RECLAIM

Refurbishment and re-manufacturing of large industrial equipment

D4.1 Circular Economy-driven lifetime-extension strategies

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[1] PU = Public

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Abbreviations and Acronyms

Abbreviation	
4IR	Fourth Industrial Revolution (Industry 4.0)
AI	Artificial Intelligence
B2B	Business-to-Business
B2C	Business-to-Consumer
BM	Business Model
CAD	Computer-Aided Design
CE	Circular Economy
CEO	Chief Executive Officer
CR	Circularity Rate
Dep.	Department
DoA	Description of Action
DSF	Decision Support Framework
DT	Digital Twin
EoL	End of Life
FU	Functional Unit
GWP	Global Warming Potential

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I4.0	Industry 4.0
IEOL	End-of-Life Index
IoT	Internet of Things
IT	Information Technology
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCES	Life Cycle Extension Strategies
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCP	Life Cycle Planning
LED	Light Emitting Diode
MCI	Material Circularity Indicator
OAP	Open Architecture Products
OEM	Original Equipment Manufacturer
PdM	Predictive Maintenance
PEF	Product Environmental Footprint
PLE(BM)	product lifetime extension (business models)
PSS	Product Service System
RF	Reference Flow
RUL	Remaining Useful Life(time)
SCF	Strategy Characterization Framework
SOM	Soil Organic Matter, sustainable operations management
SW	Software
T	Task
TPD	Technical Product Documentation
US	United States
VS	Versus
WBCSD	World Business Council for Sustainable Development
WoS	Web of Science
WP	Work Package

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Summary

This deliverable is meant to present the activities carried out during T4.1, which has a twofold objective: i. identify effective strategies to pursue Circular Economy-driven machine lifetime extension, which consider all the stakeholders belonging to the machinery value-chain (e.g. users, service providers, OEMs, components manufacturers, machine designers); ii. design a methodology to support stakeholders in the analysis of the current scenario and in the identification of which strategy to pursue, evaluating the possible choices considering economic and environmental sustainability together with the circularity level of the solution defined.

§2 of this document is dedicated to a literature review that is meant to identify the LCES to be potentially applied to production equipment. Starting from the definition of a proper taxonomy, literature findings have been classified not only to identify the life extension strategies, but also to characterize them for their actual exploitation in the industrial context and into the project pilots. In order to address the application in the companies activities, the analysis has been extended to patents and standard. As a result of the literature study, the revision of the LCES definitions found in literature is presented in order to solve inconsistencies and avoid misunderstandings, considering the strategies definition as an essential element for a clear application. The section concludes with the work carried out with demonstration partners that during a workshop has been carried out to identify the LCES the pilots would like to implement during the project.

Starting from the classification proposed in §2, §3 is addressing the description of the Strategy Characterization Framework (SCF) that is meant to provide a deeper and structured analysis on strategies for the actual application in industries of product life cycle extension concept. Indeed, industrial practice needs more detailed information about how a strategy works, how it can be put in place, which are the actors involved in its implementation and which are the costs and the benefits offered from the sustainability point of view. Also in this case, the section ends with the SCF validation performed with pilot partners that had the opportunity to propose some upgrade regarding the field constituting the framework.

In order to address the second objective of T4.1, §4 describes the methodology that allows to evaluate the environmental, economic and circularity impacts of the life extension strategies applied in a linear economy model. Starting from the identification of the opportune indicators to be calculated, a gap assessment method is then presented offering a theoretical approach for the possible advantages/disadvantages offered by the LCESs along the equipment lifecycle. The evaluation methodology proposed here represents moreover the foundation of the LCC and LCA tools that will be developed in T7.4.

Eventually, §5 is meant to identify the actions that, starting from a linear economy model, are needed to implement the life cycle extension approach. This work has been focalized on the LCES labeled by the pilots as most promising in the RECLAIM project and has been carried out with two different but complementary perspectives: the one offered by scientific literature and the one proposed by the demonstration partners. This final section thus aims to put the basis to the creations of guidelines and methods to support companies towards the transition of a CE approach in the life cycle management of the equipment.

