



Flexible **R**emufacturing using AI and Adv**a**nced Robotics for Circular Val**u**e Chains in **E**U Industry

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Executive Summary

The main purpose of this document is to describe the initial prototype of the Circular Value Chains Configuration Toolbox developed within the work package WP3. This toolbox aims to increase the capabilities for configuring circular value chains and evaluating remanufacturing scenarios along the complete remanufacturing pipeline based on AI and advanced robotics, the cores of the RENEE concept. Current production paradigms emphasize structuring and organizing labour, technology, and capital in an efficient way, without circularity and remanufacturing being central aspects of production. Therefore, it is important to start developing tools that facilitate this transition, tackling topics such as core assessment, product traceability, or product and production pipeline redesign that will enable the paradigm change towards a more sustainable industry.

Specifically, the toolbox is composed of the following modules:

- Product State Diagnosis module (PSD)
- Twin4eXcellence Framework (Twin4X)
- Digital Product Passport module (DPP)
- Toolbox for remanufacturing value chain configuration & process planning (TFR)
- Evaluation Tool (ET)

The document contains information about these five modules, including some submodules, providing details about their functionalities, architecture, incorporated technologies, and details about the development and initial prototype implementation. The presented initial prototypes will serve as the basis for the next RENEE project periods, where the different modules will be further developed and enhanced based on the end user feedback and interaction between the rest of the work packages.



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Abbreviations List

Abbreviation	Definition
AI	Artificial Intelligence
CAD	Computer-Aided Design
CRM	Customer Relationship Management
CSV	Comma-Separated Values
DfX	Design for Excellence
DLBP	Disassembly Line Balancing Problem
DLL	Dynamic Link Library
DPP	Digital Product Passport module
DPT	Disassembly Planning Tool
EOL	End-of-life
EPC	Electronic Product Codes
ERP	Enterprise Resource Planning
ET	Evaluation Tool
GUI	Graphic User Interface
IoT	Internet of Things
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LLM	Large Language Models
MES	Manufacturing Execution System
OEM	Original Equipment Manufacturer
PLM	Product Lifecycle Management
PSD	Product State Diagnosis module
QA	Quality Assurance
R&D	Research and Development
RFID	Radio Frequency Identification
RL	Reinforcement Learning
SOP	Standard Operating Procedure



TFR	Toolbox for Remanufacturing Value Chain Configuration & Process Planning
Twin4X	Twin4eXcellence Framework
UI	User Interface
XML	Extensible Markup Language



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1 Introduction

This deliverable summarizes the initial prototype of the circular value chains configuration toolbox, devoted to the design and development of tools and methodologies for product state diagnosis and core classification, as well as product redesign for remanufacturability. Additionally, the toolbox includes methodologies for process planning and means to evaluate the economic, environmental, and operational viability of the remanufacturing strategies, including the Digital Product Passport framework for traceability.

The transition from the current production paradigms, focused on time and cost efficiency (linear economy based), to a remanufacturing-driven scenario, poses a large amount of technical and organizational challenges. Although the current production organization emphasizes structuring and organizing labour, technology, and capital in an efficient way, important aspects of remanufacturing are not considered, compromising a future implementation of production paradigms where remanufacturing and circularity are major aspects of production. Therefore, it is important to start developing tools that facilitate this transition, tackling topics such as core assessment, product traceability, or product and production pipeline redesign that will enable the paradigm change towards a more sustainable industry.

The following sections provide further information on the previously mentioned modules and tools, as well as the status of the prototypes in month M18. Specifically, the different sections include a small overview of each module, its key functionalities, information about the architecture and principal technologies included. Additionally, the next lines depict the RENÉE WP3 architecture, including the aforementioned modules and their interaction mechanisms.

1.1 Circular Value Chains Configuration Modular Architecture

Within this WP3, devoted to the development of a circular value chains configuration toolbox, a set of modules tackling different aspects of remanufacturing has been designed and implemented. Specifically, the RENÉE WP3 architecture (see Figure 1) introduces the main modules and interaction mechanisms with different user interfaces in order to support a modular configuration of circular value chains.

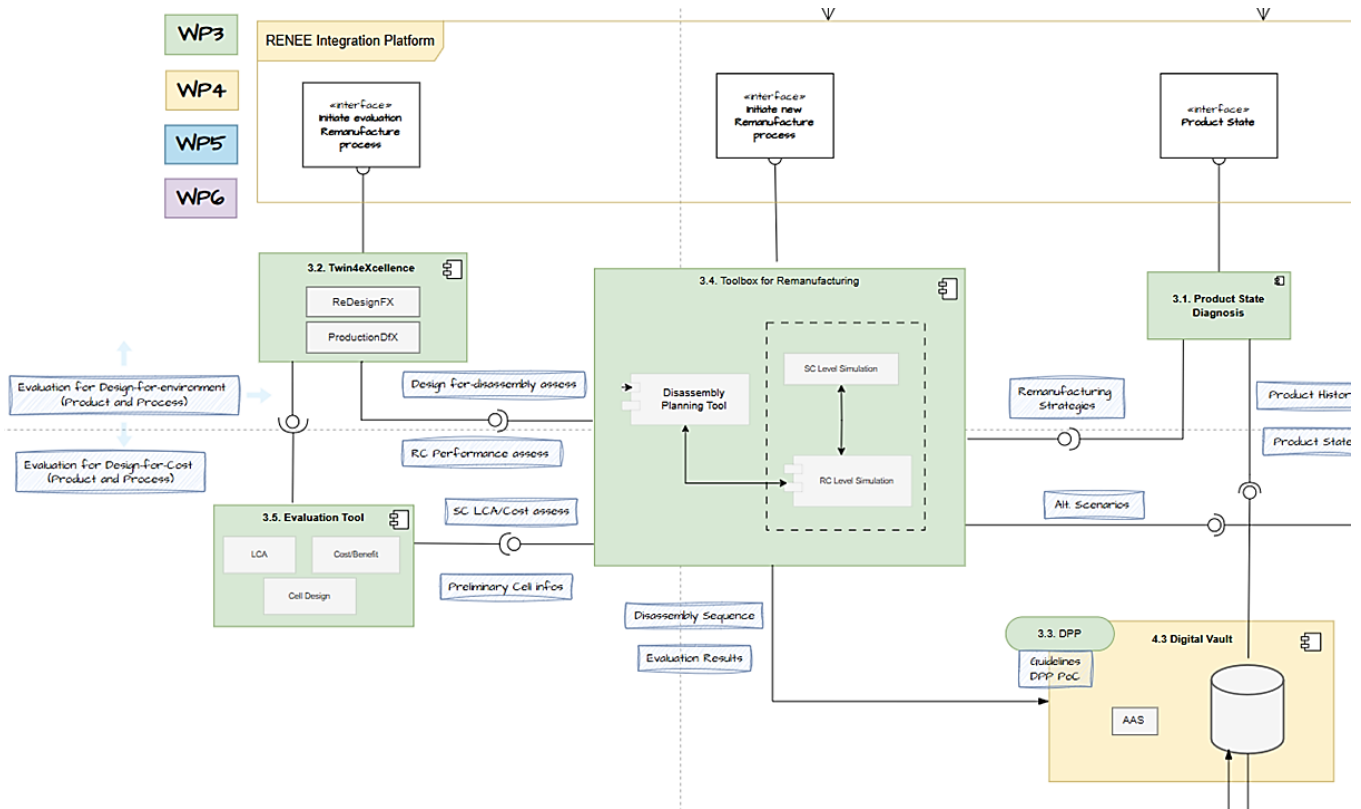


Figure 1: WP3 architecture

Specifically, the next modules are presented on the deliverable (Table 1):

Task	Module	Acronym
T3.1	Product State Diagnosis module	PSD
T3.2	Twin4eXcellence Framework (Twin4X) <ul style="list-style-type: none"> Twin4eXcellence Architecture (Evaluation, diagram “double TT” + Digital Twin link) ProductionDfX for Remanufacturing sub-module ReDesignFX for Remanufacturing sub-module 	Twin4X
T3.3	Digital Product Passport module	DPP
T3.4	Toolbox for Remanufacturing <ul style="list-style-type: none"> Simulation tools for production planning for remanufacturing Supply-chain characterization and simulation for remanufacturing Optimization tools for factory operation and value-chain Disassembly Planning tool for remanufacturing 	
T3.5	Evaluation Tool	ET

Table 1: WP3 modules

2 Product state diagnosis Module (PSD)

2.1 Product State Diagnosis Overview

The main objective of the Product State Diagnosis module is to offer tools to evaluate the status of a product, focusing on the condition of the different cores composing the product. Based on the input data, collected through different inspections carried out by operators or robots, the PSD module enables the assessment of the product state as a first step to guide the disassembly process.

The PSD module tries to offer general tools for the product state diagnosis, applicable to the different use cases tackled within the RENEÉ project, trying to avoid the specificity of any disassembly process and pursuing generalization.

The next sections provide further information about the architecture, technologies and functionalities, as well as an initial validation process carried out to evaluate the initial prototype of the PSD module.

2.2 Functionalities

The Product State Diagnosis module is the central unit to evaluate the state of a product and predict the condition of the different cores of the part. Specifically, the PSD offers two main functionalities:

- Capability to train prediction models to label the cores of a product based on training data provided in standard CSV files. The main idea is to exploit the product information gathered by end-users over time to create models that can accurately categorize the state of the cores using a simple and intuitive interface.
- A simple interface to query the state of the cores of a product based on trained models. The data from the inspections and measurements will be used to predict the status of the cores and exploit this information in further steps of the RENEÉ remanufacturing process.

The next schema (Figure 2) summarizes the process flow of model training and its use in the remanufacturing line.

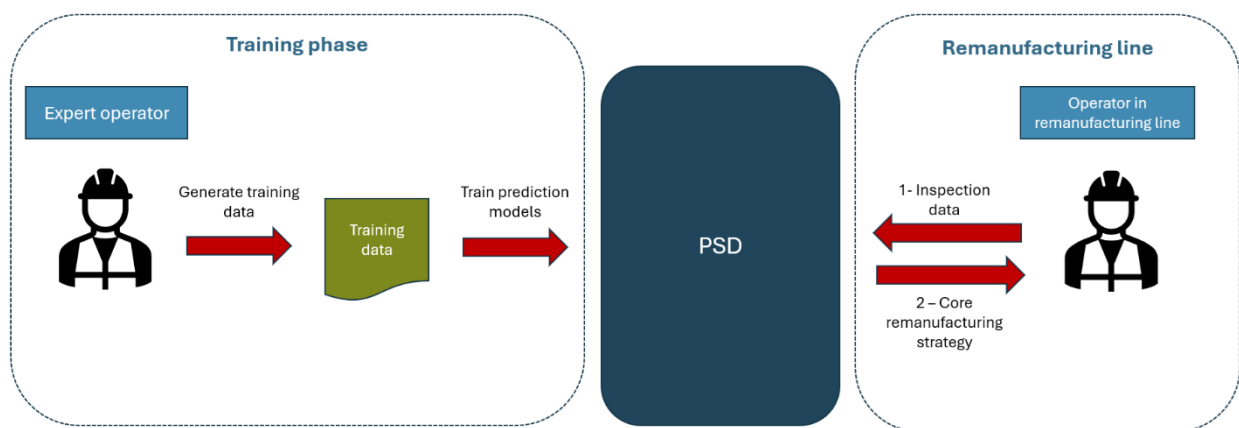


Figure 2: PSD module workflow

The proposed PSD concept relies on three main capabilities:

1. Data acquisition from expert operators to be further exploited by AI and data analysis models. The PSD must offer tools that facilitate this initial data acquisition phase as it is a critical step to enable all the capabilities of the module.
2. Creation of AI-based prediction models to categorize the different cores, as well as data analysis models that facilitate the statistical measurement of the suitability of the different inspections. This last feature allows the optimization of the product inspection procedure, providing insight into the data managed by the PSD.
3. Offer an intuitive User Interface that facilitates the interaction between the PSD and remanufacturing line operators, to ensure an effective data acquisition process, as well as an understandable management of the prediction models.

The PSD design focuses on these three aspects as key features for the successful development of the module.

2.3 Architecture & Technologies

As posed previously, the PSD module aims to assist operators in assessing the status of the different cores of a product. Nevertheless, the module must tackle different aspects of this assessment process, including data acquisition, model creation and usage, as well as the interaction between the PSD and operators. In order to cover all these facets, the PSD module is divided into three main submodules, as depicted in the next Figure 3.

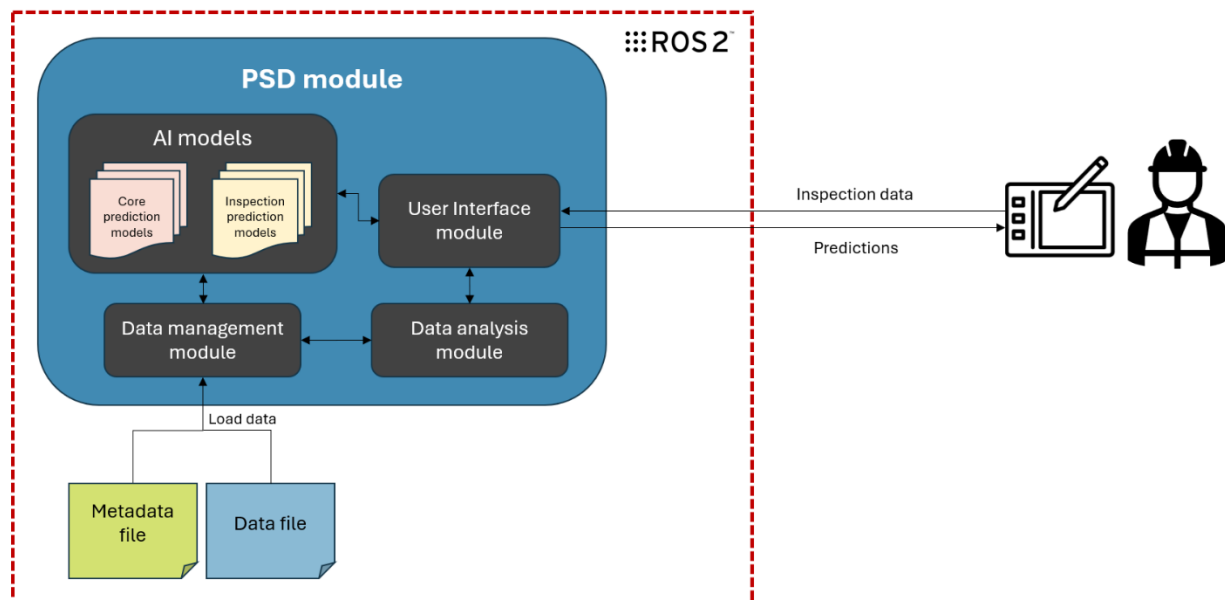


Figure 3: PSD architecture

Specifically, the architecture is composed of four modules that manage the different aspects of the PSD:

- **Data management module:** This module is in charge of loading the product and inspection data and providing it to the rest of the PSD modules. The module verifies the coherence of the metadata file associated with the remanufacturing scenario (use case), as well as the

consistency of the inspection and core classification data file. Additionally, the module includes different queries to retrieve data filtered by core or inspection type, facilitating the data management by the PSD modules. The module uses Pandas, a Python library for data analysis, that allows the creation of data frames that facilitate its use by multiple Python-based libraries and ensures interoperability between modules.

- **AI models:** This module is in charge of creating AI models based on the data files associated with a remanufacturing scenario. The main idea is to separate the whole data stored in the Data management module into different cores and create classification models, as depicted in the next Figure 4.

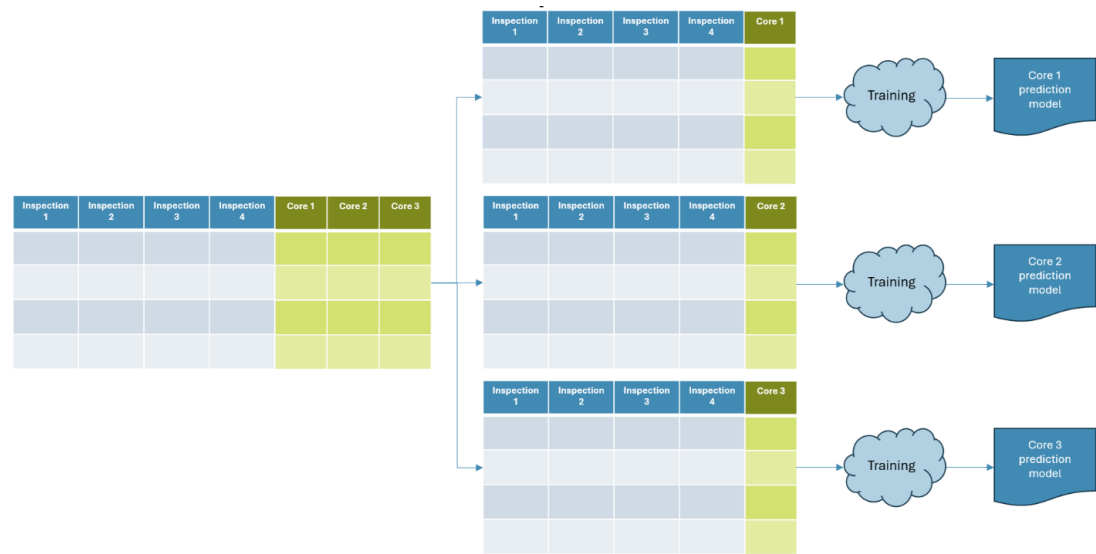


Figure 4: PSD: Data division and model creation

The AI model creation and training are based on Pandas and Scikit-learn Python libraries for data analysis and the implementation of Machine Learning models subsequently. The current model creation interface includes a parameter to define the model type, although the current implementation only includes the capability to create Decision Trees and Neural Networks. Further implementations will include the capability to analyse multiple algorithms and evaluate their performance automatically.

- **Data analysis module:** The Data analysis module offers different functionalities for analysing the data frames stored in the Data management module. Specifically, the module includes statistical analysis tools, such as Mutual Information analysis, to extract information about the correlation and relevance of the different inspections in the classification of each core. The main purpose of these analysis tools is to provide insight into the relevance of the carried-out inspections, as a first step to optimise the disassembly process. To this end, the module is able to generate reports in PDF format, including different metrics relating the inspections to the core classification variable, as shown in the next Figure 5.

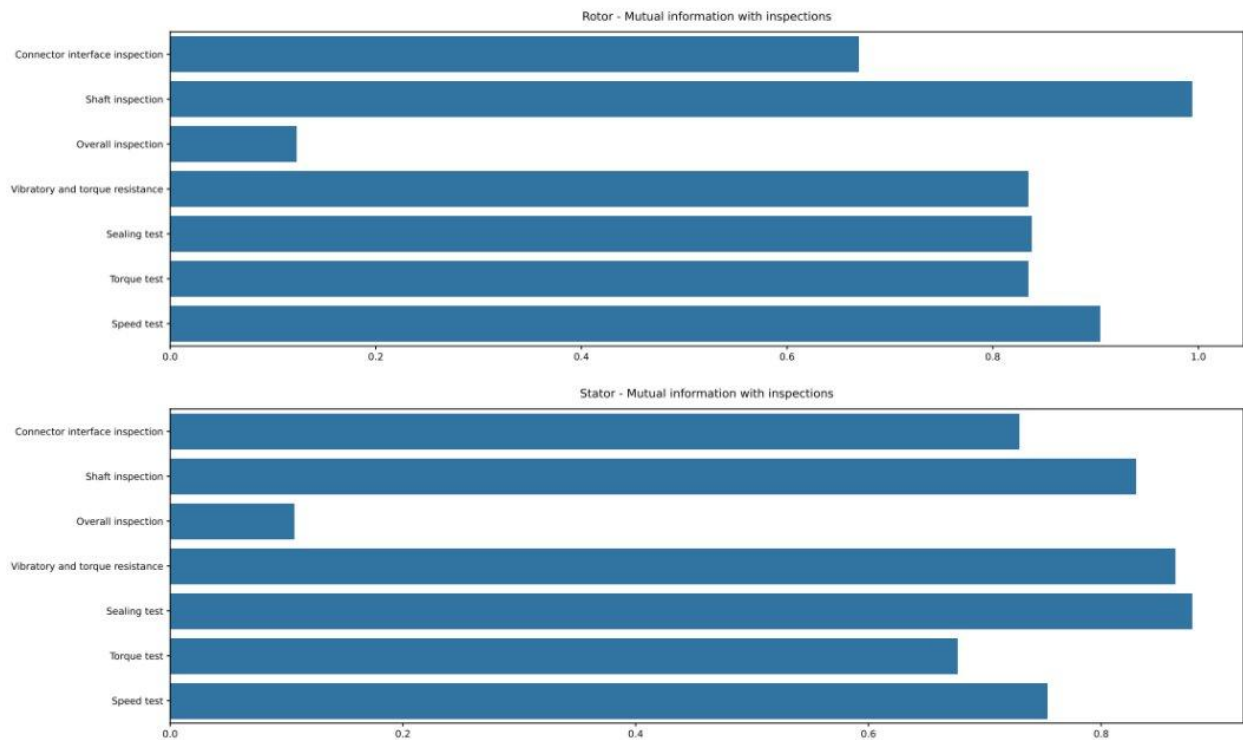


Figure 5: PSD data analysis for EMOTORS use case

The data analysis is based on Pandas, Scikit-learn, and Seaborn (Python) libraries, used for data management, data analysis, and data representation subsequently.

