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Design and implementation of a circular remanufacturing production line

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Design and implementation of a circular remanufacturing production line

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Naslov teme zaključnega dela v slovenskem jeziku: Zasnova in izvedba krožne proizvodne linije za predelavo

Naslov teme zaključnega dela v angleškem jeziku: Design and implementation of a circular remanufacturing production line

Dispozicija zaključnega dela:

The research topic is the design and implementation of a circular remanufacturing production line, specifically to design the physical layout of the remanufacturing line and implement it at the Operations Management Platform at G SCOP laboratory, in Grenoble INP, France.

The product to be remanufactured is a hydro turbine, intended to produce electricity, and is fabricated by Additive Manufacturing using ABS or PLA, and composed on eleven polymer parts and four metal components.?

In the first step, the workstations in the remanufacturing line will be determined, according to literature. Usually, the disassembly of used product, diagnostic of components, cleaning and sorting of components, repairing of components, reassembly of the product, and finally checking its quality are the stages considered.

Afterwards, the physical design of the line will be done, choosing between different layouts such as linear, U, and cell distribution among others. The performance of the remanufacturing line will be measured by choosing relevant KPIs, such as productivity (time), cost, quality, environmental impacts and ergonomics indicators.? Multiple experiments will be performed, one completely manual line, and other introducing industry 4.0 technologies such as cobots and AGVs helping with the disassembly, reassembly and transport. By analysing these indicators, the performance of both lines will be compared, and conclusions drawn.

Mentor: izr. prof. dr. Joško Valentinčič

Somentor: Helmi Ben Rejeb (Associate Professor at G-SCOP Grenoble)

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Declaration

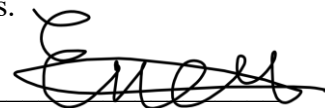
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Abstract

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Design and implementation of a pilot remanufacturing production line

Ever Alexander CENTE LOVATO

Keywords: **Remanufacturing**
 Circular Economy
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 Sustainable manufacturing
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The growing concern over resource scarcity and environmental damage has exposed the limitations of linear production models “take-make-dispose”. On this basis, circular economy and remanufacturing, provide effective solutions by extending product lifecycle, value preservation, and reducing the energy and materials consumption. This thesis presents the design and implementation of a pilot remanufacturing production line, with the objective of demonstrating its viability and evaluating its performance. A hydro turbine was selected as case study, and the remanufacturing stages – disassembly, diagnostic, cleaning, repairing, kitting, reassembly and quality control – were physically implemented, simulated and tested. Lean manufacturing principles were applied to improve workflow, while Industry 4.0 technologies were integrated to improve accuracy, ergonomics, quality, data management and decision-making.

The experiments of remanufacturing confirmed the technical feasibility of circular remanufacturing chains and demonstrated their potential advantages over linear models. Measured indicators such as value-added time, Material Circularity Index, and carbon footprint revealed improvements in productivity, quality, and sustainability.

Overall, the thesis contributes to bringing together theory and practice in circular economy by offering a replicable framework for research and education, supporting the ecological transition towards more sustainable and digitalized manufacturing systems.

Povzetek diplomskega dela

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Zasnova in izvedba krožne proizvodne linije za predelavo

Ever Alexander CENTE LOVATO

Ključne besede: Ponovna izdelava
Krožno gospodarstvo
Industrija 4.0
Trajnostna proizvodnja

Naraščajoča zaskrbljenost zaradi pomanjkanja virov in okoljske škode je razkrila omejitve linearnih proizvodnih modelov »vzemi-izdelaj-zavrzi«. Na tej podlagi krožno gospodarstvo in predelava zagotavljata učinkovite rešitve s podaljševanjem življenjskega cikla izdelkov, ohranjanjem vrednosti ter zmanjšanjem porabe energije in materialov. Ta diplomska naloga predstavlja zasnovo in izvedbo krožne proizvodne linije za predelavo s ciljem prikazati njeno izvedljivost in oceniti njeno delovanje. Kot študija primera je bila izbrana hidroturbina, faze predelave – demontaža, diagnostika, čiščenje, popravilo, kompletiranje, ponovna montaža in nadzor kakovosti – pa so bile fizično izvedene, simulirane in preizkušene. Za izboljšanje poteka dela so bila uporabljena načela vitke proizvodnje, tehnologije Industrije 4.0 pa so bile integrirane za izboljšanje natančnosti, ergonomije, kakovosti, upravljanja podatkov in odločanja. Poskusi predelave so potrdili tehnično izvedljivost krožnih verig predelave in pokazali njihove potencialne prednosti pred linearnimi modeli. Izmerjeni kazalniki, kot so čas dodane vrednosti, indeks krožnosti materialov in ogljični odtis, so pokazali izboljšave v produktivnosti, kakovosti in trajnosti.

Na splošno diplomsko delo prispeva k povezovanju teorije in prakse v krožnem gospodarstvu, saj ponuja ponovljiv okvir za raziskave in izobraževanje ter podpira ekološki prehod k bolj trajnostnim in digitaliziranim proizvodnim sistemom.

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List of symbols used

Symbol	Unit	Meaning
<i>VAT</i>	s	Value Added Time
<i>Tt</i>	s	Throughput time
<i>Wt</i>	s	Waiting time
<i>Trt</i>	s	Transport time
<i>Qi</i>	-	Quality index
<i>Ec</i>	€/h	Equipment cost
<i>Oc</i>	€/h	Operator cost
<i>Rf</i>	%	Reused mass fraction
<i>Mc</i>	€/kg	Material cost per kg
<i>V</i>	Kg	Virgin feedstock
<i>FR</i>	Kg	Feedstock derived from recycled sources
<i>FU</i>	kg	Feedstock from reused sources
<i>FS</i>	kg	Feedstock from biological material
<i>W₀</i>	Kg	Unrecoverable waste
<i>LFI</i>	%	Linear flow index
<i>X</i>	-	Utility of a product
<i>Cm%</i>	%	Circular mass fraction
<i>Cc%</i>	%	Circular cost fraction
<i>CF</i>	CO ₂ -eq	Carbon footprint
<i>BORG</i>	-	Borg Rating of Perceived Exertion
<i>NASA TLX</i>	-	Nasa Load Task Index
Indexes		

List of abbreviations used

Abbreviation	Meaning
3DPfR	3D printing for repair process
ABS	Acrylonitrile butadiene styrene
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AR	Augmented Reality
CAD	Computer Aided Design
CE	Circular economy
CT	Cycle time
DET	Detectability
DI	Dissemblability Index
DUBS	Dutch Scale of Boredom
FDM	Fused Deposition Modelling
FMEA	Failure Mode and Effects Analysis
GHG	Greenhouse gases emissions
HMA	Hot melt adhesives
I4.0	Industry 4.0
IN	Integrity Index
IoT	Internet of Things
M2M	Machine to Machine Communication
MCI	Material Circularity Indicator
NVAT	Non-Value-Added Time
OCC	Occurrence
PLA	Polylactic acid
RemPI	Remanufacturing Potential Index
RFI	Relative functional importance
RPN	Risk Priority Index
SEV	Severity
UR	Universal Robots
VAT	Value Added Time

1 Introduction

1.1 Background of the problem

The circular economy is an effective strategy for reducing the overall environmental impact of our consumer society [1]. It aims at decoupling economic growth from parallel current resource consumption. On this manner, circular economy offers a wide range of strategies to achieve this concrete objective and reduce the need for raw materials and energy consumption for obtaining the same results in terms of embodied value and quality of a certain good [2].

The aim of this project is to design an integrated physical chain to optimize circular industrial processes such as diagnosis, disassembly, repair, recycling and remanufacturing. Building on the existing Operations Management platform, the project aims to combine the scientific principles of circularity with industrial methodologies and advanced digital technologies to deliver an innovative and operational solution [3].

The main objective is to define the equipment and flows needed to deploy such a chain, based on an in-depth analysis of existing platforms, and therefore projecting the physical architecture and functionality of such production facility, up to the operational state and integral assessment of a forward-looking circular production line.

1.2 Objectives

Main objective

- Design and physical implementation of a functional remanufacturing production line at the S.mart platform of Grenoble INP, which include workstations for all remanufacturing stages: disassembly, diagnosis, cleaning, repairing, reassembly and quality control.

Specific objectives

1. State of the art: Carry out a literature review about the existing remanufacturing production lines, and the methodologies used in each stage of the remanufacturing processes.

-
2. Platform design: Develop the physical architecture of a remanufacturing production line that incorporates industry 4.0 technologies to help with the remanufacturing stages, such as robotics and digital tools, and to automate certain key stages.
 3. Performance measuring: Develop a methodology or tool to measure the performance of the remanufacturing production line, taking into account strategic indicators such as time, cost, quality, environmental impact and ergonomics.
 4. Assess the potential benefits of such a circular chain and determine based on aforementioned indicators the attractiveness of implementing this production model and the potential advantages of integrating industry 4.0 technologies.

1.3 Problematic

The principle of traditional linear economy model i.e. take-make dispose is incapable of managing the supply and demand balance in consumption of natural resources. This imbalance is affecting the planet's sustainability as well as affecting the environmental and socio-economic condition. In order to resolve the issue, industries are systematically shifting their production model towards a Circular Economy (CE) in terms of increasing product shelf life, handling the waste, achieving sustainability by the predisposition of customer priority towards substitute goods and services.

Fortunately, the advent of Industry 4.0 has provided immense opportunities for unlocking the potential for remanufacturing by reducing the cost of transformation into a higher level of connectivity and efficiency [4].

In this sense, universities play a great role as formative and research institutions, capable of catalyse and speed up the adoption of circular production models in any industry and research sector. They can and have the obligation to provide education and research how the application of circular operations can forge more efficient production and economic models, based on the use of circular principles to reduce the environmental impact and resources dependency, and at the same time the introduction of digital technologies that can support this operations.

Currently, within the Operations Management area of the platform S.mart, hosted by Grenoble Institute of Technology, a linear manufacturing chain was designed and operated, which consists on the use of different modular adjustable workstations, with the support of collaborative robots, AGVs, tracking, and other 4.0 technologies for logistics. This linear manufacturing chain is studied and developed by professors and engineering students into some academic courses at Grenoble INP. This teaching exercise comprises the assembly of the product and its quality testing.

However, due to the current trends for designing and developing a more sustainable manufacturing practices and products, many institutions have started to research how to impulse circularity of resources within production chains. One of this research points correspond to remanufacturing of durable goods, for which they have started to develop circular remanufacture production chain by integrating new intelligent technologies that aid make this process more efficient and economically attractive.

This is exactly what laboratory G SCOP is trying to develop, a remanufacturing chain that consists of modular workstations that include the diagnostic, disassembly, cleaning, repairing or manufacturing of obsolete and broken components, reassembly and testing. This model presents more complexity than linear manufacturing, since the "raw material" of the manufacturing chain is not homogeneous, but each product at its end-of-life scenario

presents different characteristics, has a different diagnostic, and consequently different needs and manufacturing and repairing technologies adapted to each of them.

Research questions:

- ✓ Is a remanufacturing line an economically and environmentally attractive option compared to a traditional linear production model?
- ✓ Can the implementation of Industry 4.0 technologies support the implementation of a remanufacturing line in terms of reducing cycle time, costs, and negative environmental impacts, and increasing the quality and ergonomic standards of line operators?

2 Theoretical foundations and literature review

2.1 Circular economy

The principle of linear economy model i.e. extract-make-dispose is incapable of managing the supply-demand balance in consumption of natural resources. This imbalance is affecting the planet's sustainability as well as affecting the environmental and socio-economic condition [5]. In order to resolve the issue, industries are systematically shifting their production model towards a Circular Economy (CE) in terms of increasing product life, handling the waste, achieving sustainability by the predisposition of customer priority towards substitute goods and services. [6]. Circular economy is a model where materials never become waste and thus natural environment is regenerated. In a circular economy model, products and materials are kept in circulation transiting through processes like repairing, reuse, refurbishment, remanufacture, recycling, composting [7].

Circulation of the technical product life cycle is enabled through several end-of-life (EOL) channels, including recycling, remanufacturing, reusing, refurbishing, etc. Among these end-of-life strategies, remanufacturing model shows big advantages thanks to its effectiveness in keeping the added-value of products and at the same time assuring their quality as comparable to new products of the same kind. Remanufacturing is the process of bringing products at their end of life, back to good-as-new condition through operations such as disassembly, cleaning, inspection, sorting, repairing, and reassembly. [4] It also creates and opens up new business and job opportunities in the after-sales service market. Another main advantage of remanufacturing lies in protection of the environment by reducing the usage of raw materials, carbon footprint, and number of components being scrapped. Nevertheless, the incursion of remanufacturing faces several obstacles, which need to be resolved properly through collaboration among multiple players through business, government, investors, society, and research communities [8].

As mentioned previously, manufacturing industry is undergoing transformation from linear to circular economy. The digital transformation enabled by the digital technologies is now known as Industry 4.0 (I4.0). It is related to developments in cyber-physical systems (CPS) building on the three previous revolutions pertaining to mechanization, electrification and information technology. [9] CPS are mechanisms that are controlled or monitored by software integrating computers, networks and physical processes [10]. In this direction, Industry 4.0 is considered as key innovative technology [11]. To promote transition from linear to circular economy in a supply chain and manufacturing process [12] value networks are integrated for transparency which is possible with the aid of Industry 4.0 technology.

Specifically, Industry 4.0 is based on the integration of advanced digital technologies (as the Internet of Things, complex data analysis, robotics, digital twins, artificial intelligence, etc), as well as non-traditional manufacturing technologies (as additive, laser technologies, smart tools, smart materials, composites, cobots, etc) to transform production processes, making them more efficient, flexible and customized [13].

Fortunately, the advent of Industry 4.0 has provided immense opportunities for unlocking the potential for remanufacturing by reducing the cost of transformation into a higher level of connectivity and efficiency [4].

Figure 1.1 below describes the three application areas and technical enablers from Industry 4.0. The technologies that support remanufacturing are presented in the outer ring of the circle, and include smart sensors, cloud computing, robotics, machine-to-machine communication (M2M), additive manufacturing, monitoring tools.

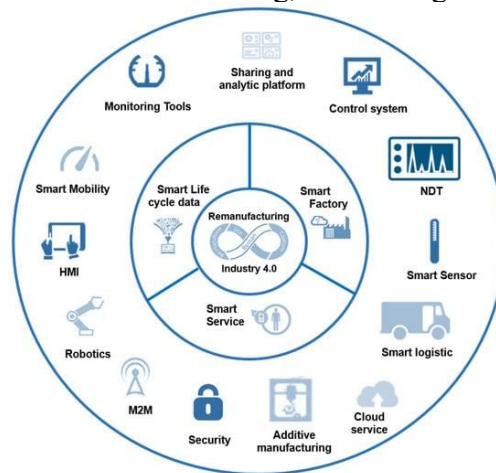


Figure 2.1. Pillars of Industry 4.0 and Remanufacturing association [4]

The flow of product information still remains mostly unestablished because of ineffective data extraction, loss of data during product transfer between stakeholders, lack of platforms to support information sharing, and other policies restrictions. Ineffectiveness of data circulation has significantly decreased the efficiency of its lifecycle management and the quality of service provided [14].

To restore this product to an as-new quality level, remanufacturers have to recreate or simulate product knowledge which existed at the product design stage. Under this regard, the digital transformation of Industry 4.0 has opened an opportunity to address this concern

by improving data transferability and constructing the knowledge and data sharing platform. This could be enabled by using sensors, embedded systems, and connected devices (IoT), as well as an adapted data management platform. For example, when information regarding computer-aided design (CAD), bill of materials, parts information, manufacturing and assembly instruction, information from use phase, and repair/refurbishing history are stored in a central system and are easily accessed by remanufacturers, the repair decisions during the remanufacturing phase can be made in a easier way and the required operations can be done in a more assertive manner [4].

In the same direction, when looking to the smart factories, in the future, machines could obtain important information through scanning a barcode attached to the main product, adapt the remanufacturing operations through self-optimization and smart managing capabilities, update the process-related information to a database via wireless, and store remanufacturing knowledge obtained from experience. This could bring a substantial reduction of the labour force and lessen the dependency on high-skilled operators [12].

Further innovative technologies, such as additive manufacturing, 3D scanning, automated guided vehicles, inspection drones, hybrid manufacturing/process, and XR tools, will continuously reduce the cost of remanufacturing operations while also delivering substantial improvements in the quality of the remanufactured product [4].

2.2 Remanufacturing operation

The remanufacturing process starts with the arrival of the used product at the remanufacturer's facilities, workshop or factory, where it will pass through several stages that include: complete disassembly, cleaning of its components, inspection and diagnosis, reconditioning or repairing of the parts that will be reused, replacement of non-manufacturable components, and reassembly, giving birth to a remanufactured product. This product is then tested to ensure that its quality is comparable to that of a new product [15].

Below, a description of the stages of remanufacturing process are given, according to [16]:

- Product disassembly: The purpose of this step is the dismantling of the product. This is one of the most time-consuming activities as it involves using tools and equipment not completely adapted to dismantling operations.
- Cleaning of the parts: Each of the components is cleaned with a dedicated cleaning agent, according to the material which is made of. Four process variants exist that enable cleaning: chemical effects, temperature, and mechanical action (e.g., removal by high-pressure water jetting), and time of exposure.
- Inspection, diagnosis and storage of components: This stage consists of an inspection to determine whether a component should be replaced or sent for other purposes, such as cannibalization, repair, or recycling. Storage refers to the site where the material will be kept for subsequent reassembly operations of the final assembled products.
- Reconditioning, repairing and replacement of components and parts (reprocessing): Components and parts are collected. Components that still have useful life remaining can be repaired. Finally, some of them are replaced with

new ones because they do not satisfy the minimum necessary requirements to assure the quality of a final remanufactured product.

- Product reassembly: This consists of the assembly of the remanufactured product. A final test will ensure that the remanufactured product performs similarly to a new one, with the same features, functions, and perceived quality, unless otherwise specified.

A graphical description of the remanufacture operation is shown in Figure 2.1, down below.

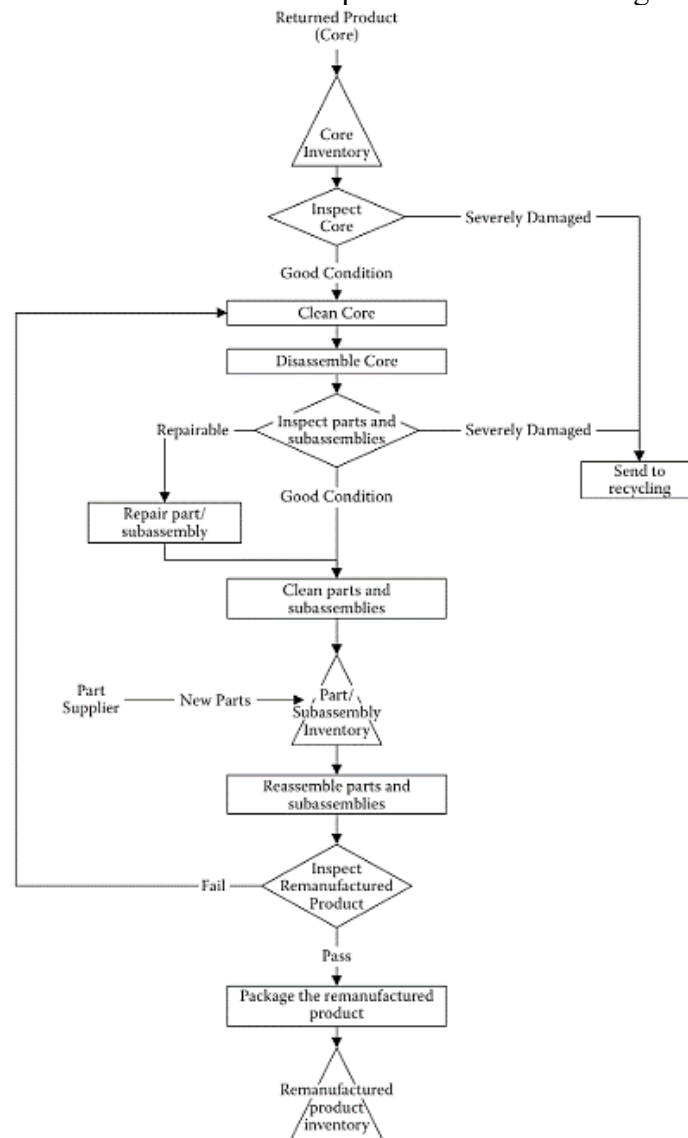


Figure 2.2. Manufacturing process flowchart [17]

2.2.1 Disassembly

Disassembly means much more than just reverse assembly. This is a fact, because there is no easy opposite operation for assembly operations like gluing, riveting, pressing, welding, among others.