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1 Introduction

Earth's ecosystem is showing the tremendous effects of the linear consumption model that distinguishes our society. Resources are relentlessly drained in the sake of a consumerism-based consumption model, with the effect that the global ecological footprint of human activities has increased from less than one planet Earth in 1961, to more than 1.4 planet Earths in 2005, with projections leading to two planet Earths around 2030 (Milios, 2018).

Against this trend, the concept of Circular Economy has been coined, referring to an industrial economy that is restorative by intention; aims to rely on renewable energy; minimizes, tracks, and hopefully eliminates the use of toxic chemicals; and eradicates waste through careful design (Jones et al., 2019). According to the CE message, the inner circles of Figure 1 (reuse, remanufacturing and refurbishment) demand fewer resources and energy than conventional recycling of materials as low-grade raw materials. The time spent by the resources within the inner circles should be maximized and the adoption of Lifecycle Extension strategies (LCES) favored (Korhonen et al., 2018).

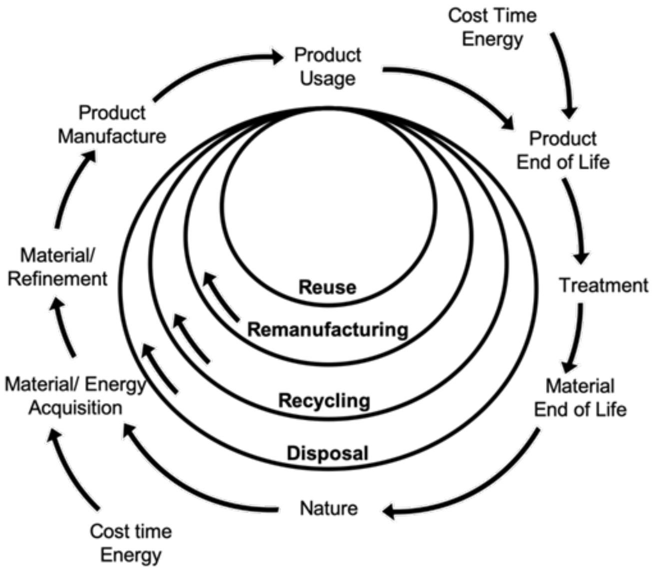

Figure 1. Product value retention in a Circular Economy (CE) model. Adapted from (Mihelcic et al., 2003)

According to the presented model, the product value chain and life cycle retain the highest possible value and quality as long as possible and is also as energy efficient as it can be.

Trying to put the theoretical definition into action, the European Commission is pushing the boundaries of its implementation by promoting founding schemes and initiatives to support and drive the systemic integration of circular behaviors into the European economic and social system (European Union Commission, 2020). As a matter of fact, CE is nowadays shifting from a nice to have marketing operation, to a business development strategy central to the restoring and preservation of our natural ecosystem (Planing, 2018). However, despite the motivated promoting efforts, the concrete application of the model at the micro-level is still in its infancy due to several challenges that companies face (Bressanelli et al., 2019; Hopkinson et al., 2018; Rajput & Singh, 2019).

One of the key aspects being nowadays explored related to the next generation of manufacturing systems is the focus on the reuse of waste materials and equipment in End of Life (EoL). The impact of Circular Economy strategies, in particular for LCES has gained strength and was somehow refreshed with the introduction of digitalization, mainly through the 4th industrial revolution (Antikainen et al., 2018; Neligan, 2018; Sarc et al., 2019). Based on the concept of the digital twin, which simplistically is a digital replica of shop-floor equipment, data can be collected, processed and synchronized with Information Systems

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and more knowledge can be generated and gained for wiser and more informed decisions (Demestichas & Daskalakis, 2020). As for LCES, the digitalization process allowed for a better understanding of the exogenous properties —such as physicochemical properties and dynamics of the process— together with the endogenous properties — focusing on the behavior of each component that composes the equipment. These aspects are particularly important for CE taking into account strategies related to equipment lifecycle extension. Without collected data and information about machine process capabilities and machine degradation/health, LCES is a very hard job to achieve (Rosa et al., 2020).

