easier and faster but also more enjoyable and motivating.

7 Conclusions and future actions

7.1 Conclusions

We have examined the key factors necessary to design and implement employee-centric human-AI collaboration in the remanufacturing processes. Drawing from the literature across the fields of HTI, WOP, and ergonomics, we proposed foundational design guidelines to support effective, safe, and meaningful interaction and collaboration between operators and AI systems. Particular attention was given to interface design, AI explainability, job and task characteristics, psychological factors, and physical and cognitive ergonomics.

Additionally, by analyzing interview data from the RENÉE remanufacturing use cases as well as observing the current work process, we identified critical skill gaps and workplace needs. These insights informed the development of targeted skill development strategies, including both hard-skill and soft-skill training, with an emphasis on job crafting and leadership development. Together, these findings offer a comprehensive framework for guiding the RENÉE industrial partners towards a successful transmission to HAIC in remanufacturing, prioritizing both performance and employee well-being.

7.2 Future actions

WP6 activities will proceed with the development of human-centric RENÉE interfaces and the design and development of the training activities. Briefly, the upcoming actions will include:

- Finalize the analysis of job demands as well as skills gap assessment for the household appliances use case by conducting and analysing interviews
- Validation of skills gap by relevant project stakeholders
- Drafting & validation interface design guidelines
- User evaluation of interfaces
- Implementation of operator support using voice commands, sensors and technologies such as AR and SAI modules
- Development and empirical tests of job crafting and leadership training interventions

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Appendix

Software tools

Name	Interpretability	Transparency	Visualization	Links
Lime (Local Interpretable Model-agnostic Explanations)	- Human-readable explanations - Local interpretability	- Feature importance	- Graphical explanations	- https://github.com/marcotcr/lime
SHAP (SHapley Additive exPlanations)	- Human-readable explanations - Local interpretability	- Feature importance	- Graphical explanations	- https://shap.readthedocs.io/en/latest/ - https://github.com/shap/shap
Skater (SHap Kernel Explainer)	- Human-readable explanations - Local interpretability - Global interpretability	- Model transparency - Feature importance - Decision rules	- Graphical explanations	- https://github.com/GapData/skater (maybe deprecated) - https://towardsdatascience.com/explainable-artificial-intelligence-part-3-hands-on-machine-learning-model-interpretation-e8ebe5afc608/
ELIS (Explain Like I'm 5)	- Human-readable explanations - Local interpretability	- Model transparency - Feature importance	- Graphical explanations - Model behavior analysis	- https://github.com/TeamHG-Memex/eli5 - https://eli5.readthedocs.io/en/latest/
Shapash	- Human-readable explanations - Local interpretability	- Model transparency - Feature importance	- Graphical explanations - Interactive dashboards - Model behavior analysis	- https://github.com/MAIF/shapash

Captum	- Human-readable explanations - Local interpretability	- Feature importance	- Graphical explanations	- https://captum.ai/ - https://github.com/pytorch/captum
Alibi	- Human-readable explanations - Local interpretability - Global interpretability	- Model transparency - Feature importance	- Graphical explanations - Model behavior analysis	- https://github.com/SeldonIO/alibi - https://docs.seldon.io/projects/alibi/en/stable/
What-If Tool	- Human-readable explanations - Local interpretability	- Model transparency - Feature importance	- Graphical explanations - Interactive dashboards - Model behavior analysis	- https://github.com/PAIR-code/what-if-tool - https://pair-code.github.io/what-if-tool/
AIX360	- Local interpretability - Global interpretability	- Model transparency - Feature importance - Decision rules	- Graphical explanations	- https://github.com/Trusted-AI/AIX360 - https://aix360.res.ibm.com/
InterpretML	- Human-readable explanations - Local interpretability - Global interpretability	- Model transparency - Feature importance	- Graphical explanations - Interactive dashboards - Model behavior analysis	- https://github.com/interpretml/interpret - https://interpret.ml/