The disassembly task also includes a starting identification and immediate scrapping of components, which are not reconditionable like broken housings, broken casings, bended components etc. It also includes the separation of all components which are fundamentally not reusable like gaskets, rivets, worn screws etc.

Disassembly is also more difficult than assembly because dirt, oxide and oil can cause the job of the workers to be slower. This encourages efforts to develop new solutions for the mechanization or even automation of disassembly processes. In recent years, also some experiments with industrial robots for disassembly operations have taken place and/or collaborative robots.

For the disassembly of the product, it is important to use a given methodology to orderly and neatly but most important easily take apart every component of the product and keep record of the different operations needed for each disassembly operation.

Disassembly mapping

The Disassembly mapping method, designed by [18], allows to keep track of different parameters concerning the disassembly operation:

- Disassembly sequence
- Disassembly time
- Type of tools required.
- Level of complexity of operations

The Disassembly Map, a representation method that can be used to map the architecture of a product in order to provide guidance to (re-)design for facilitating repairability. Below are presented the main features of this new method: general logic representations, action blocks, action block codes, penalties, and target indicators.

- General logic representations: Components are represented by a circle, containing a component number. The Disassembly Map begins with a circle representing the entire assembled product. Each circle is branched to the others with arrows that communicate the disassembly direction. Each component circle is indicated only when a component is completely removed. The Disassembly Map is based on three main logic representations: dependent sequential operations, independent operations, and multiple dependant operations, these are represented in Figure 2.3.

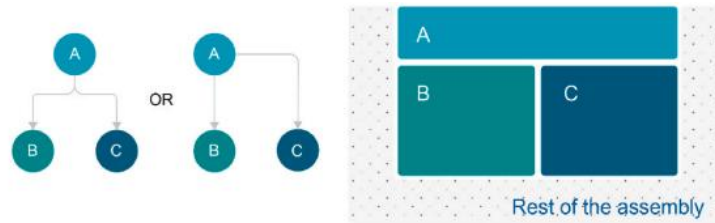


Fig. 2. Representation of sequence independent disassembly.

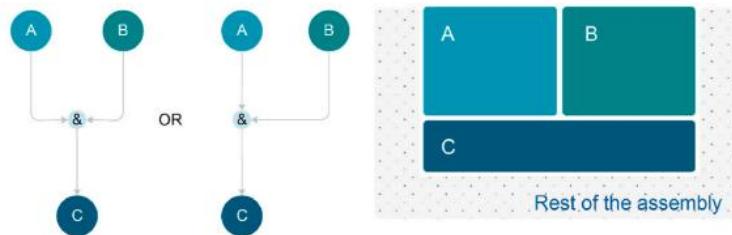


Fig. 3. Representation of multiple dependency.

Figure 2.3. General logic representations [18]

- Cluster blocks: Expanding on the logic described above, it is possible to depict even more complex disassembly scenarios. Clusters of components are represented by a single circle containing all the components' name or number, separated by commas. The representation of such clusters is important as correctly grouping components which share similar End-of-life processes or failure rates can greatly improve the repair, refurbishing or recycling of the cluster.
- Representation of alternative disassembly sequences: Both sequences should be represented in the Disassembly Map as they show the fastest sequences to two different but related target components, but which require a different disassembly sequence. This can be achieved by drawing multiple paths in the disassembly map.
- Disassembly action blocks: The degree of difficulty of separate disassembly actions influences disassembly time and thus the overall ease of disassembly. Disassembly difficulty depends on the nature of the operations required to remove a component, and thus finishing a stage of the disassembly process. Two main features are identified that influence disassembly time and difficulty: 'type of disassembly motion' and 'intensity of the required force'. The Disassembly Map uses action blocks to symbolize these features. Action blocks are placed next to the line between the component circles. If the same disassembly action (same fastener type and same tool used) is repeated multiple times, the number of repetitions can be indicated next to the block, facilitating the count of tool changes. Its visual representation is found at figure 2.4.

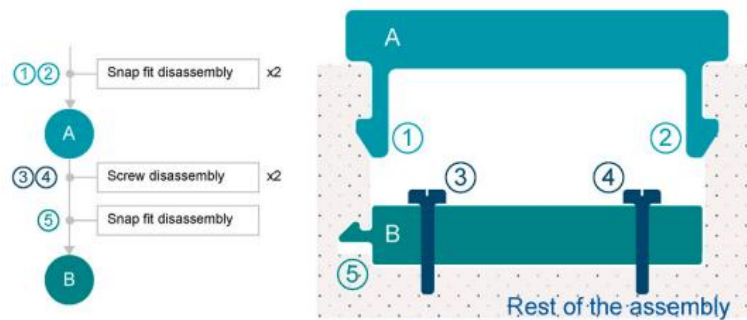


Figure 2.4. Representation of action blocks [18]

- Action block coding: Both the disassembly motion used for every disassembly procedure and the force intensity needed for joint loosening influence disassembly time, and they are represented by the use of the action blocks (Figure 2.5). Using different shapes, colours, tones and labels) to visually provide relevant process information. There are three different disassembly motions: hand motion, tool motion and multiple tool motion.

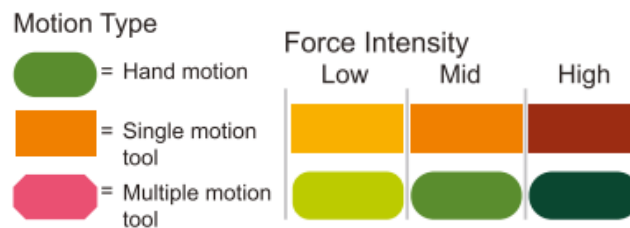


Figure 2.5. Action block coding [18]

- Disassembly penalties: Penalties indicate design details that are opposite to disassembly modular principles, as they negatively affect disassembly time and increase overall difficulty. Four aspects that negatively affect disassembly are: difficulty with product manipulation, low visibility, uncommon tool, non-reusable connector.
- Target component indicators: Indicators have been used to facilitate the localization of target components (Figure 2.6). These indicators identify those components that are more likely to fail or with functional importance, those with the highest embodied environmental impact and those with the largest economic value.

Target indicators representation.

Target indicator	Indicator icon	Use description
Failure indicator		It indicates the components with the highest failure rate or functional importance
Environmental indicator		It indicates the most environmentally harmful components or those with the highest embedded environmental impact
Economic indicator		It indicates the components with the highest embedded economic value

Figure 2.6. Target indicators representation [19]

2.2.2 Diagnostic

In order to identify the different steps and operations that are needed to repair, refurbish and/or remanufacture the product, it is needed to diagnose all the defects present on the product. According to [20], a recommended diagnose framework must be based on the identification of defects and identification of its localisation, rank them according to criticality, then identify the type of reconditioning or repairing operations to perform, decide reconditioning process sequence, risk and reliability assessment, and finally report on the diagnosis.

A more detailed explanation of these points is exposed below:

1. Identify defects and their locations: All the defects present in the principal component have to be identified, and one of the ways is by analysing the waste stream data. The locations and occurrences of the defects are mapped out over the core's shape. The surfaces, which are subject to the same loading and having the same design requirements, are clearly identified. The defects identification process is described in Figure 2.7.

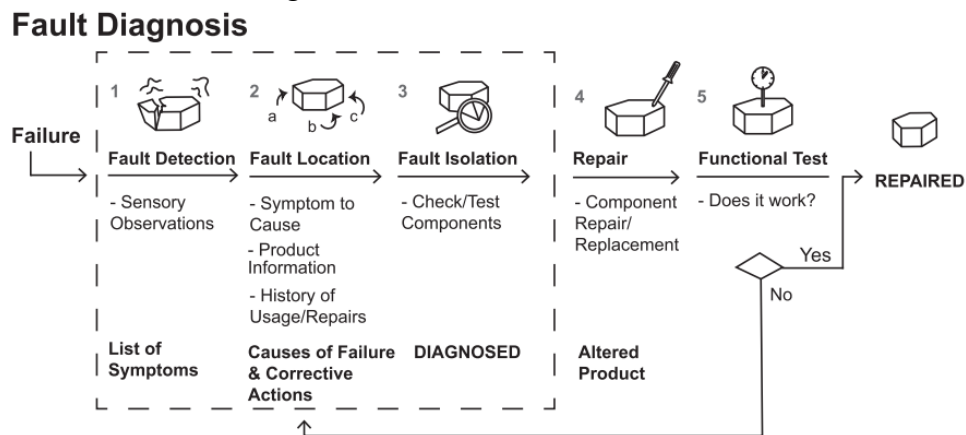


Figure 2.7. Fault diagnosis of components

Retrieved from: [21]

2. Assess defect criticality: In this step, a product Failure Mode and Effect Analysis (FMEA) is carried out. The different defects of the components must be grouped and scored using indicators: Occurrence (OCC), severity (SEV), and detectability (DET), and then ranked based on Risk Priority Number (RPN); where $RPN = OCC * SEV * DET$. This analysis takes into account the location of defect to the product's intended function, loading capacity and environmental condition. For example, a crack at the external surface of an engine is less critical than in the cylinder bore, which is subjected to contact pressure, sliding motion and higher heat.
3. Identify the nature of reconditioning operations for each defect: The final necessary properties of the principal product with respect to its material properties, condition and surface tolerances, such as surface roughness and hardness specifications, are determined from the engineering product attributes.

From the product design information, the desired technical attributes for each surface are identified and translated into product attributes. These will set the objectives of the reconditioning operations. Based on these objectives or requirements, the necessary operations can be chosen, for example: welding, surface treatments, electrolytical or chemical treatments, type of cleaning, etc.

4. Determine precedence relationships: They are determined based on three factors, which are defect priority, finish quality and the secondary effects of each reconditioning operation. The defect with the highest RPN obtained from step 2 is treated first. The reasoning behind is that it is preferable for the whole remanufacturing effort to fail in the first step rather than last step, when multiple defects are present in one component, so as to minimize costs. If the restoration of the critical defect is not successful, subsequent operations will not be performed to bring the component back to quality since the item will no longer be safe for utilization.
5. Risk and reliability assessment: A process Failure mode and effects analysis (FMEA) is performed to increase the reliability of the processes. Potential failure of the operations is identified through their high OCC and SEV and appropriate control measures are identified, that may increase the chances of success of the identified reconditioning processes.
6. Preliminary selection: The optimal reconditioning sequence satisfies scheduling needs and reliably delivers components of high-quality while being cost effective and environmentally benign.

RemPI methodology

Another new methodology proposed by [22] for diagnosis of the product and its components is the Remanufacturing Potential Index method (RemPI), which consists on assigning to each product, cluster or individual components a score based on three main parameters:

- Disassemblability index (DI) which depends on the product structure and disassembly complexity and is calculated based on the accessibility of the joint, the disassembly requirements, and the type of joint associated with each component.
- Integrity index (IN) which focuses on the condition and quality of the individual components of the product once they have been taken apart.
- The Relative functional importance (RFI) is defined as the degree of importance of a component concerning the product in terms of the number of components in contact and the number of functionalities that depend on such component.

The RemPI is calculated by multiplying the relative functional importance (RFI) and the square root of the product between Disassemblability Index (DI) and Integrity Index (NI). This calculation is performed for each component, so that it is possible to find a specific RemPI value for each component and globally for the product.

The first step is to receive the product and do a visual inspection to identify the disassemblability condition of each component (if the product uses reversible joints to disassemble the components). If the component is not disassemblable from the product, a score of 1.0 is assigned and continues with a destructive extraction and cleaning. If the

component is disassemblable, a separation of the component is performed to measure the RFI based on the number of joints within the product and the DI score considering the accessibility of the joints, the disassembly tool and force requirements, and the type of joint. In the case a defective component is identified in this first stage, then recycling is the recommended option. Later, a cleaning process is done, and the integrity of the product is validated, verifying whether the component is suitable for reuse, involving an assignation of 5.0 as NI score, or if it is necessary to perform repair or reconditioning. In case of not repairing possibilities, the component is classified as defective, and then recycling is again the recommended option. Otherwise, potential repairing technologies need to be identified, and the NI value is assigned to this task. Finally, with the scores for RFI, DI, and NI, the RemPI can be calculated. Relative weights in the RemPI tool are assumed to be equals for the parameters DI, NI, and RFI. However, it is suitable to be modified including relative weights according to the remanufacturer's interests. The process of inspection and score assignment is found in figure 2.8.

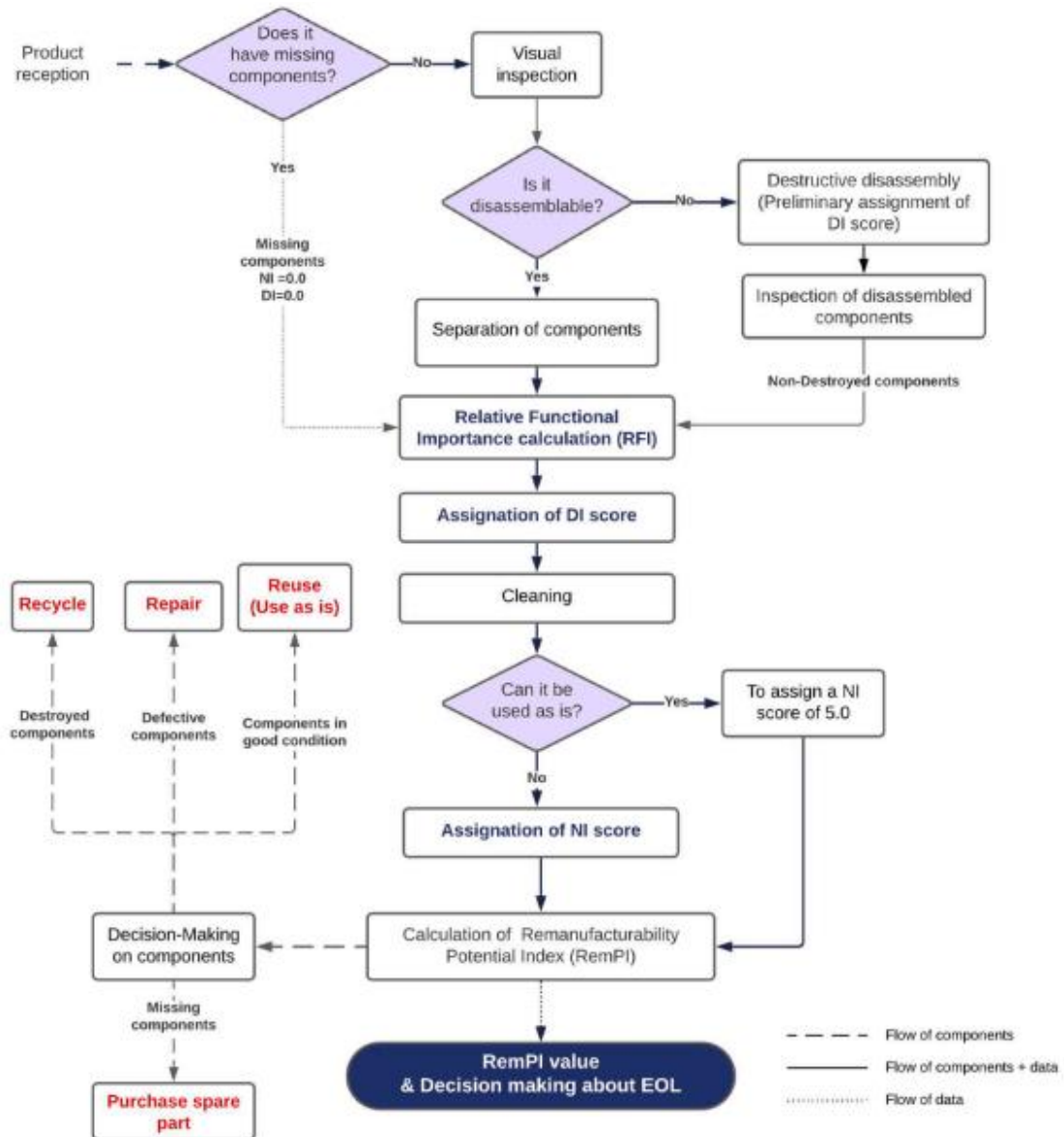


Figure 2.8. Methodology for implementing the RemPI methodology [22]

2.2.3 Repairing and reconditioning

The remanufactured product should be ideally free from any damage from its previous use phase and lifecycle, as well as from other effects from the repairing or reconditioning processes. Therefore, in selecting the process sequence, the side effects of each step on the component need to be taken into account to avoid reworking the component and saving time and money. According to [20] the types of reconditioning processes can be classified into five main categories:

- A. Remove surface and shape defects.
- B. Material addition or surface replacement
- C. Restore material properties.
- D. Assembly and fastening manipulation.
- E. Surface finish

A more detailed description of each reconditioning family is below:

- a) Remove surface and shape defects: Defects, such as cracks, scratches, holes, burnt or corroded regions, and inclusions are removed by machining processes such as turning, milling, drilling, grinding, etc. Surface finish and components tolerances are not the first priority but rather the removal of the inducers of residual stresses. However, if a part is in good condition and does not need to be further processed, machining with the final surface quality can be performed if it is technically feasible. When surface defects such as cracks are deep, the material around the defect is removed if refilling of such crater does not compromise the strength and safety requirements of the part. Shape defects, such as bends, warps, are also removed if technically feasible and the design and requirements considerations allow.
- b) Surface addition or surface replacement: A part with “cavities” or “holes” can be restored to its intended shape and gross dimension through material additive processes, such as welding, powder coating, laser cladding, or cold spray. According to the requirements and nature of the product surface, the appropriate method is chosen.
- c) Restore material properties: Desired material properties are restored through treatment processes, such as heat treatment, which either remove unwanted residual stresses (annealing, normalizing, and demagnetization), or prepare the part to be more resistant to its loading and environmental future operating condition. Such treatments can be either throughout the whole material or limited to a certain layer below the surface, such as in case hardening (carburizing, nitriding, induction hardening, shot peening).
- d) Assembly and fastening: In the case of sub-assemblies with many constituent components, assembly manipulation is needed as the parts are put back together. Such manipulation might alter dimensions, which require specific tolerances and cause them to be pulled out of nominal dimensions.
- e) Surface finishing: Fine surface finishing where final high-quality finish or dimensional tolerances such as roughness are required, can be achieved using procedures, such as grinding, reaming, honing, hard turning, and burnishing. In other types of surfaces, painting, coating, polishing and similar operations relevant to the

part are performed. This step is performed last because any subsequent process will affect the quality of the surface.

Reconditioning is the remanufacturing step assuring a “new” quality condition on the component again. It is the most important step in many applications. Depending on the product or unit remanufactured, it can occupy up to one-half of the workplaces of a remanufacturing plant, as a case study of automotive engine remanufacturing has shown [16].

The chosen product for this research internship consists of a hydraulic turbine for energy production, but for a pedagogical use, and is mostly composed of polymer components, fabricated by additive manufacturing, more specifically Fused Filament Deposition Technology. Because of this reason, the reconditioning or repairing techniques will be focused on polymer processing technologies, mainly to repair additive manufacturing made components, which is the original fabrication method for this product.