Taking Resell and Reuse as an example, which is closely related with the concept of servitization in industry, without the correct machine data about maintenance logs, used parameters, product quality and degradation data, it is very hard to reliably resell a machine to a company, or even reuse a machine for different purposes (Bressanelli G., Adrodegari F., Perona M., Saccani N., 2018). In the case, an Original Equipment Manufacturer (OEM) resells equipment, and quality assurance should be given to the customer. The problem is that a different customer uses the machine, and hence, no information about its use is known. However, with the servitization concept software modules can be installed in the machine itself, as a digital twin, and predictive models about maintenance, degradation and quality can be built based on collected data, and afterward resold to the new customer. Complemented with other relevant information and contracting, this can be seen as the required assurance for the new customer, taking into account also the importance of economic, social and psychological factors that affect customers to engage in the CE purchasing durable products and seeking to repair products instead of disposing of them. In this context, the capability of businesses to exploit technological advancements as enablers for the adoption and diffusion of CE models and practices, together with the strong consumer engagement that allows making these models flourish, is a prerequisite for the success of the CE model itself.

The deliverable focuses on a systematic literature review of lifetime extension strategies for CE, adopting the PRISMA guidelines (Page et al., 2021). Compared to the available literature reviews in this context, that consider LCES as a part of CE, this work focuses on LCES and is specifically devoted to providing academia and industry concrete elements to guide the implementation of LCES into daily activities. In doing so, it aims to answer two main questions, both motivated by the limited and somehow scattered literature related to LCES, and by the need of providing academia and practitioners instruments to support a better understanding of which CE strategies are most relevant and indicated for each specific situation:

- What is the state of research related to equipment lifetime extension strategies and their definition?
- What are the possible elements to be extracted from literature to implement the LCES from the technical and business point of view?

The results of the work are meant to extend the current theoretical knowledge related to LCES by providing a thorough review of the current edited works, either in terms of literature studies, patents and standards. The works are systematically analyzed through a taxonomy designed according to the identified research questions.

As a result of the review, a set of definitions of the identified strategies is proposed. The definitions have the scope of homogenizing the different perspectives found in the literature domain for the same aspect or, whenever needed, proposing new definitions merging the different contributions and filling the identified literature gaps.

On top of the previous analysis, the Strategy Characterization Framework (as one of the input of Decision Support Framework) is proposed in §3. The model, focusing its application on electromechanical machines and robotics systems, guides the identification of the

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optimal LCES, offering machine lifetime extension plans that, together with the environmental benefits, guarantee increased productivity.

On the other hand, D4.1 is meant also to design a methodology to support stakeholders in the analysis of the current scenario and in the identification of which of the LCES to pursue, evaluating the possible choices considering economic, environmental and circularity performances. This is addressed in §4 through the identification of opportune sustainability indicators and the development of an associated evaluation methodology that is meant to highlight the differences between the linear strategy and the CE ones. The methodology presented here puts the theoretical basis for the development of the LCA and LCC tools to be developed in T7.4.

Eventually, the deliverable ends with the identification of the action needed to put in place a selection of LCES that, amongst the ones collected in literature, has been identified as the most promising and interesting for an actual application in RECLAIM.

The majority of the results obtained during T4.1 activities (i.e. the strategies definitions, the SCF and the actions) have been validated with the RECLAIM partners via a dedicated workshop.

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2 Life Cycle Extension Strategies identification

The first chapter of this deliverable focuses on a literature review oriented to identify Life Cycle Extension Strategies (LCES) that could shift the life cycle management of production equipment from the linear economy approach to the CE one. This analysis not only allows to better understand which strategies might be suitable to explore and apply into the RECLAIM project, but it is also meant to lay the basis to: i. provide academia and industry concrete elements to guide the implementation of LCES into the daily activities; ii. implement a Decision Support Framework (DSF). This work in fact is meant to identify the strategies and, via the taxonomy described hereinafter, prepare their characterization that is deepened in §3.