- **User Interface module:** Finally, the User Interface module acts as a bridge between the PSD modules and the User Interface through ROS2 services. Due to the number of interaction types between operators and the PSD, ranging from data acquisition for training purposes to the classification of cores in the disassembly line, the User Interface module offers a set of ROS2 services to facilitate this interaction and open the door to extend them in a scalable way.

These four sub-modules constitute the complete PSD module, providing the functionalities to load and manage data, as well as create prediction models. Additionally, the User Interface module allows a simple and intuitive way to interact with the PSD, a key feature to facilitate its use by non-expert operators.

2.4 First Prototype Development

From the implementation perspective, the PSD module is a ROS2 life cycle node coded in Python. The decision to select managed life cycle nodes is motivated by their capability to allow greater control over the state of the ROS2 system, enabling the possibility to re-launch the PSD module in case of system failures. Besides, the PSD module makes use of the following Python libraries:



- **Pandas** as a data management library, as the defined data frame classes are widely used by the data analysis and AI libraries of Python. It also includes a wide set of functions to filter, sort, and split data, simplifying the management of datasets.
- **Scikit-learn** library, which includes a large variety of Machine Learning and variable analysis algorithms. This library is the core element for the creation of AI models, as well as for the prediction of the core's remanufacturing strategy.
- **Seaborn** library for plotting and creating documents with variable analysis information.

Additionally, to ensure interoperability and simple integration with the rest of the modules and functionalities (such as the User Interface), a set of ROS2 services was defined to tackle the different aspects of the PSD module. The next lines provide a list of ROS2 services implemented, with a brief description of the functionality, grouped by PSD functionality:

- **Data management**
 - **Load data:** Service for loading the metadata and data files in the PSD module. During the loading phase, the PSD initially verifies the coherence of the metadata file (e.g. number of inspections, inspection types, categories...) as well as the consistency of the data (e.g. column number, inspection categories...). In case of erroneous data loading, the service provides feedback about the found issue.
 - **Export process data:** As the PSD module requires converting categorical values to numbers for its further use by the data analysis and Machine Learning algorithms, categorical data is converted and stored internally during the data loading phase. This service allows exporting this numerical data into a CSV file for verification purposes, as well as to facilitate third-party data analysis.
- **AI model creation and analysis**
 - **Analyse data:** This service activates the data analysis process on the loaded data. Specifically, this data analysis includes a Mutual Information analysis of all the inspection variables towards each of the core inspection variables, highlighting the relevance of each inspection in the classification of the different cores. The service output is a PDF file containing charts summarizing the Mutual Information analysis.
- **Inspection**
 - **Get inspection list:** This service provides the inspection list for the currently loaded data file, as well as the categorical data information. This service facilitates the interaction between the PSD and User Interface during the inspection process.
 - **Set current inspection value:** This service allows setting the value of a specific inspection in the internal "current inspection" variable. This service facilitates the interaction between the PSD and User Interface during the inspection process.
 - **Get current inspection value:** This service allows getting the values of the internal "current inspection" variable. This service facilitates the interaction between the PSD and User Interface during the inspection process.
- **Core prediction**
 - **Predict:** This service allows predicting the remanufacturing strategy of a given core based on the provided inspection values and the previously generated AI-based prediction models stored in the PSD module.

- **Predict all:** This service allows predicting the remanufacturing strategy of all the cores based on the provided inspection values and the previously generated AI-based prediction models stored in the PSD module.
- **User Interface**
 - **Get inspection list:** This service provides the meta-information of the currently loaded data on PSD. It contains the number of inspections, as well as the different inspection result values. This information is used to dynamically create the required buttons and ComboBoxes by the web interface.
 - **Set current inspection value:** This service allows setting a result value for a specific inspection of the list. Once the user selects a result of an inspection, this service is used to store it on the PSD.
 - **Get current inspection values:** This service provides all the inspection results set on the PSD by the user.

Regarding the User Interface, it is implemented as an HTML5 web interface using Node.js as a JavaScript runtime environment. The different interface elements are based on Material UI open-source React library components. The communication with the ROS2 framework relies on the roslibjs library, a library that uses WebSockets to connect with a rosbridge to exchange topics and call ROS services and actions. The initial prototype of the User Interface allows the following functionalities:

- Loading the inspection data, including the selection of the use case through a ComboBox where the user can choose between the ARCELIK or EMOTORS demonstrator (Figure 6).

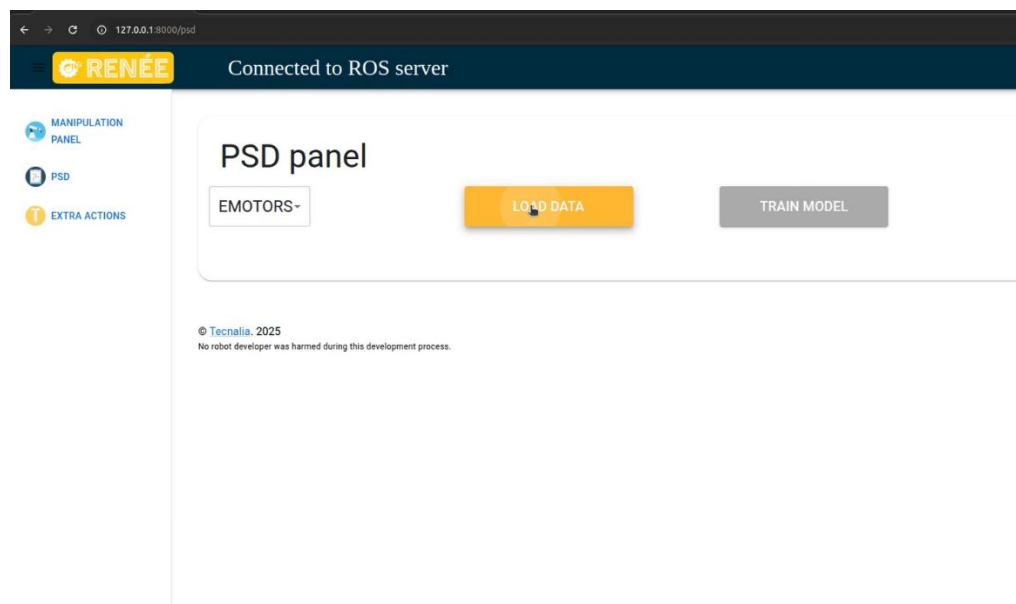


Figure 6: Data loading of the PSD through the UI

- Once the required data is loaded in the PSD, the interface enables a button for the creation of the prediction model. This button triggers the creation of the ML models for the prediction of the cores' remanufacturing strategy (Figure 7).

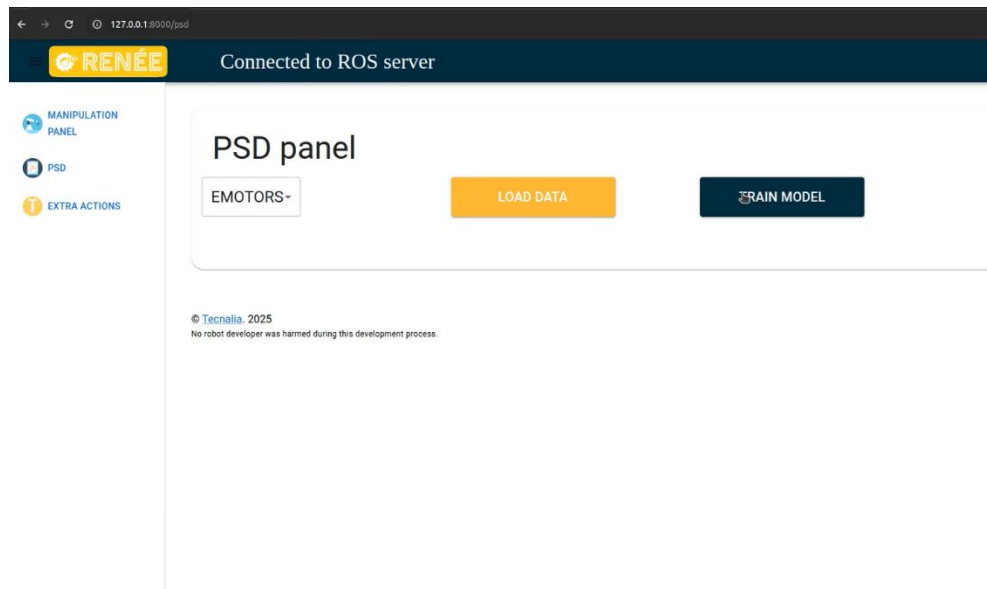


Figure 7: PSD prediction model creation through the UI

- After the data loading and model training phase, the user starts introducing the inspection results. Based on the data loaded on the PSD module, the User Interface creates the inspection button list dynamically based on the metadata of the specific use case, generalizing this User Interface for any scenario with an arbitrary number of inspections (Figure 8).

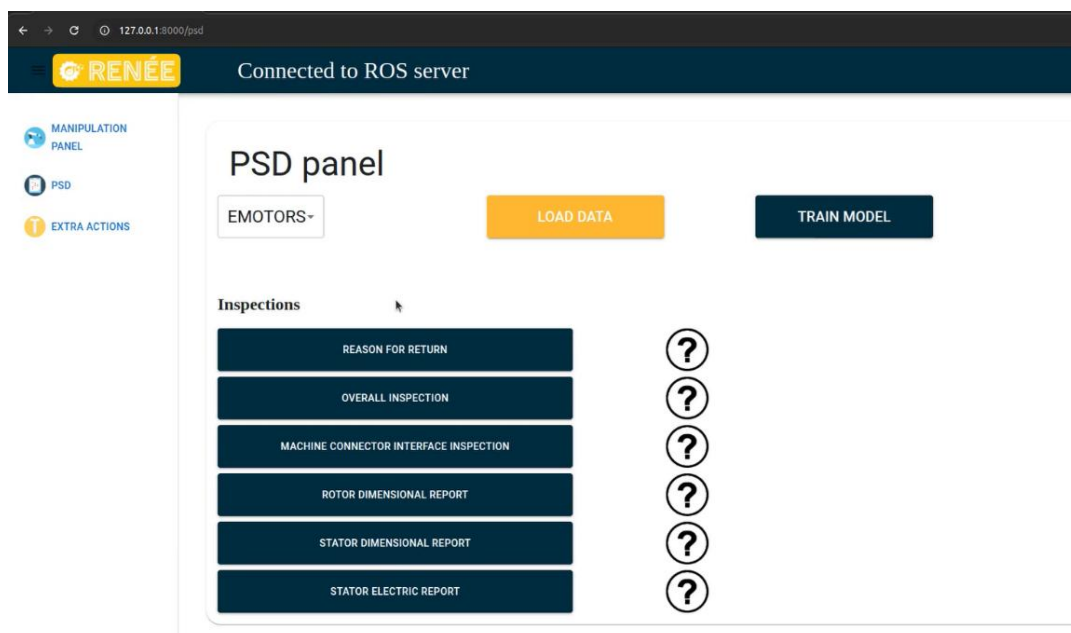


Figure 8: Inspection buttons generated based on the PSD inspection list

To insert the result of a specific inspection, when the user pushes the inspection button, a pop-up is opened in the User Interface with a brief description of the inspection and a ComboBox with the different possible results. This information is dynamically generated based on the metadata provided by the PSD module (Figure 9).

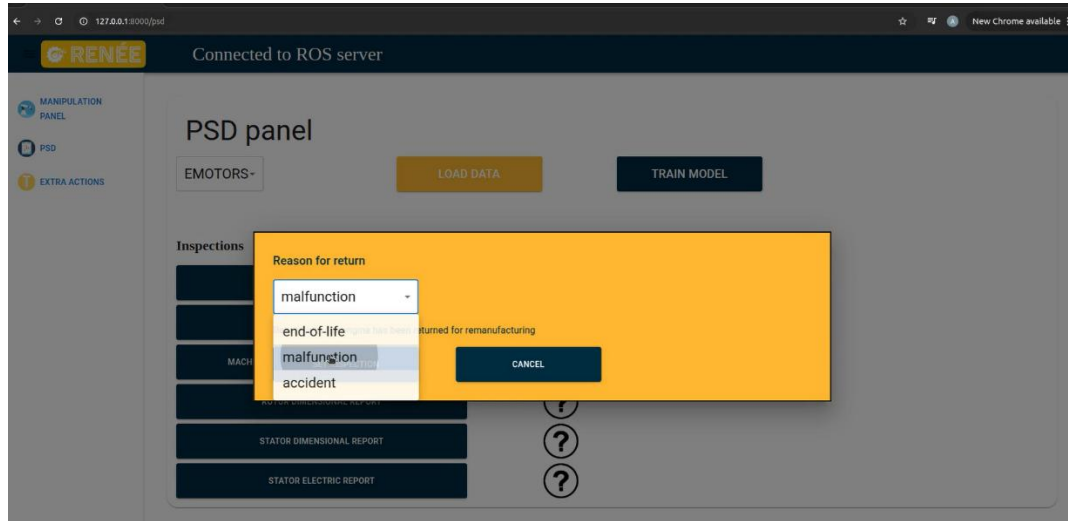


Figure 9: Selection of the result of an inspection

When the results of all the inspections are introduced, a core status button is enabled. This button triggers the core remanufacturing strategy prediction inside the PSD module, predictions that are presented to the user through a pop-up window (Figure 10).

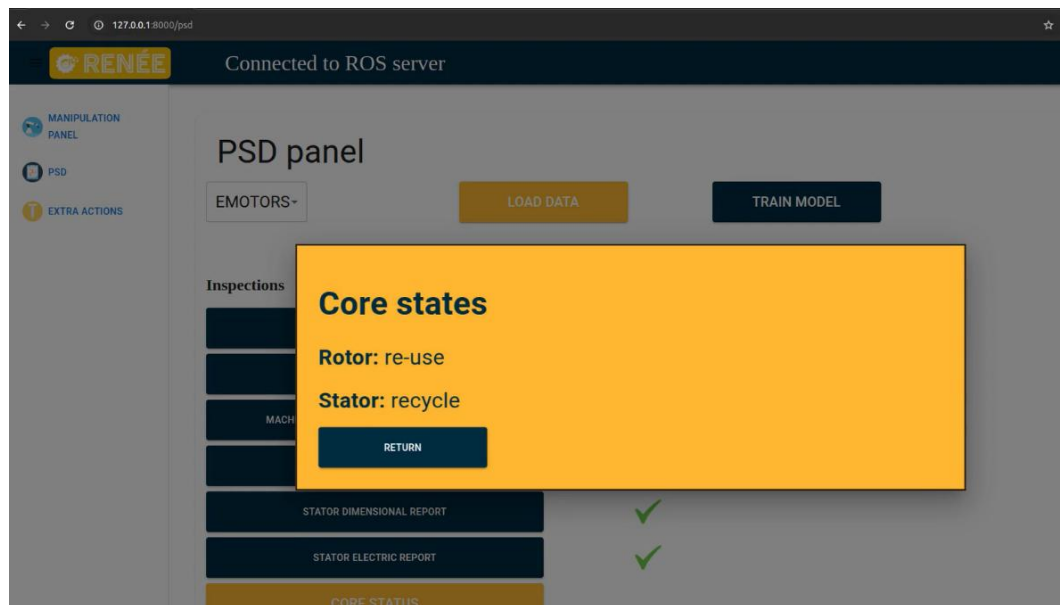


Figure 10: The core remanufacturing strategy predicted by the PSD

This first prototype covers the different aspects of the whole PSD pipeline, starting from the data loading/management, continuing with AI model creation and querying, and finishing with the interaction with operators. This prototype will serve as the basis to extend the PSD module to the specific needs identified along the RENEE project for supporting the remanufacturing process.

2.5 First Prototype Testing

For testing purposes, two different validation processes have been carried out:

1. The complete pipeline of data loading, AI model creation, and core status queries has been tested with synthetic data generated for ARCELIK and EMOTORS use cases. Based on the current and expected inspection lists, the appropriate metadata and data files were created and inserted in the shared folder of the Docker image created with the PSD and User interface. Both use cases have been successfully validated, as shown in the next Figure 11.

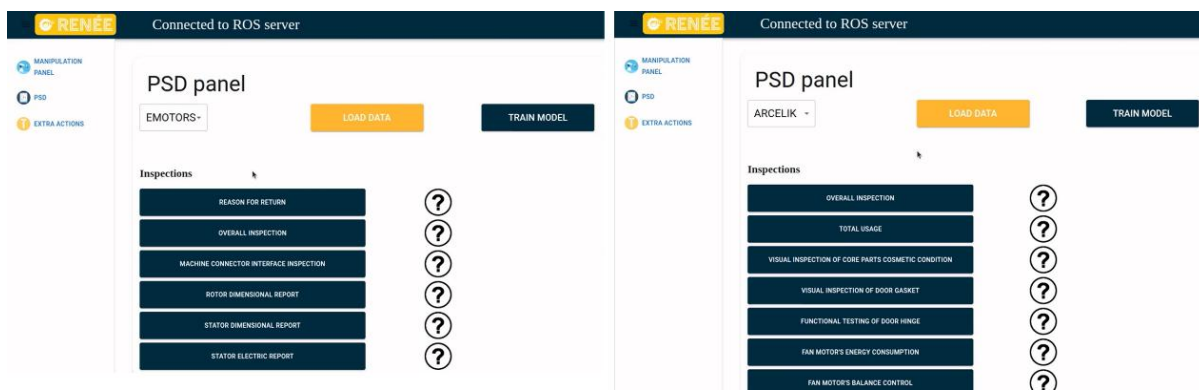


Figure 11: Validating PSD and User Interface for ACELIK and EMOTORS use case

2. In order to validate the data analysis, the electric motor remanufacturing use case has been with EMOTORS. Looking at the future disassembly process, where motors will be received from different sources (end-of-life, malfunction, car accidents), data from different EMOTORS experts have been collected to check if there are some scenarios where operators can skip steps of the disassembly (e.g. time-consuming rotor and stator analysis and measurements). As it is a future scenario, initial conversations surfaced with slight discrepancies between experts depending on their role in the electric motor assembly/disassembly process. Therefore, it was chosen as an ideal task to gather data from experts and make use of the data analysis tools of the PSD to have an insight into the data features and model quality.

The data acquisition consisted of a poll of 9 possible scenarios with different motor sources (end-of-life, malfunction, or accident) and different states of the motor and shaft (correct or damaged). Data from 5 experts was collected, resulting in 45 different training cases for the model. Initially, the mutual information charts were created (see Figure 12) and verified, in order to check the information provided by the different variables.

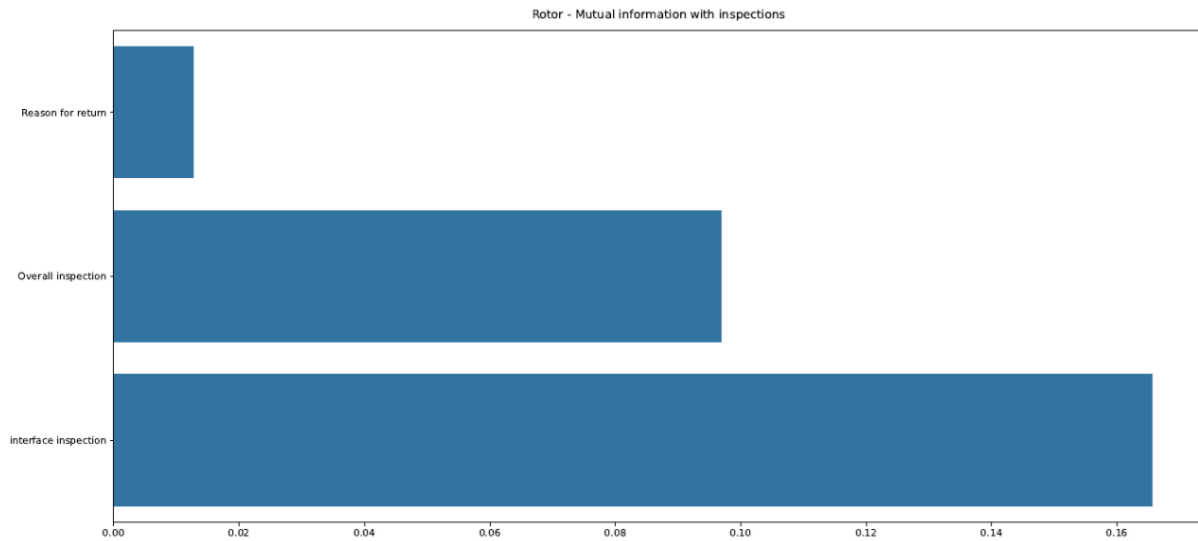


Figure 12: Mutual information charts

Additionally, as discrepancies between experts were expected, the PSD also creates confusion matrices, which could also be used to assess the level of discrepancy. The confusion matrix obtained is shown in Figure 13, which points out that even if there are discrepancies, it is still possible to generate a relatively precise prediction model. In the same way, all this information and charts can also be used as the basis to generate a discussion between experts to get a consensus about the addressed disassembly process and optimize future workflows.