Currently, 3D printed parts are generally repaired by one of four different means: hot melt adhesives (HMA), super glue, acetone, and acrylic welding cement [23]. HMA can be applied with a hot glue gun, a handheld device. This means that HMA may be applied to surfaces underneath an object, which liquid agents would have trouble achieving. HMA are popular due to their low processing cost and fast bonding time.

Super glue may be used to repair fractures or delamination of a 3D printed parts. This is a common repair method for many hobbyists and DIY enthusiasts as they usually have it on hand and is commercially available. While the glue will work to keep two pieces of polymer together, the actual strength of the glue varies on the material being bonded and manufacturer of the glue.

Acetone is another product that may be used to for some repairs in 3D printed parts [24]. Acetone is a liquid substance generally used to smooth the surface texture of 3D printed parts, as well as being able to join two ABS components back together. This is achieved by applying acetone to the surface of the components that are to be joined. The acetone will dissolve the plastic, and these regions can then be held together.

Acrylic welding cement is currently industrially used for repairing 3D printed components as it creates a strong chemical bond and may be used to fill in gaps, cracks and holes. The exact strength of the bond created with acrylic welding cement depends on the material that is being bonded and its manufacturer.

2.2.3.1 Reprinting Methodology: 3DPfR

According to [25] one of the most optimized and easy methodology for repairing of circular products made mainly of polymers is the 3D printing for repair process (3DPfR), which consists on a generic framework reduced to four steps, that can be applied to a wide variety of consumer and industrial products. This methodology is used mainly when there is no availability of the digital version of the components (ex. CAD), or the components nominal measures are missing; it is also efficient when the original components were fabricated by other forming technologies and not additive manufacturing. The process is described below:

The 3DPfR process is structured into four phases: analysis, (re)design, manufacture, and test. These phases form an integrated iterative process.

1. **Analyse part and product** studies the part and product in detail to determine the part requirements. Analysis of component interaction (refers to how the part is connected within the product), part geometry (refers to what the part itself looks like), and part functionality, shows what part features and functions are critical, and which ones can be simplified. Reverse engineering applied to the original part can recreate the initial design intentions. This aids in finding the best design and manufacturing approximation and to indicate the process difficulty. The analyse steps that define tolerance/fit and identify performance requirements have the most significant influence on the repair result.

The steps for the analyse phase are the following:

- Define tolerance and fit.
 - Identify part reference points and critical features.
 - Recognize assembly joints.
 - Identify performance requirements.
 - Determine (missing) part geometry.
2. **(Re)Design process and digitalize part:** Ideate and model a component geometry that meets the part requirements from the analysis. Idea generation involves creative thinking to bring up suitable repair solutions. The part design should be adjusted and optimised for 3D printing according to design for 3D printing guidelines. Parts can be joined, separated, or simplified to an easier geometry with the same functionality.

The steps for the redesign phase are the following:

- Design a 3D printable part.
 - Design a functional part.
 - Simplify complex geometry.
 - Adapt accuracy and tolerances.
 - Adapt connectors and assembly.
 - Apply added value to improve part function.
 - Reduce excess material in design.
 - Reconfigure unsuitable part size.
 - Scan part measurements.
 - Model part geometry.
3. **Manufacturing phases** include two components, on one hand the manufacturing by **3D printing** that creates the physical object. The preparation steps for this include the CAD file as an STL file, which can be sliced to generate printer path coordinates. Part slicing can be influenced by printer settings, like supports, infill, layer thickness, wall thickness, and bed adhesion. Printer settings influence part functionality and aesthetics, as well as printing facility, time, and material consumption.

The main steps are the following:

- Choose optimal printing direction.
- Choose optimal printing settings.
- Export model to STL file.
- Post processing of the printed part if needed.

On the opposite, **repairing** restores the product to a functional state by using the 3D printed part. This involves component replacement. Components can be also locally restored by using spare materials, glue, melted material, etc. It can also be understood as a phase that implements the decisions and solutions to restore product functionality.

4. Finally, the **testing phase** verify that the printed component fit the requirements. Testing the part can include verifying print errors, part appearance, checking correct part dimensions, and proof testing (destructive or non-destructive) the mechanical behaviour. Requirements can be very varied, but according to [25], the most common requirements are (in order of frequency): mechanical properties, high accuracy/level of detail, aesthetic features, water contact, thermal performance, UV resistance, chemical resistance, food safety and water tightness.

2.2.3.2 Repairing methodology: material deposition

According to some researchers [23], deposition of fused material can be used to repair 3D printing components obtained by FDM. The tool used for performing the deposition is a 3D printing pen, which extrudes, and deposits fused ABS filament. This fused filament is deposited over the cracks and defects following a selected pattern such as “U”, “8”, “U & 8 combination” and “dot” patterns.

According to the author, the material must be deposited along the hole crack or joint line intended to be repaired. A figure showing the deposition of fused filament following a “U” pattern is shown below, in figure 2.9.



Figure 2.9. ABS broken specimen repaired with fused filament by 3D printing pen, following “U” deposition pattern [25]

The next step was to make tensile tests again of the specimens recently repaired. The results showed that most of the repaired components did fail at a certain tension load, but the location of the failure did not correspond to the location of the repairing portion. The results also showed that the “U” deposition pattern accounted for the highest maximum tension, and that it retained on average 85% percent of the original maximum tensile stress it can withstand.

2.2.4 Reassembly

The reassembly of the parts to conform final remanufactured products takes place on small batch assembly lines and employs the same power tools and equipment that is used in new product assembly operations. [16].

Opposite to what it may be believed, reassembly poses a greater challenge compared to disassembly, it consists not just the opposite operation, or the same as for the assembly of a new product, but the combination of components and spare parts is basically infinite, giving a great variance on the quality level of the remanufactured product, which is inconsistent with the desired quality and cost outcome for the product. In order to reduce this variability and assure that most remanufactured product share the desired quality, many reassembly methodologies have been researched and proposed by different authors.

As said previously, most of the reassembly methodologies proposed by different authors have as an objective to homogenize the quality of a certain quantity of products, while creating instead of a product range with one mode and normal distribution. A distribution with multiple smaller modes that can be commercialized as products with different quality levels, and consequently adapted to a broader market and willingness to pay [26]. Figure 2.10 shows the usual process of reassembly system, where spare parts are collected from used returned products, they join a central stock and then are reused to be reassembled without distinction to the product they belonged to. These parts are chosen purposely and not by chance, to comply with the objective quality for each product.

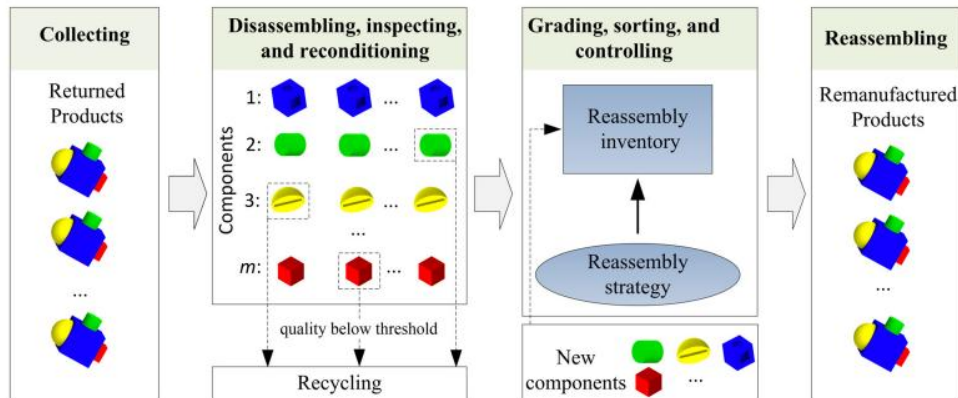


Figure 2.10. Reassembly strategy [27]

The Component oriented reassembly methodology is one of these proposed methods, it bases its principle on assigning a score to each spare component during the inspection procedure, so that all the components may be classified according to different categories, such as quality, remaining useful life, appearance, damage, etc. The components are paired with one another, and chains of component pairs are used to assemble and evaluate products based on product scores, under the control of a reassembly strategy. These reassembly strategies are evaluated, and the product scores are calculated using different objective functions, which represent different goals or remanufacturing scenarios [27].

Another proposed methodology is the optimization control model based on dynamic programming. Where, firstly, the state space model of reassembly process and its transfer matrix of reassembly reveal the coupling relationship of reassembly process. Then, the optimization decision model of the reassembly process based on dynamic programming is

established, and the online guidance in the reassembly line is created to optimize the control of remanufacturing assembly process [28].

2.3 Design of manufacturing line

When designing a new product, nowadays, more companies are considering a remanufacturing line or process following business models that support the return of used products rate and thus participate in a circular economy system. This involves a mean to receive these used products, disassemble them, clean and diagnose them, repair them and reassemble them. Following this idea, according to [29] the design of a remanufacturing line involves many key aspects, such as layout and production planning, including tools and equipment, material arrangement and handling, inventory management, and technology integration. In addition, according to these same authors, when designing a remanufacturing line, it is essential to adopt key enabling technologies for Industry 4.0 that contribute toward manufacturing optimization and the digital transformation of industry.

Citing [30], lean manufacturing is a set of principles that aims to maximize value for customer by eliminating waste, meaning it seeks to optimize processes by using fewer resources and focusing on what is essential to meet customer demands. This production model can be distinguished by being an integrated approach, focusing on eliminating activities that do not add value to the final product. Lean uses tools and techniques to identify and eliminate “wastes”, that may take the form of overproduction, transportation, overprocessing, and defects.

Circular production lines, such as refurbishing or remanufacturing, are similar to linear production lines from the assembly process and forwards, but additions previous stages that must be physically allocated, including a disassembly, diagnostic, cleaning, repairing, sorting, and other complementary operations.

From the very first stage of a circular production line, challenges are found, as disassembly is similar to reassembly one, but adds another degree of complexity, since analogously it can process different product variants (as reassembly), but this entry products presents also different conditions at their End-of-Life situations. Therefore, disassembly is an important process in remanufacturing industries, and it widely already exists in many recovery and circular industries. Many vehicle companies, such as Toyota, have disassembled EOL vehicles to remanufacture high-value components such as engines, starter motors, and alternators for many years [31]. Increasing demand for customized products results in various new products, and the quantity and variety of end-of-life products is rapidly expanding in the recycling and remanufacturing market. Because of that, the traditional single-product disassembly line is inappropriate and uneconomical to disassemble such increasing EOL product variants. [32]

This justifies the necessity of different strategies to optimize the operation of such a line, for example by using Lean Manufacturing principles that can smoothen the flux, saving resources as money and time, and preventing errors.

Feliz-Jacquez et. Al [29], developed a circular remanufacturing line integrating components, methods, and principles from both: lean manufacturing and industry 4.0. They collected information from previous papers, and identified what tools or principles can be applied into remanufacturing lines, those are listed in the table 2.1 below:

Table 2.1. Strategies and core tools, methods, and techniques

Lean Manufacturing	Industry 4.0
Value Stream Mapping	IoT
Kanban	ERP
Just in time	Robotics
Single Minute Exchange of Dies	AI
5S	AR/VR

Lean manufacturing consists on a methodology that can help optimize production operations, the core idea of lean manufacturing, (i.e., lean production) is actually quite simple; relentlessly work on eliminating waste from the manufacturing process [33]. On this way, Just-In-Time methodology seeks to deliver what is needed, at the right time, to the right place, and in the right quantity. And all this while using the minimum of resources. According to [34], lean manufacturing provide different tools that can be adopted in order to avoid the waste found in traditional production due to practices such as batch fabrication, in work stock between stations, long and frequent transports, big facilities, long lead time, and wrong or delayed detection of errors. Some tools are explained below.

- ✚ **Cycle time** consists of the necessary time for a trained operator, for performing a certain task or operation to which he/she is capable of. It is measured at normal speed, taking into account a correct disposition of materials within the workstation, ergonomics, and with the best proven operation technique. It allows to calculate costs, allocate resources, operators, divide tasks.
- ✚ **Line balancing** seeks to make all workstations and operations, to last a very similar amount of time, ensuring a smooth flow within the production line, without bottle necks and stock accumulation. Thanks to cycle times, operations can be either divided or either allocated more human resources or equipment to balance the time of each workstation.
- ✚ **Spaghetti diagram** can provide an insightful view of the transport flows of in work products and its components inside the production plant. It helps to visualize graphically the path that a product or operators follow in a certain zone. It can show the complex transport operations within the facilities and thanks to this, is possible to rearrange stations, operations to reduce the complexity of the path to the minimum, and reduce transport time, cost and delivering errors.
- ✚ **The U production line** allows for increased flexibility when dividing up workstations. Also, one operator can move from one workstation to another is necessary, as they are placed very close to each other, so minimizing transport times and balancing problems. The U line adds flexibility to the line and increases the productivity by square meter. The U line is adapted to manual or semi-automatic production models, in small or moderate series, and for products with moderate variants. It also seeks to place stations next to each other following a logical sequential order and make material delivery by the front on the station, external to the line.
- ✚ **Workstations ergonomics** seeks to adapt the workstations and work task to the operator and not vice-versa. This method is intended to reduce the wideness and complexity of operations motion, especially the arms. It also applies a principle

called economy of movement, to save time, where the most used tools or materials are closer to the operator to facilitate the reaching. By doing this, inutile motions are eliminated, over costs are avoided, and musculoskeletal disorders and accidents are avoided as well.

- ✚ **Mizusumashi** means water spider in Japanese, it is an analogy for characterize the logistician and deliver within the line, which moves inside the facility to transport the work-in-progress products. Most commonly is assured by a logistician operator, or an autonomous vehicle, its work is standardized and make transport cycles at regular periods following a standardized path.
- ✚ **Kitting** looks to deliver to a certain workstation, a kit specific for a product model or variant, with the correct components in variant and quantity. Kitting allows to reach many objectives: reduce the physical surface required at the edge of the line, increase quality by decreasing errors, decrease the assembly manipulations, reduce the lead time of assembly process.
- ✚ **Shadow boards** provide a dedicated place for small equipment such as cleaning utensils and hand tools. Whenever equipment is not in use, returning it to the shadow board means it will be found next time.

Example of a case study of a remanufacturing line

There are very few case studies of functional remanufacturing lines in literature, and among them, very few explore different scenarios and line configurations with the aim of comparing them.

The case study proposed by [29] was one of the few case studies with similar objectives to the present research thesis, and consists on the design and implementation of a remanufacturing facility for railway diesel engines. The work answers the customers' needs by incorporating strategies such from Lean Manufacturing, Supply Chain Management, and Industry 4.0, which were introducing in different stages and each of them evaluated.

Their objective was to supply a precise production plan capable of maximizing the use of workstations in variable environments. In their design plan, the engine arrives for remanufacturing and departs already repaired and ready to be delivered to the customer. The identified production flow is shown below in figure 2.11, that comprises the following six basic operations in the remanufacturing line:

- P1. Engine disassembly. The parts are extracted and classified to be reused or reworked.
- P2. Qualification of parts. The parts are identified through the bill of materials (BOM) and selected for repair, recycling, and reuse using the critical to-quality tool.
- P3. Engine assembly. The desired transformation from the initial engine model to one that produces fewer carbon emissions.
- P4. Test Cell. A series of tests to verify that the engine meets the quality standards.
- P5. Torque. The engine passes the process of bolt and screw tightening.
- P6. Painting. The engine is painted and packed as a final product.

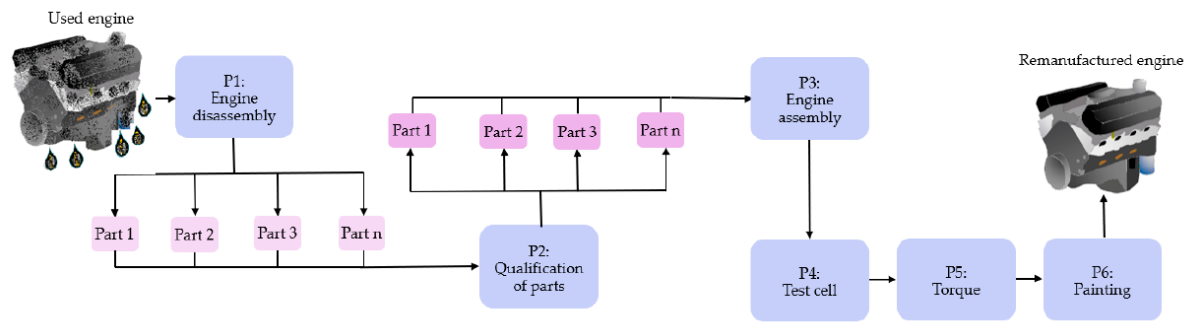


Figure 2.11. Flowchart of the remanufacturing process [29]

In their case example, they implemented four different scenarios, going from the least to the most complex, and gradually introducing LM, SC and I4.0 tools and principles. The table 2.2 below describes the four scenarios evaluated.

Table 2.2. The strategies applied to the scenarios in the remanufacturing line

Scenario	Description	Strategies LM, SC and I4.0	Core Tools
1	Remanufacturing line initial conditions. A forklift hauls materials from the warehouse to stations, a crane transports engines, and a warehouse holds materials.	Basic model	-
2	Scenario 1, plus the change in the layout distribution that decreases the distance by 66% from P3 station to P2 and P4 to reduce personnel trips, CT, and throughput.	LM1: Layout redesign to reduce travel times in the process.	VSM, SD, LR
3	Scenario 2, plus the supply of SM type materials for a better disposition of the materials, using a forklift to station P3 reduces delivery time by 9.91%.	LM2: Reduction in operator down time. SC1: New arrangement of materials.	KA, SM
4	Scenario 3, plus the employment of MK ready to use at P3 station, previously checked BOM at P2, the materials are ordered and sent to continue the flow of a piece with KN systems.	LM3: Installation of material kits at the point of use. SC2: Order of materials by kit.	MK, KN
5	Scenario 4, plus IoT for communication in the areas, exploiting CC, statistics, and information. A synchronization between P2 and the warehouse occurs for the arrival of the MK to P3.	I4.0: Integration of IoT and data in the cloud.	IoT, CC

VSM: Value stream mapping; SD: Spaghetti diagram; LR: Layout redesign; KA: Kaizen; SM: Supply management; MK: Material kits; KN: Kanban; CC: Cloud computing.

Results

From the analysis carried out with the incremental strategies integration, the statistics obtained are the work-in-process (WIP) inventory measured in engine units, the value-added time (VAT), and the non-value-added time (NVAT) measured in hours. The indicators that represent the dependent variables are throughput and total production time or CT.

Table 2.3 exhibits the strategy applied incrementally, followed by the throughput values, WIP inventory, CT, and VAT considering the average time process (ATP). NVAT is defined by the average time in move logic (ATML), the average time waiting (ATW), and the average time blocking (ATB). The results for the scenarios are as follows, in table C:

Table 2.3. Results of the scenarios, remanufactured engines, and average times [29]

Scenario	Strategies	Throughput (Engines)	WIP (Components)	CT (h)	ATP (h)	ATML (h)	ATW (h)	ATB (h)
1	Basic model	29.0	1.0	269.89	125.54	90.08	47.28	6.99
2	LM1	29.0	1.0	238.41	123.65	104.33	6.69	3.46
3	LM2, SC1	31.0	1.0	213.18	122.17	81.73	3.48	5.80
4	LM3, SC2	34.4	0.0	216.12	115.18	88.01	3.94	8.99
5	I4.0	40.0	0.0	214.45	115.06	90.11	3.30	5.99

As it can be appreciated, from their results, the cycle time is strongly reduced from scenario 1 to scenario 3, corresponding to the implementation of supply chain and layout design principles, but did not decrease in posterior scenarios with the introduction of lean manufacturing and I4.0 technologies.