§2.1 focuses on the review methodology used for selecting and analyzing the most suitable papers given the current topic of LCES in the perspective of both existing papers and patents. §2.2 provides a summary and brief individual evaluation of all the selected papers through a taxonomy lens, which was essential to uniform the understanding of the multiple strategies. Additionally, a complete and condensed review of the results is presented. Finally, and to better contextualize the importance of the paper review, a set of standards is presented related to Maintenance and Remanufacturing. Further on, as a complementary activity, a small set of standards in maintenance and remanufacturing strategies was performed. As a result of the performed review and standard analysis, the section closes presenting the revised definitions of the LCES.

2.1 Review methodology and Trend Analysis

This section is meant to present the review protocol exploited in this work, based on the approach suggested by (Pullin & Stewart, 2006). This resulted in four different stages, from gathering all publications to the classification of each paper into the defined taxonomy. Additionally, a paper and patent trend analysis are presented, covering the last 10 years of developments. A perspective on the evolution of this area is thus contemplated, together with a set of related standards, giving indications on regulations driving CE implementation in the industrial domain.

2.1.1 Review methodology

2.1.1.1 Gathering the publications and patents

As the first step of the literature review, publications were gathered exploiting the database and the keyword reported in Table 1.

Table 1. Main boundaries of literature and patents review

Boundary	Description
Database used	Science direct (Elsevier); Web of Science; Lens patent; Google patent.
Research Keywords	Circular economy strategies, Lifecycle extension strategies, Lifecycle extension industrial/production equipment, Digitalization and lifetime extension.
Year considered	From 2002 up to 2020, with the majority of the studies concentrated from 2010. The only exception is a 1995 publication, considered as the ancestor of life extension topic.
Language	Scientific articles in English were considered for the analysis.
Article type	Scientific papers and conference papers.
Publication status	Published.
Patent status	Granted.

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2.1.1.2 *Identifying topic references*

Figure 2 shows the adopted research strategy. Starting from a first search of the Research Keywords in the field “Topic” in the Web of Science search engine, and “Title, abstract and author-specified keywords” in the Science direct search engine, the records identified by searching the database are 2539, 1671 form Web of Science and 868 from Science direct. After duplicates are removed, 1200 papers are taken into consideration. The second step of the review implies a first screening of the bibliographic references through title and abstract analysis, in order to identify the ones that are providing a valuable contribution to the understanding of the LCES subject. A total of 989 scientific papers were excluded, thus 211 publications remain with titles and abstracts dealing with the identified topics and were fully assessed for eligibility. Finally, by applying the two research questions above mentioned as a refining criterion, a final amount of 75 documents was considered as reference literature and assessed in detail.