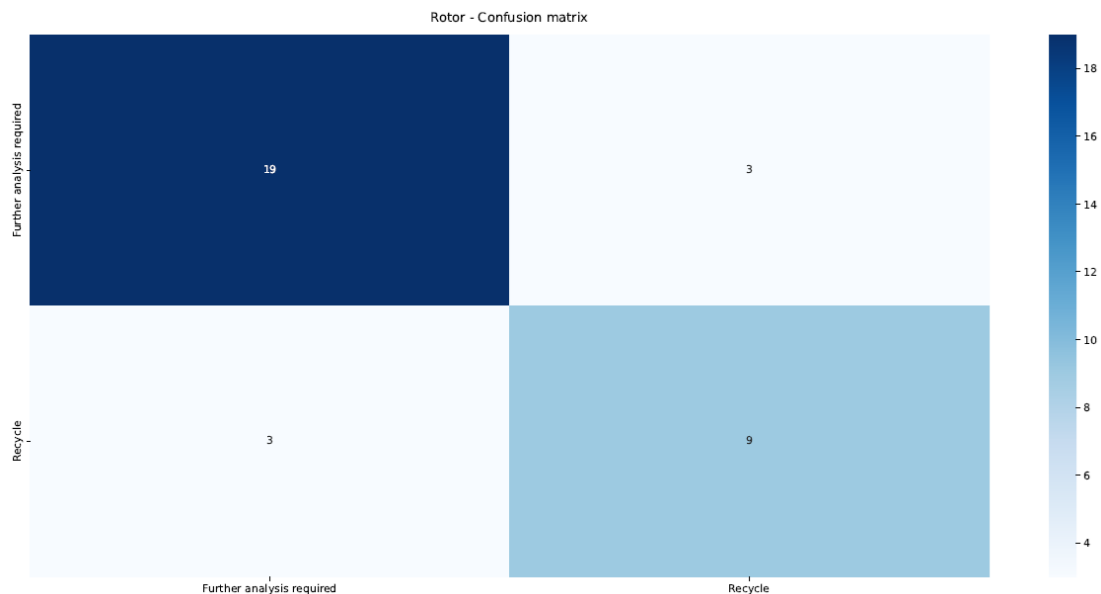


Figure 13: Confusion matrix generated through the PSD

These two validation processes supported the developments in order to finalize a fully functional first prototype even with a reduced scope. Further iterations of the PSD will tackle the new issues that might surface during the development of the RENÉE project.

3 Twin4eXcellence Framework (Twin4X)

3.1 Twin4X Framework Overview

In the last decades, namely with the vast dissemination of industrial globalization and the implementation of the Industry 4.0 paradigm, product development has become increasingly complex. This is due also to the needed concurrent engineering of product and production systems design, with more robustness and flexibility required in associated production systems. Therefore, this demands a holistic approach to assessing the integrated performance of both product and production systems across their respective life cycles. Within the context of Product Design-for-X (DfX) methodologies applied to complex product development, concurrent engineering has been facilitating the multidisciplinary integration of knowledge and expertise throughout all product life cycle phases. Simultaneously, given the increasingly demanding landscape of business competitiveness and regulatory compliance, production systems must embed life cycle-oriented design principles, from the earliest stages of conception and subsequent development and construction. In particular, within the framework of the circular economy and sustainability-driven business models, production lines and manufacturing facilities should incorporate holistic performance assessment methodologies, together with product redesign, to unblock for instance R-Strategies such as remanufacturing. In this section, it is presented the novel framework - Twin4eXcellence (Twin4X) - and its key modules. It includes a double DfX-oriented approach aimed at delivering a twin assessment of the performance of both product and production systems throughout their life cycles.

3.2 Functionalities

For the development of Twin4X Framework, it was necessary to first develop two key methodologies and associated tools: ReDesignFX and ProductionDfX.

The main functionality of ReDesignFX is to support complex products redesign in a holistic manner. In common Design-for-X methodologies, the product design adopts a concurrent form, mixing different product design disciplines and domains of expertise (Design-for-manufacturing, -assembly, -cost, -environmental, etc.). Nonetheless, in the context of Circular Economy R-Strategies, namely retrofit or remanufacturing, the approach must consider different perspective scenarios, other than “blank-sheet design”. Thus, ReDesignFX includes a functional approach to address different scenarios a product may face during/at the end of its use-phase. The product can be redesigned in different scenarios and the adopted strategies, from the product owner (OEM), may differ for instance, operating design modifications and/or improvements to facilitate inspection, disassembly, and remanufacturing to the entity that will perform an intervention in a given product, e.g. improving/updating a product in the context of remanufacturing.

The main functionality of ProductionDfX consists in supporting the Remanufacturing Production System, in a holistic way to include DfX-orientated management of different disciplines and Production domains. The tool will include support for efficiency-oriented process steps evaluation, machine machine-level performance assessment, including auxiliary equipment selection. To better

define the strategic framing of a given remanufacturing operation, a strategic vision mapping is included as a functionality of the tool.

Twin4eXcellence will also include the possibility of cross-linking the trade-offs between the design stage of the Product Redesign and the Remanufacturing (Production) System Design so that both entities can be simultaneously improved and optimized.

3.3 Twin4X Architecture

The Twin4eXcellence architecture (Figure 14) is supported in this conceptual proposal by the integration of two DfX methodologies, product design-for-X assessment [Baptista et al. 2025] and a production system assessment [Branco et al. 2024]. Figure 14 presents the composed architecture where the key aspects rely on a consistent life cycle management foundation, for both product and production system development, and the concurrent engineering consensual approach of Design-for-X techniques.

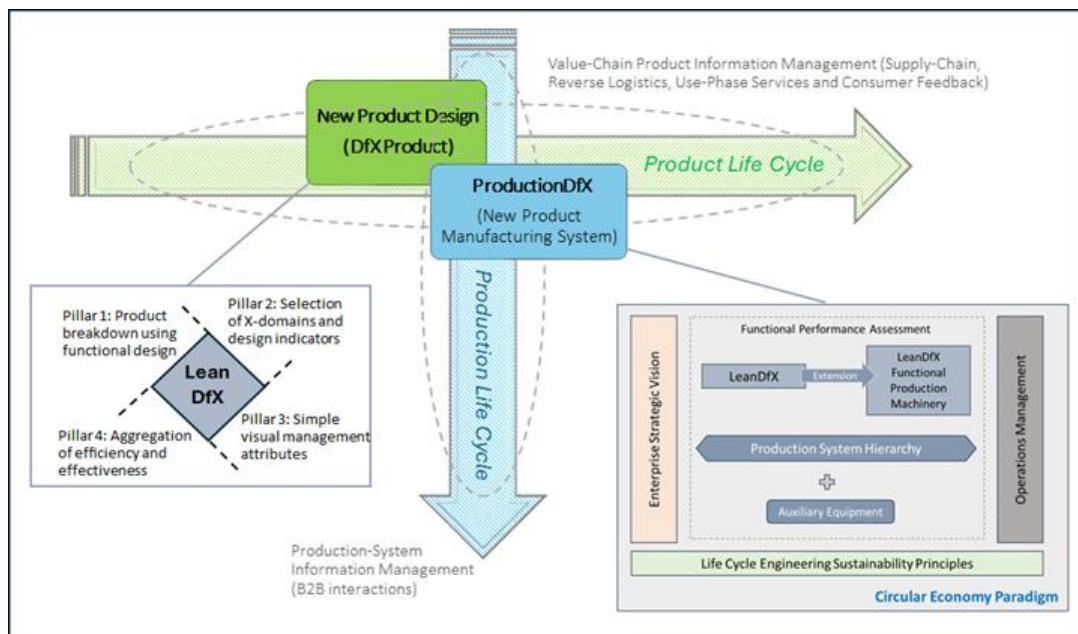


Figure 14: Twin4eXcellence general architecture

For the life cycle axis associated with the product (horizontal green arrow), the performance assessment can be attained via integrated methodologies such as LeanDfX. For the life cycle axis associated with the production system and manufacturing processes (vertical blue arrow), the performance assessment in a multi-dimensional form can be achieved with concepts such as referred above for the, here named “ProductionDfX”. The Twin4X architecture proposed in this work is therefore the articulated combination of the LeanDfX architecture and the “ProductionDfX” method architecture. To integrate the cross-analysis product-production, the data consolidation across the life cycle stages, namely via Product Life Cycle Management platforms (PLMs), is envisioned, both for product information and production system life cycle information.



3.4 Twin4X Base Methods

ProductionDfX Module provides a multidimensional approach for a given production system, in the context of Remanufacturing. It consists of an extension of LeanDfX to allow the performance evaluation of both machines and auxiliary equipment, while also allowing the incorporation of Circular Economy guidelines, the organization's own vision and principles and operations management. With this tool, the user will be able to make a complete depiction of the organization's production system, in a "waterfall model":

- **Balanced Scorecard (BSC)** - for the strategic vision definition, a Balanced Scorecard is defined, through its 4 perspectives: Financial, Customer, Internal Processes and Learning&Growth. In this phase, the strategic KPIs for the production system are defined. These originate the strategic X domains (for a DfX approach), contrary to the typical approach in DfX;
- **Tactical and Operational X definitions** – With the strategic X domains well defined, there will be the definition of both the tactical X domains (focused on the production system line) and operational X domains (focused on machine and auxiliary equipment);
- **Process Steps definition** – in this phase, all the processes within the entire production system must be defined, in a sequential manner. This should map all the necessary steps to achieve the desired output;
- **Production System Machinery Definition** – in this phase, all the machinery should be defined, as well as the respective hierarchy, dependencies and interactions. In this phase, different levels of importance in these interactions should be defined through a weight system;
- **KPI's Definition** – in this phase, for each process step previously defined, KPIs must be defined, as well as for all the operational machinery and auxiliary equipment;
- **Machinery Performance Assessment** – in this phase, the machinery's performance is assessed similarly to LeanDfX. However, due to the introduction of the different weights, it is necessary to change the equations used for effectiveness and efficiency calculation;
- **Machinery Performance Aggregation** – following the X ramification from the strategic to the operational level, there will be a bottom-up evaluation of the performance for each X, leading all the way up to the strategic X's on the BSC.
- **Overall Process Efficiency Assessment** – as the final stage of production system evaluation, the process step individual and aggregated efficiency is assessed by means of a systematic methodology application, including lean manufacturing cost assessment.

3.5 First Prototype Development

The ReDesignFX Module can support companies in two concrete scenarios of Product Redesign (Figure 15):

- **New Product Redesign (New Version)** - in this scenario, the tool will support the development of a new version of an existing product (mainly for the context of R-Strategies – Remanufacturing, Refurbish, etc). This new product will ideally follow the design criteria identified as vital for Remanufacturing, which means there is a need for a previous



identification of design flaws. To achieve this, the tool will provide historical information on the product's use phase, direct feedback obtained from end-users and quality reports, if available. This information is intended to support the Engineering Department (or equivalent), which will be responsible for the new design while considering these guidelines and parameters. This phase is done foresees constant feedback loops, until the optimal design is achieved.

- **Redesign Existing Product** (Instance-based) - in this scenario, the tool will support the redesign of an existing product instance, designed in the past (and most likely not following DfX and eco-design guidelines). If available, supporting documentation regarding this product will be provided (Mechanical, Electrical, etc), vital for the necessary process of Reverse Engineering that the instance will have to undertake. This will ultimately support the product's decomposition into simpler/essential components. This procedure can be skipped if CAD models (or similar) are available – these are to be provided by the tool too. With the product's instance decomposed, it is possible to assess which components can be improved in the context of R-Strategies. This will lead to the definition of a new set of specifications for the product and respective modules, to have it align better with Circular Design guidelines.

Both scenarios, leading to new design proposals and solutions, must follow Lean Design principles (Figure 15). To assess this, the Module will support the integration of a tool (such as LeanDfX) capable of providing an analysis of a given design proposal regarding its effectiveness and efficiency, for a specific Design-for-X domain and respective Design Variables.

The Twin4eXcellence complete framework will have a dedicated software suite platform. For its key module ProductionDfX, the prototyping of the new platform tool was modelled, and mock-ups were developed namely to test its detail definition, transposing the methodology into software artefacts, and also to elaborate the user interface of the ProductionDfX Module Tabs in the first simulation modelling steps. Figure 16 shows the overall ProductionDfX main page, the new platform tool, and the methodology's first step, in which the Balanced Scorecard is created.

On this page, the user must select the perspective to work on and then proceed to adding the desired KPIs, using the toolbar.

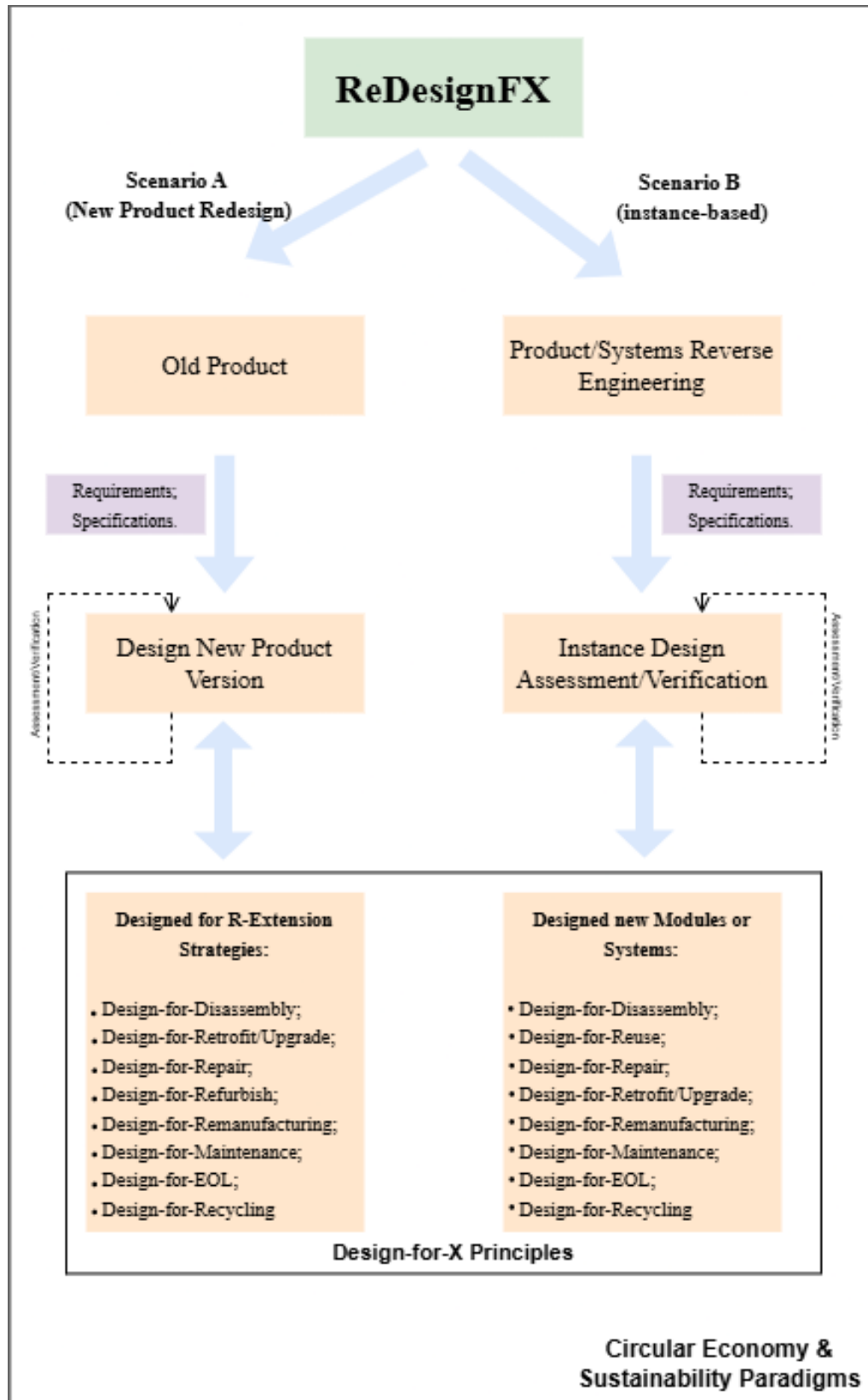


Figure 15: ReDesignFX architecture and two considered scenarios

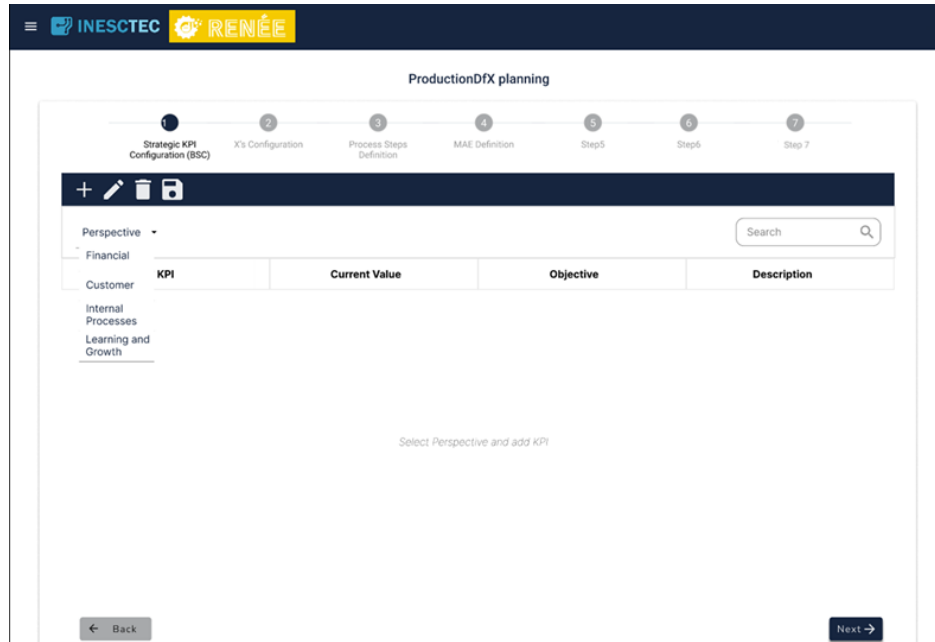


Figure 16: ProductionDfX Tool: Perspective selection for Balance Scorecard Step 1 TAB.

Figure 17 shows all the necessary fields the user has to fill in when creating a strategic KPI.

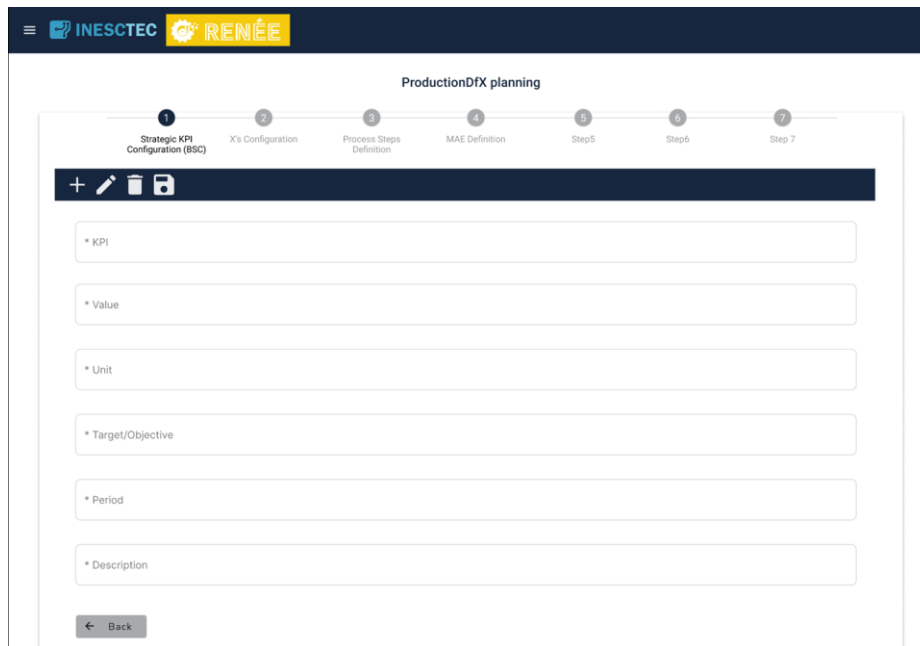


Figure 17: ProductionDfX Tool: ProductionDfX Tool: Strategic KPI in Balance Scorecard Step 1 TAB.

Figure 18 shows the main page of the second step, where the user will define all the X dimensions for the production system, in a consecutive manner. Starting again with the 4 perspectives and all the strategic KPIs previously defined, the user must then assign to each all the strategic X dimensions, then tactical X dimensions and finally the operational X dimensions (the figure shows the operational X dimensions table).