However, with the introduction of lean manufacturing and I 4.0 technologies such as internet of things and cloud data sharing, the quality of engines produced was increased approximately by 25%. The % of Value-Added Time just increased by 7% from the scenario 1 to scenario 2, but it's mainly increase was due to the introduction of lean manufacturing and IoT and cloud data sharing.

2.4 Industry 4.0

The fourth industrial revolution is commonly known as Industry 4.0. This fourth revolution fusions physical systems and biological systems, to generate an intelligent production network where diverse components interact and collaborate with one another [35]. Industry 4.0 describes the digitalization of the systems and industrial processes and its interconnexion by IoT and services internet, in order to achieve a higher flexibility and individuality of the productive processes. During the production phase, for example, the efficient transformation of the raw materials into finished products can be overviewed by multiple I4.0 technologies, such as autonomous robots to assure process automation and Digital Twin and Artificial Intelligence to simulate and optimize processes [36].

According to [36], several technologies from Industry 4.0 have the potential to be applied in pro of circular economy production models, as they can help optimize, predict, and adapt to each individual (re)manufacturing processes or refurbishing processes, through IoT, AI, closed loop feedback, Machine Learning, customized components, etc. A summary of the identified technologies is found below:

- Additive Manufacturing: Manufacturing process that consists of building a 3D object by adding layer by layer,, guided by a digital model or 3D CAD data.
- Artificial Intelligence: Development of information systems that execute operations comparable to those of human mind, such as learning or logical reasoning [37].
- Autonomous robots: Robotic systems that are capable of doing tasks without direct human intervention or guidance. It can independently navigate the environment, take decisions, move, interact with objects and perform tasks.
- Big data and analytics: Is large amounts of data, generated from various sources at high velocity and high complexity degree. Big analytics consists of extracting insights and conclusions from large and complex datasets.

-
- Cyber-Physical Systems: Integrates physical components with digital environment through sensors and communication networks that creates a smooth interaction between the physical and the virtual world [13].
 - Digital twin: Virtual representation of a physical object, system or process that exists in a digital environment. It's a computer-generated model that mirrors its real-world counterparts, behaviour and characteristics.
 - Virtual and Augmented Reality: Creates a computer modelled digital environment, in where a person can explore and interact with. Can help visualize a certain operation before takes place in the real world. Augmented reality enhance user's real-world environment by adding layers of object onto real objects, such as images, videos, animations, 3D objects [36].

2.5 Key Performance Indicators for production lines

Key Performance Indicators (KPI) are management methods used to enable efficient and effective business operations monitoring, and are generally acknowledged to be a set of measures critical to the current and future success of any organization, operations, business [38]. Key performance indicators (KPI) act as decision-support tools for decision-makers to control and improve system performance. Nevertheless, the nature of circular remanufacturing makes it difficult to determine suitable KPIs to choose and employ [39].

According to the authors Mejia-Moncayo, Chaabane, Kenne & Hof [39], the most common and most mentioned KPIs in literature are in order of frequency:

Economic: With 703 indicators in total, and the most common mentioned below.

1. Cost: The most common indicator to measure remanufacturing operations and circular supply chains, including but not exhaustively, transport, fixed, recovery, remanufacturing, total, production, investment costs, etc.
2. Disassembly time
3. Core quality condition and product quality.
4. Products price.
5. Capacity
6. Revenue
7. Distance

Environmental: With 334 indicators in total, and the most frequent cited below.

1. Energy, consumption, saved, embodied, renewable.
2. Environmental impact
3. Greenhouse gases emissions
4. Recycling materials
5. Remanufactured parts
6. Reused parts.

Social: With 116 indicators in total, and the most common listed below.

1. Health and safety
2. Job creation
3. Employment stability

These indicators bring a better picture of the condition and situation of remanufacturing operations, including production lines, supply chains, redesign, etc. The main and more pertinent indicators to evaluate a remanufacturing line are better explained next, including some simplifications for these indicators.

3 Research methodology

Different methodologies have been used to the development of the remanufacturing line, for the choice and design of workstations, such as disassembly, diagnosis, repairing, and reassembly methodology. In the same way, different methods and tools have been used for the physical distribution of the remanufacturing line, such as lean manufacturing tools, and digital technologies that may improve the line operation. Different experimentations have been organized as well based on the line design, so they could be tested, and valuable information were collected from these simulations, regarding cost, times, quality of the product, environmental impacts and ergonomic situation.

3.1 Materials

3.1.1 Product

Proposed case study

The chosen product for the design, simulation and implementation of the remanufacturing production line is a hydraulic generator, which primary function is to produce electricity when installed in small water conducts that make the blade turn thus converting kinetic energy into electrical energy. The detailed description of the product is described below:

The proposed product is a hydro turbine (Figure 3.1), whose purpose is to produce electricity by the turning of the propeller, and is intended to be installed on water channels or water currents. However, at the moment, this product is used only for pedagogical use, in the simulation of the industrialization of a product, production chain, and flux. This proposed product has been conceived and developed for multiple circular production models that have been tested at S.mart Platform, Grenoble INP [40].

The functioning of the hydro turbine is simple, is composed of three main assemblies: the propeller, the body and the rear cap with the generator. The propeller has the blades attached to it. So, when it turns, by friction, make the rotor of an internal generator turn with it. This way, the internal generator produces electricity. All the components of the hydro turbine, its classification and associated cost are shown in figure 3.2.

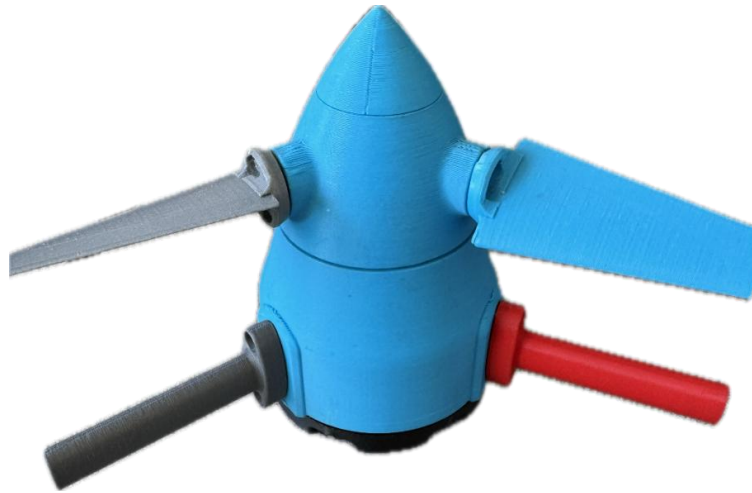


Figure 3.1. Picture of the hydro turbine, chosen product for the implementation of the circular chain

3.1.2 Available equipment at the S.mart platform

Smart worktables

Industrial workbenches are modular workbenches that have many channels where different accessories can be attached or hanged, for example secondary platforms to put material or tools, video projectors or cameras, extendible arms support for devices, etc. The height of the tables can also be adjusted depending on the height of the operator. The workbench needs to be connected to electricity to work and has several plugs at the table level height.

Tablets

Tablets available at Operations Management Platform were Samsung Galaxy brand. An app downloaded on the tablet, called Scan-It-to-Office, was necessary in order to scan the QR codes of each product component and successfully sending the information to the database datasheet.

Cobots

Two cobots were available at the Operations Management Platform, the description of both can be found below:

Franka Emika Panda Cobot

The Franka Emika Panda robot is a 7-axis robot arm (Figure 3.3), it has a payload of 3 kg and a reach of 850 mm. Manufacturing applications include Remote TCP [41].

Hydro Turbine Component breakdown

Subsystem	#	Component	Material*	Shaping process**	Mass (g)	Cost (\$)
Propeller	1	Nose	ABS	Fused Filament deposition	4,9	0,25725
	2	Screw CHC M4	Steel	Bought from supplier	0,8 *6	0,0048
	3	Blade	ABS	Fused Filament deposition	6,5 * 3	1,023
	4	Propeller body	ABS	Fused Filament deposition	72,2	3,7905
Body	5	Rubber ring	Nitrile Rubber (NBR)	Bought from supplier	2,1	0,0084
	6	Body	ABS	Fused Filament deposition	72,8	3,822
	7	Fixation arm	ABS	Fused Filament deposition	6,7 * 3	1,05525
	8	Screw CHC M3	Steel	Bought from supplier	1,6	0,0096
	9	Bearing	Stainless Steel	Bought from supplier	125,5 * 2	2,6
	10	Spacer	ABS	Fused Filament deposition	8,4	0,441
	11	Circlip	Stainless Steel	Bought from supplier	6,2	0,0558
Generator	12	Ring	ABS	Fused Filament deposition	1,4	0,0735
	13	Rotor	Steel	Bought from supplier	12,3	0,0123
	14	Generator stator	Copper	Bought from supplier	21,8	0,1635
	15	Screw M2.5	Steel	Bought from supplier	0,3	0,0012
	16	Rear cap	ABS	Fused Filament deposition	40,5	2,12625
	17	Elastic ring	Nitrile Rubber (NBR)	Bought from supplier	0,4	0,0016
	18	Screw CHC M3	Steel	Bought from supplier	1,6	0,0096
Total						\$ 15,455

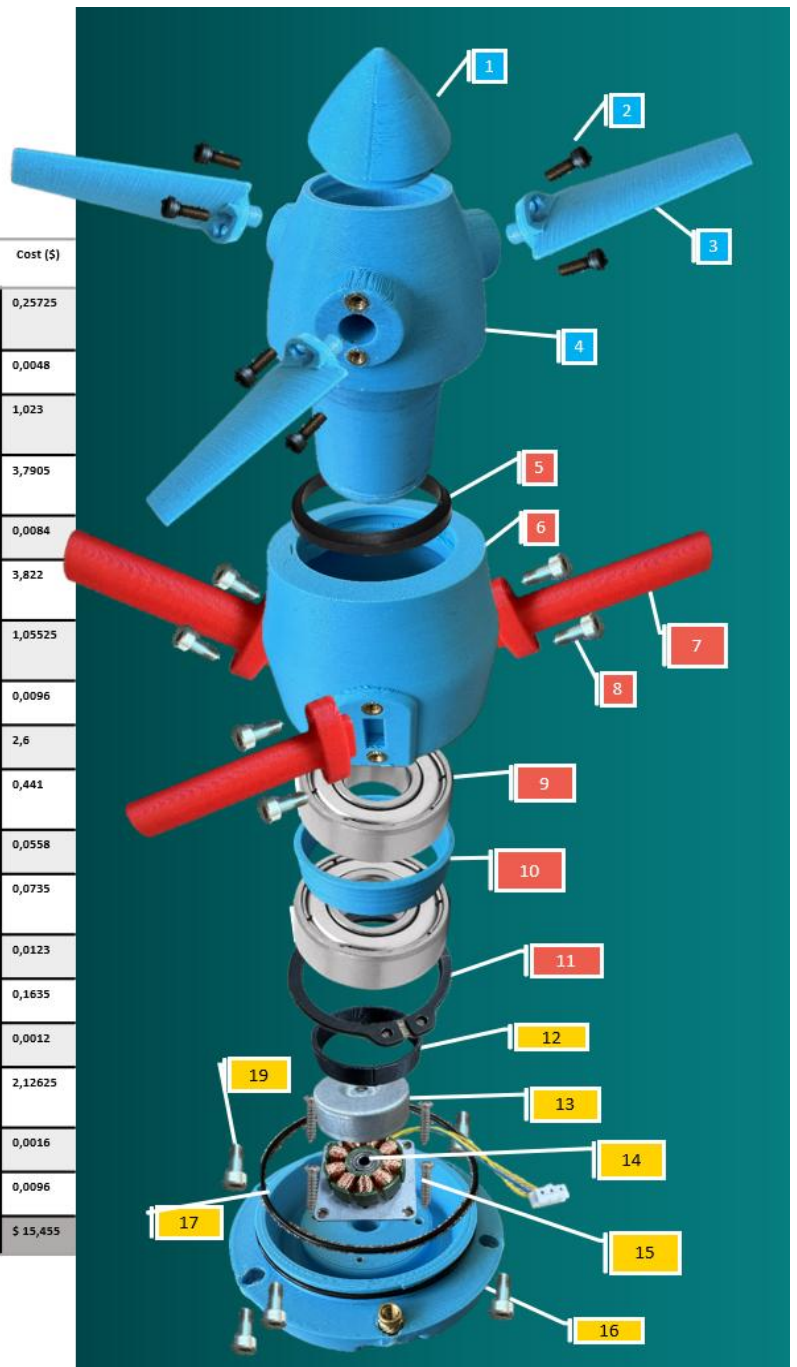


Figure 3.2. Components of the hydro turbine, materials, weight and costs.

Common applications of the Franka Emika Panda include Assembly, Collaborative, Dispensing, Material Handling, Remote TCP.

The specifications of the Panda Cobot are the following (Table 3.1):

Table 3.1. Specifications of Franka Emika Panda Cobot [41]

Brand	Franka
Model	Emika Panda
Type	Robot Arm
Axes	7
Payload	3.0 kg
Reach	850 mm
Repeatability	0.1 mm
Weight	18 kg



Figure 3.3. Diagram of Franka Emika Panda Cobot [41]

Universal Robots Cobot

The UR3e is the smallest industrial collaborative robot arm in our portfolio. Benefit from its compact form when automating processes in tight workspaces, such as on bench-tops or within production machinery. Table 3.2 shows the specifications of UR robot.

Table 3.2. Specifications of Universal Robots cobot [42]

Brand	Universal Robots
Model	UR3e
Type	Robot Arm
Axes	7
Payload	3.0 kg
Reach	500 mm
Footprint	128 mm
Weight	24.7 kg

Spectrometer miROSpark 2.0

The spectrometer miROSpark 2.0, is a polymer-specialized spectrometer including two different spectrometry methods. NIR, the diffuse near infrared reflection spectroscopy where the characteristic absorption patterns of different polymer types in a typical spectral region are used, as the polymer sample is radiated with infrared light and the reflected light of the measuring place is analysed by a near infrared detector array.

The other method consists of the Sliding Spark technology that is the thermal vaporization of a small amount of the plastic surface using a train of energy-defined high current sliding sparks. The material components in the spark plasma are vaporized, ionized and activated to emit radiation [43].

In order to identify the polymer type, one of the pistols must be simply pressed to the sample and actioned the pistol grip.

The technical data of the spectrometer is on the table 3.3 below:

Table 3.3. Specifications of the miROSpark 2.0 spectrometer [43]

Dimensions	364 x 200 x 376 mm
Weight	14 kg
Power supply	100, 110 or 230 VAC, 50/60 Hz

3.2 Design of remanufacturing operations

Each of the different operations within a remanufacturing line have been developed by using specific research methodologies adapted to each task requirements, which have been taken from literature, in some cases have been straightly followed, while in other cases simplifications have been made. These methods have been applied to all of the core stages of remanufacturing such as disassembly, diagnostic, repairing and reassembly, and the details of each one can be found in this section.

3.2.1 Disassembly

Disassembly operation consisted of taken apart all the components of the hydro turbine product. The hydro turbine is composed by three main subassemblies: the propeller assembly, where the blades and nose are attached; the body assembly, which works as the fixed part of the turbine, and where the fixating arms are attached; and the rear cap, which closes the rear side of the turbine, and holds the generator that produces electricity.

The disassembly mapping methodology, whose description can be found in chapter II, was used to determine the progressive disassembly steps for the product, and at the same time used to determine the division of the task between the operators implied in the disassembly workstation.

Through this mapping methodology, subassemblies were marked, required tools were identified and the disassembly tasks were divided. Afterwards, times for each disassembly subassembly task were recorded, and the whole disassembly operation divided, and subassembly tasks allocated to the operators. The results of the disassembly mapping can be consulted in chapter III.

The picture of the disassembly station can be found in appendix A.

3.2.2 Diagnostic

The diagnostic operation was one of the most critical operations of all the line. At this station all the disassembled components were analysed, compared to a defects database and the operator decided whether the component state was well enough to be directly reused, not so damaged so it can be repaired, or unrecoverable and sent to recycling. The cleaning state was also assessed so, it was also decided whether or not a component was clean or dirty.

A database of defects was created to enable comparing to be easily done by the operator. This database was based on the diagnostic methodology found in literature, presented in chapter II.

An example of the defects database, specifically for the propeller component can be found in appendix B.

A picture of the diagnostic station can be found as well, in appendix C.

3.2.3 Cleaning and Sorting

- First, every component labelled as dirty, or labelled for recycling, underwent a cleaning operation, which consisted, in a simplified way, to remove by hand, all the contaminants, stuck paper, waste, scrap, except by the QR identificatory, from the polymer component.
- Second, every component labelled for repairing or recycling, was sorted by material type, using a material detection spectrometer, mIROSpark 2.0. Components were then classified according to their material composition, either ABS, PLA, or other/undetermined. The components were then sent to the repairing operation, if labelled to be repaired; or remained in unrecoverable sorted stock, waiting to be sent for recycling.

A picture of cleaning/sorting workstation can be found in appendix D.

3.2.4 Repairing

Only components labelled as to be repaired at the diagnostic station had to pass through this station. Here, damaged components were repaired using a Material Deposition methodology, mentioned in chapter II.

Components small sections with slightly broken or plasticized volumes were melted using a soldering iron, and the material was rearranged. Afterwards, new polymer filament, corresponding to the material type, was added, following a zig zag pattern, in order to reinforce the weakened section. An example of the results of the application of this methodology is shown in chapter III.

Repaired components were then sent to main stock at kitting station, same as directly reused components.

A picture of repairing workstation can be found in appendix E.

3.2.5 Kitting

Kitting station was idealized from the necessity to facilitate product reassembly operations, by adopting Lean manufacturing practices, such as the use of kits. Kits include all the components needed for the reassembly of one product, components are in their correct quantity and variant, so that reassembly operators don't have to add any other new component.

The main stock of new, reused and repaired components was located at this workstation, so that the operator can pick all the required components to make a kit and send it to reassembly. The operator had a specific list of components' variety and quantities that must be respected. To facilitate the picking operation, and ensure it is correctly done, another Lean Manufacturing practice was taken, the shadow board, which is commonly used for placing, storing and not missing tools; but in this case was adopted as a mat with all the components figures, to whom the operator put the correct piece over it. In chapter III, the kitting shadow mat is shown.

After all the components were put together in the mat, they were transferred together to a blue industrial bin, which had a QR code assigned to it.

A picture of kitting workstation can be found in appendix F.

3.2.6 Reassembly

Reassembly operation consists of putting back together all the components of a hydro turbine, such as in a standard linear production model.

Kits were received at the reassembly station, and then similarly as the disassembly stations, different sub-assemblies were allocated to two operators on this workstation.

Analogously to disassembly station, times the reassembly of each subassembly were recorded, and the tasks divided, and allocated to the operators.

A picture of the disassembly station(s) can be found in appendix G.

3.2.7 Quality control

After having reassembled the hydro turbine, the next and last stage in the remanufacturing line is the quality control. Every product must pass by quality control, where they are checked basically in three aspects:

- a) General integrity: The operator evaluated the outside state of the hydro turbine, verifying if there are cracks, delamination or other surface defects.
- b) Joints check: The operator checked every join between two components to verifying its state, whether or not has been correctly and firmly screwed.

-
- c) Functional check: The operator verified if the propeller can properly and smoothly turn into the hydro turbine body axis.

These checks were done manually, and a specific form was filled for each product, which were afterwards digitalized.

The checklist form used for checking product quality can be found in appendix H, as well as a picture of this workstation can be found in appendix I.

3.3 Design of remanufacturing line and experimentations

Experiment 1: Exploratory manual line

First, an exploratory remanufacturing production line was planned and performed, putting together into a U line all the remanufacturing steps mentioned in section 3.2. Each stage was assigned to a different physical workstation, and operators were assigned to them.