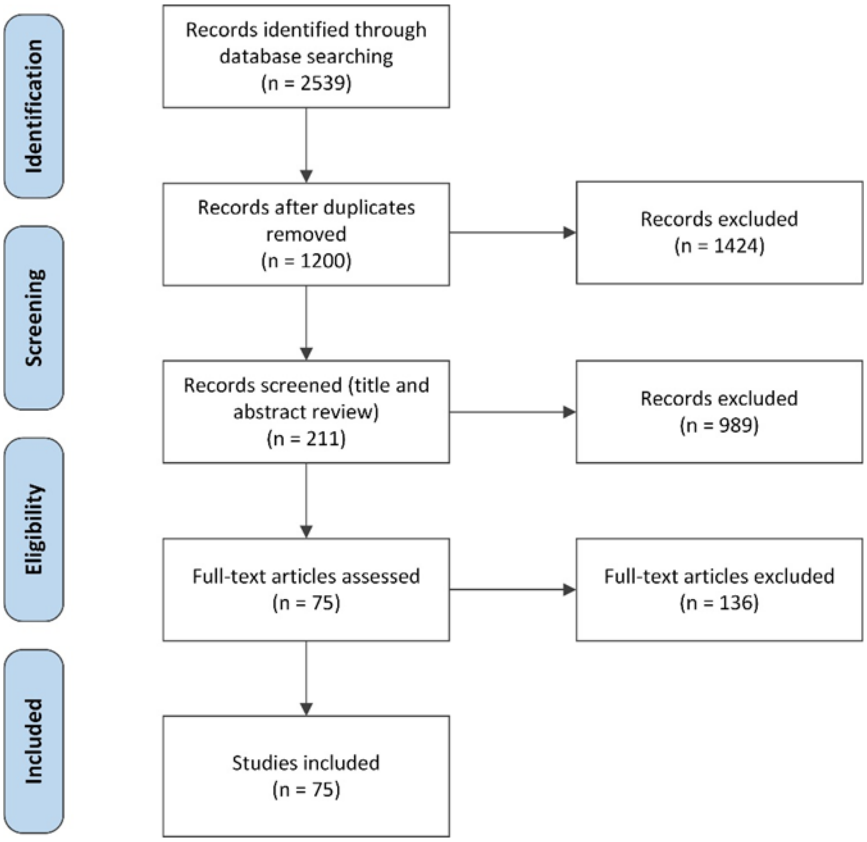

Figure 2. PRISMA flow diagram applied to the work

2.1.1.3 *Taxonomy Definition*

The third phase of the review methodology is a reasoned examination of the papers’ text to understand the possible contribution of the literature to the topic considering a wide perspective (e.g., economic and environmental impacts, indicators, business consequences, etc.). This evaluation was guided by the development of a Taxonomy that was exploited to pre-classify the publications and then classify the contributions. As suggested by (Chakraborty & Stewart, 2012), the taxonomy was designed with the intent of delimiting and classifying the different contributions on the topic discussed in the paper. As a taxonomy not only includes the classification system but also, the theory on which the classification system is built and the methods employed to construct it (Chrisman et al., 1988). The taxonomy definition takes the steps from the research questions above mentioned. Concerning the state of research, the literature findings were classified grouping the ones related to literature analysis on the field of CE strategies. Special attention was also dedicated to the publications specifically addressing life cycle extension amongst CE

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strategies, production equipment and LCES. A focal point related to state of the art is moreover related to works providing definitions of LCES so that strategies are clearly identified. In order to satisfy these research needs, the following taxonomy fields were thus introduced: *Literature Review*, *Life cycle Extension*, *Production Equipment*, *Strategies*, *Definition*. With regards to the possibility to extract from literature elements for the implementation of LCSE (the second research objective), the taxonomy field identification was based on different publications that investigated the development of implementation frameworks for corporate sustainability (Chofreh & Goni, 2017; Gallotta, B., Garza-Reyes, J.A., Anosike, T., Lim, M.K., Roberts, 2016; Nawaz, W., Koç, 2018; Tasleem, M., Khan, N., Shah, S. T. H., Saleem, M., Nisar, 2017).

All these works share a common approach for the actual implementation of sustainability concepts (and thus, extending the scope, applicable also to the CE ones) that is funded in planning, activate initiatives and measure the results and the impacts obtained. Following this framework, literature findings were categorized considering the following taxonomy fields: *Description and Implementation Guidelines* (planning), *Business Models and Digitalization and Lifetime Extension* (activate initiatives) and *Metrics and Evaluation Methodologies* (measure).

Hereinafter, the definition of the taxonomy fields is detailed in Table 2**Errore. L'origine riferimento non è stata trovata.**.

Table 2. Taxonomy fields

Taxonomy Field	Research Question	Field Scope
Literature Review	State of research	It is meant to select the papers that are providing an extensive literature review on the LCES or on the related topics.
Life cycle Extension	State of research	It investigates whether the publication is considering the life cycle extension concept, directly or indirectly mentioning it.
Production Equipment	State of research	It discriminates if the publication is specifically dealing with production equipment.
Strategies	State of research	It discriminates if the publication in analysis is presenting strategies to extend the life cycle of products.
Definition	State of research	It allows identifying the papers providing a precise definition of the LCES. This field was introduced since a preliminary analysis of the research results revealed that some unclear or even conflicting definitions of strategies are proposed in the literature.
Description and Implementation Guidelines	Implementation	It is meant to establish whether the publication in analysis is providing a description of the strategy application in the industrial context, or even is proposing guidelines that could actually support the implementation of the strategy presented.
Metrics and Evaluation Methodologies	Implementation	It investigates if the paper presents metrics and indicators to evaluate the effects of the strategy implementation from the economic and environmental point of view, or evaluation methodologies enabling discrimination between the diverse LCES.
Business Models	Implementation	It is meant to identify the publications presenting a business view related to the LCES application in the form of a possible business model to be concretely applied in the industrial application.
Digitalization and Lifetime Extension	Implementation	It describes how digitalization plays a crucial role to enable more sustainable Circular Economy and how a product's lifetime is extended thanks to digital innovation, with a specific focus on the extension of the lifespan of machinery, equipment and product.