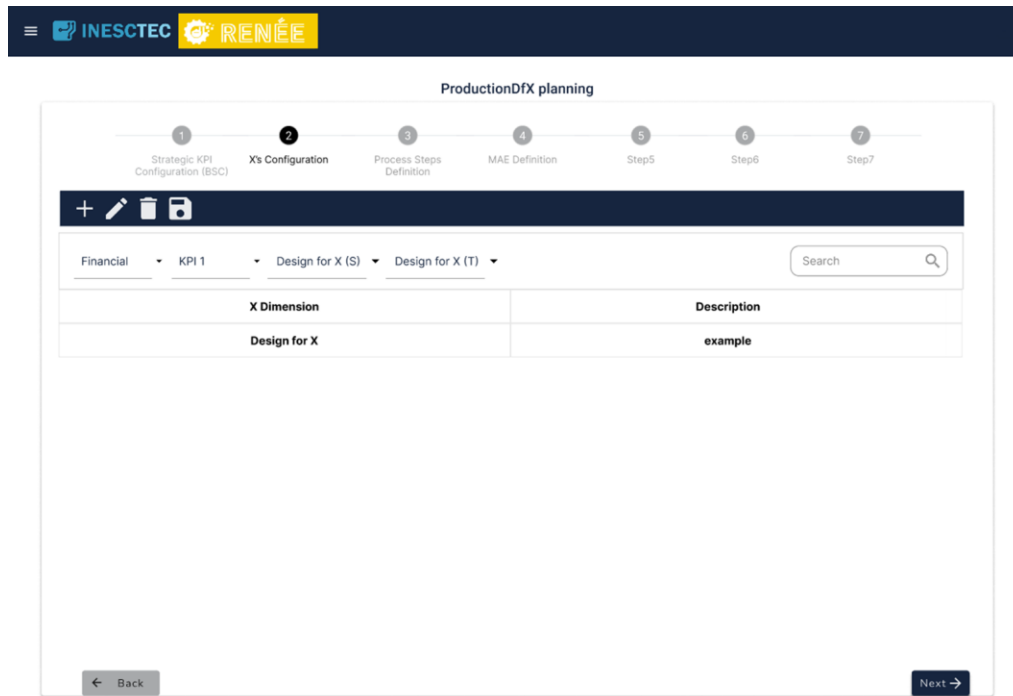


Figure 18: ProductionDfX Tool: KPI Selection for each X-Dimension in Step 2 TAB.

4 Digital Product Passport Module (DPP)

The Digital Product Passport (DPP) plays a critical role in enabling transparent, reliable, and structured access to product and component information across multiple lifecycle stages (EC 2024). This section proposes functional and operational specifications of DPP architecture that may be tailored to the specific remanufacturing use cases. Unlike regulatory-driven DPP initiatives, the focus here is rather on operational functionality, namely, tracking the lifecycle of products, ensuring component and sub-component level traceability, supporting data continuity throughout the remanufacturing process and maintaining traceability even after the product has been sold.

4.1 Proposed Functionalities of the DPP

To support efficient and traceable remanufacturing processes, the following core functionalities are proposed for the DPP. At this stage, the focus is not on tailoring functionalities to a specific use case, but rather on establishing a broad and adaptable foundation that can support multiple scenarios. These functionalities are designed to ensure that essential data about products and their components is consistently captured, structured, and made accessible throughout the lifecycle from manufacturing to remanufacturing and beyond. Each functionality addresses a key aspect of traceability, lifecycle tracking, or data continuity. The table below (Table 2) summarises the identified functionalities that may be considered for the proposed use cases.



Functionality	Description
Customer / owner identification	Maintains a record of previous and current owners, including transfer dates and locations
Unique identification of product	Assigns a persistent and unique identifier to each product (e.g., QR code, UID)
Unique identification of sub-components	Applies individual identifiers to key sub-components or modules to enable nested traceability
Lifecycle event logging	Records key events throughout the product lifecycle with time, location, and actor metadata
Repair and remanufacturing history	Logs all service, repair, and reman activities including procedures, outcomes, and timestamps
Condition & inspection reports	Stores diagnostic results and condition evaluations upon intake or during maintenance
Usage data logging [optional]	Captures usage metrics (hours, cycles) thanks to sensor data or service logs
Disassembly & reassembly instructions [optional]	Provides digital instructions or media for product handling, servicing, and reassembly
Status tracking & passport updates	Enables real-time updates of remanufacturing status, readiness, or certification levels

Table 2: DPP functionalities under the focus of traceability, lifecycle tracking, and data continuity

- **Customer / Owner identification:** This functionality records historical and current ownership data. It captures identifiers, ownership transfer dates, and basic contextual information such as region or customer type. This capability supports also warranty and transferability claims.
- **Unique identification of product:** This functionality assigns a persistent and unique identifier to each product. The identifier can be generated using either various technologies or methods such as a QR code, RFID tag, or serial number. It serves as the primary entry point into the DPP while ensuring the product can be tracked throughout its lifecycle, enabling the consolidation of all relevant historical, usage, and service data under one reference.
- **Unique identification of sub-components:** In addition to product-level tracking, the DPP includes unique identifiers for sub-components or modules. These identifiers allow each component to be traced independently, providing insight into its manufacturing origin, usage conditions, repair history, and compatibility with other systems. This layered traceability is essential in remanufacturing, where individual parts may be reused, repaired, or replaced.
- **Lifecycle event logging:** The DPP will chronologically record (or extract from existing database) major lifecycle events associated with a product or component such as initial assembly, shipment, return, disassembly, remanufacturing, and resale. Each event is accompanied by contextual data like timestamps, locations, and responsible entities. This log creates digitalized lifecycle data of the item, which is crucial for traceability, process auditing, and operational insights.
- **Repair and remanufacturing history:** This functionality captures the full history of service and remanufacturing actions performed on the product or any of its components. It includes



information on inspection results, repairs conducted, components replaced, and testing outcomes. Recording these activities helps validate product quality and supports future diagnostics while maintaining quality consistency.

- **Condition & inspection reports:** When a product or component is returned for remanufacturing, the DPP will store condition reports created during the initial inspection. These reports can include wear assessments, test results, failure modes, and visual checks.
- **Usage data logging (optional):** Where available, the DPP can store sensor-derived or manually recorded usage metrics, such as runtime hours, and load cycles. This data supports decisions about component wear and life expectancy, especially for assets where operating conditions vary significantly. While not mandatory, this functionality adds value in use cases with IoT or service data integration.
- **Disassembly & reassembly instructions (optional):** To streamline operations and reduce errors, the DPP can provide access to standardized disassembly and reassembly guides. These may include diagrams, videos, safety warnings, and tool specifications. This functionality ensures that remanufacturing steps are repeatable and safe, even across different facilities or third-party service providers.
- **Status tracking & passport updates:** This feature allows the DPP to reflect the real-time status of the product or component such as “awaiting inspection,” “under repair,” “remanufactured,” or “ready for resale.” This continuous update capability ensures that digital records stay aligned with the physical item, improving visibility and process coordination across stakeholders.

4.2 DPP Functionalities and Associated Stakeholders

The successful implementation of the DPP relies not only on the definition of relevant functionalities but also on the clear involvement of the appropriate stakeholders. Each functionality within the DPP serves a specific purpose and requires input, validation, or use by distinct actors across the product lifecycle. The table below outlines the key functionalities proposed for the DPP and identifies the primary stakeholders responsible for contributing to, managing, or interacting with each one (Table 3).

Functionality	Primary stakeholders involved
Customer / owner identification	Customer service, CRM teams, after-sales teams
Unique identification of product	Customer, engineering, quality, R&D, supply chain
Unique identification of sub-components	Engineering, R&D, quality teams, supply chain
Lifecycle event logging	Production operators, logistics, IT support, after-sales teams
Repair and remanufacturing history	Workshop technicians, quality assurance, service managers
Condition & inspection reports	Field technicians, workshop technicians, quality assurance teams
Usage data logging [optional]	IoT engineers, maintenance teams, product managers

Functionality	Primary stakeholders involved
Disassembly & reassembly instructions [optional]	Technical writers, workshop supervisors, service engineers
Status tracking & passport updates	Workshop operators, field technicians, workshop technicians, product managers, quality assurance teams, engineering, R&D

Table 3: DPP functionalities mapped with associated stakeholders

4.3 Data Ownership and Responsibilities of the DPP

To support the effective implementation of the DPP in manufacturing/remanufacturing, it is essential to clearly define the distribution of responsibilities related to data ownership and contribution. The table below maps key DPP functionalities to the respective roles of suppliers (e.g. OEMs), users (e.g. remanufacturers or service providers), and customers (e.g. end users or asset operators). This clarification ensures that each stakeholder understands their involvement in generating, maintaining, or accessing DPP data, thereby enabling seamless collaboration and reliable traceability across the product lifecycle.

It was deliberately considered the manufacturer (e.g. OEM or supplier) and the remanufacturer (e.g. service provider, refurbisher) as separate entities. This approach allows for more flexible and realistic integration of varied scenarios, including third-party remanufacturing or extended value chains. The table below (Table 4) maps key DPP functionalities to the respective roles of suppliers, users, and customers, clarifying who is responsible for generating, maintaining, or accessing specific data throughout the product lifecycle.

Functionality	Owned/provided by supplier (OEM, Manufacturer)	Owned/updated by user (Remanufacturer, service)	Visible or provided by customer (End User)
Customer / owner identification	Yes (initial delivery data)	Yes (transfers, returns)	Yes (QR code)
Unique identification of product	Yes (initial UID, metadata)	Yes (metadata)	May access via DPP interface (optional)
Unique identification of sub-components	Yes (for OEM-supplied parts)	Yes (adds identifiers for replaced parts)	Usually not involved
Lifecycle event logging	Yes (manufacturing events)	Yes (remanufacturing, inspection, logistics)	Yes, may view only some information (timeline overview, logs)
Repair and remanufacturing history	No	Yes (entirely user-generated)	May access basic service history
Condition & inspection reports	No	Yes (diagnostics, quality checks)	May view summary reports

Functionality	Owned/provided by supplier (OEM, Manufacturer)	Owned/updated by user (Remanufacturer, service)	Visible or provided by customer (End User)
Usage data logging [optional]	Optional (if telemetry is embedded)	Yes (service records, logs)	Yes (via IoT platforms)
Disassembly & reassembly instructions [optional]	Yes (original manuals)	Yes, may extend to local procedures	Yes, but basic information for self-maintenance
Status tracking & passport updates	Shared (depends on platform design)	Yes (process updates, readiness state)	Yes (may access final status)

Table 4: Data ownership and responsibilities of the DPP

4.4 DPP High-Level Architecture

To support the seamless implementation and interoperability of the DPP within remanufacturing workflows, a system architecture has been designed in order to support use-case requirements and needs (Figure 19). From the initial discussions with use-case providers, it was captured the need to accommodate multiple data sources, ensure robust lifecycle tracking, and provide secure, role-based access for suppliers, remanufacturers, and customers. By structuring the DPP across four functional layers, from source systems to user access, the design promotes data continuity, traceability, and operational scalability across complex value chains. The following diagram illustrates the proposed digital architecture and its key components.

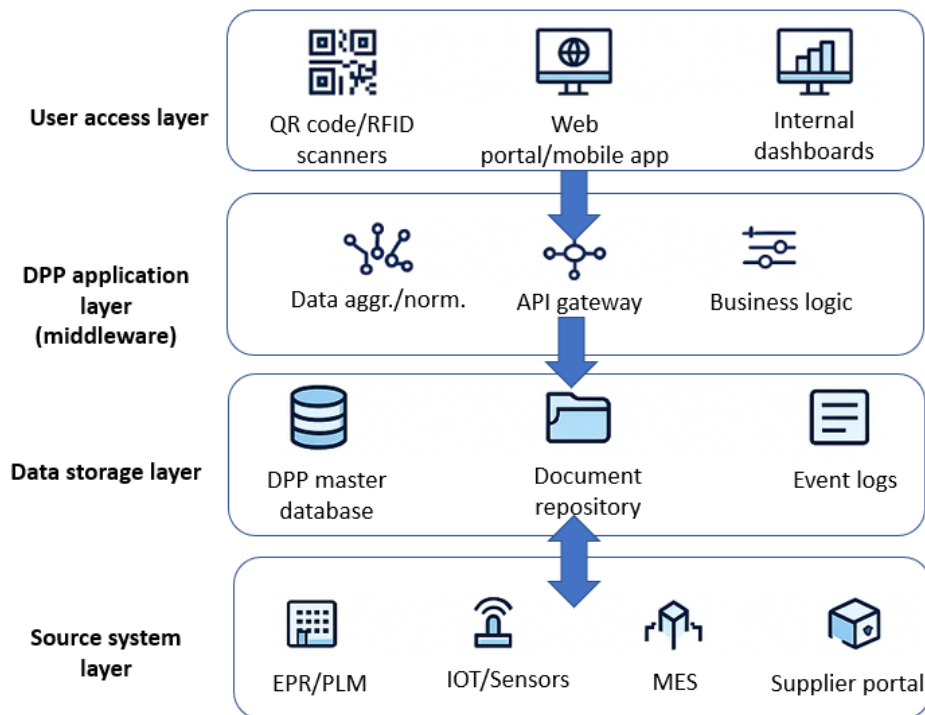


Figure 19: High-level overview of DPP architecture and its layers

In the following section, it is described the role and potential components of each layer.

1. **User access layer – Interfaces for real-world interaction:** This layer provides the touchpoints through which stakeholders access, interact with, or update the DPP.

Components:

- **OEM interface:** Input product master data, design revisions, service bulletins.
- **Remanufacturer interface:** Input/track repair history, inspections, part replacements.
- **Customer interface:** View product history, usage logs, service instructions, ownership records.
- **Shared tools:** QR/RFID scanners, mobile apps, web portals, dashboards.

2. **DPP application layer – intelligence, governance, and interoperability:** This middleware layer orchestrates how data flows through the system, enforces business logic, and ensures that the DPP behaves consistently across stakeholders and use cases.

Components:

- **API gateway & integration services:** connect to ERP, MES, and IoT systems to automate data flow.
- **Data validation & harmonisation logic:** ensures consistent data formatting and semantics between OEM and reman partners.
- **Lifecycle engine:** models and validates the chronological sequence of events from manufacturing to reman and resale.
- **Status tracking service:** dynamically updates a product's DPP with real-time condition or processing status.
- **Access control engine:** enforces who can read, write, or update specific data (role-based).

3. **Data storage layer – Digital backbone of the DPP:** Acts as the central or distributed repository for structured and unstructured data collected from various stakeholders and processes.

Components:

- **Structured product/component data:** stores product identifiers and unique tracking data.
- **Event logs:** records lifecycle events, service interventions, ownership changes, etc.
- **Document repositories:** hosts manuals, disassembly guides, SOPs, inspection forms.
- **Condition & usage data:** archives diagnostics, wear assessments, and IoT sensor data.

4. **Source Systems Layer – Data origin and traceability foundation:** This layer consists of all external and internal systems that generate or manage operational, technical, and lifecycle-related data across the product's lifetime, from design to remanufacture.

Components:



- **Supplier systems** (e.g. ERP, PLM, supplier portals): provide manufacturing data such as product structure, serial numbers, materials, and disassembly instructions.
- **User systems** (e.g. MES, workshop software, QA tools): capture lifecycle events such as repairs, inspections, testing, remanufacturing processes, and condition reports.
- **Customer systems** (optional): input ownership details, usage logs, self-diagnosis, or return initiation data.

4.5 Data Standards and Formats

In the following section, a tentative definition proposal is given for the data standards and formats that may be followed for the implementation of the DPP. These initial recommendations aim to support interoperability across systems, ensure consistency in data exchange between stakeholders such as OEMs, remanufacturers, and customers, and align with emerging industry standards. This definition is intended as a starting point and will be further refined through discussions and validation with the use-case providers as the project progresses.

To ensure the interoperability, scalability, and long-term viability of the DPP, the underlying data model must rely on widely adopted standards and formats. These standards enable seamless integration across diverse systems and stakeholders including OEMs, remanufacturers, and customers. In particular, we will also draw on **ISA-95**, an established standard for integrating enterprise and control systems, to support alignment between production-level data and higher-level digital passport information.

At the core of the DPP data structure, we propose to use lightweight, machine-readable formats such as **JSON** and **XML**. JSON is particularly well-suited for RESTful APIs and real-time system interactions, while XML may be used in legacy environments that still require structured, schema-driven data exchange. For tabular data, such as bills of materials or inspection logs, formats like **CSV** or JSON Table Schema can support easy import/export and data manipulation across systems. Rich content such as manuals, images, and videos used for disassembly instructions, condition assessments, or user guidance should follow conventional formats like **PDF**, **JPEG/PNG**, or **MP4**, which ensure compatibility with common platforms and user devices.

The data model should align, as much as possible, with emerging **product passport standards** to support future compliance and cross-industry collaboration. These include **IEC 63395**, which is being developed specifically for DPP. For instance, the **Catena-X**, a cross-sector initiative promoting data sovereignty and traceability and the **Asset Administration Shell (AAS)** model, which supports modular, semantically rich representations of assets in Industry 4.0 environments are good candidates. To link digital records with physical products, **GS1 Digital Link** may be adopted for QR-code-based identification, while **UUIDs** or **Electronic Product Codes (EPCs)** may be used for assigning globally unique identifiers to products, components, and events.

In addition to the content itself, each record in the DPP should include essential **metadata** to ensure traceability, reliability, and version control. This metadata should consist of fields such as the unique identifier (UUID), version number, timestamp, source system, and the stakeholder or organisation

responsible for generating the data. Optional fields like confidence levels or status flags can also be added to help resolve data conflicts and prioritise verified information.

To facilitate reliable and secure data exchange, the DPP should support **API-based integration**, particularly through RESTful services using JSON payloads. Real-world access to the passport (e.g., in a repair centre or customer-facing scenario) should be enabled via **QR code or RFID-based lookups**, compatible with GS1 or internal resolution protocols. For dynamic data capture (such as from IoT devices), event-based messaging protocols like **MQTT** or **Kafka** can be considered.

Finally, robust **data governance and access control** mechanisms must be in place. These should include role-based permissions that define who can read, write, or update data; clear attribution of data ownership (e.g., supplier vs. remanufacturer); and comprehensive audit trails. To maintain trust and compliance, all sensitive information should be encrypted both at rest and in transit, and access should be monitored through system-level logging.

As a summary, the following table (Table 5) outlines the possible standards and formats that may be considered for the implementation of the DPP in the RENÉE project.

Category	Suggested standard or format
Data encoding formats	JSON, XML (structured data); CSV (tabular); PDF, JPEG/PNG, MP4 (documents and media)
Identifiers	UUID (products, components, events); GS1 Digital Link (QR code-based IDs)
Metadata fields	UUID, version, timestamp, source system, data owner
Data standards	IEC 63395 (Product Passport), Catena-X, ISA-95, Asset Administration Shell (AAS)
Data exchange	RESTful APIs (JSON), file uploads (CSV/XML)
Access technologies	QR code / RFID resolution (GS1-compatible), web portals, mobile apps
Governance features	Role-based access control, data attribution, version history, encryption (in transit & at rest)

Table 5: Data standards and formats

5 Toolbox for Remanufacturing Value Chain Configuration & Process Planning (TFR)

5.1 Toolbox For Remanufacturing Overview

The Toolbox For Remanufacturing (TFR) is a simulation-based decision-support environment composed of a collection of integrated tools designed to assist in the configuration, evaluation, and optimisation of remanufacturing strategies. As a “toolbox,” TFR brings together multiple analytical and modelling tools within a single framework, each addressing different stages and dimensions of the remanufacturing process.



At the core of TFR lies a simulation environment, which serves as the central platform for testing and analysing alternative strategies under conditions of uncertainty and variability. By simulating both supply chain and shop floor operations, the toolbox provides users with data-driven insights into the potential performance of remanufacturing scenarios before implementation. This simulation-driven approach enables stakeholders to evaluate trade-offs, anticipate disruptions, and optimise decision-making across operational and strategic levels.

TFR supports a variety of real-world use cases, and its modular structure allows for the integration of specialised tools. Among them is the Disassembly Planning Tool (DPT), a SolidWorks-based add-in that aids in disassembly-oriented product design and planning. Embedded within the TFR ecosystem, DPT ensures that design-level decisions are aligned with downstream operational needs, strengthening the overall remanufacturing workflow.

5.2 Functionalities

The **Toolbox For Remanufacturing (TFR)** offers a set of integrated tools designed to support decision-making at both strategic and operational levels in remanufacturing environments. These tools are grouped into four core functionalities: **simulation**, **process planning** and **disassembly planning tool**. Together, they provide users with the means to explore, evaluate, and optimise remanufacturing strategies across different levels of the value chain:

- **Simulation:** Simulation is at the centre of the TFR. It enables users to model and analyse remanufacturing scenarios before implementation, making it possible to test ideas, compare alternatives, and assess the impact of uncertainty on system performance. Two levels of simulation are supported: supply chain and shop floor:
 - **Supply Chain Simulation:** At the supply chain level, the toolbox allows users to model value chain configurations, including key actors such as manufacturers, consumers, and retailers. These models capture the flow of products and materials, along with the variability that naturally arises from factors such as product return rates, demand fluctuations and the condition of returned products. The simulation results help assess the efficiency, responsiveness, and sustainability of different supply chain configurations using indicators such as inventory levels, costs, and service availability.
 - **Shop Floor Simulation:** At the shop floor level, TFR enables the detailed modelling of remanufacturing operations, including disassembly, inspection, reconditioning, and reassembly tasks, among others. These simulations allow for the assessment of resource usage, task sequencing, and production throughput, helping identify bottlenecks and layout inefficiencies, and providing data to improve operational productivity. In addition, TFR interacts with the Disassembly Planning Tool (DPT) to retrieve and evaluate optimal disassembly sequences, analysing the resources, time, and feasibility associated with each path to support efficient process planning.