EthicalML-XAI	- Human-readable explanations - Local interpretability - Global interpretability	- Model transparency - Feature importance	- Graphical explanations	- https://github.com/EthicalML/xai - https://pypi.org/project/xai/
DALEX (moDel Agnostic Language for Exploration and eXplanation)	- Human-readable explanations - Local interpretability - Global interpretability	- Model transparency - Feature importance	- Graphical explanations	- https://github.com/ModelOriented/DALEX - https://dalex.drwhy.ai/
iNNvestigate	- Human-readable explanations - Local interpretability	- Feature importance	- Graphical explanations	- https://github.com/albermax/innvestigate
explainx	- Human-readable explanations - Local interpretability - Global interpretability	- Model transparency - Feature importance	- Graphical explanations - Interactive dashboards - Model behavior analysis	- https://github.com/explainX/explainx
Vertex Explainable AI	- Human-readable explanations - Local interpretability	- Model transparency - Feature importance	- Graphical explanations	- https://cloud.google.com/vertex-ai/docs/explainable-ai/overview - https://github.com/GoogleCloudPlatform/vertex-ai-samples/tree/main/notebooks/official/explainable_ai
LIT (Learning Interpretability Tool)	- Human-readable explanations - Local interpretability	- Model transparency - Feature importance	- Graphical explanations - Interactive dashboards - Model behavior analysis	- https://github.com/pair-code/lit - https://pair-code.github.io/lit/
tf-explain	- Human-readable explanations	- Feature importance	- Graphical explanations	- https://github.com/sicara/tf-explain - https://data-ai.theodo.com/en/technical-blog/tf-explain-interpretability-tensorflow

	- Local interpretability			
Pair Saliency	- Human-readable explanations - Local interpretability	- Feature importance	- Graphical explanations	- https://github.com/PAIR-code/saliency - https://pair-code.github.io/saliency/#home
Quantus	- Human-readable explanations - Local interpretability	- Feature importance	- Graphical explanations	- https://github.com/understandable-machine-intelligence-lab/quantus - https://github.com/climatechange-ai-tutorials/quantus-x-climate
Xplique	- Human-readable explanations - Local interpretability	- Model transparency - Feature importance	- Graphical explanations - Model behavior analysis	- https://github.com/deel-ai/xplique - https://deel-ai.github.io/xplique/latest/
Tensorflow playground	- Local interpretability - Global interpretability	- Model transparency - Feature importance	- Graphical explanations - Interactive dashboards - Model behavior analysis	- https://playground.tensorflow.org/ - https://cloud.google.com/blog/products/ai-machine-learning/understanding-neural-networks-with-tensorflow-playground
Activation Atlas	- Local interpretability - Global interpretability	- Model transparency - Feature importance	- Graphical explanations - Interactive dashboards - Model behavior analysis	- https://distill.pub/2019/activation-atlas/
XAI tools	- Human-readable explanations - Local interpretability	- Model transparency - Feature importance	- Graphical explanations - Model behavior analysis	- https://github.com/intel/intel-xai-tools

xaitk-saliency	- Local interpretability	- Feature importance	- Graphical explanations - Model behavior analysis	- https://github.com/XAITK/xaitk-saliency - https://xaitk.org/
OmniXAI	- Human-readable explanations - Local interpretability - Global interpretability	- Model transparency - Feature importance	- Graphical explanations - Model behavior analysis	-https://github.com/salesforce/OmniXAI

Guidelines for the design and evaluation of HRI in Manufacturing

Workstation and Robot System

1. Locate the robot system at a comfortable distance from the user's position according to the required level of interaction
2. Design workstation elements aligning user inputs with corresponding system outputs in a manner that reflects natural human behaviour (e.g., a left button press on an alarm on the left side of the screen)
3. Provide functions of the workstation systems (including the robotic system) that adapt to the user's preferred working methods
4. Realize a fluent and smooth aesthetic robotic system design (i.e., avoid bulky joints, wires, external arm components, and mechanized shape)
5. Avoid similar types, colours, and appearance of multiple robotic systems that have to interact with the user (a group of similar robots can be seen as threatening)

Robot System Performance and Interaction Patterns

1. Provide measures for the adaptation of robotic system behaviour and interaction patterns to correspond with a user, considering the capabilities and skills of the user
2. Make the robotic system able to understand, interpret and anticipate the user's actions, intentions and decisions like in human - human interactions (i.e. goal-oriented)
3. Allow the robotic system to adapt its behaviour and communication mode considering previous interactions and works made in collaboration with the user (i.e., adaptability by learning)
4. Design a consistent and coherent behaviour of the robot system that is comprehensible for the user (e.g., avoid supposedly arbitrary actions of the system)
5. Avoid (frequent) variations in robot system velocity (by considering a slow velocity as a reference starting value)