After having decided on the remanufacturing stages and workstations operations, the next step is putting all together into a physical platform such as the Operations Management Platform. It is important to put all operations in the correct order so the flux in the remanufacturing line can be smooth and no logistic problems to be found.

The decided order of operations was as in 3.2 section: disassembly, diagnostic, cleaning/sorting, repairing, kitting, reassembly and quality control.

In order to compare different models, including and excluding technology, an exclusively manual line was planned.

All the operations would be done manually, including transport, manipulations, except screwing operation.

The description of each workstation of the manual remanufacturing line is as follows:

1. Disassembly: Three operators take apart all the product's components, by using supports to hold on the product on an appropriate position, and electronic screwdrivers to remove all the screws.
2. Diagnostic: One operator has a printed database to compare each arriving disassembled component to it, and determine by using plain sight, if the component can be directly reused, cleaned, repaired or sent to recycling.
3. Cleaning and material detection: First, one operator takes each component that has been classified to be cleaned, recycled or repaired. The operator removes manually all the dirtiness and stains from the component and then uses an optical spectrometer to determine the polymer material type and be able to classify it correctly. For the exploratory experiment, cleaning and material detection were two different workstations.
4. Kitting: Here, all the reused, and repaired components are stored, together with new ones. The operator picks all the components needed to assembly one product, in its required exact quantity and places it in a bin, which composes a kit to be sent to reassembly.
5. Reassembly: Three operators perform the assembly of the product, dividing the product subassemblies in three sections, to make the operation faster. The three divisions are: reassembly of propeller, reassembly of main body, and reassembly of rear cap together with the final assembly.
6. Quality control: Quality control is assured by checking three main aspects at the end of the remanufacturing line: overall state, that is the correct rotation of the propeller

with the blades; the number of defects such as cracks, holes; and the correct joints screwing of the components.

7. Transport between stations: All transports are done by a logistician operator with a carrier; components are picked and then delivered at the different workstations.

The layout of the exploratory remanufacturing line is shown below in figure 3.4. It was completely manual, and helped understand the flux of material, information, operation times, and improvement ideas.

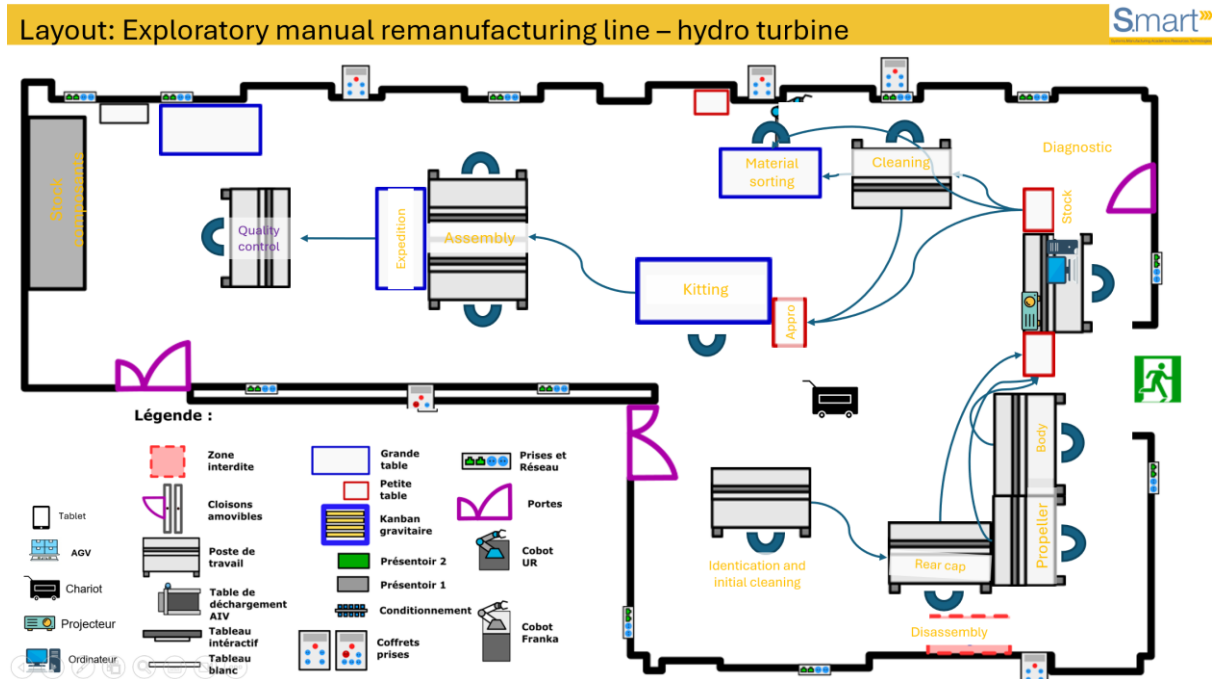


Figure 3.4 Layout of first exploratory production line experiment.

The first experimentation lasted for one hour, and around four products exited the line, however the information was not completely correctly collected, and many bottleneck problems arose. The results of this exploratory experiment were used for modelling the two following experiments.

Line balancing

In order to equilibrate the flow of material and components through the remanufacturing line, an approximate line balancing process was implemented. Factors to take into account for the line balancing are the following, it is supposed that from each arriving hydro turbine, all of its 11 polymer components pass through disassembly and diagnostic, then from those 11 only 7 components need cleaning and sorting, and 3 need repairing. From the first experiment, operations time were measured, and these times were used as input for line balancing procedure, to ensure a smooth flow through the line. Results of line balancing can be found in chapter 4.

Three different experiments were conducted. As mentioned previously, the first one was an exploratory experiment, to determine and evaluate the flux on the production line, identify bottlenecks, communication problems, transport problems, and measure operations times.

Thanks to this experiment, the following two were planned as follows, each with a duration of one hour:

Experiment 2: Manual line

In order to compare different models, including and excluding technology, an exclusively manual line was planned.

All the operations would be done manually, including transport, manipulations, except screwing operation.

The description of each workstation of the manual remanufacturing line is as follows:

8. Disassembly: One operator takes apart all the product's components, by using supports to hold on the product on an appropriate position, and electronic screwdrivers to remove all the screws.
9. Diagnostic: One operator has a printed database to compare each arriving disassembled component to it, and determine by using plain sight, if the component can be directly reused, cleaned, repaired or sent to recycling.
10. Cleaning and material detection: First, one operator takes each component that has been classified to be cleaned, recycled or repaired. The operator removes manually all the dirtiness and stains from the component and then uses an optical spectrometer to determine the polymer material type and be able to classify it correctly.
11. Repairing: The operator uses the same material 3D printing filament to repair and reinforce the component, which is melted using a soldering iron carefully to melt, deposit and spread the molten polymer over the component defects.
12. Kitting: Here, all the reused, and repaired components are stored, together with new ones. The operator picks all the components needed to assembly one product, in its required exact quantity and places it in a bin, which composes a kit to be sent to reassembly.
13. Reassembly: Three operators perform the assembly of the product, dividing the product subassemblies in three sections, to make the operation faster. The three divisions are: reassembly of propeller, reassembly of main body, and reassembly of rear cap together with the final assembly.
14. Quality control: Quality control is assured by checking three main aspects at the end of the remanufacturing line: overall state, that is the correct rotation of the propeller with the blades; the number of defects such as cracks, holes; and the correct joints screwing of the components.
15. Transport between stations: All transports are done by a logistician operator with a

After having designed the remanufacturing workstations, and decided on the order, line shape and operators' allocation, a physical layout were made. Below, figure 3.5 shows the physical layout for the manual line carrier; components are picked and then delivered at the different workstations.

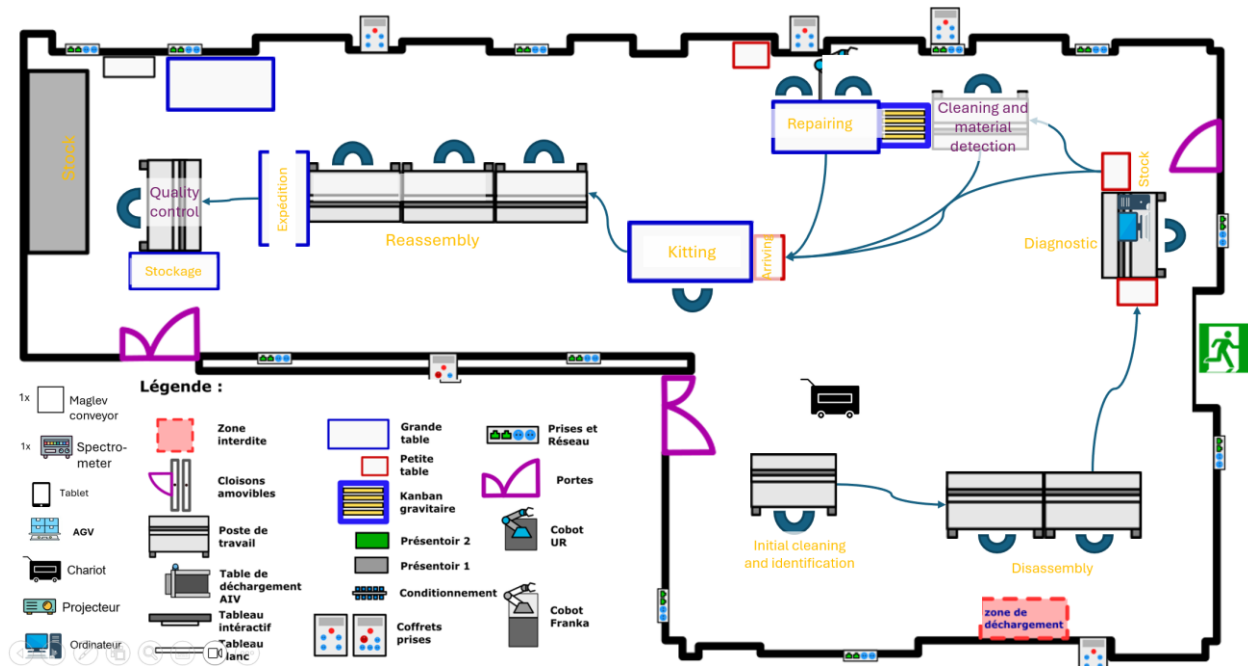


Figure 3.5 Layout of manual remanufacturing line at Operations Management Platform

A draft picture of the complete manual remanufacturing line can be found in appendix J.

Experiment 3: Mixed manual and Industry 4.0 line

In order to compare different models, including and excluding technology, a second line was planned, including industry 4.0 technologies devices available at Operations Management platform.

Some operations will be done with the help of I 4.0 technologies for handling or transporting. The description of each workstation of the mixed remanufacturing line is as follows:

1. **Disassembly:** One operator takes apart all the product's components, by using supports to hold on the product on an appropriate position, and electronic screwdrivers to remove all the screws. However, transport between this station and the diagnostic station is assured by a cobot, Panda Franka Emika, who picks the bins with disassembled components and delivers it to the next operator on the diagnostic workstation.
2. **Diagnostic:** One operator has a printed database to compare each arriving disassembled component to it, and determine by using plain sight, if the component can be directly reused, cleaned, repaired or sent to recycling. However, transport between this station and the AGV is done by a cobot, Panda Franka Emika, who picks up the bins with classified components and places it in
3. **Cleaning and material detection:** First, one operator takes each component that has been classified to be cleaned, recycled or repaired. The operator removes manually all the dirtiness and stains from the component and then uses an optical spectrometer to determine the polymer material type and be able to classify it correctly.

4. Repairing: The operator uses the same material 3D printing filament to repair and reinforce the component, which is melted using a soldering iron carefully to melt, deposit and spread the molten polymer over the component defects.
5. Kitting: Here, all the reused, and repaired components are stored, together with new ones. The operator picks all the components needed to assembly one product, in its required exact quantity and places it in a bin, which composes a kit to be sent to reassembly.
6. Reassembly: Two operators perform the assembly of the product, in actively collaboration with one cobot, Universal Robots brand. The work is divided in two sections, to make the operation faster. The two divisions are: reassembly of main body and reassembly of rear cap, done by one operator individually; and reassembly of propeller and final product reassembly, done in collaboration by an operator and a cobot. This collaboration consists of the suppression of the helping position supports for screwing, as the cobot holds the components and moves the assembly to different positions so the operator can easily screw the joints.
7. Quality control: Quality control is assured by checking three main aspects at the end of the remanufacturing line: overall state, that is the correct rotation of the propeller with the blades; the number of defects such as cracks, holes; and the correct joints screwing of the components.
8. Transportation: All transportation between stations is done by two different Automated Guided Vehicles (AGVs), Sherpa Robot AGVs, that follow a separated determined pick and delivery path to assure efficient transport.

Figure 3.6 shows the physical layout for the manual & I4.0 remanufacturing line:

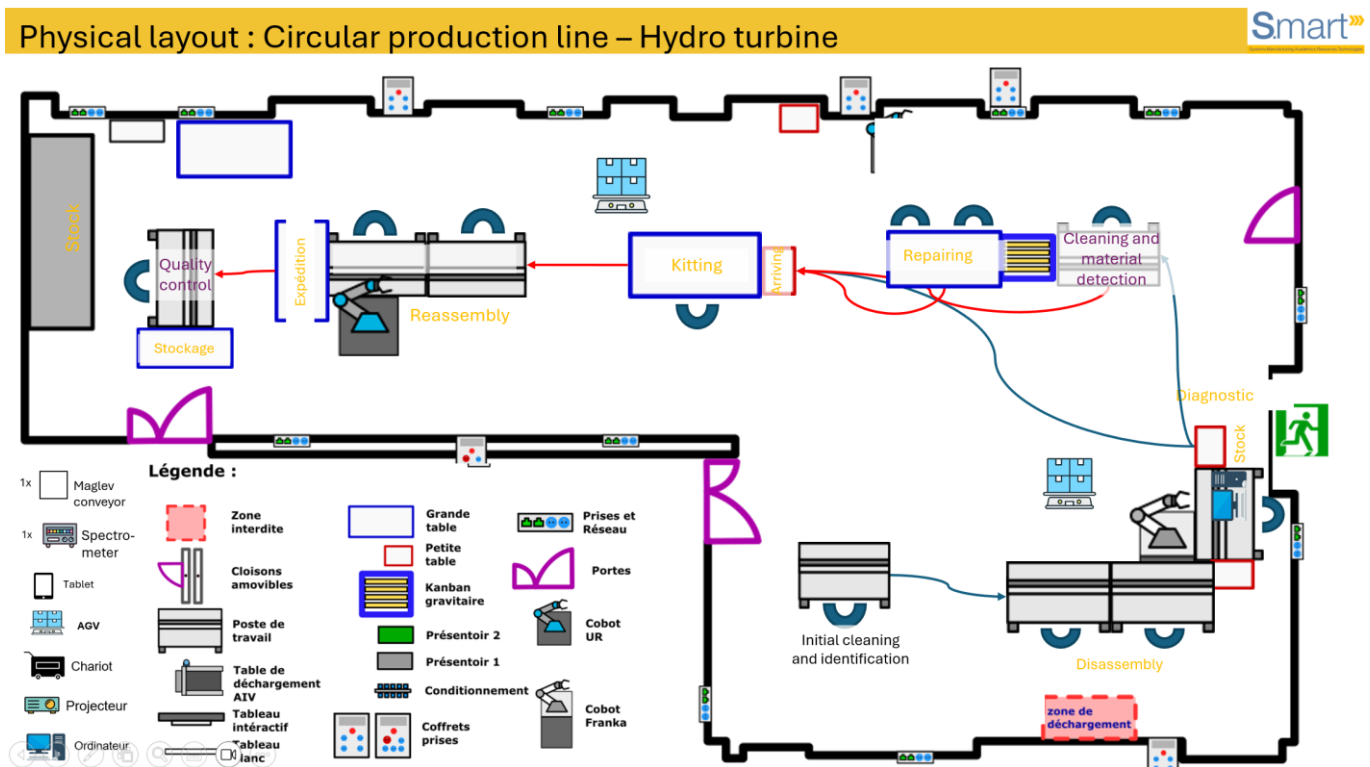


Figure 3.6 Layout of mixed (manual & I4.0) remanufacturing line at Operations Management Platform

3.4 Data collection

Data collection is assured through various mechanisms, being the main one time, operation and station identification data collection through the scan of QR codes at each workstation at both times, when starting an operation to a component or product and when finishing the operation.

Every individual polymer component belonging to the hydro turbine, located at Operations Management stock, has a unique alphanumeric code assigned, which is encoded into a QR code stuck to each component. This would allow a unique identification of a component that can be easily tracked through the line, until it is assembled into a specific product.

A MS datasheet was created, where all the raw data of the scans would appear, thanks to a QR code scanning App, called Scan IT to Office. When a QR code is scanned with the app, the data including component unique code, hour, and workstation is sent to the datasheet, where a new line is added with the aforementioned data.

This datasheet automatically processes the received data to filter it by workstation, component, product, and even calculate automatically KPIs about the performance of the line.

3.5 KPI identification and calculation

According to literature and experts, and to the objectives of this research project, five key performance indicators KPIs categories have been identified, which can help make visible the advantages and drawbacks of each production and remanufacturing model.

The five categories are listed below, together with the individual indicators. Their definition and simplified calculations for this research work is explained next.

KPIs categories

Productivity (time):

- Value Added Time (VAT): is the addition of the time when a certain component or product has been actively processed, or worked on, by an operator or a machine. It excludes waiting or transport times. The calculation of VAT is as follows:

$$VAT = T_t - W_t - T_{rt} \quad (3.1)$$

Where:

T_t = Component throughput time or total time

W_t = Waiting time

T_{rt} = Transport time

- Throughput time: Is the total time a product needs to go along all the production line, from the start of the processing of individual components, to the last operation where all components are already joined.

$$Tt = T_0 - T_f \quad (3.2)$$

Where:

T_0 = Starting time when a component enters the line

T_f = Final time when a component exists the line ensembled into a final product

Quality:

- Quality index: Each product is composed of eleven individual polymer components, and each individual components is assigned a quality score depending on their state; new (3), reuse (2), repaired (1). All the individual scores are sum up, and it gives the total quality index score of the product.

$$Quality\ index = 3 * \#New + 2 * \#Reu + 1 * \#Rep \quad (3.3)$$

Where:

New = Quantity of new components

Reu = Quantity of reused components

Rep = Quantity of repaired components

- Number of defects: is the quantity of defects, which means cracks, craters, holes, and other broken features, present in a final product.
- Number of screw defects: Is the quantity of joints that have been wrongly or uneven screwed, and so they are loose.

Cost:

- Cost of production of one hydro turbine: Corresponds to the addition of all manufacturing costs for producing one product, materials cost, equipment and electricity costs and operators' salary. Production costs are composed of three different categories, including fixed costs, variable costs, and material costs. Fixed costs include the rent costs, depreciation, equipment amortization, administration, etc. Variable costs include the operator costs, electricity of equipment needed for product processing, maintenance [44]. Material costs include the cost of the raw materials and consumables needed for the product manufacturing.

$$Production\ cost = \sum (Ec + Oc) * t + (1 - Rf) * Mc \quad (3.4)$$

Legend:

Ec = Hourly equipment cost

Oc = Hourly equipment cost

t = operation duration in hours

Rf = Reused mass fraction in kg

Mc = Material cost per kg

Environmental impact:

- Circularity index: The Material Circularity Indicator (MCI) for a product measures the extent to which linear flow has been minimised and restorative flow maximised

for its component materials, and how long and intensively it is used compared to a similar industry-average product [45].

This indicator that measures the circularity of the product, takes into account the recycled raw materials used for its manufacturing, the end-of-life scenario, intended to be reused, recycled, composted, etc, and its collection rate at the end of life. Finally, each material has different values for upcycling or degradation after each life cycle, which is also taken into account. The MCI takes into account the efficiency of recycling, both upstream (production of recycled materials) and downstream (product recycling). Its calculation is based on four main steps, combined with a performance factor called utility.