- **Process Planning:** The second core functionality of the TFR is process planning, which focuses on the generation of optimised plans for organising tasks and allocating resources. These tools support both high-level strategic decisions and more detailed operational planning. Process planning within TFR is closely connected to the simulation environment. Depending on the industrial problem, whether it contains uncertainty or variability, optimisation can build directly on simulation results, or planning tools can operate independently if the necessary input data is available. This flexibility allows users to apply the right approach to the problem at hand.
- **Disassembly Planning Tool:** The DPT, presented by (Costa et al. 2018), is an add-in for SolidWorks that has the capability of computing disassembly sequences by analysing CAD models with geometric constraints (named as mates in SolidWorks). It can be used to help engineers during the design of products, by allowing them to quickly check if their product is easy to disassemble or if it needs improvements, such as reducing the disassembly steps or increasing the reachability of parts to avoid collisions with the tools that will be used during production. On the other hand, it can be useful for providing disassembly sequences for replacing damaged components and for extracting parts for remanufacturing or recycling. Moreover, the automatically computed part decoupling directions can be used to help automate the programming of robotic arm motions for disassembling the parts.

5.3 Architecture & Technologies

To address the various stages and dimensions of this process, the TFR is organized into five main submodules (Figure 20). Each submodule is responsible for a specific set of functionalities, ensuring modularity, interoperability, and adaptability across different use cases within the RENÉE project.

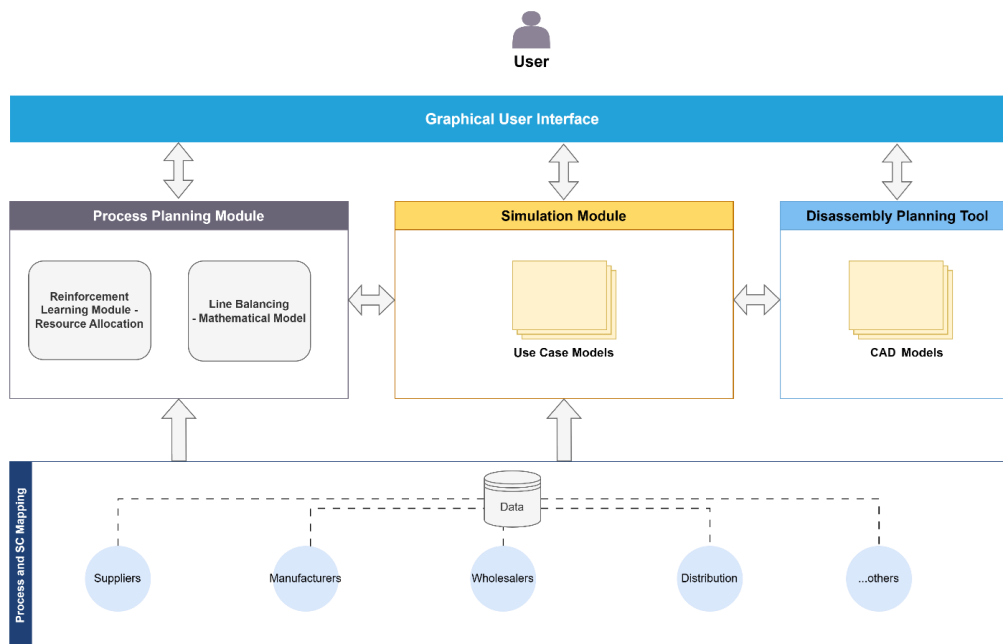


Figure 20: TFR General Architecture



- **Process and Supply Chain Mapping:** This submodule serves as the foundation for both simulation and process planning activities. Its main role is to collect and structure relevant information about remanufacturing supply chains and associated operations. Data collection involved a multi-method approach, including an online questionnaire, document analysis, and semi-structured interviews with key stakeholders from the participating companies. The questionnaire, distributed via Google Forms, served to gather initial insights into the remanufacturing process, product characteristics, and supply chain structures. These responses informed the design of follow-up interviews, which were conducted with managers and professionals directly involved in remanufacturing activities. The interviews explored in more detail the flow of components and information, roles of supply chain actors, and visibility of critical remanufacturing-related data. Topics covered included:

- Product characteristics and reusable components;
- Current and future supply chain configurations, including gaps;
- Actor roles, locations, and information flow;
- Quality, timeliness, and accuracy of shared information;

The result is a structured representation of each case study's remanufacturing supply chain, providing a reliable basis for scenario modelling and performance analysis in the TFR's simulation and planning modules.

- **Simulation Module:** The simulation module is responsible for executing dynamic analyses of both shop floor operations and supply chain configurations. It is composed of multiple simulation models developed for each project case study, with some focused on the internal production processes and others on the broader supply network.

These simulations are built using FlexSim, a discrete event simulation platform that supports both visual and data-driven modelling. The structural and modelling data required to build the simulation is provided by the Process and Supply Chain Mapping submodule. However, parameter inputs, such as demand profiles, return rates, or processing times, can be either retrieved dynamically from the Digital Vault, particularly when TFR is instantiated by other modules within the RENÉE ecosystem, or entered manually by users through the TFR User Interface when used as a standalone tool.

Simulation results can be visualised directly within the FlexSim platform or passed to the TFR User Interface, where they are displayed using scenario dashboards and performance metrics. The most suitable model for a real scenario will be deployed into a Digital Twin, meaning that an instance of this simulation model will interact in real-time with resources and workstations.

- **Process Planning Module:** This module provides optimization capabilities to support tactical and operational decision-making in remanufacturing systems. It integrates both mathematical modelling and AI-based approaches, allowing users to generate actionable plans based on realistic constraints and uncertainties. The module interacts closely with the simulation component, using simulation feedback to evaluate and improve generated plans.
 - **Mathematical optimisation models:** A mathematical model is being implemented in the toolbox to address the disassembly line balancing problem, specifically in the context of End-of-Life (EOL) products. An EOL state-oriented, multi-objective disassembly line balancing problem is proposed to account for the variability in

product conditions commonly observed in remanufacturing environments. The model aims to minimise both the number of active workstations and the overall idle time across the line, promoting resource efficiency and supporting circular economy goals. It is being implemented using the Google OR-Tools optimisation library.

- **Reinforcement learning algorithms:** Reinforcement learning will be used within the toolbox to support resource allocation in dynamic and uncertain shop floor environments. Once trained, the agent will be deployed in Process Scheduler and Orchestrator (PSO), as discussed in more detail in D4.1, acting in real time to allocate resources based on the current state of the system, such as task availability, processing durations, and resource status. This method provides flexibility and adaptability in situations where static planning may fall short due to unexpected disruptions or variability in operations.
- **Disassembly Planning Tool (DPT):** The DPT is implemented as a C# DLL that is loaded into SolidWorks as an add-in, in order to access its extensive API and provide disassembly planning capabilities. Namely, using the part geometric constraints (mates), the DPT is able to compute the part decoupling directions, which alongside a surface interference algorithm, adds to SolidWorks the ability to compute disassembly precedencies, which are dynamically explored using a branch-and-bound algorithm. The DPT starts by exploring the disassembly tree using a best-first search approach, to find a feasible solution, after which it can stop and show the user the results or continue and rely on the first solution as an initial upper bound for the branch-and-bound algorithm, which uses a cost function that includes the travel distance of the disassembly tool along with a tool change penalty.
 - **DPT GUI:** The DPT adds inside the SolidWorks GUI two buttons to trigger the search for the best first or the optimal disassembly sequence. The project that is currently open inside the SolidWorks GUI is then analysed and after finishing the computation, the DPT generates inside the SolidWorks GUI an exploded view that shows an animation of the disassembly sequence using the part decoupling directions. Moreover, the feasible disassembly sequences along with the search tree graph are exported to files in the Graphviz DOT format, to allow easy logging of results and integration with other modules.
 - **DPT ROS action:** SolidWorks currently only runs on the Windows operating system, but to allow the DPT to be integrated with other systems, it can provide a ROS action that receives as input the path to the CAD file to load into SolidWorks, along with the list of target parts to disassemble, and then returns the disassembly sequence and its metadata (decoupling direction, tool and cost for each disassembly step).
- **User Interface:** The user interface (UI) acts as the access point for interacting with the TFR modules. It allows users to define scenarios, configure simulations, initiate process planning routines, and visualize results.

The UI is being developed using a web-based architecture, with a Vue.js frontend, Spring Boot backend, and MySQL database for data storage and management. Its core features include:

 - Interactive mapping tools for supply chains and process layouts
 - Parameter selection panels for simulations and optimizations
 - Dashboards for comparing scenario performance across different metrics



The UI is designed to support both technical users (e.g., simulation or optimisation experts) and non-technical stakeholders, and is being developed with a strong focus on user experience (UX) principles to ensure it is intuitive, efficient, and inclusive across user profiles.

5.4 First Prototype Development

5.4.1 Process and SC Mapping

As part of the process of mapping SCs for the remanufacturing process, information was collected from companies through an online questionnaire, semi-structured interviews with key stakeholders and document analysis. The online questionnaire, as well as the document analysis, was used to gather initial data, providing a foundational understanding of the companies' remanufacturing processes and guiding the subsequent interviews. Interviews were conducted with managers and other stakeholders directly involved in remanufacturing processes in order to capture detailed information about the current practices, challenges, and opportunities within the remanufacturing process and supply chain. The data collection process covered the following topics:

1. Product characteristics
 - Products that are part of the remanufacturing process
 - Components that can be "reused"
2. Supply Chain Mapping (current situation, future situation and "gaps")
 - Actors involved (suppliers, customers, transport companies, other intermediaries)
 - Geographical location of the actors
 - Role of each actor
 - Flow of information regarding "end-of-life" products and components entering the remanufacturing process
 - Interaction among actors (information systems)
3. Analysis of supply chain visibility regarding information relevant to the remanufacturing process.
 - Information that is currently shared and that should be shared in the context of the remanufacturing process
 - Classification of the amount of information shared with the partners
 - Classification of the quality/accuracy/absence of errors of the information shared with partners
 - Classification regarding the timeliness with which relevant information is shared or received

The online questionnaire was shared using Google Forms (Figure 21, Figure 22) due to its accessibility and ease of use, and was distributed electronically to a representative from each of the four companies, and responses were collected over two weeks. By analysing the responses, a preliminary understanding of key themes was obtained, which helped refine the interview questions and focus on specific issues during the subsequent interviews.



RENÉE Project

Dear Reneé Project partners.

We request your contribution in responding to this questionnaire. The objective is to understand the current and future remanufacturing process of participating companies and map the supply chain actors involved.

This work is developed within the scope of Task 3.4 of the Reneé project. The information shared here will be used exclusively within the scope of the project and will not be shared beyond the project partners. After the analysis of this enquiry, feedback and further information will be provided by means of interviews to each Reneé's pilot company.

We thank you in advance for your collaboration. If you have any questions, you can contact us via email at ricardo.a.zimmermann@inesctec.pt and antonio.baptista@inesctec.pt.

Figure 21: Questionnaire header

8. Which of the following scenario describes the current reverse logistic for the remanufacturing process? (You can choose more than one) *

- Consumer -> Retailer Facility
- Consumer -> Retailer Facility -> [logistic company] -> OEM Factory
- Consumer -> [logistic company] -> Retailer Facility -> [logistic company] -> OEM Factory
- Consumer -> Technical assistance -> [logistic company] -> OEM Factory
- Retailer facility -> [logistic company] -> OEM Factory [logistics damaged products]
- Consumer -> [logistic company] -> OEM Factory
- Other: _____

Figure 22: Questionnaire sample

The following tables consolidate key quantitative indicators derived from the interviews for each pilot case. These provide a comparative view of product usage patterns, data exchange practices, and supply chain visibility levels. Due to confidentiality reasons, some sensitive data/information elements were distorted or omitted in the tables or diagrams.

Table 6 presents an indicative average duration of product use. This metric is essential for understanding the return cycles and potential availability of products for remanufacturing. Table 7 details the types of information currently exchanged among supply chain actors. It highlights the level of data availability that supports decisions around remanufacturing feasibility and planning. Table 8 complements this by assessing how much information is shared, the quality of that

information, and its timeliness, offering a proxy for overall supply chain transparency and coordination.

Company	Average duration of the product use phase (by the end consumer)
DECATHLON	120 – 180 months
EMOTORS	120 – 180 months
ARCELIK	120 months
CAMPETELLA	180 months

Table 6: Average duration of the product use phase (by the end consumer)

Information to be shared among supply chain actors	DECATHLON	EMOTORS	ARCELIK	CAMPETELLA
Product ID	X	X	X	X
Product technical characteristics	X			X
Date of production	X		X	
Date of sale to the client (end user)	X			X
History of product interventions	X	X	X	X

Table 7: Information to be shared among supply chain actors

Company	SC visibility assessment (1-4 Satisfaction Likert Scale)		
	Amount of information shared among SC partners	Quality of information shared among SC partners	Timeliness of information shared among SC partners
DECATHLON	3	2	2
EMOTORS	2	3	4
ARCELIK	2	2	3
CAMPETELLA	3	3	3

Table 8: SC visibility assessment

Regarding the results of SC flow mapping, several shared features were identified across the different pilot cases. Reverse logistics processes typically involve the collection of products through service centres, retail locations, or original equipment manufacturer (OEM) facilities. Transportation is generally handled in coordination with third-party logistics providers. However, the effectiveness of reverse logistics is often limited by traceability issues, low return volumes, and processing capacity constraints.

Most pilots have focused their efforts on the recovery of high-value components such as motors, printed circuit boards, mechanical assemblies, and structural elements like frames. These components are primarily reused as spare parts rather than being reincorporated into new manufacturing lines. The assessment of components for potential reuse is generally performed manually and subjectively, which restricts standardisation across operations.

The remanufacturing processes observed range from basic refurbishment activities to more complex operations involving disassembly, inspection, upgrade, and reassembly more typical of remanufacturing. These processes are largely manual and frequently face technical challenges such as the difficulty of disassembly and the degradation of components over time.

In terms of traceability and supply chain visibility, most pilots utilise some form of tracking systems. However, these systems tend to be still fragmented and often depend on consumer-related data. The quantity, accuracy, and timeliness of information shared among supply chain partners vary significantly. There remains a notable gap in achieving comprehensive lifecycle traceability and in consistently capturing post-sale product history. The typical reverse and forward logistics flows and associated roles can be visualized in the diagrams compiled in Figure 23, Figure 24, Figure 25 and Figure 26. These schematics, despite of its degree of simplification (regarding also some confidentiality level) offer a standardised overview of remanufacturing loops as applied in different industrial contexts.

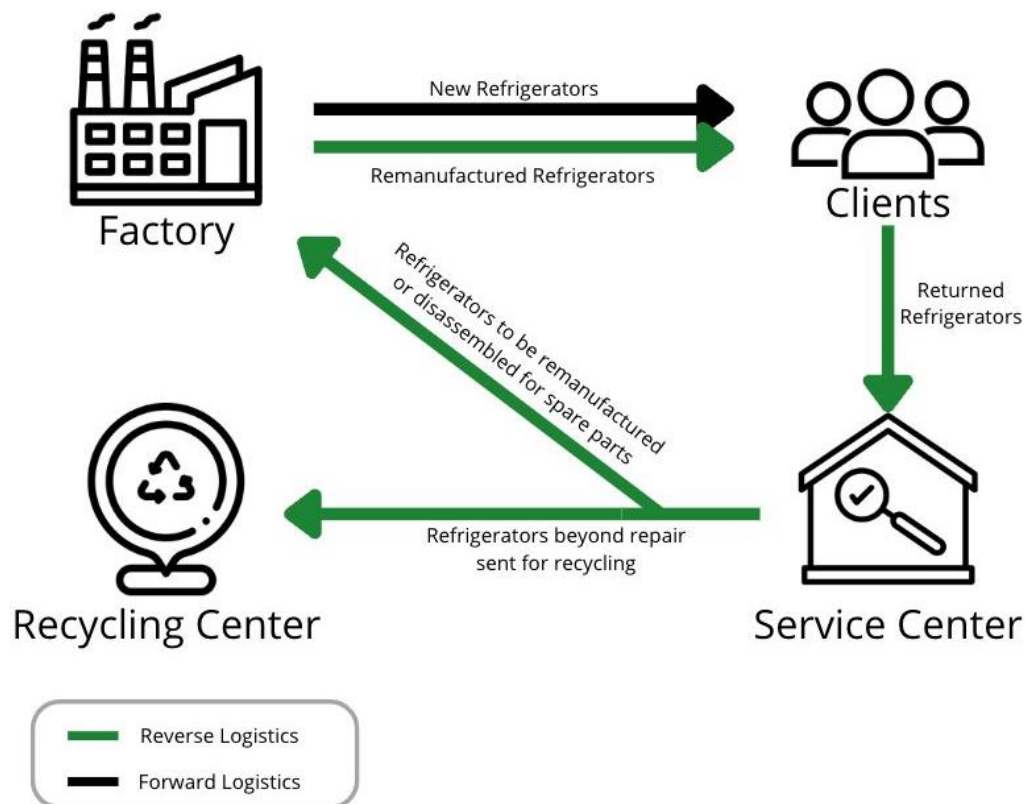


Figure 23: ARCELIK Supply Chain flow and main actors

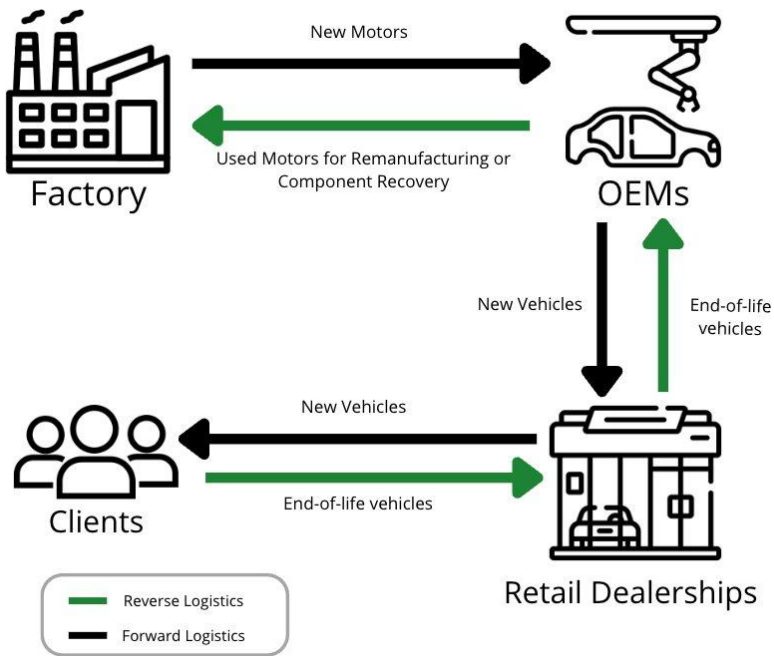


Figure 24: EMOTORS Supply Chain flow and main actors

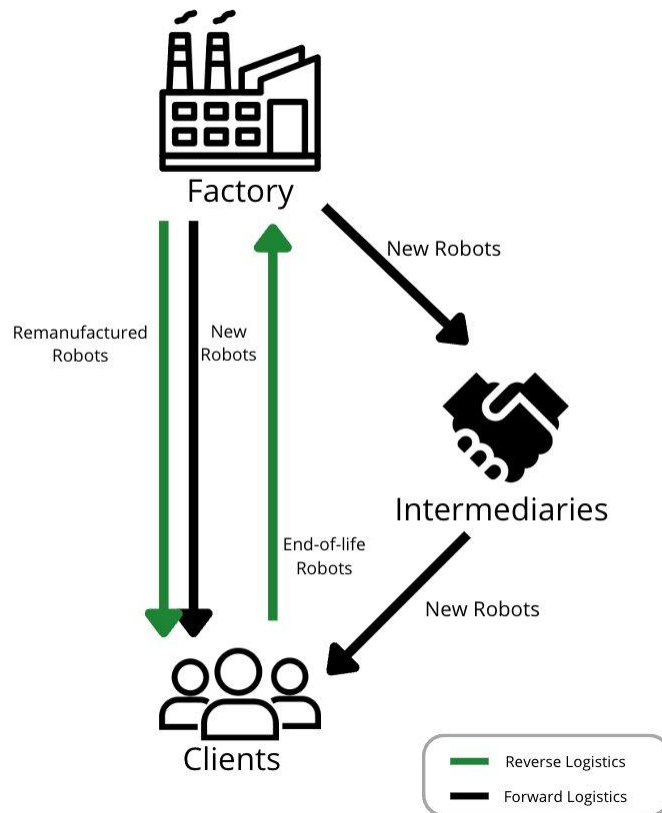


Figure 25: CAMPETELLA Supply Chain flow and main actors

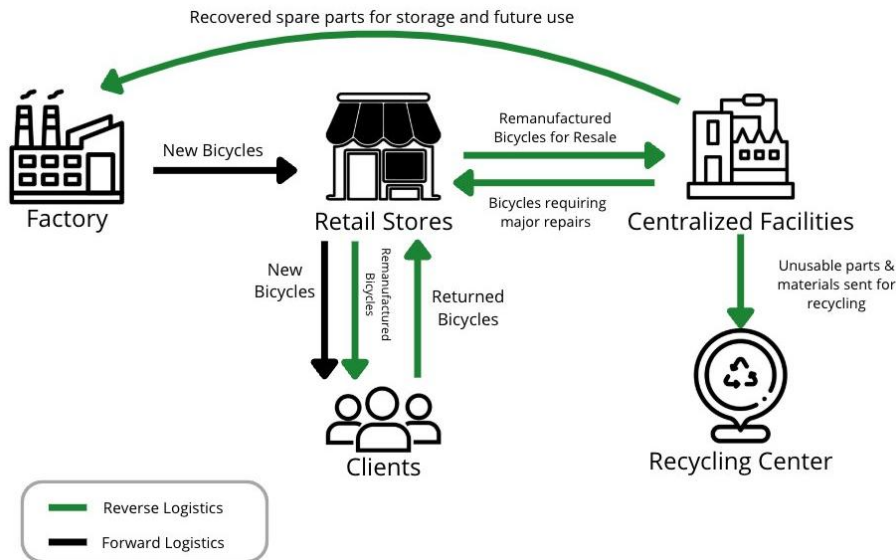


Figure 26: DECATHLON Supply Chain flow and main actors

Several recurrent challenges were identified across the pilots. From an operational standpoint, refurbishment efforts are constrained by limited processing capacity, inconsistent return volumes, and variability in product conditions. Furthermore, the lack of centralised systems for managing and redistributing returned products reduces efficiency.