6. Avoid similar behaviour (e.g., movements, tasks, decisions) of multiple robotic systems that have to interact with the user (a group of similar robots can be seen as threatening)
7. Ensure that the robotic system transfers objects to the user within the comfortable reach zone
8. Enable the robotic system to foresee user's intentions to physically interact with it and deal with their intended actions in advance
9. Enable the robotic system to disregard the user's unintended actions that may mistakenly trigger a response (false positive actions).
10. Plan the actions of both the user and robotic system to avoid conflicts (e.g., motions that can lead to collisions, actions that can lead to misunderstandings, etc.)
11. Adopt user-centred approaches to design pleasant interaction patterns and corresponding human-machine interfaces (e.g., through usability methods based on focus groups, thinking aloud, questionnaires, and expert evaluation)
12. Prevent the communication of an erroneous intent by the robotic system through the use of social conventions (e.g., handing over a screwdriver by offering its handle)

Human-Robot Communication and Interfaces

1. Support users and robotic systems to share the same communication model (e.g., language) and use vocabulary that is simple and easy to understand
2. Suggest adequate work breaks to improve user's performance and concentration
3. Make the robotic system request interactions without distracting or interfering with the user's motor activities, attention and comprehension
4. Make the user intuitively and immediately aware of the robotic system status, behaviour (e.g., movements, tasks, decisions) and intentions when relevant and necessary
5. Personalize information amount, form, content, and communication mode considering user's interaction preferences
6. Allow the user to provide feedback to the robotic system to confirm or reject a proposed action plan if needed
7. Provide measures that allow the robotic system to explain its decisions to the user when necessary and applicable
8. Inform the user about the type and functioning of specific safety measures used during the interaction
9. Design the interfaces (i.e., notification modality/format/timing) to support the user in easily and unambiguously understanding the information
10. Make the robotic system able to communicate apology statements (i.e., acknowledge errors and take responsibility) in case of errors or mistakes
11. Simplify robot-to-user communication by avoiding sending unnecessary and overly complex information
12. Ensure that the information received by the user is clear and unambiguous (e.g., avoid potential contradictions, conflicts, or delays in the information exchange)
13. Provide multimodal (e.g., visual, auditory, haptic) and complementary communication channels in a redundant way

14. Provide measures to communicate with the user without losing focus on the task (e.g., transfer the graphic user interface onto the collaborative workspace or design on-board devices for visual communication)
15. Allow the user to understand a forthcoming task in advance (e.g. by using preparatory notifications)
16. Allow the user to intuitively understand beforehand the intentions of the robotic system, the spatial occupancy of its planned motions and signal its target and interested workpieces

Control Measures

1. Make the control of the user on the robotic system as natural, intuitive and explicit as possible
2. Provide workstation systems (including the robotic system) that adapt safety strategies to the user's preferences
3. Design the robotic system to value the expertise and skills of the operators (e.g., employ her/his competences properly)
4. Allow the user to provide real-time corrections to key arbitrary robotic system's state and in case of disagreement with its autonomous behaviour
5. Allow the user to set the preferred level of autonomy of the robotic system (by considering a medium level as a reference starting value)

Organizational Measures and Training

1. Demonstrate to the user the effectiveness and reliability of safety measures of the robotic system prior to starting the interaction
2. Demonstrate to the user the efficiency and reliability of the robotic system elements prior to start the interaction (e.g., show the capability of the end-effector to firmly hold a workpiece during the whole task)
3. Make the robotic system perceived by the user as a useful, effective and reliable workmate (and not only as a tool) instead of a competitive entity
4. Use common language and human-like terminology when presenting the robotic system to the users and terminology that highlights its cooperativeness

Guidelines for the Design and Evaluation of Design People-centric Digital Re- & Upskilling Solutions

1. **Fostering a Lifelong Learning Culture in the Organization**

   Establishing a vibrant lifelong learning culture is essential to fostering a people-centric organization. This requires robust investment in resources and time for employees to embrace this mindset.
2. **Develop a Dedicated Space on Digital Re-& Upskilling Platforms for Collaborative Learning and Mentorship Opportunities**

Digital mentoring networks are key to enhancing employee development and career growth. Accordingly, it is necessary to set up online mentoring and community spaces to facilitate exchange and, thereby, a learning culture.

3. **Incorporate Small-Sized Learning Modules into the Daily Workflow**

   Implement microlearning in daily workflows by breaking down complex training into short modules that easily integrate into daily tasks. Further, microcredentials can be used to formally recognize and record employee learning achievements, providing tangible evidence of their development.