It has a complex calculation methodology, including several components Virgin Feedstock, Unrecoverable Waste, Linear Flow Index and Utility Factor.

Virgin feedstock

$$V = M(1 - F_R - F_U - F_S) \quad (3.5)$$

Where:

V = Virgin feedstock

M = Total mass of product

FR = Feedstock derived from recycled sources

FU= from reused sources; FS= from biological material

Unrecoverable waste

$$W_0 = M(1 - C_R - C_U - C_C - C_E) \quad (3.6)$$

$$W = \frac{W_F + W_C}{2} \quad (3.7)$$

$$W_C = M(1 - E_C) * C_R \quad (3.8)$$

$$W_F = M * \frac{(1 - E_F) * F_R}{E_F} \quad (3.9)$$

Where:

CR= mass fraction collected for recycling.

CU=mass fraction going to reuse.

CC= mass fraction to compost.

CE = mass fraction to energy recovery

EC = Efficiency of the recycling process used for the portion of a product collected for recycling

EE = Efficiency of the energy recovery process for biological materials satisfying the requirements for inclusion

EF = Efficiency of the recycling process used to produce recycled feedstock for a product

W₀ = Mass of unrecoverable waste through a product's material going into landfill, waste to energy and any other type of process where the materials are no longer recoverable

W = Mass of unrecoverable waste associated with a product

W_C = Mass of unrecoverable waste generated in the process of recycling parts of a product

W_F = Mass of unrecoverable waste generated when producing recycled feedstock for a product

Linear Flow index

The LFI measures the proportion of material that follows a linear flow (virgin materials + final waste)

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}} \quad (3.10)$$

Where: LFI = Linear flow index

Utility and MCI

$$X = \left(\frac{L}{L_{av}} \right) * \left(\frac{U}{U_{av}} \right) \quad (3.11)$$

$$MCI_P = 1 - LFI * F(X) \quad (3.12)$$

Where:

MCI_P = Material Circularity Indicator of a product

X = Utility of a product

L : Lifetime of product.

U = Actual average number of functional units achieved during the use phase of a product

L_{av} = Average lifetime of an industry-average product of the same type

U_{av} = Average number of functional units achieved during the use phase of an industry average product of the same type

$F(X)$ = Utility factor built as a function of the utility X of a product

- Circular mass fraction: Is the percentage of the total mass of the product that comes from reused or recycled sources.

$$Cm\% = \frac{Cm}{Tm} * 100 \quad (3.13)$$

Where:

$Cm\%$ = Circular mass fraction

Cm = Circular mass kg

Tm = Total product mass kg

- Circular monetary value fraction: Is the percentage of the total cost of the product, which is embodied in reused or recycled components, and perhaps then saved, compared to a new product.

$$Cc\% = \frac{Cm}{Tm} * 100 \quad (3.14)$$

Where:

$Cm\%$ = Circular monetary value fraction

Cm = Monetary value of the circular components kg

Tm = Total product monetary value kg

-
- Carbon footprint: Is the total greenhouse gas emissions that are produced by the manufacturing, materials, electricity and other resources needed to produce one product. The carbon footprint is transferred and expressed in kg of CO₂ equivalent. The carbon footprint is calculated through simplified life cycle assessment, more specifically, IDEMAT, with the Environmental Footprint EF method database.

Ergonomics:

- BORG: The Borg Rating of Perceived Exertion (RPE) scale is a subjective measure of how hard an individual feels they are working during physical activity [46]. The Borg CR-10 scale, the most widely used in the workplace, assigns a strength score between 1 and 10 [47]. If the force used in the task is "very, very weak" or almost absent, the score is assigned 0.5. Conversely, if the force required is maximum, the score is 10. The scores are also related to the percentage of maximum voluntary contraction (MVC), where 0% means the muscle is completely relaxed, supported, and exerting no effort, and 100% refers to the maximum effort the worker exerts while performing the task. The BORG scale can be consulted in Annex J.
- NASA TLX: NASA Task Load Index (TLX) is a common methodology for measuring subjective mental workload. It consists on a multidimensional construct to derive an overall workload score based on a weighted average of ratings on six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration level [48].

Scoring according to the author Anacleto Filho [46]:

0 - 20: Very Low Workload

The task was perceived as very easy, requiring minimal demands and effort.

21 - 40: Low Workload

The task was generally easy, with manageable demands.

41 - 60: Moderate Workload

This is often the target range for many tasks, indicating a reasonable balance between challenge and manageability. The task required a fair amount of mental or physical effort.

61 - 80: High Workload

The task was perceived as demanding, requiring significant effort and potentially leading to a feeling of being rushed or frustrated. This level might be sustainable for short periods but could lead to fatigue or errors if prolonged.

81 - 100: Very High Workload / Overload

The task was perceived as extremely demanding, pushing the limits of the individual's capacity. This often indicates excessive mental, physical, or temporal pressure, high frustration, and potential for performance decrements or errors. This level is generally undesirable and unsustainable.

4 Results

4.1 Workstations dispositions

Each of the different operations within a remanufacturing line have been developed by using specific research methodologies adapted to each task requirements, which have been extrapolated from literature methodologies, in some cases have been clearly followed, while in other cases simplifications have been made. These methods have been applied to some of the key remanufacturing stages, and its results is described next.

4.1.1 Disassembly

The disassembly mapping methodology, whose description can be found in chapter II, was used to determine the progressive disassembly steps for the product, and at the same time used to determine the division of the task between the operators implied in the disassembly workstation. Through this mapping methodology, subassemblies were marked, required tools were identified and the disassembly tasks were divided.

The disassembly map is shown in the figure 4.1 and 4.2 below:

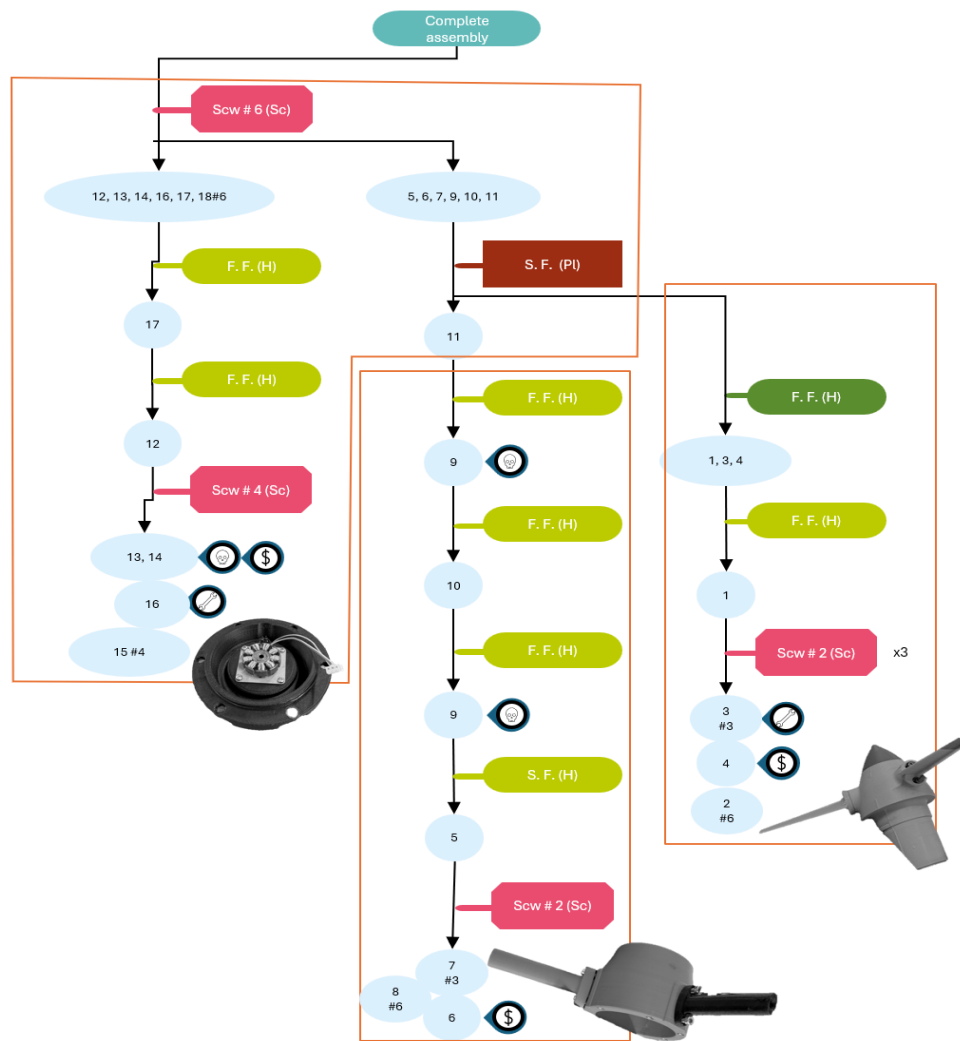


Figure 4.1. Disassembly map of the hydro turbine disassembly operations.

Subsystem	Ref	Component	Qty
Propeller	1	Nose	1
	2	Screw CHC M4	6
	3	Blade	3
	4	Propeller body	1
Body	5	Rubber ring	1
	6	Body	1
	7	Fixation arm	3
	8	Screw CHC M3	6
	9	Bearing	2
	10	Spacer	1
	11	Circlip	1
Generator	12	Ring	1
	13	Rotor	1
	14	Generator stator	1
	15	Screw M2.5	4
	16	Rear cap	1
	17	Elastic ring	1
	18	Screw CHC M3	6

LEGEND

Connectors
S. F. = Snap Fit
F. F. Friction Fit
Scw = Screwed

Type of tool
(H) = Hand
(Pl) = Pliers
(Sc) = Screwdriver

#x = multiple components or motions

Motion Type

Hand motion
Single motion tool
Multiple motion tool

Force Intensity

Low Mid High

LEGEND

Most likely to fail
Most environmental harmful
Most embedded value

Figure 4.2. Labels of the disassembly map of the hydro turbine.

Afterwards, times for each disassembly subassembly were recorded, and the tasks divided, and allocated to the operators as shown in table 4.1:

Table 4.1. Disassembly operations allocation and times.

Manual remanufacturing line	(subassembly) Task	Time
Operator 1	Rear cap (generator) + circlips	Approx. 2 min
Operator 2	Propeller and Body	Approx. 2:45 min
Manual and I 4.0 line		
Operator 1	Rear cap (generator) + circlips	Approx. 2 min
Operator 2	Propeller and body	Approx. 2:45 min

4.1.2 Repairing

Only components labelled as to be repaired at the diagnostic station had to pass through this station. Here, damaged components were repaired using a Material Deposition methodology, mentioned in chapter II.

Components small sections with slightly broken or plasticized volumes were melted using a soldering iron, and the material was rearranged. Afterwards, new polymer filament, corresponding to the material type, was added, following a zig zag pattern, in order to reinforce the weakened section. The most common defects that were repaired were small crack lines, or holes' edges that had been thinned. Below, in figure 4.3, the same component is shown, before and after the repairing operation.

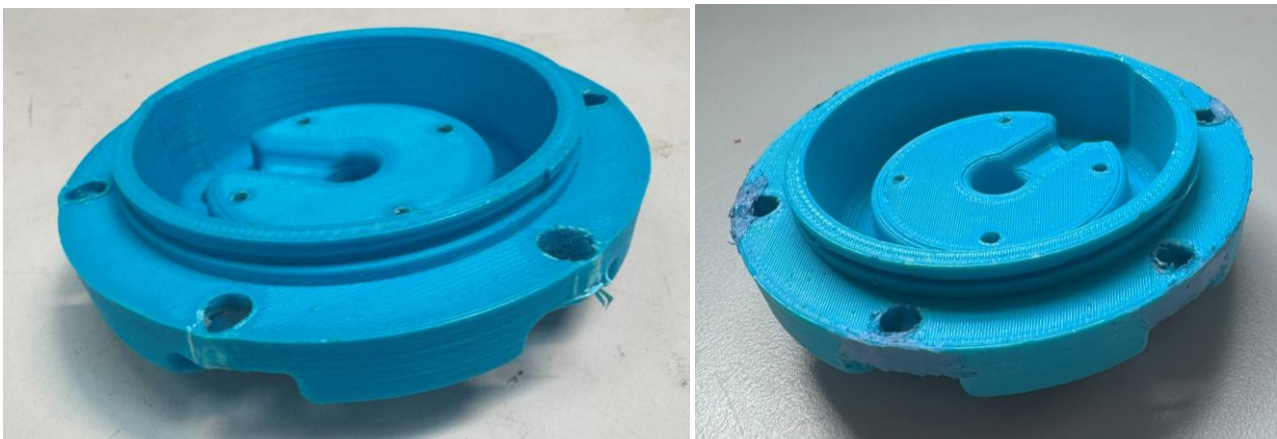


Figure 4.3. Left, a damaged component before repairing. Right, damaged component after repair operation.

Repaired components were then sent to main stock at kitting station, same as directly reused components.

4.1.3 Kitting

Kitting station was idealized from the necessity to facilitate product reassembly operations, by adopting Lean manufacturing practices, such as the use of kits.

The main stock of new, reused and repaired components was located at this workstation, so that the operator can pick all the required components to make a kit and send it to reassembly. The operator had a specific list of components' variety and quantities that must be respected. To facilitate the picking operation, and ensure it is correctly done, another Lean Manufacturing practice was taken, the shadow board, which is commonly used for placing, storing and not missing tools; but in this case was adopted as a mat with all the components figures, to whom the operator put the correct piece over it. It was printed on a A3 format. The hydro turbine kit shadow board mat is shown below, in figure 4.4.

Kit for one hydro turbine

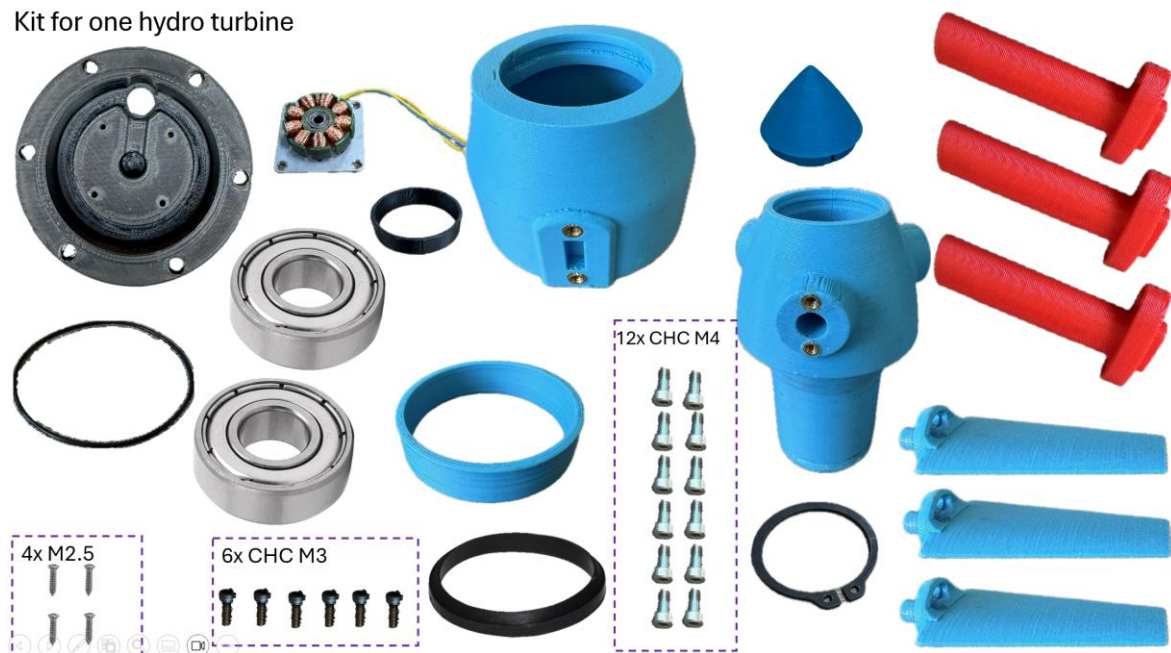


Figure 4.4. Shadow board mat for hydro turbine kit.

After all the components were put together in the mat, they were transferred together to a blue industrial bin, which had a QR code assigned to it.

4.1.4 Reassembly

Reassembly operation consists of putting back together all the components of a hydro turbine, such as in a standard linear production model.

Analogously to disassembly station, times the reassembly of each subassembly were recorded, and the tasks divided, and allocated to the operators as shown in table 4.2:

Table 4.2. Reassembly operations allocation and times.

Manual remanufacturing line	Reassembly Task	Time
Operator 1	Body	Approx 1:30 min
Operator 2	Propeller	Approx 1:50 min
Operator 3	Rear cap + final operator	Approx 2:20 min
Manual and I 4.0 line		
Operator 1	Rear cap + body	Approx 2:50 min
Operator 2 + Panda Cobot	Propeller and final reassembly	Approx 3:50

4.2 Line balancing

In order to equilibrate the flow of material and components through the remanufacturing line, an approximate line balancing process was implemented. Factors to take into account for the line balancing are the following, it is supposed that from each arriving hydro turbine, all of its 11 polymer components pass through disassembly and diagnostic, then only 7 need cleaning and sorting, and 3 need repairing. Thus, times per operation can be found in the table 4.3 below, obtained from first exploratory experimentation:

Table 4.3. Times of each operation, when done by one operator

Task #	Task name	Time (s)
2	Disassembly	4:45
3	Diagnostic (for 11 pcs)	4:00
4	Cleaning (for 8 pcs)	2:45
5	Material detection (for 6 pcs)	1:18
6	Repairing (for 3 pcs)	~10:00
7	Kitting	3:00
8	Reassembly	12:00
9	Quality control	3:00

The tasks from table 4.4, have been allocated between seven workstations, the allocation can be seen below, in figure 4.5.

Table 4.4. Task allocation to each workstation and assigned times.

Station	Task	# of operators	Time	Time not assigned
A	9	1	3:00	2:00
B	2	1	4:45	0:15
C	3	1	4:00	1:00
D	4, 5	1	4:03	0:57
E	6	2	10:00 / 2	0:00
F	7	1	3:00	2:00
G	8	3	12:00 / 3	1:00

Below, in figure 4.5, can be found a diagram of the workstations with the allocated tasks:

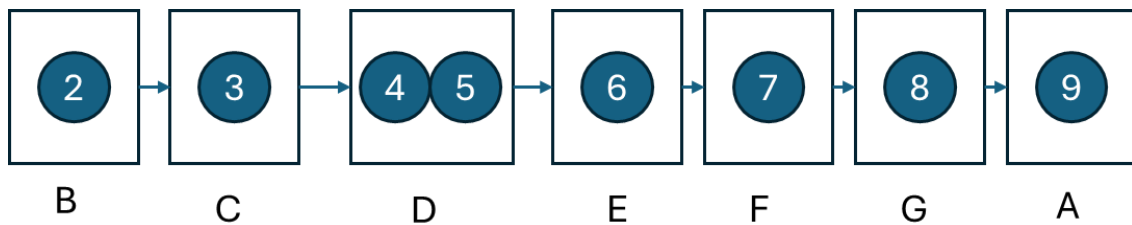


Figure 4.5. Diagram showing the workstations division with their allocated tasks.

Taking into account the dimension and form of the physical platform, and the times that each of the previous operations take, the allocation of operators, workbenches, and operation times can be seen below in table 4.5, taking into account that there is one operator per workbench.