Technical and design barriers also slow down progress. Many products were not originally designed for disassembly, which complicates the recovery process. Additionally, the obsolescence of some components and component degradation over time restricts their potential for reuse.

Economic viability represents another major constraint. The costs associated with remanufacturing are often high, particularly in cases where the resale value of the refurbished product is insufficient to offset the expenses. Furthermore, long product life cycles mean that items return at low frequencies, limiting the volume of material available for remanufacturing.

In terms of information systems, there is in general a lack of standard guidelines for making refurbishment decisions. The current lack of integrated digital platforms also hinders real-time supply chain visibility. Collaboration among supply chain partners is often minimal, particularly in relation to data exchange.

5.4.2 Simulation

The simulation module of the Toolbox for Remanufacturing (TFR) is being developed to support detailed analysis and evaluation of remanufacturing scenarios at both the supply chain and shop floor levels. Two distinct lines of work are currently underway, each addressing a different level of the remanufacturing system.

5.4.2.1 Supply Chain Level Simulation

At the supply chain level, simulation focuses on modelling the flow of returned products, remanufacturing centres, and distribution networks, capturing variability in returns, demand, and product condition. This work started its development through a case study in the bicycle repair and

remanufacturing industry, using DECATHLON as the primary reference. The primary objective is to develop a framework that enables a collaborative network among different DECATHLON workshops, facilitating the exchange of bicycle components to improve repair efficiency and resource utilisation.

To support the development and validation of the full-scale DECATHLON model, a smaller preliminary case study was first implemented. This early prototype enabled testing the model structure, simulating simplified return and demand patterns, and refining core modelling assumptions before applying them to the more complex case study. Synthetic data was used during this phase to test system behaviour, and 4 scenarios were defined varying the fleet size of trucks and type (diesel, electric and others).

With a special emphasis on analysing global versus local SCs, this model deals with the optimisation of truck routes and transportation missions, with the dual goal of minimising both transportation costs and CO₂ emissions. Specifically, the model captures:

- The geographical distribution of repair workshops and collection points
- Reverse logistics flows from consumers to remanufacturing centres
- Delivery flows of remanufactured bicycles back to retail or redistribution points
- Trade-offs between centralised and decentralised remanufacturing strategies
- Environmental and economic performance under different what-if scenarios

The resulting conceptual model provides a flexible framework for evaluating alternative supply chain configurations and testing strategic decisions related to remanufacturing logistics and sustainability. A sample of results is presented in Figure 27 and Figure 28.

Next steps in this work include the expansion of the case study to incorporate the full set of supply chain actors identified during the supply chain mapping activities, enabling a more comprehensive representation of the operational network and its interdependencies.

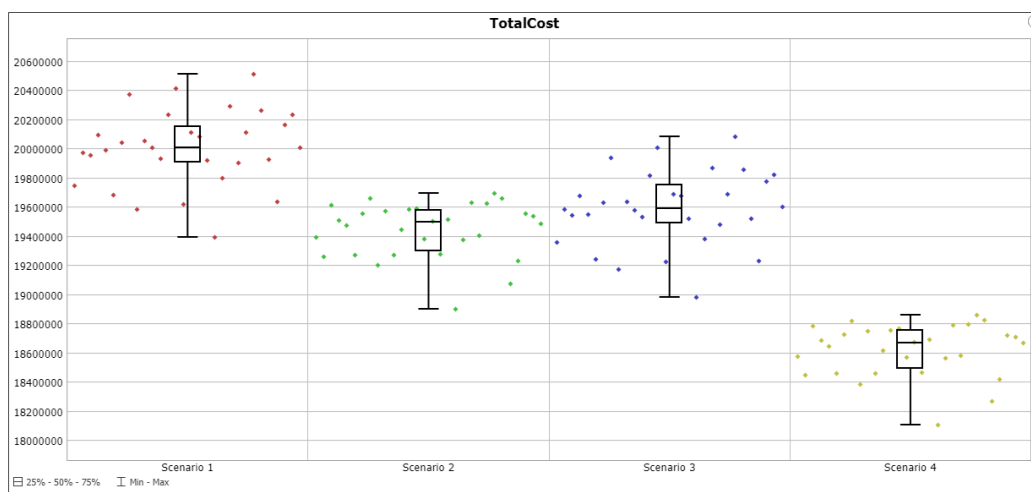
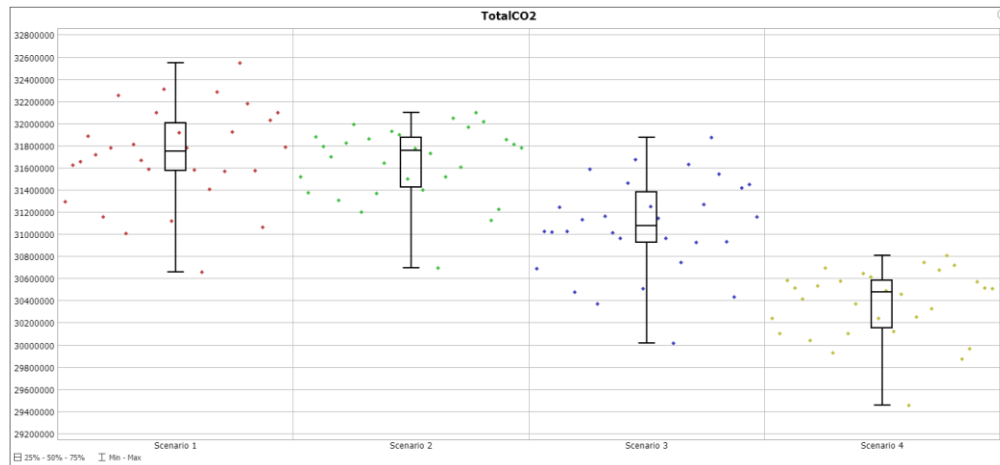


Figure 27: Total cost for each scenario.

Figure 28: Total CO₂ emissions (in kgCO₂eq) for each scenario

5.4.2.2 Shopfloor Level Simulation

At the shop floor level, simulation focuses on modelling the operational aspects of the remanufacturing process within a workshop environment, aiming to evaluate process performance, resource utilisation, task sequencing and production throughput under different configurations.

This line of work is being developed through a case study of bicycle remanufacturing. The primary objective of this case study is to simulate the physical flow and operational decisions involved in restoring used bicycles, to optimise production efficiency while ensuring high product quality and compliance with safety standards.

To support the development and validation of the full-scale DECATHLON model, a smaller preliminary case study was first implemented (Figure 29). This simplified pilot enabled early testing of the simulation framework and process parameters. For this case, the following key remanufacturing steps were considered:

- Initial Inspection: Initial assessment identifies major defects to determine if remanufacturing is feasible.
- Disassembly: The bicycle is broken down into its core components.
- Cleaning: Parts are cleaned and prepared for inspection.
- Inspection and Sorting: Components are assessed to determine which can be reused, refurbished, or replaced.
- Reconditioning: Usable components are repaired or restored to working condition.
- Reassembly: The bicycle is reassembled using both reused and new parts – remanufacturing line.



Figure 29: Simulation Model of Bicycle Remanufacturing Line

The process begins with an initial intake and inspection phase, where bicycles are assessed for suitability. This step is critical to ensure that only bicycles with remanufacturing potential enter the process, thereby optimising the use of time, labour, and materials. At the end of the chain, final testing is conducted on each remanufactured bicycle to ensure it meets all performance and safety standards, guaranteeing reliability comparable to that of a new product. A sample of results is presented in Figure 30 and Figure 31.

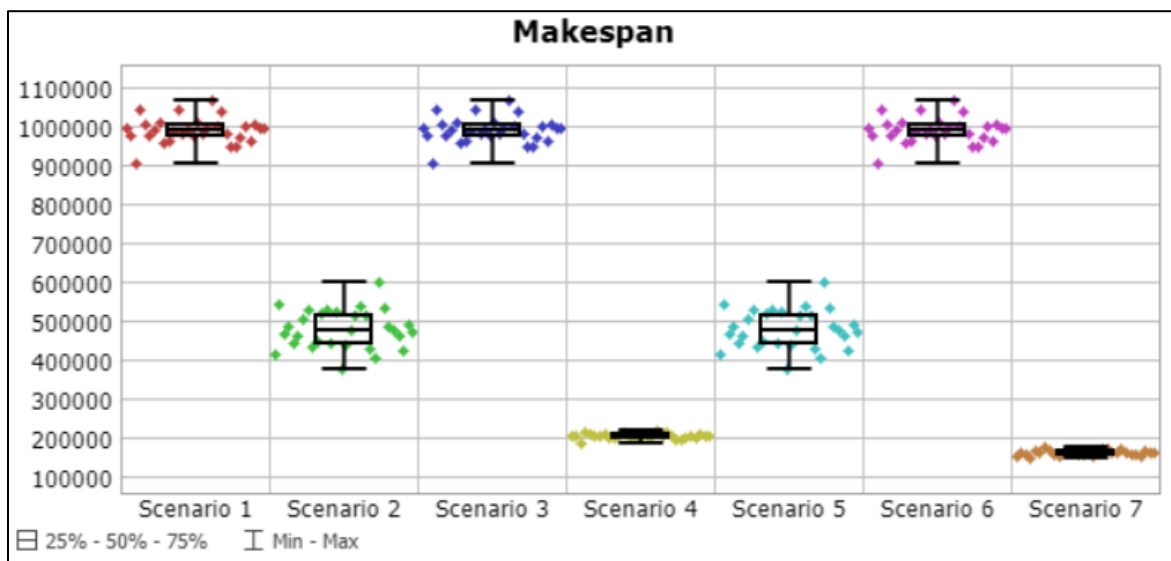


Figure 30: Comparison of Make span Across Different Scenarios

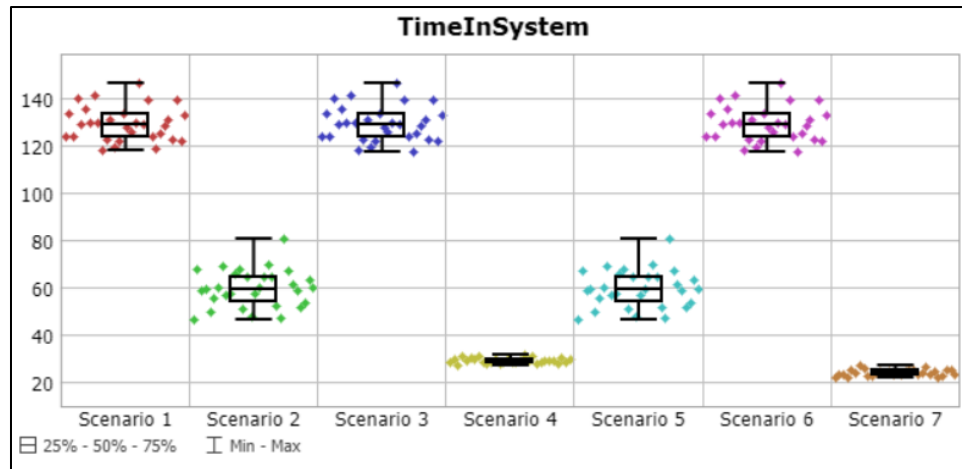


Figure 31: Comparison of Time In System Across Different Scenarios

5.4.3 Process Planning

The process planning functionality within the Toolbox for Remanufacturing (TFR) focuses on the optimisation of remanufacturing operations. It aims to support decision-makers in the tactical configuration of disassembly and reassembly processes by generating feasible and efficient task-resource plans. Two main lines of development are currently being pursued: one based on mathematical optimisation models, and another exploring ML-based approaches.

5.4.3.1 Mathematical Model For Disassembly Line Balancing

One of the central components under development is a mathematical model formulated to address the Disassembly Line Balancing Problem (DLBP) for End-of-Life (EOL) products. This problem is particularly relevant in remanufacturing environments, where products returned from the field often exhibit high heterogeneity in terms of condition and composition.

The model explicitly incorporates this heterogeneity by defining multiple EOL condition combinations across a product's main components. These combinations influence the disassembly time required for each task, which may vary significantly depending on the presence or absence of damage, wear, or missing parts. The formulation is designed to:

- Determine the optimal number and configuration of workstations;
- Assign disassembly tasks and mobile resources to specific stations based on task precedence and processing requirements;
- Maintain a fixed cycle time across all stations to ensure consistent throughput under varying conditions.

The objective function of the model is twofold:

- Minimize the total number of active workstations, promoting a compact and efficient line layout;

- Minimize the total idle time across all stations, improving resource utilization and workflow balance.

By achieving this dual objective, the model enables:

- Efficient allocation of human and technical resources;
- Reduction in energy consumption and operational costs;
- Support for sustainable disassembly practices, aligned with the principles of the circular economy.

The model is being implemented using the mathematical programming solver OR-Tools and is currently undergoing early testing using data sourced from existing literature. This phase allows for the verification of model logic and performance under generic, yet realistic, product configurations and EOL scenarios.

The next step in the validation process involves testing the model using specific data from the ARÇELIK use case. This will allow the model to be evaluated against actual disassembly line conditions, enabling more robust calibration and refinement.

Preliminary results demonstrate the model’s capability to generate efficient disassembly plans that adapt to the variability in product condition, while maintaining operational constraints. This development provides a foundational tool for integrating optimization into remanufacturing process planning. A sample of results is presented in Figure 32.

	A	B	C	D	E	F	G	H	I
1	Scenario	Workstations Used	Cycle Time	Avg Station Time	Total Idle Time	Mobile Resources Used	Total Movements	Total Movement Time	Total Task Time
2	1	5	118	52,82	435,9	['4', '5', '6', '7', '8']	4	7,7	219
3	2	2	135	110,5	59	['4', '5']	0	0	196
4	10	5	114	52,02	439,9	['4', '5', '6', '7', '8']	4	7,7	217
5	11	2	131	108,5	63	['4', '5']	0	0	194
6	34	5	118	43,52	482,4	['4', '5', '6', '7', '8']	4	7,7	176,5
7	26	2	128,5	119,25	41,5	['4', '5']	0	0	213,5
8	48	5	122,5	42,72	486,4	['4', '5', '6', '7', '8']	4	7,7	172,5
9	72	5	138,5	63,06	384,7	['4', '5', '6', '7', '8']	2	4,6	274,5
10	78	5	130,5	53,82	430,9	['4', '5', '6', '7', '8']	4	7,7	228

Figure 32: Sample of optimisation results for a set of scenarios

5.4.3.2 Reinforcement Learning for Adaptive Resource Allocation

The Toolbox for Remanufacturing (TFR) also includes the development of a reinforcement learning (RL)-based process planning tool aimed at dynamic and adaptive resource allocation on the remanufacturing shop floor. This approach is particularly suitable for highly variable and uncertain environments, where fixed planning assumptions may no longer hold during execution due to disruptions, unexpected task durations, or resource unavailability.

The RL-based framework leverages Deep Reinforcement Learning (DRL) principles, where a trained agent is responsible for making real-time task assignment decisions in response to current system

states. The agent operates in conjunction with the simulation models developed in the TFR simulation module, ensuring a realistic and integrated environment for training and deployment.

The system is structured in two phases:

- **Training Phase:** A baseline task-resource assignment solution is first generated using a classical Assembly Line Balancing (ALB) optimizer. When deviations from expected performance occur, such as task execution time divergence or resource unavailability, the control is handed over to the RL agent. The agent is trained using simulated data from the TFR environment. During training, the agent interacts with the simulation by selecting actions (i.e., assigning tasks to resources), receiving feedback (rewards), and updating its policy to maximize cumulative performance.
- **Execution Phase:** Once a stoppage criterion is met, either a predefined number of training episodes or achievement of a target reward, the trained agent is deployed as a real-time decision-maker. It dynamically adjusts task assignments during runtime based on the evolving state of the production system. This particular phase is part of PSO (Process Scheduler and Orchestrator) functionalities, described in detail in Deliverable 4.1, ensuring high flexibility and a strong correlation between training and real-time execution.

The agent receives as input the state of the shop floor environment, including:

- Available tasks (with task precedence constraints);
- Execution times of current tasks;
- Availability of human and technical resources.

The reward function is defined as a weighted sum of key performance indicators, primarily the number of completed tasks and finished products. Negative rewards are applied when the agent selects infeasible actions (e.g., violating precedence or assigning unavailable resources), in which case the simulation is reset to maintain learning consistency.

This RL-based tool provides a flexible and adaptive planning mechanism, able to respond to disturbances and system variability in real-time. It complements the deterministic mathematical model by offering reactive intelligence, helping ensure robustness in actual remanufacturing environments where process variability is the norm.

5.4.4 Disassembly Planning Tool (DPT)

After analysing the CAD models provided by the RENÉE partners, it was decided to start the DPT tests using the EMOTORS use case because it had similar geometry and disassembly steps when compared with the starter motor and internal combustion engine in which the DPT was initially developed and tested (in previous research projects).

For the best user experience and efficient usage of the DPT, the CAD model should be developed within SolidWorks and follow its CAD engineering guidelines, which include having no interferences between parts and using geometrical constraints (mates) for the placement of the parts. However, EMOTORS relies on Catia instead of SolidWorks and since they could not share the original CAD



model to protect their intellectual property, the motor model was shared as a STEP file, for having a neutral and standard format to exchange the CAD data. However, the STEP format has the drawback of not being able to export geometrical constraints and also reducing the accuracy of the parts when approximating the surfaces during the conversion. As such, the EMOTORS CAD model had to be pre-processed to be usable by DPT. Namely, the part interferences had to be fixed, and the geometrical constraints (mates) were also added to speed up the disassembly planning. Currently, this is a manual process, but a automated version of preprocessing operations is being considered.

5.4.4.1 STEP part interferences

For the DPT to be able to work as expected, the CAD parts must not have intersections with each other. The DPT automatically computes part decoupling directions and then validates their disassembly feasibility by moving the part slightly along the decoupling direction to check if the part can be removed without collisions/intersections with other parts. If the CAD model provided already has interferences between the parts, the DPT calls to the SolidWorks API will not be able to differentiate between the initial interferences and the new collisions/interferences caused by moving the part along the decoupling direction. As such, it was analysed the EMOTORS CAD model using the SolidWorks interference detection tool and fixed all the part intersections that were present, namely:

- All the screws were changed to use their internal thread diameter because all of them were intersecting with their respective holes, which were modelled with the external screw thread diameter.
- All the rubber gaskets were removed (from the closing cover, main housing water inlet, inverter coupling to the main housing, inverter refrigeration piping, along with the venting caps from the inverter and closing cover) because they were causing intersections due to being modelled in their expanded state. They were removed instead of being changed because they do not affect the disassembly order (given that a rubber gasket is preassembled with its respective part).
- The main housing gasket was compressed to avoid intersections with the closing housing.
- The path of the cable that connected the inverter to the stator busbar was adjusted because it was intersecting with the main housing.
- The inverter cable connector that attaches to the position sensor was trimmed to avoid internal intersections between the 2 parts.

Besides part modelling problems that cause interferences, the DPT cannot yet disassemble parts that must be bent or change their shape to be removed. As such, they were remodelled from their natural state into their disassembling state, namely:

- The clip connector of the thermal sensor was bent from its default lock state in order to be in its open state to allow its removal from the stator.
- The 2 circlips that hold the 2 ball bearings on the rotor were bent from their locked state into their disassembling state to allow their removal from the rotor.
- The spring washer was remodelled in its compressed state because in its expanded state it was intersecting with the closing housing.