4. **Use of People Analytics to Provide Data-Based Feedback**

   Use data analytics to provide personalized feedback, emphasizing strengths and areas for improvement, with regular updates, and integrate these technologies seamlessly to gain a complete perspective on employee development.

5. **Leave behind one-size-fits-all learnings but instead tailor them to individual learning needs and outcomes.**

   Invest in learning technologies and commit to learner-centric course designs that are regularly assessed for their relevance and effectiveness in meeting workforce needs. Implement adaptive learning technologies, including AI, to offer dynamic, tailored educational experiences that integrate seamlessly with existing systems.

Guidelines for Human-Centred Work Design in a Digitally Transformed World of Work

Work Intensification

1. The ratio of work quantity and working time must balance each other properly.
2. If the work intensity is high, correspondingly more recovery time should be available.

Decision Latitude

1. Degrees of freedom in task processing should be preserved, and where possible and beneficial, expanded through system design.
2. The degree of system support must be determinable by the human.
3. Individual responsibility in the processing of tasks needs limits; organizational responsibility must occur in an appropriate way.

Technology Reliability

1. The use of digital technologies must have a reliability appropriate to the application, protected against manipulation at all times, especially by third parties.
2. The decision of machine algorithms (AI) in technical processes must be safe and verifiable in all functional areas by suitable specialist personnel.
3. Work support technology should be available without disruption.

Social Interaction and Support

1. Digital work must adhere to opportunities for direct and non-digitally mediated communication.
2. Digital work must promote collegial exchange and social support.

Technical and Social Innovation

1. Technical innovations must harness human experiential knowledge.
2. All human criteria are imperative for the design and evaluation of technical innovations and their application.
3. Within this idea of man, the human ability to learn has an independent merit and a correspondingly high value.

Transparency

1. Interaction with, as well as the result of, autonomous systems must be immediately recognizable to users.
2. Functions of technical systems must be transparent to the user at all times with regard to data use and decision making.

Human Decision-Making Authority

1. Humans retain decision-making authority over both the functions of a technical system and how to deal with the results.
2. If system data are relevant for decision making, humans must check it regularly for plausibility and fairness.

Organizational Change

1. Even in agile organizational structures and processes and flat hierarchies, employers must take responsibility for the safety and health of employees and communicate this clearly.
2. OSH structures also experience effective implementation in the new diverse forms of work and employment.
3. Even in spatially and temporally distributed forms of work, managers should be able to fulfil their responsibility for caring satisfactorily for themselves and their employees.

Inclusion, Diversity, Individuality

1. Users can adapt digital technologies themselves inter- and intra-individually; the competencies required for this must be ensured in order to achieve positive, health-related effects.
2. Digital technologies should come into play with the support of disadvantaged and low-ability people in mind; no groups of people should experience exclusion.
3. Digital technologies aim to support physically or mentally impaired individuals (performance-disabled employees) to increase their skills and employability.

Fostering Learning

1. An implementation of digital (assistance) systems/technologies must maintain and promote sufficient/multiple learning opportunities at work.
2. In (prospective) work design, opportunities for work-integrated (informal) learning must receive special (intensive) consideration.

Dissolution of Boundaries

1. Working hours and availability for work must be limited.
2. In order to counteract interested self-endangerment, measures are necessary to make the stress of colleagues working on the move visible.
3. Digital communication should promote work–life balance—without extending working hours.

Error Culture

1. Assuming technical transparency, the assignment and communication of process and decision-making responsibility must be unambiguous.
2. Algorithms convert personal data into an anonymized form for medium-term storage. Thus, employees receive the right of having their personal data "forgotten".
3. Real-time evaluations of personal services occur only according to established criteria (preferably with the participation of those evaluated).

Human Consequences

1. Physical requirements must be integrated when designing the workflow, for instance via activity-promoting exercise concepts.
2. Technology design must be such that interaction with the system remains part of the task processing.
3. When designing the work, sufficient changes of activity must be provided, e.g., to avoid monotony (psychological requirements).

Holistic Work Design

1. The holistic nature of a work activity must also be a central criterion in the digital age when deciding on the division of labour in the production and service process.

Ensuring holistic work tasks needs to begin during the design or development of a digital technology and it must also guide decisions and actions during its implementation and evaluation in the work process.