Table 4.5. Operator and cobot allocations for the remanufacturing lines

	Manual remanufacturing		Manual & I 4.0 remanufacturing		
Operation	Time	#Operator	Time	#Operator	#Cobot
Disassembly	4:45	1	6:30	2	0
Diagnostic	4:00	1	3:00	1	1
Cleaning/Sorting	4:00	1	4:00	1	0
Repairing	10:00	2	10:00	1	0
Kitting	3:00	1	3:00	1	0
Reassembly body	4:00	1	4:00	1	0
Reassembly propeller	4:00	1	4:00	1	1
Reassembly rear cap and final	7:00	1			
Quality control	3:00	1	3:00	1	0

4.3 Experiments results

Results were collected for both, manual remanufacturing line and mixed (manual and I4.0) remanufacturing line. Main raw data collection consists of components identification and the time they passed by each workstation. Complimentary data collection consisted of quality control forms, ergonomics forms filled by operators, time measurements and videos/photos.

When a product (hydro turbine) or single component passed through each workstation within the remanufacturing line, it was scanned and information collected, at the entrance and at the exit of the product/component in each workstation. An example of this is shown below in figure 4.6.

	A	B	C	D	E
12	07EDA17F586FFF6E	SM-T830	04/06/2025 15:00	A044	
13	07EDA17F586FFF6E	SM-T830	04/06/2025 15:01	S002	
14	7188B8E1438EAF06	SM-T830	04/06/2025 15:01	R025	
15	AD421CD604108027	SM-T830	04/06/2025 15:01	A053	
16	7188B8E1438EAF06	SM-T830	04/06/2025 15:02	R025	Recycle
17	AD421CD604108027	SM-T830	04/06/2025 15:02	N029	
18	7188B8E1438EAF06	SM-T830	04/06/2025 15:02	A040	Reuse

Figure 4.6. Registered raw data example after QR code is scanned

Then all this information is filtered, making it possible to have a better visualization of the data. It can be filtered to see the sequence of operations that a component followed through the line, and their time. An example of the visualization applying searching or filtering by component is shown below in figure 4.7.

Another filtering option enabled is searching by workstation, through this filter, all the components that passed by this workstation are shown. This tool can help identify bottlenecks, unused times, average operation times, etc. An example of the visualization through this filtering is shown below, in figure 4.8.

Path of piece:	P010		Search		
	Device	Hour	State	Station	Time per station
	AD421CD604108027	16/06/2025 11:04		Disassembly	
	AD421CD604108027	16/06/2025 11:10		Disassembly	0:05:54
	7188B8E1438EAF06	16/06/2025 11:17		Diagnostic	
	7188B8E1438EAF06	16/06/2025 11:18	Repair	Diagnostic	0:00:22
	81639A510A955F6E	16/06/2025 11:27		Cleaning / Mat detection	
	81639A510A955F6E	16/06/2025 11:27		Cleaning / Mat detection	
	81639A510A955F6E	16/06/2025 11:28		Cleaning / Mat detection	0:01:40
	A0B2ADCEBF2B2C3B	16/06/2025 11:37		Repairing	
	A0B2ADCEBF2B2C3B	16/06/2025 11:43		Repairing	0:05:25
	07EDA17F586FFF6E	16/06/2025 11:55		Kitting	
	07EDA17F586FFF6E	16/06/2025 11:50		Kitting	
	07EDA17F586FFF6E	16/06/2025 11:57		Kitting	0:01:42
	Total time	0:52:48			0:15:03

Figure 4.7. Visualization of operations path through filtering by component

Workstation:	Disassembly	AD421CD604108027	Search	
	Part	Hour	State	Station
	V008	16/06/2025 10:31		Disassembly
	B007	16/06/2025 10:37		Disassembly
	B025	16/06/2025 10:37		Disassembly
	B031	16/06/2025 10:37		Disassembly
	N047	16/06/2025 10:38		Disassembly
	P003	16/06/2025 10:38		Disassembly
	V009	16/06/2025 10:52		Disassembly
	S022	16/06/2025 10:53		Disassembly
	R019	16/06/2025 10:53		Disassembly
	N025	16/06/2025 10:54		Disassembly
	A038	16/06/2025 10:56		Disassembly
	A008	16/06/2025 10:56		Disassembly
	A022	16/06/2025 10:56		Disassembly
	D005	16/06/2025 10:56		Disassembly
	P005	16/06/2025 10:57		Disassembly
	R054	16/06/2025 10:57		Disassembly

Figure 4.8. Data visualization through filtering by workstation

After kits are made in the kitting station, components are assigned to a specific kit, which will become a new/remanufactured product. Through another filtering mode, applied to a kit or a product, the list of all components that are assigned to this product is displayed. An example of this, is shown below in figure 4.9.

	A	B	C	D
1	Kitting:	V007	Search	
2	State	Code	Piece	Condition
3	07EDA17F586FFF6E	16/06/2025 11:54:05	A053	Reuse
4	07EDA17F586FFF6E	16/06/2025 11:54:11	A002	Reuse
5	07EDA17F586FFF6E	16/06/2025 11:54:37	A014	Reuse
6	07EDA17F586FFF6E	16/06/2025 11:54:43	D005	Repair
7	07EDA17F586FFF6E	16/06/2025 11:55:15	S019	New
8	07EDA17F586FFF6E	16/06/2025 11:55:38	P010	Repair
9	07EDA17F586FFF6E	16/06/2025 11:55:43	B040	Reuse
10	07EDA17F586FFF6E	16/06/2025 11:55:47	B020	Reuse
11	07EDA17F586FFF6E	16/06/2025 11:55:51	B037	Reuse
12	07EDA17F586FFF6E	16/06/2025 11:56	N032	New
13	07EDA17F586FFF6E	16/06/2025 11:56	R011	New

Figure 4.9. Individual components included in a specific kit, in this example V007, in the mixed production line, third experiment.

For each remanufacturing model, for both experiments: manual and mixed line, five products that exited the line were well documented and its QR codes and data correctly collected. The list of products, which were correctly manufactured in each line is shown below, in table 4.6.

Table 4.6 List of remanufacturing finished products of each experiments, whose data was correctly collected

Experiment 2: Manual line	Experiment 3: Mixed manual & I4.0 line
V018	V010
V017	V002
V019	V015
V005	V011
V010	V007
Total: 5	Total: 5

4.4 KPIs results

With the information collected, and as described in the previous chapter III, a series of indicators were calculated, regarding productivity of the line in terms of time, cost, quality of the products, environmental impact and even ergonomic situation of the different models. These indicators are given for a specific product, and as an example, the indicators for one individual product are shown below in figure 4.10 and was remanufactured through the manual line.

Product KPIs V010	
Time	
Average throughput	0:49:38
Average VAT	0:16:15
Avg % VAT	35,34%
Quality	
Quality score	26
#of screw defective	1
#of components defective	1
Cost	
Cost of production	36,39901633
Environmental	
RPI (Circular mass fraction)	16,77%
PLCM (Circular \$ value fraction)	31,31%
Material Circularity Indicator	0,46
Carbon footprint	0,704
Ergonomics	
Line Borg	3,285714286
Line Nasa TLX	43,25
Line DUBS	2,595

Figure 4.10. Indicators calculations for one specific product, in this case V010, of the experiment 3, mixed remanufacturing line

Then, by taking the average of all sample products in the same experiment, we can estimate the indicators value for each remanufacturing line. In the same manner, by taking only a section of the remanufacturing line, from the kitting station and forward, it is possible to have an idea on a linear model production line for both manual and mixed arrangements. The raw comparison of indicators of the three models: manual remanufacturing, mixed manual & I 4.0 remanufacturing, and linear model, can be seen below in figure 4.11.

As it can be appreciated, there is not a single model that dominates according to the calculated indicators, but all models have its own advantages and drawbacks, it depends on the indicators or performance prioritized to be able to choose one model or another.

KPI	Linear line	Manual line	Industry 4.0 line	Unit
Time				
Average throughput	23	29 ~ 30	34 ~ 35	Min
Average VAT	13 ~ 14	19 ~ 20	11 ~ 12	Min
Avg. % VAT	66	68.5	43.14	%
Quality				
Avg Quality score	33	24.2	27.5	
Avg # of screws defective	2.25	2.5	2	Qty
Avg # of defects	1	1	1	Qty
Cost				
Avg Cost of production	33.76	50.716	38.8	€
Environmental				
Avg RPI (Circular mass fraction)	0	27.32	19.31	%
Avg PLCM (Circular \$ value fraction)	0	71.63	46.804	%
MCI	0.4	0.466	0.454	
Carbon footprint	1.054	0.5768	0.7096	Kg-CO2 eq
Ergonomics				
BORG	3.28	3.25	3.28	Low
NASA TLX	44.42	47	43.25	Moderate workload
DUBS	2.86	2.79	2.59	Moderate

Figure 4.11. Indicators average for each remanufacturing model.

Productivity (time)

Now, to analyse in depth indicator by indicator, and starting by productivity indicator measured in time, which can be seen in figure WWW, the reasons for this behaviour in each model are explained as well. Figure 4.12 shows the average throughput time of a product, which is to say, the average time that a product takes from the beginning of the first operation of one of its components until the final product exists the line.

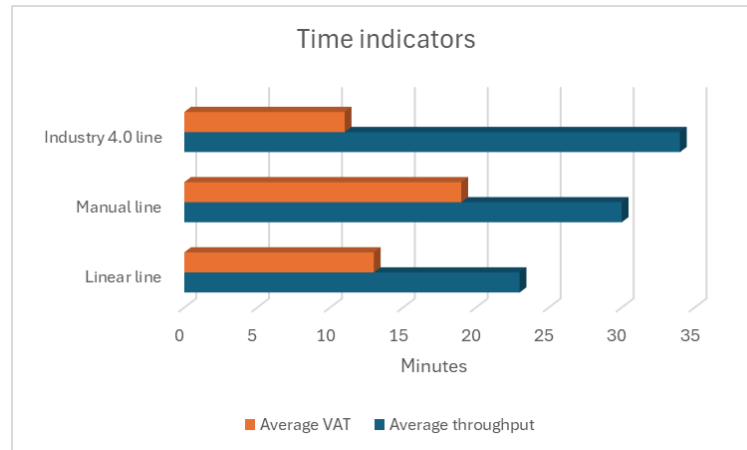


Figure 4.12. Average throughput time and value-added time.

On the other hand, Value Added Time (VAT), means the time in which a certain product is actively being processed by an operator. The difference between throughput and VAT is time spent in waiting or transporting between stations.

The results show that on average a hydro turbine takes the longest time to exit a mixed (manual and I4.0) remanufacturing line, in which the throughput is the longest and takes around 34 minutes. On the opposite side, a linear manufacturing line can manufacture a hydro turbine in just 23 minutes on average.

However, when studying in detail the value added time, is possible to observe that the introduction of industry 4.0 technologies actually reduce product operations time compared to exclusively manual line, more concretely the disassembly, but mostly in the reassembly of the products, thanks to the use of cobots. It is also possible to conclude that the use of AGVs for transport have made transport times longer compared to transport made by a logistician operator. The linear model, both manual and mixed averaged indistinguishable, is placed in the middle of both circular models experiments.

The following chart, figure 4.13, show the Value-Added Time in percentage of the total throughput, which give a better idea what model has a better productivity, and which has more time wasted.

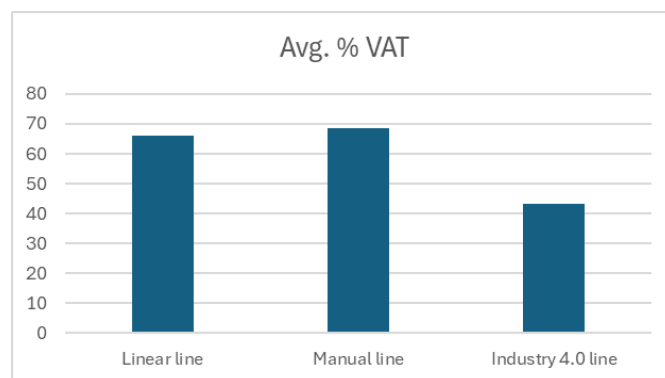


Figure 4.13. Average VAT as percentage of total throughput

It is possible to determine that the manual remanufacturing line is the one that make better use of the total throughput time, however, there is the opportunity that when optimizing transport and waiting times in the mixed line, this could surpass the productivity of the manual remanufacturing and the linear model.

Product quality

Quality has been harder to determine, as it is a very subjective indicator, depending on operator or customer perception. In this case, two different approaches have been studied. Traditionally, quality can be understood as lack of defects, in this sense, as hydro turbines have been examined at the end of the remanufacturing lines, the results obtained are the following, being shown in figure 4.14.

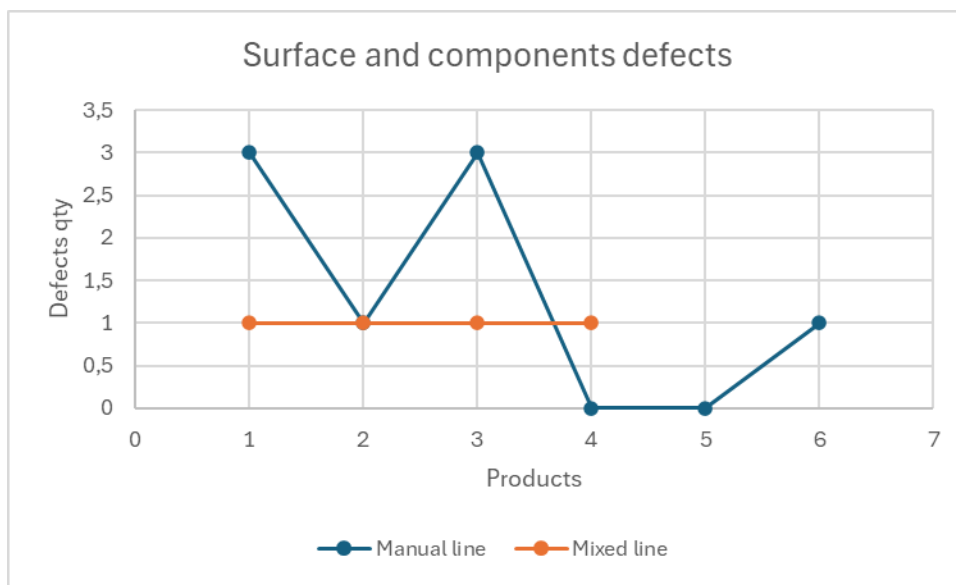


Figure 4.14. Control chart showing defects repeatability in remanufactured products.

As it is possible to observe, the introduction of technologies 4.0, most specifically the use of cobot in reassembly, helps reduce the appearance of defects in the finished remanufactured products, that is to say, cracks, broken components, holes, etc. It reduces the variability of the appearance of defects as well, as it is less fluctuating. The average of defects appearance was reduced from 1.33 in the manual line, to only 1 in the mixed line. The same can be said for the product joints that have been incorrectly screwed. In figure 4.15 below, it is possible to observe that with the introduction of a cobot in the reassembly station, the defective joints and its variability are reduced, from an average of 2.5 defective joints for the manual line, to only 2 joints incorrectly screwed for the mixed line.

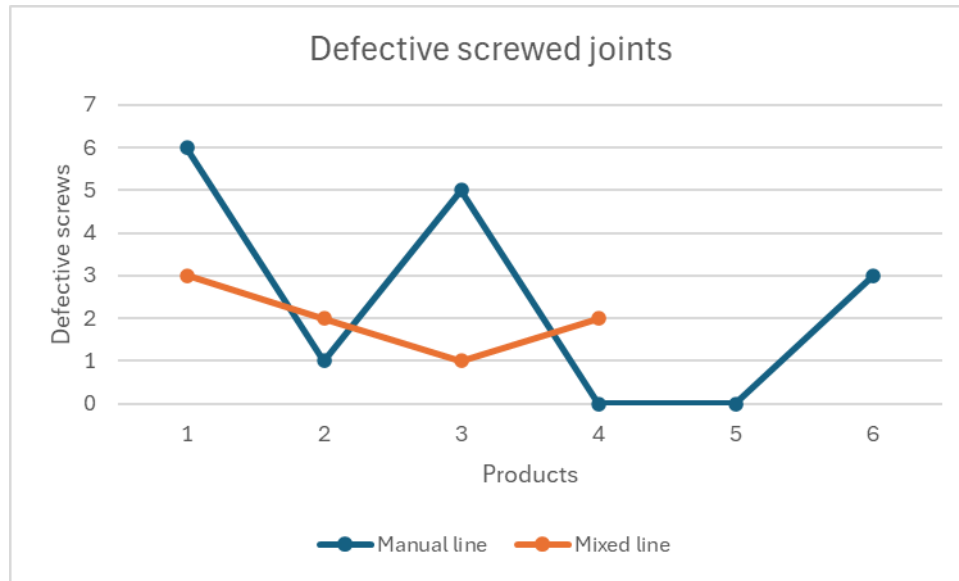


Figure 4.15. Control chart showing defective screwed joints apparition in remanufactured products.

Production cost

As mentioned in the research methodology chapter, the production cost or in this case, remanufacturing cost for one product depends on multiple factors, being the most important the materials cost, the equipment cost and the operators cost. The cost of production of one hydro turbine for each remanufacturing model is shown in figure 4.16 below. Note: Waiting time cost have not been taken into account.

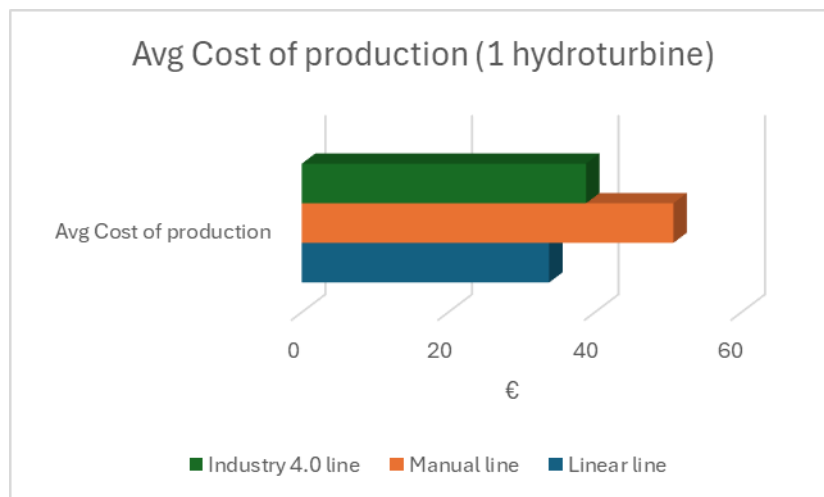


Figure 4.16. Average cost of remanufacturing of one (1) product by each fabrication model

It is possible to affirm that the manual line has the highest production cost by unit produced, with an average of around 50 euros per product. Material costs are comparable between mixed I4.0 line and manual line, so the difference can be directly attributed to the different ratio between equipment use and operators' requirements. On one hand, the mixed line has higher energy and equipment costs, but as seen previously, the value-added time is lower,

so the use of this technological resource is lower as well, translating into lower costs. On the opposite hand, the manual line has a higher VAT, so it means an operator needs to invest greater time for each product processing, meaning a higher cost to be spent in salaries. It is possible to visualize as well that the difference in production cost between the mixed remanufacturing line and the linear production model is not so significant, since the cost of use of more I4.0 equipment, is comparable to the necessity to spend more in raw materials in the linear production model; both being between 30 and 40 euros cost per product.

Environmental impact

Environmental impact and environmental performance can be evaluated through two different perspectives, from the direct impact of the operations and materials to the environment, and to the potential that a product has to reduce future environmental impacts meaning for example the circularity of a product.

First, the circularity of a product can be measured, as presented in previous chapter, through a proposed methodology called Material Circularity Indicator (MCI), which takes into account multiple factors such as the percentage of recycled, reused input materials, and the percentage of output materials that are collected for recycle, reuse, compost, energy recuperation and landfill. As this indicator is based solely on materials, it is not dependant of the use of manual or I 4.0 technologies for the remanufacturing. Both accounting for an MCI around 0.47. In any case, figure 4.17, shows the MCI value for the different models.