5.4.4.2 Part geometric constraints (SolidWorks mates)

The DPT uses the geometric constraints to compute the part decoupling directions because they encode the assembly intentions of the engineer, which in turn allows us to use this component metadata for efficiently finding a way to decouple the parts for disassembling them. The DPT currently supports two main categories of mates. The first is the planar mates (coincident, tangent and cam follower), in which the plane normal vector provides 1 decoupling direction. If several planar mates are combined in a single part, to align a part to a corner for example, then the DPT computes the fusion of the planar mates' normal vectors. The second category is the cylindrical mates (concentric, screw, gear and hinge), in which the central axis provides two decoupling directions. If a part has no geometrical constraints, then DPT will try to decouple it using the 6 vectors aligned with the plus and minus directions of the XYZ coordinate system. This allows DPT to be used even without geometrical constraints, since a lot of assemblies have parts that can be decoupled in the XYZ directions. However, this is slower when compared to using decoupling directions computed from mates, because instead of having 1 or 2 reliable decoupling directions, the DPT will try 6 generic decoupling directions that may not be suitable to remove that specific part.

The EMOTORS CAD only required the manual addition of coincident and concentric mates to properly place the parts and allow DPT to reliably compute the decoupling directions. The STEP format cannot yet specify geometrical constraints, and as such, even if the Catia CAD from EMOTORS had this kind of information, the STEP file would not be able to convert and encode it. However, even if the STEP format added support for limited part mating information, it was stated by EMOTORS that they use geometrical constraints in Catia to place the parts in place, but then they remove them after they apply them, to avoid the risk of moving a lot of parts in an assembly due to a bad specification of a geometrical constraint. This approach has the drawback of not having the mating information available to DPT, while also requiring repeated work by EMOTORS because they will likely need to add again the geometric constraints when there are motor design changes. As such, it would be better to keep the geometric constraints and lock the parts (both SolidWorks and Catia support making the parts fixed in place to avoid accidental movement, which keeps the constraints inactive but available for future use).

5.4.4.3 Disassembly sequence planning

The DPT is integrated into the SolidWorks GUI and provides to the end user 2 buttons. Both trigger the branch-and-bound planning algorithm, but the first (left button of Figure 33) stops the computation after reaching a feasible solution when using the best-first search heuristic, while the second button lets the branch-and-bound algorithm continue to find the optimal solution (while using the first solution as an upper bound).

The planning algorithm always performs the disassembly optimization even if the goal is to assemble the product, because from an optimization point of view, it is always possible to dismantle a product, but a partial assembly sequence may lead to an incomplete assembly of the complete product by not allowing some parts to be assembled because other parts are blocking the way. As such, by performing disassembly optimization, we avoid all the partial infeasible assembly sequences. When the goal is to assemble a product, we reverse the order of the computed disassembly sequence.



The cost function used for the disassembly planning includes the travel distance of the disassembly tool along with a penalty when that tool is changed. There is also the option to add a penalty for each mate that a part has, for having an onion disassembly approach, that gives priority to removing the outer parts first, which typically have a smaller number of mates when compared with the inner parts.

After the computation of the disassembly sequence, the DPT creates inside the SolidWorks GUI an exploded view with the order of removal of the parts, as can be seen in Figure 33, that allows the end user to view an animation of the disassembly process in which the parts are extracted according to the decoupling directions.

By default, the DPT starts with the part closest to the CAD origin, but a specific part can be used as a starting point for the best-first search algorithm. As shown in Figure 33, the disassembly sequence started by removing the carbon brush and its nearby circlip D35 (that was holding the ball bearing 6207 and the rotor in relation to the main housing, due to the retainer plate). Then it was removed the water inlet tip screws and the water inlet tip, followed by the screws of the closing housing and closing cover. Later on, it was extracted the closing cover and the position sensor screws.

The next step was the removal of the position sensor, which included the disconnection of the inverter cable connector and the disconnection of the thermal sensor connector from the stator. This is one of the hardest steps to automate with robots because it involves the manipulation of flexible cables in small spaces and the bending of the 2 clips to allow the removal of the 2 connectors. The DPT was able to perform this step because the parts were remodelled to be in the bent/disassembling state.

The next step included the removal of the closing housing along with its gasket, the spring washer, circlip D30, ball bearing 6206 and rotor. This group of parts was grouped together because if the closing housing was removed while the rotor was still inside the main housing, it would lose one of its 2 opposing supporting structures, causing a lot of torque on the ball bearing on the right side of the main housing, which could compromise the magnetization of the rotor if it touched the stator. As such, this group of parts was considered as a single part to be extracted together and dismantled after it was outside of the main housing. For removing this group of parts, it is necessary a press machine capable of around 20000 Newtons (for decoupling the closing housing from the main housing) and it must force the rotor perfectly along its axis to avoid contact between the rotor and the stator. Later on, for removing the ball bearing 6206 from the rotor, it is necessary a press machine capable of around 8000 Newtons.

The next step was the removal of the stator busbar screws that were connecting the inverter to the stator, followed by the retainer screws and the retainer plate. Later on, the removal of the ball bearing 6207 requires a press machine capable of around 10000 Newtons. The inverter screws and the inverter were removed next, freeing the stator to be extracted with the help of an oven or an induction heating coil inside the main housing for expanding it for releasing the stator from its shrink fit.

The DPT was able to plan the disassembly sequence presented earlier using the best-first search algorithm, which achieved a good and feasible result in a short amount of computation time (around 5 minutes). The search for the optimal and near-optimal disassembly sequence can take several

hours to compute and we are planning on computing it in the near future, after adding more metrics to the search cost function and improving the speedup and caching optimizations.

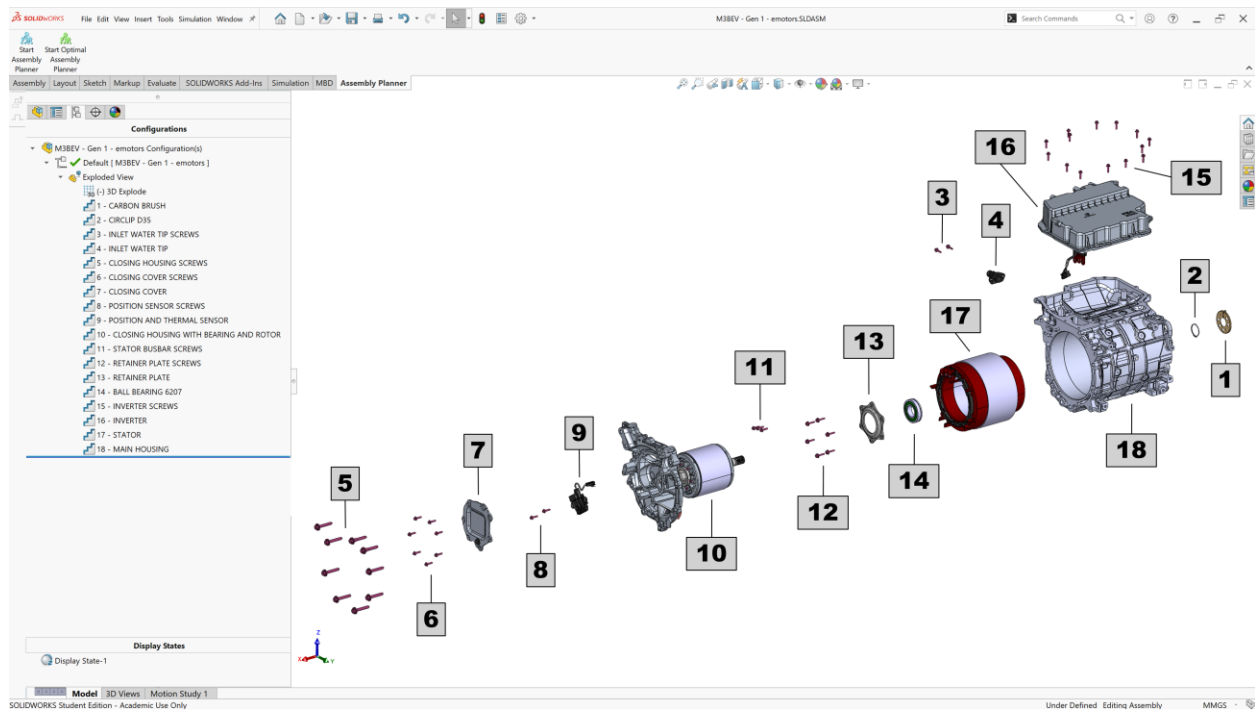


Figure 33: Disassembly sequence generated by DPT for the EMOTORS use case

5.4.5 User Interface

The **User Interface (UI)** of the Toolbox for Remanufacturing (TFR) is being developed as the main access point for interacting with the toolbox’s simulation, planning, and disassembly tools. Current work focuses on the design of UI mock-ups (Figure 34), developed using Figma, with a strong emphasis on user experience (UX) and ease of navigation. These mock-ups are structured around the key functionalities of the toolbox, including:

- Visual configuration of supply chain networks and shop floor layouts;
- Parameter selection for simulations and process planning routines;
- Access to disassembly planning data and evaluations;
- Visualization of results and performance indicators through interactive dashboards.

The next phase of development will involve usability testing of the designed interfaces. The results of the usability tests will guide adjustments to layout, functionality, and interaction logic before implementation in a working front-end. Ultimately, the UI will be developed using previously mentioned tools, ensuring full integration with the underlying modules of the TFR.

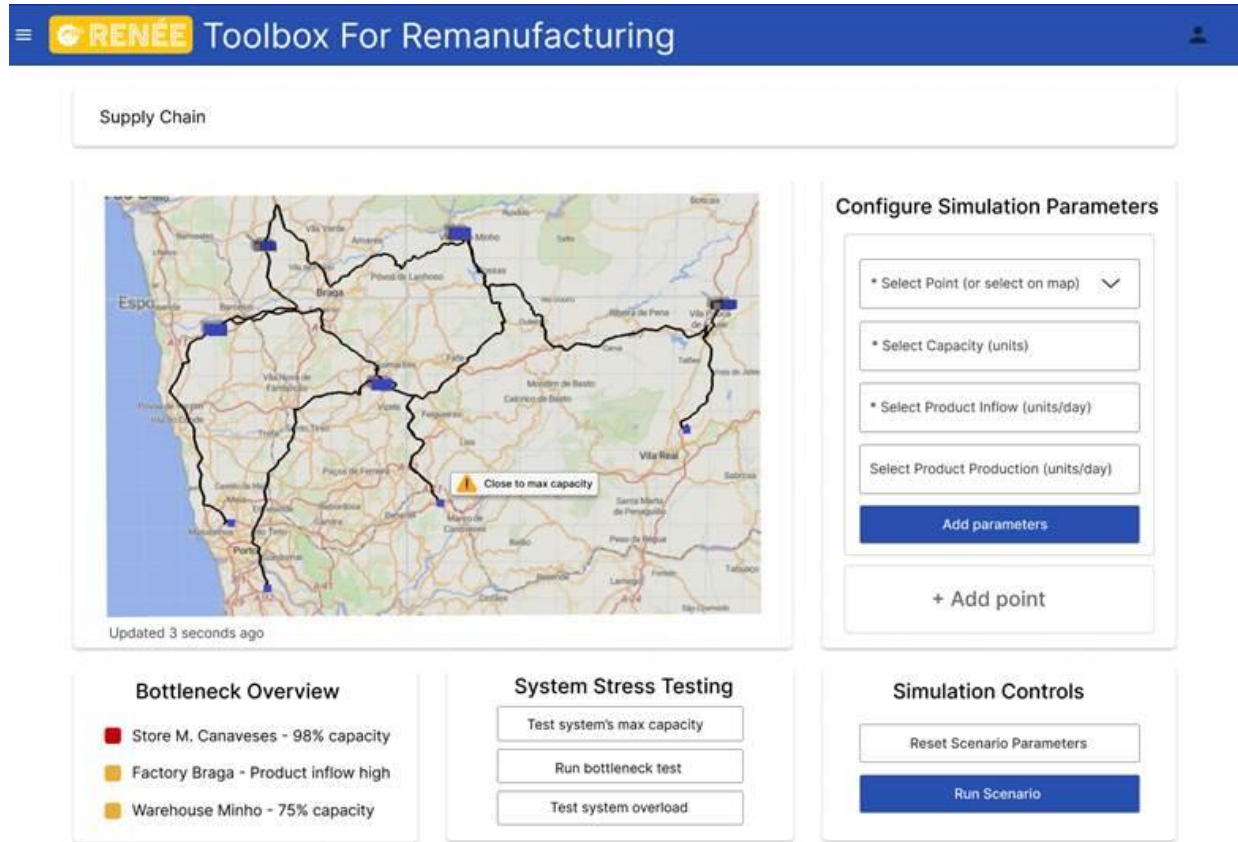


Figure 34: Example of UI Mock-up part of TFR

6 Evaluation Tool (ET)

6.1 Evaluation Tool Overview

The Evaluation Tool is responsible for evaluating the quality as well as the environmental, social, and economic consequences of potential remanufacturing processes. In the context of evaluating the configuration of a remanufacturing workstation, multiple potential scenarios are generated by the Task Scheduler based on input provided by the user, different in terms of resources utilized. These generated alternative configurations are automatically evaluated and quantified using specific quality and sustainability metrics, through a two-stage LLM framework and LCA tool.

6.2 Functionalities

The Evaluation Tool (ET) offers a comprehensive framework for assessing alternative remanufacturing scenarios through an automated, data-driven process. This framework incorporates various functionalities to streamline the evaluation process. These functionalities are the following:

- **Scenario Generation:** The system automatically generates multiple remanufacturing configurations based on user-selected product IDs and available resources and passes each

one to the scheduler. Each generated scenario is encoded in a structured JSON-based Scenario Description Format (SDF), containing metadata, resource-task mappings, task durations, and precomputed KPIs.

- **Dual-Index Evaluation System:** Each scenario is assessed using two main indices: the Quality Index (QI), which evaluates aspects related to the process execution quality and resources collaboration; and the Sustainability Index (SI), which considers environmental and societal impacts.
- **LLM-based Quality Evaluation:** The tool utilizes a large language model to assign qualitative scores to process quality metrics based on structured prompt templates. The LLM interprets scenario-specific information such as task assignments, robot usage, and workspace data, producing normalized and comparable QI scores across scenarios.
- **LCA-based Sustainability Assessment:** For each scenario, the system models process inputs and outputs in OpenLCA, computes environmental metrics, and conducts a Life Cycle Assessment using historic data databases. These values are translated into normalized sustainability scores, contributing to the overall SI.
- **Natural Language Summary Generation:** Once the highest-ranked scenario is identified, a second LLM pass generates a human-readable summary of the configuration, which is provided to the user through the tool UI.

These integrated functionalities are built upon a modular architecture, outlined in the following section, and form the core of the tool’s automated and user-friendly evaluation workflow.

6.3 Architecture & Technologies

The proposed system features a modular architecture (Figure 35) with an orchestration layer, scenario database, LCA tool and two-stage LLM reasoning pipeline.

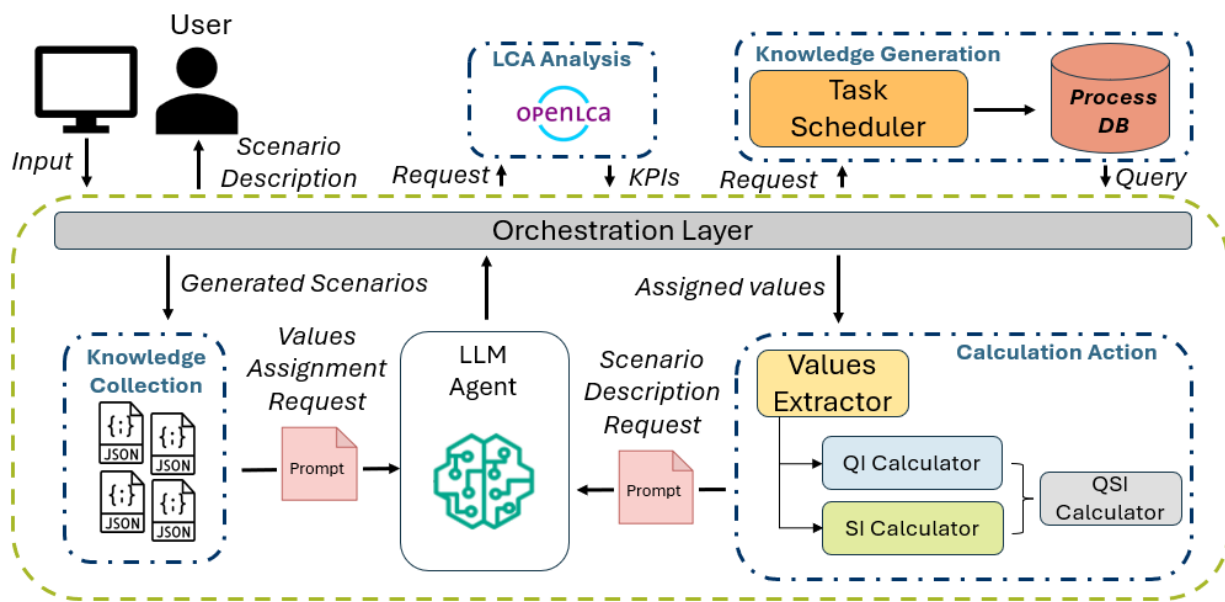


Figure 35: Evaluation Tool Architecture

Given a product ID and available resources by the user, the framework generates alternative remanufacturing scenarios stored as structured JSON files. This information is used to evaluate each scenario in terms of quality and sustainability. The evaluation process uses two indices, namely the Quality Index (QI) and the Sustainability Index (SI). These are then combined into one universal index, the Quality & Sustainability Index (QSI), which is used for the final comparison and ranking of the existing scenarios.

For calculating the QI-related metrics, an LLM-based approach is followed. More specifically, the orchestration layer retrieves each scenario and combines it with a static prompt, forming a complete query for the LLM. In the first stage, the LLM assigns process quality metrics, which are parsed to compute each scenario's QI. Along with each scenario's QI, the SI value is also computed based on calculated sustainability-related metrics and analysis through the OpenLCA.

These two indices are then merged into the QSI, using user-defined weights for each scenario. The highest-ranked configuration is then passed through a second LLM prompt to generate a natural language summary, returned to the user via the UI.

6.3.1 Model Structure and Scenario Input Encoding

6.3.1.1 Process Model

Each scenario is captured in a JSON-based Scenario Description Format (SDF) file that encodes all required operational details for evaluation. Scenarios are generated based on user-defined inputs and stored centrally. Each SDF begins with metadata (ID, timestamp, process title) and includes resources and task schedules. Tasks define titles, assigned resources, start times, and durations.

As shown in Figure 36, this uniform encoding supports machine-readable evaluation, consistent processing, and batch comparisons. Each file also includes precomputed KPIs used for metric calculations.

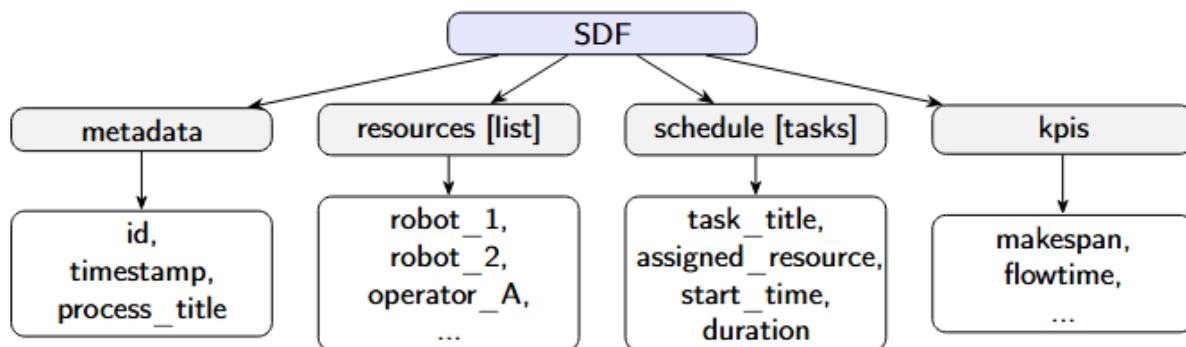


Figure 36: Generic Scenario Description Format (SDF)

6.3.1.2 LCA Model

For each scenario, a corresponding process is modelled in OpenLCA following the format presented in Figure 37. After creating the processes inside the OpenLCA tool and defining the inputs and outputs of each one, the analysis is run to compare the alternative processes based on an impact assessment method that follows European environmental standards. Based on the results of the

compared processes, the needed data are extracted to evaluate the environmental sustainability-related metrics.