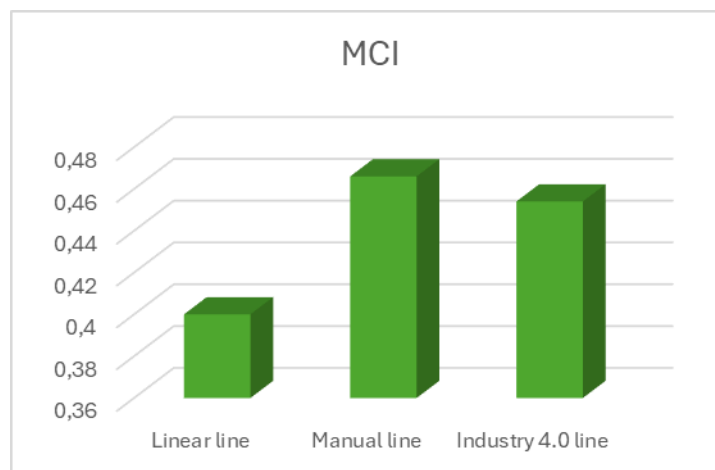


Figure 4.17. Average Material Circularity Indicator for each production model

It is easily to observe, however, that the linear model has considerably lower MCI than the circular models, as none of its raw materials come from circular sources but only virgin materials. The value it gets, around 0.4 is justified because its components can be recuperated at the end of life, and reused, recycled or composted.

Another interesting point of view is the examination of the other complimentary circularity indicators, such as the circular mass fraction, and the circular monetary value fraction. Below, in figure 4.18, is possible to see more in detail these indicators.

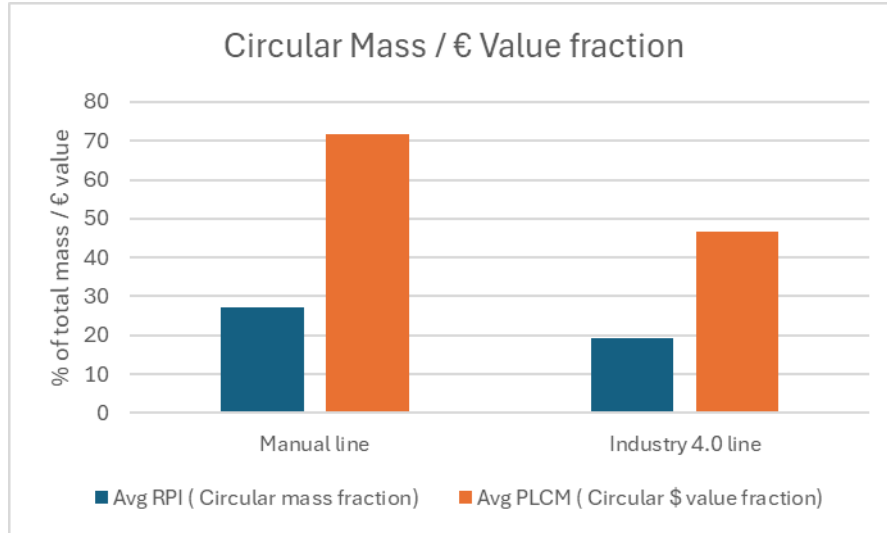


Figure 4.18. Circular mass / monetary value fraction of each circular model

Both models present the same pattern, with the circular components mass combined accounting for less than 30% of the total mass of the final product, principally because of the metallic components being much heavier compared to polymer materials. On the other hand, even though the circular mass fraction does not surpass 30%, the monetary value of this mass accounts for near 45 to 70% of the total monetary value of the final product, explained by the higher cost of polymer materials compared to common metals such as iron and steel.

The other perspective to evaluate environmental impact consists of Life Cycle Assessment methodology, which measures the direct emissions of harmful substances to the environment, and the impact these emissions have in different domains, locally or globally, either in atmosphere, land, ecosystems, human wellbeing, etc. One of the most visible indicators nowadays is the Emissions of Greenhouse Gases, also known as Carbon Footprint, measured in Kg of CO₂ equivalent. These emissions have been estimated for each remanufacturing and linear models and is presented below in figure 4.19.

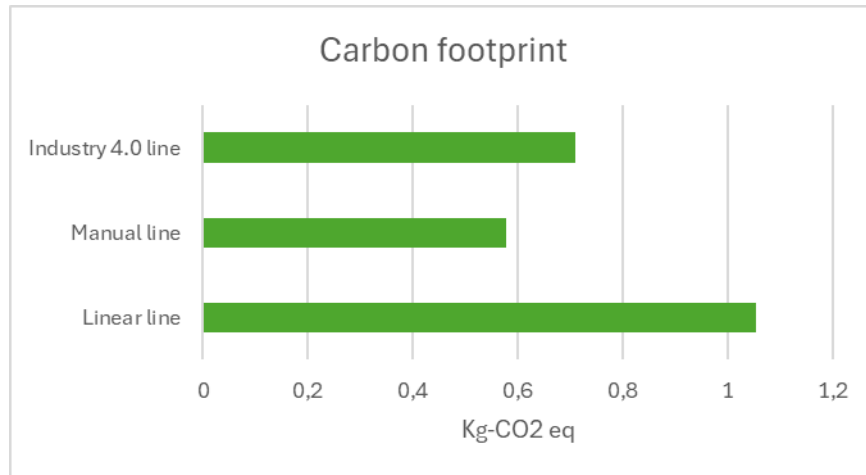


Figure 4.19. Carbon footprint of each production model, production of one hydro turbine.

As seen on figure MMM, the linear production model has the highest emission of greenhouse gases by far, emitting more than 1 kg of CO2 equivalent gases by unit product. On the second place, the mixed manual and I4.0 remanufacturing line has a moderated emissions around 0.7 kg CO2 equivalent per product, principally due to the higher energy consumption and the emissions attributed to equipment such as cobots and AGVs, but presents a strong reduction in emissions attributed to raw materials extraction and production. The manual remanufacturing line presents the lowest carbon footprint, as requires significantly lower energy consumption while requiring less raw materials as well.

Ergonomic conditions

Differently than previous indicators results, the data for this indicator has been collected other way, by the completion of forms and checklist by researcher and by operator. It is therefore an average of the perception of the operators and not an average of calculations based on product flow.

The first indicator is the BORG indicator, which as mentioned before, is a subjective measure of how hard an individual feels they are working during physical activity. The results of BORG questionnaire are shown in figure 4.20, next.

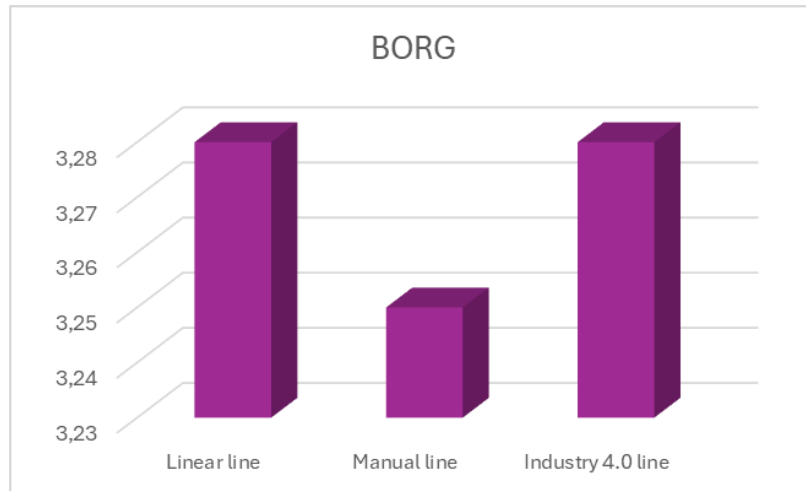


Figure 4.20. BORG questionnaire results for each model

As it is visible, there are almost no differences between the results of the three models, as the manual line presents almost no differences compared to the other two models. The three of them fall under the low score, which suggests very light to moderate exertion. An operator can typically carry on a conversation easily.

Then another ergonomics indicator is the NASA TLX, that is a widely recognized and utilized subjective, multidimensional assessment tool designed to measure perceived workload. The Nasa TLX score is shown below in figure 4.21.

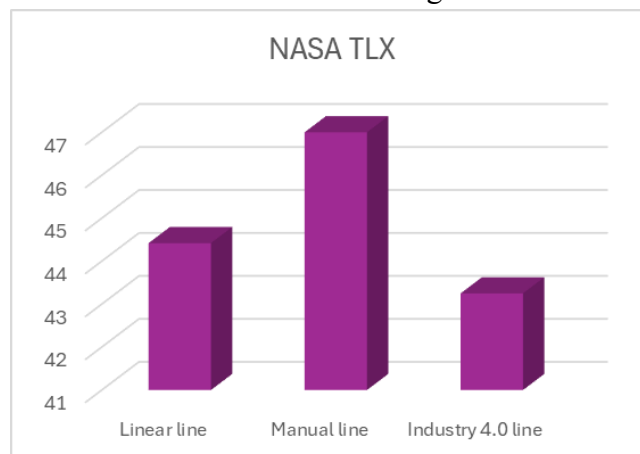


Figure 4.21. Nasa TLX questionnaire results for each remanufacturing and production model

The scale of this indicator goes from 0 to 100. Again, there is no highly noticeable difference between the three models, and all of them fall under moderate perceived workload. This is often the target range for many tasks, indicating a reasonable balance between challenge and manageability. The tasks required a fair amount of mental or physical effort.

These results for the ergonomics indicators suggest that the perceived physical and mental workload were not influenced by the implementation of one specific manufacturing or remanufacturing model, neither it was alleviated after the introduction of some industry 4.0 technologies such as cobots to help in some workstations.

5 Discussion

Research questions reminder:

- ✓ Is a remanufacturing line an economically and environmentally attractive option compared to a traditional linear production model?
- ✓ Can the implementation of Industry 4.0 technologies optimize a circular remanufacturing line in terms of reducing cycle time, costs, and negative environmental impacts, and increasing the quality and ergonomic standards of line operators?

The research questions, and equally the objectives of this investigation, sought to clearly and conclusively answer whether a remanufacturing line optimized and outperformed a traditional manufacturing line in terms of costs, productivity, quality, and environmental impact; that is, the dilemma between a circular and a linear production model.

The production models compared were two circular remanufacturing lines, one exclusively manual, and the other a mixed, manual model using Industry 4.0 technologies. Furthermore, the model was compared with a linear production model, considering only the assembly and reassembly section of the aforementioned production lines.

However, the results are mixed, and no clear model completely outperforms the others. The three models were compared in different aspects, measured through key performance indicators. These indicators were grouped into five categories: unit production cost, unit production time, product quality, environmental impact and circularity, and ergonomics.

On the one hand, the production cost indicator shows that the lowest cost is found in a linear production model, despite the higher cost of raw materials due to the fewer operations and processes. A manual remanufacturing line increases the production cost of a finished product due to the greater number of operations and the longer time a product must be handled by an operator, which increases salary costs. However, thanks to the introduction of Industry 4.0 technologies, it is possible to close the cost gap between the linear and circular models, as it reduces the necessary operating times, which optimizes human resource costs, and makes a circular production chain more financially attractive.

Regarding productivity indicators, specifically production times, as expected, a linear model presents the shortest total unit production time. This is because the circular model requires more operations, which translates into an increase in the total time the product takes to enter and exit the line. However, putting this into perspective, in terms of the percentage of value-

added time, a circular manual remanufacturing line demonstrates the greatest use of total production time, since of this total production time, it shows the highest percentage of time in which the product is actively processed by an operator. Therefore, the manual remanufacturing line presents the best cost-benefit ratio because it presents the least amount of wasted time and reduces the number of bottlenecks and imbalances on the line.

On the other hand, the clear winner in terms of product quality is the linear model, because, as it consists of completely new components, it intrinsically has, although perhaps slightly, a higher quality and perceived quality of the finished product, with a longer useful life and fewer surface or aesthetic defects. Despite this, by combining new components with reused components that are in excellent and good condition, it is also possible to obtain product qualities that are completely satisfactory from a functional standpoint.

When analysing environmental indicators, circular models present a clear advantage over the linear production model. On the one hand, in terms of the circularity measure, hydro turbines assembled on a remanufacturing line show a higher material circularity index, using reused materials and components; while the linear model has a lower circularity index and achieves an intermediate score due to its end-of-life scenario, where its components have the potential to be recycled and used in other products. However, the greenhouse gas emission indicator, or carbon footprint, shows a more striking difference, with the circular remanufacturing chain presenting approximately 40% lower emissions than a linear production model; and the mixed manual and I4.0 remanufacturing line, 30% lower than linear production. This significant decrease is almost entirely attributed to the reduction in virgin raw materials.

Finally, the three models scored virtually the same on the ergonomic indicators. There is no notable difference between the different models that justifies one over the other. The scores indicated a demand for light physical activity and a moderate workload.

In any case, if more accurate results are desired, it is necessary to perform more iterations of the different experiments conducted to increase the number of samples taken from finished products and all the information they generate during the manufacturing phase. Likewise, the models need to be further refined, primarily through more optimized line balancing and improved learning curves for tasks, which would help minimize wasted time due to waiting and provide more accurate data for time indicators. It is also necessary to review the use and programming of IoT 4.0 technologies, more specifically the various robots, to ensure they are more precise, faster, and coordinated with operators.

6 Conclusions

This master thesis has addressed the **design and implementation of a circular remanufacturing production line**, having the aim of demonstrating its feasibility and evaluating its performance at different operational models. This research has combined an opportune literature review with the practical experience of a pedagogical case study, an industrial product being a hydro turbine, and integrating consecutive stages: disassembly, diagnostic, cleaning, repairing, reassembly and quality control operations. In addition, the thesis has sought to explore how Industry 4.0 technologies can improve the functioning of such circular line, and how the adoption of lean manufacturing principles and digital tools contributes to efficiency, sustainability, and ergonomic performance. A summary of what has been done and found is explained next.

- 1) We designed and physically implemented a complete circular remanufacturing production line, including disassembly, diagnostic, cleaning, repairing, kitting, reassembly and quality control stages.
- 2) We demonstrated that the integration of lean manufacturing principles (line balancing, kitting, shadow boards, and ergonomic workstation design) significantly improved process flow and reduced bottlenecks.
- 3) The obtained results showed that the introduction of Industry 4.0 technologies (cobots, AGVs, QR-based data collection, and spectrometric material identification) enhanced accuracy, repeatability, and sustainability, while also improving data traceability across the remanufacturing chain.
- 4) We measured differences in throughput time and value-added time across several experimental configurations, confirming that line balancing and adequate task allocation are decisive factors in improving efficiency.
- 5) We recognized the opportunities that Industry 4.0 technologies provide for optimizing and reducing value-added time to reach a similar productivity as a linear production model.

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- 6) We found that remanufacturing production models achieved higher sustainability performance compared to linear ones, as reflected in environmental indicators such as an important carbon footprint reduction and improved Material Circularity Indicator.
 - 7) We observed that remanufactured products provided insightful information regarding production simulations and has advantages as increased flexibility and, demonstrating the technical feasibility of pedagogical remanufacturing chains as platforms for both research and education.

This thesis provides a practical framework for the design and experimental implementation of circular remanufacturing lines, bringing together theory and practice. In literature there are few case studies of operating remanufacturing lines to assess its feasibility, but only separate studies on different remanufacturing stages and practices; and this research thesis sought to combine this isolated knowledge into an operating remanufacturing model. It demonstrates that circular models can be technically and operationally feasible, environmentally advantageous, and research valuable, thus contributing to the advancement of sustainable industrial practices and manufacturing innovation.

Suggestions for further work

Future research should expand the framework to more complex and industrially relevant products (example: automotive, aerospace, or heavy-duty equipment), or mass consumer products (example: macro and microelectronics). The integration of more advanced Industry 4.0 technologies such as digital twins, augmented reality, and artificial intelligence predictive diagnostics should be explored to achieve real-time flexible optimization. A complete life cycle assessment (LCA), and possibly a Social LCA, is recommended to quantify the environmental and social benefits at a systemic level. Additionally, the pedagogical use of circular remanufacturing platforms could be developed further to train engineering students and professionals in sustainable and digital manufacturing practices, in universities, such as Grenoble Institute of Technology.

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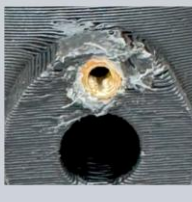
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Appendix

Appendix A. Disassembly station



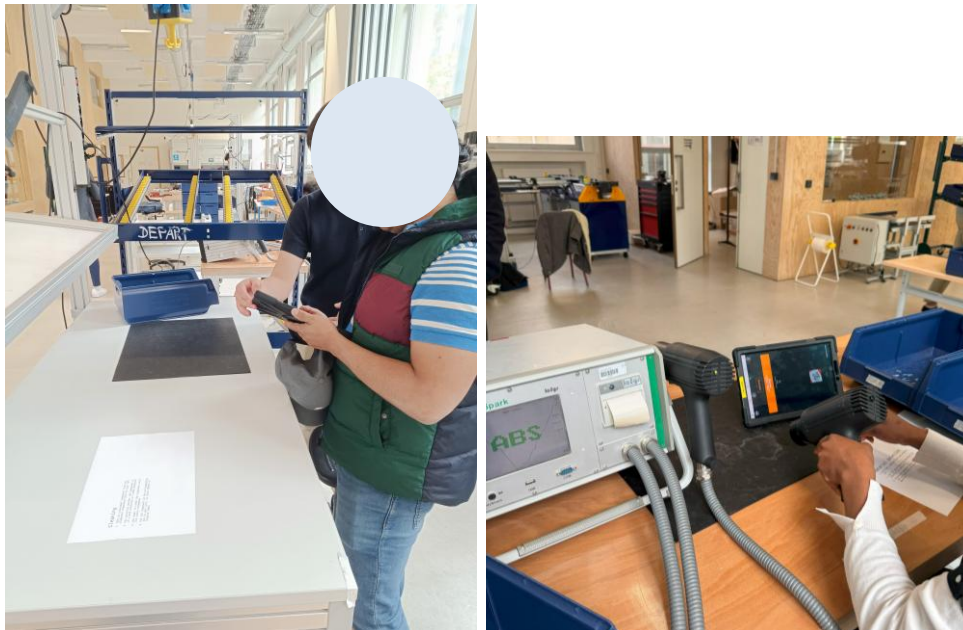
Appendix B. Short defects database example

	Propeller in perfect condition	Stains	Loose anchor with broken fibers	Delamination	Plastic deformation
Defect					
Can be re-used?					
Action	Kitting	Cleaning	Recycling # if loose anchor but no broken fibers then repairing	Reparation	Reparation
Score	3	3	0 #2	1	1

Appendix C. Diagnostic station



Appendix D. Cleaning and repairing station.



Appendix E. Repairing station



Appendix F. Kitting station



Appendix G. Reassembly station



Appendix H. Quality control checklist form

Quality control of Hydro turbine

Product code: V_____

Please complete the following questions regarding the quality of the product:

1. Can you write the code of the visible components:

Blades: B_____, B_____, B_____

Arms: A_____, A_____, A_____

Propeller: P_____, Rear cap: R_____

Nose: N_____, Body: D_____

2. Can the propeller turn smoothly? Yes No

3. Is any of the components broken or cracked? Yes No

If no, please write what components are broken or cracked? If multiple, please write the number of defective components (example: 2 blades, 3 arms)

Blades: _____

Arms: _____

Propeller: _____

Rear cap: _____

Nose: _____

Body: _____

4. Now, please verify that the screws are correctly adjusted:

• Are the blades correctly screwed? Yes No

If the blades are not correctly screwed, how many screws are defective? _____

• Are the arms correctly screwed? Yes No

If the arms are not correctly screwed, how many screws are defective? _____

• Is the rear cap correctly screwed? Yes No

If the rear cap is not correctly screwed, how many screws are defective? _____

5. Any other comment:

Appendix I. Quality control station



Appendix J. Complete manual remanufacturing line