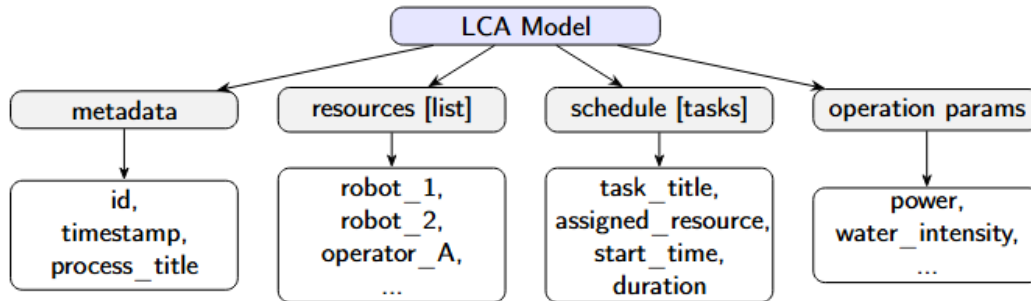


Figure 37: LCA Analysis Model Format

6.3.2 Evaluation Metrics

6.3.2.1 Process Quality Evaluation

To evaluate the quality of each remanufacturing scenario, the QI is used, based on established evaluation frameworks for (re)manufacturing environments (Kokotinis et al. 2023). The QI consolidates multiple qualitative and quantitative aspects of the process, enabling a structured, comparative assessment of alternative HRC configurations. The index is composed of several domain-specific metrics, grouped into four primary categories: Robot Performance, Workspace Utilization, Operational Efficiency, and Human Factors. Each metric is either derived directly from process data (e.g., flowtime, number of operators) or assigned by the LLM through a reasoning process informed by scenario features.

The LLM assigns metric values using a predefined rubric, with scores linked to qualitative levels from literature. Continuous metrics are derived from scenario data. All scores are normalized and aggregated into a single QI, allowing direct comparison of workstation configurations. Table 9 summarizes the included metrics and their corresponding data inputs.

Metric Category	Metric	Value
Robot Performance	Robot Autonomy (RA)	Discrete (1-5)
	Robot Manipulation Ability (RMA)	Discrete (1-5)
	Mobility (M)	Discrete (1-5)
Workspace Utilization	Workspace (W)	KPI-delivered
	Workpiece Sharing (WS)	Discrete (1-5)
Operational Efficiency	Flowtime (Fl)	KPI-delivered
	Human Availability (HA)	Discrete (1-2)
Human Factors	Human Safety (HS)	Discrete (1-5)
	Num. Operators (NoO)	Discrete (1-3)

Table 9: Process Quality Metrics and Associated Data Inputs

6.3.2.2 Process Sustainability Evaluation

To evaluate the sustainability of each remanufacturing scenario, the SI is applied, built upon a multi-dimensional framework that integrates both environmental and societal criteria. These criteria are reflected in a set of measurable indicators—such as energy consumption, water usage, carbon emissions, and user experience—as summarized in Table 10. The approach utilizes objective, KPI-derived data with subjective, experience-based ratings to enable a comprehensive evaluation of process sustainability.

Metric Category	Metric	Value
Environmental Sustainability	Energy Usage	KPI-delivered
	Water Footprint (WFP)	KPI-delivered
	Carbon Emissions	KPI-delivered
Societal Sustainability	Ergonomics	Discrete (1-5)
	User Experience (UX)	Discrete (1-3)
	Interaction Ability (IA)	Discrete (1-6)

Table 10: Process Sustainability Metrics and Associated Data Inputs

Economic sustainability is also considered and dedicated metrics will be integrated as part of the Cost/Benefit Analysis functionality of the Evaluation Tool during the second development phase, similar to additional metrics related to the recovered useful material from each process. Moreover, an ergonomics calculation process based on standardized ergonomics assessment tools (RULA, REBA, etc.) will be integrated into the Evaluation Tool to calculate the accumulative strain for the human operators in each generated scenario.

6.3.3 Metrics Mapping via Prompt Engineering

In this framework, the LLM evaluates the quality metrics based on structured remanufacturing scenarios. Prompt engineering ensures consistent, domain-relevant outputs by guiding interpretation through a fixed template that defines metrics, rating scales, and scenario-specific task and resource details. JSON features—like task descriptions and KPIs—are translated into natural language (e.g., “Operator1 performs task2 using tool A”) to support grounded assessments. Rule-based heuristics govern metric assignment; for instance, Human Availability scores 1 if an operator is involved. The model strictly follows these rules, selecting justifications from a predefined list.

The prompt design evolved through multiple iterations and experimenting. Early versions produced inconsistent outputs due to vague input structure. The current design uses standardized inputs and zero temperature but remains sensitive to incomplete or ambiguous data.

6.4 First Prototype Development

6.4.1 Data Pipeline and LLM Interaction

The evaluation pipeline consists of a modular orchestration layer coordinating a scenario database, an OpenLCA Interface, and a two-stage LLM reasoning process. Given product and resource inputs, the system generates multiple remanufacturing scenarios in the format of SDF files with task-level details.

In the first stage, the backend combines scenario data with a metric template, task descriptions, and a fixed prompt. A deterministic LLM (temperature=0) returns structured metric scores, which are validated, normalized, and aggregated into a final QI score. Scenarios are then ranked and stored.

Simultaneously, the LCA evaluation is conducted using OpenLCA. Based on the generated remanufacturing processes, corresponding models are created in the software, compared across scenarios, and the resulting data is used to compute the SI score.

In the second stage, with a new prompt and the results of the previous stage, the LLM then produces a natural language summary for the best scenario, which is presented to the user to support informed selection.

6.4.2 Process LCA Analysis

As discussed above, for the sustainability evaluation of the generated alternatives, an LCA Analysis based on the open-source OpenLCA tool is conducted. To formulate the assessment procedure in the tool, some reference values of the selected evaluation metrics related to each process need to be calculated. These metrics are the following:

- Electricity consumption (measured in kilowatt-hours, kWh)

Electricity consumption is calculated using the following equation:

$$Elec. cons. = \sum_{n=1}^m Power_n(kW) \times Time_n(h) \quad (1)$$

Where:

- Power: Power ratings of each robot and electric tool/device (in kW)
 - Time: Duration of use of each robot and electric tool/device during the process (in hours)
 - m: Total number of robots and electric tools/devices used in the process
 - Water intensity: This is related to the energy sources and their water demands. For our implementation, an EU-estimated value of 1.5 (L/kWh) is used considering the average electricity mix of the EU (Vanham et al., 2019).
- Carbon dioxide (CO₂) emissions (measured in kilograms, kg)

CO₂ emissions are calculated using the following equation:

$$CO_2 Em. = Electr. cons. (kWh) \times Emission factor (kg CO_2 - eq/kWh) \quad (2)$$

Where:

- Electricity consumption: Based on Equation 1

- Emission factor: For our implementation, the estimated value of 0.231 (CO₂/kWh) is used¹.
- Water Footprint (WFP – measured in litres)

The WFP is calculated using the following equation:

$$WFP = Direct\ cons. + Electr.\ cons. (kWh) \times Water\ intensity (L/kWh) \quad (3)$$

Where:

- Direct consumption:
- Electricity consumption: Based on Equation 1

The calculated values are used to model the inputs and outputs of each process in the OpenLCA (Figure 38). Upon modelling each process, an analysis based on a dedicated method is conducted to calculate the environmental footprint of each process (both direct and indirect impact) considering relevant historical data from its databases. In this study, the Environmental Footprint 3.0 (EF 3.0) Method – adapted was chosen as the impact assessment approach. This method was selected not only to ensure compliance with European standards but also for its ability to deliver quantitative results suitable for comparison against predefined Key Performance Indicators (KPIs). Based on the selected method the values of the selected KPIs are calculated incorporating also indirect factors. These KPIs are then used for the SI final calculations, as presented in the following sub-sections.

Inputs			
Flow	Category	Amount	Unit
electricity	Energy carriers and technolo...	0.02430	kWh

Outputs			
Flow	Category	Amount	Unit
Refrigerator Disassembly		1.00000	kg
Carbon dioxide	../Emission to air/high popul...	0.00562	kg
Water	../Emission to water/unspeci...	0.03650	l

Figure 38: Process input/output modelling in OpenLCA

¹ [Greenhouse gas emission intensity of electricity generation in Europe | European Environment Agency's home page](#)

6.4.3 Evaluation Metrics Calculations

6.4.3.1 QI Calculations

After the metric values are assigned by the first LLM pass, the QI is computed through a normalization-based scoring method. For each evaluated scenario, raw metric values are compared against the defined minimum and maximum values from the metric scale. These values are normalized to a 0–1 range using Equation 4 ensuring that each metric contributes proportionally regardless of its original scale, as they are not equal for every metric.

$$Q_t = \frac{\sum_{m=1}^M \left(\frac{v_m - v_m^{\min}}{v_m^{\max} - v_m^{\min}} \right)}{M} \quad (4)$$

where:

- Q_t is the cumulative score for a specific task,
- m is the number of the metrics examined, while M is the total number of metrics,
- v_m is the value set after the evaluation of the task under each metric,
- v_m^{\min} , v_m^{\max} are the min and max values of each metric according to the index scale. Once all metric values are normalized, the QI is calculated as their average, based on Equation 5. This approach allows for a consistent comparison of quality across different scenarios while preserving the influence of all metrics.

$$QI = \frac{\sum_{t=1}^T Q_t}{T} \quad (5)$$

where:

- QI is the total quality score for a specific process,
- Q_t is the value calculated from Equation 4 for each task,
- T is the total number of tasks considered.

6.4.3.2 SI Calculation

The computation of the SI follows the same equation used for the calculation of the QI, utilizing the sustainability metrics defined for each scenario.

$$S_t = \frac{\sum_{m=1}^M \left(\frac{v_m - v_m^{\min}}{v_m^{\max} - v_m^{\min}} \right)}{M} \quad (6)$$

where:

- S_t is the cumulative SI score for a specific task,
- m is the number of metrics examined, while M is the total number of metrics,
- v_m is the value which is set after the evaluation of the task under each metric
- v_m^{\min} , v_m^{\max} are the min and max values of each metric according to the index scale.

Respectively with QI, the SEI for the whole process is calculated based on Eq. (4).

$$SI = \frac{\sum_{t=1}^T Q_t}{T} \quad (7)$$

where:

- SI is the total score for a specific process,
- S_t is the value calculated from Equation 6 for each task,
- T is the total number of tasks considered.

6.4.3.3 QSI Calculation

The final QSI score is stored per scenario for the definition of the optimal one, through the indices' comparison, for it to be forwarded to the second LLM pass, to generate its layout description. The QSI is calculated by Equation 6, with w_1 and w_2 being defined by the user, as discussed in Section 10.4.3.

$$QSI = w_1 * QI + w_2 * SI \quad (8)$$

where:

- QSI is the cumulative score for a specific process,
- QI & SI are the values calculated from Equations 3 and 5,
- w_1 and w_2 are the weights allocated to each index.

6.4.4 User Interface and System Workflow

The User Interface (UI) is designed to offer a streamlined experience for configuring and evaluating remanufacturing layouts (Figure 39). Users begin by selecting the ID of the product to be remanufactured and choosing available resources via a dropdown menu and checkboxes. Subsequently, users can assign weights to the QI and SI according to their specific needs, which significantly influences the computation of the overall ranking. Once selections are made, clicking the "Execute" button triggers the backend workflow—sending the input to the LLM for metric evaluation.

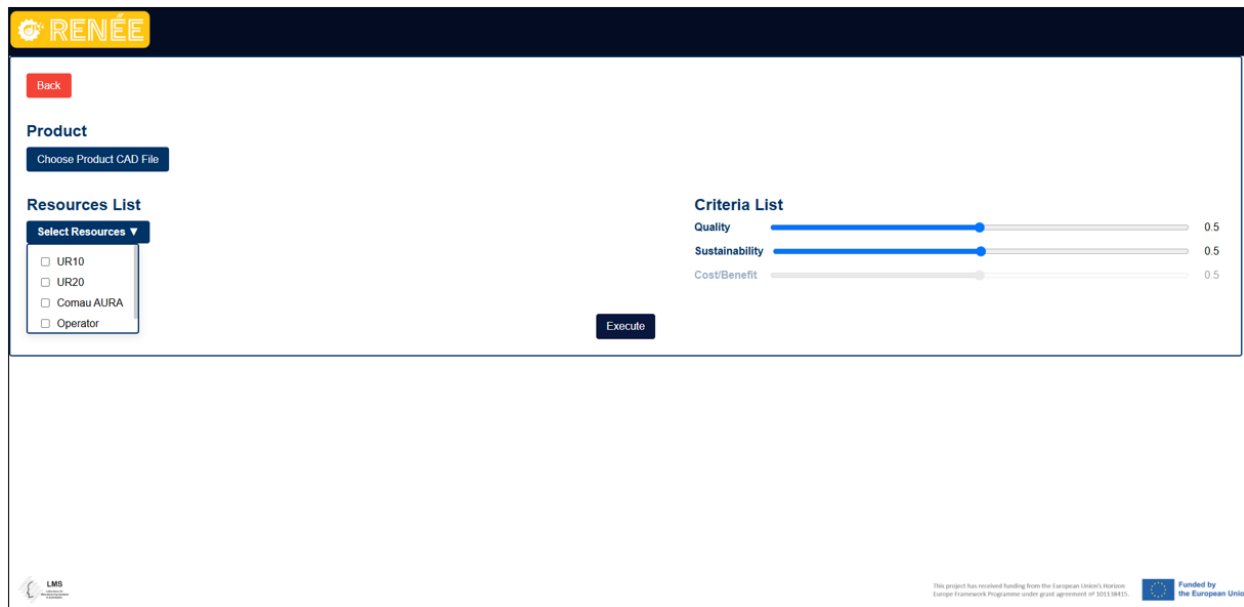


Figure 39: Evaluation Tool UI

The results, including both the structured metric output, containing the QI, SI and QSI for the scenario that has the biggest QSI, and a human-readable layout summary, are then returned and displayed through the same user interface. This design allows users to explore trade-offs and make informed decisions about resource selection and process setup.

6.5 First Prototype Testing

The initial prototype of the Evaluation Tool has been tested in the ARCELIK Use Case regarding the disassembly of the refrigerator. The product ID and two available resources (a human operator and a UR20 robot) have been provided by the user through the UI.

Task Scheduler automatically generated four alternative remanufacturing scenarios, differing in task distribution and sequencing across resources:

- **Scenario 1:** Collaborative HRC setup with shared task execution.
- **Scenario 2:** Sequential tasks with limited overlap between resources.
- **Scenario 3:** Fully automated scenario (robot-only).
- **Scenario 4:** Fully Manual (operator-only).

Each alternative was encoded as an SDF file containing task definitions, timing, resource assignments, and precomputed KPIs.

6.5.1 Process Quality Analysis

These files were processed through the LLM evaluation pipeline introduced in Section 10.3.1. A summary of the results is presented in Table 11. The first three metrics were not assigned values for the manual scenario, as they are specific to robot-oriented performance and do not apply to manual operations.

Scenario	RA	RMA	M	W	WS	Fl	HA	HS	NoO	QI
S1	5	5	1	3	5	4	1	5	2	0.731
S2	5	5	1	3	1	3	1	4	2	0.528
S3	5	5	1	3	1	3	2	1	3	0.611
S4	-	-	-	3	1	5	1	5	2	0.583

Table 11: QI Evaluation Results

6.5.2 Process LCA Analysis

For each scenario, the electricity consumption was calculated from the robot's consumption and its operation time during each scenario. From these values, the CO₂ and Water FP were calculated as presented in Table 12.

Scenario	Electricity (kWh)	CO ₂ Emissions (kg)	WFP (L)
S1	0.0160	0.00370	0.0240
S2	0.0146	0.00337	0.0219
S3	0.0243	0.00562	0.0365
S4	0	0	0

Table 12: Environmental Sustainability Metrics Values

Each alternative was modelled in OpenLCA, based on the mentioned calculations and the three scenarios were subsequently compared. The SI metrics were derived from the results, with a summary presented in Table 13. These values were calculated based on the calculated KPIs and the used scales after normalization (Equation 6).

Scenario	En. Usage	CO ₂ Em.	WFP	Ergon.	UX	IA	SI
S1	4	4	4	4	3	5	0.8
S2	4	4	4	3	2	2	0.575
S3	2	2	2	5	1	1	0.292
S4	5	5	5	1	1	1	0.5

Table 13: SI Evaluation Results

6.5.3 Scenario Final Evaluation

From the combination of the two indices, the QSI is computed for the three sample scenarios, using 0.7 as a weight factor for QI and 0.3 for SI. The summary is presented in Table 14.

Scenario	QI	SI	QSI
S1	0.731	0.8	0.752
S2	0.528	0.575	0.542
S3	0.611	0.292	0.515
S4	0.583	0.5	0.558

Table 14: QSI Evaluation Results

Figure 40 outlines the system’s complete evaluation workflow: (a) user input via the interface, (b) automated generation of task-resource allocation scenarios in SDF, (c) LLM-based evaluation of process quality metrics and LCA-based evaluation of process sustainability metrics, and (d) generation of an interpretable layout summary for the top-performing scenario.

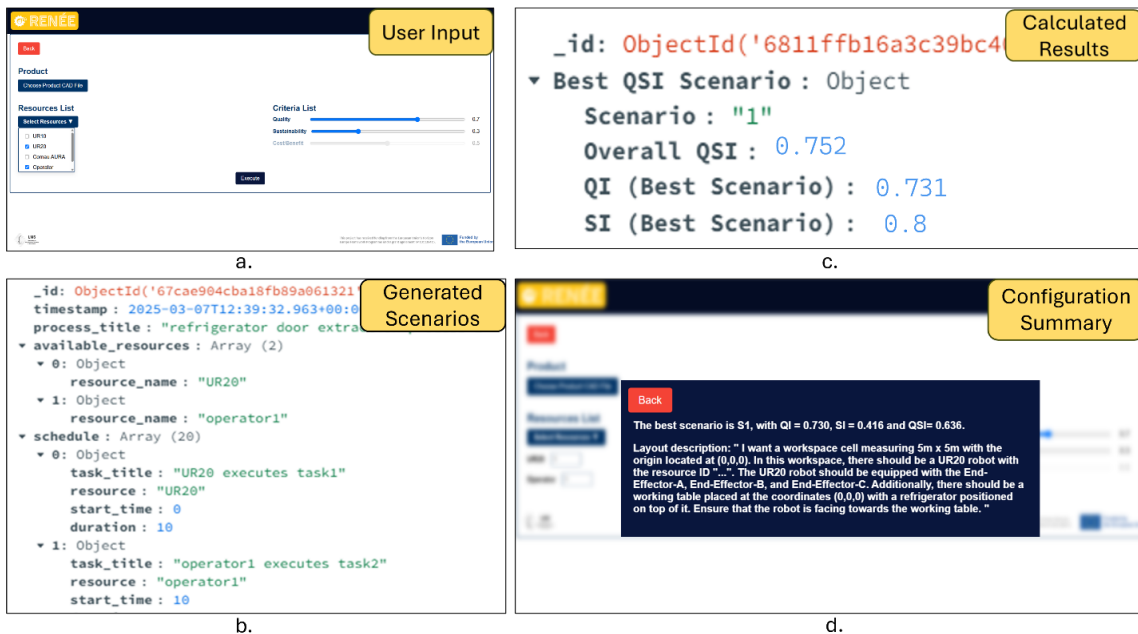


Figure 40: Evaluation Workflow Overview



7 Conclusions

The initial prototype of the RENÉE Circular Value Chains Configuration Toolbox represents a significant step toward enabling systematic, data-driven remanufacturing processes in European industries. This deliverable consolidates key modules developed within WP3, including the Product State Diagnosis (PSD), Twin4eXcellence Framework (Twin4X), Digital Product Passport (DPP), Toolbox for Remanufacturing (TFR), and Evaluation Tool (ET). The methods development and testing are occurring according to the plan. The first versions of these tools provide a solid technological and methodological foundation for configuring circular value chains and evaluating remanufacturing scenarios. Their integration into a modular architecture ensures interoperability and user-centric interaction across the different tools. Initial validations namely to the architectures and methods requirements confirm the tools' capability to support remanufacturing diagnostics, redesign, planning, and evaluation workflows. The current stage of development emphasizes usability, robustness, and adaptability to real-world industrial contexts, setting the stage for further refinements.

Future iterations of the RENÉE Toolbox will culminate in the development of a final prototype, which will extend the current work and integrate the various modules into a comprehensive, fully functional system. This phase will focus on deploying the toolbox in real-world case studies to validate its effectiveness, refine functionalities based on feedback, and demonstrate its impact across diverse industrial settings. Continued development will also include deepening tool integration, enhancing AI-based decision-making capabilities, and ensuring the scalability and interoperability required for widespread adoption. The final prototype will serve as a pivotal milestone toward realizing digitally enabled, circular manufacturing systems that are both sustainable and industry-ready.

As it regards the Evaluation Tool, future development activities will focus on enriching the tool's capabilities through the integration of additional evaluation dimensions including the incorporation of cost/benefit analysis metrics, enabling a more holistic assessment of each remanufacturing scenario. Interfaces with the core RENÉE modules will be deployed (e.g. the Digital Vault for centralized data storage and retrieval and the Cell Digital Twin for dynamic, visual representation of workstation layouts), while further iterations will be performed to support the remaining of the RENÉE use cases.



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