2.1.1.4 Classification through the taxonomy

The last step of the review methodology here considered is the classification of the research results via the taxonomy, presented in Table 3.

Table 3. Publications per Taxonomy field

Taxonomy Field	Publications
Literature Review	(J. A. Mesa et al., 2019), (Muztoba Ahmad Khan et al., 2018), (Ertz et al., 2019a), (Rossi et al., 2020), (Reike et al., 2018), (Ding & Kamaruddin, 2014), (Ertz et al., 2019b), (Elia

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	et al., 2017), (Hu et al., 2015), (de Jonge & Scarf, 2020), (Tang et al., 2002), (Muztoba Ahmad Khan & Wuest, 2018)
Life cycle Extension	(J. A. Mesa et al., 2019), (Muztoba Ahmad Khan et al., 2018), (Ertz et al., 2019a), (Rossi et al., 2020), (Reike et al., 2018), (Ding & Kamaruddin, 2014), (Alamerew & Brissaud, 2019), (Blomsma et al., 2019), (Blomsma et al., 2018), (Um & Suh, 2015), (Morseletto, 2020), (Dehghanbaghi et al., 2016), (Thierry et al., 1995), (Go et al., 2015), (Bauer et al., 2016), (Bocken et al., 2016), (Den Hollander & Bakker, 2012), (Paterson et al., 2017), (Gharfalkar et al., 2016), (Linton & Jayaraman, 2005), (Ziout et al., 2014), (Mulders & Haarman, 2017), (Vermeulen et al., 2018), (Kobayashi, 2005), (Bakker, J D., H.J. van der Graaf, J.M. van Noortwijk, 1999), (Moraga et al., 2019), (Rezinskikh & Grin', 2013), (Simons, 2017), (Barberá et al., 2012), (F. Giudice, G. La Rosa, 2003), (March & Scudder, 2019), (Coulon et al., 2019), (Moseichuk et al., 2010), (Mourtzis et al., 2018)
Production Equipment	(Moseichuk et al., 2010)
Strategies	(J. A. Mesa et al., 2019), (Muztoba Ahmad Khan et al., 2018), (Ertz et al., 2019a), (Rossi et al., 2020), (Reike et al., 2018), (Ertz et al., 2019b), (Elia et al., 2017), (Hu et al., 2015), (Tang et al., 2002), (Alamerew & Brissaud, 2019), (Blomsma et al., 2019), (Blomsma et al., 2018), (Um & Suh, 2015), (Morseletto, 2020), (Dehghanbaghi et al., 2016), (Thierry et al., 1995), (Go et al., 2015), (Bauer et al., 2016), (Bocken et al., 2016), (Den Hollander & Bakker, 2012), (Paterson et al., 2017), (Gharfalkar et al., 2016), (Linton & Jayaraman, 2005), (Ziout et al., 2014), (Mulders & Haarman, 2017), (Vermeulen et al., 2018), (Simons, 2017), (Barberá et al., 2012), (F. Giudice, G. La Rosa, 2003), (March & Scudder, 2019), (Coulon et al., 2019), (Moseichuk et al., 2010), (Wu et al., 2020), (Y. Wang et al., 2014), (Muztoba A. Khan et al., 2020), (Guerra et al., 2016), (Yin et al., 2018), (J. Mesa et al., 2020)
Definition	(Muztoba Ahmad Khan et al., 2018), (Rossi et al., 2020), (Reike et al., 2018), (Ertz et al., 2019b), (de Jonge & Scarf, 2020), (Alamerew & Brissaud, 2019), (Blomsma et al., 2019), (Morseletto, 2020), (Thierry et al., 1995), (Go et al., 2015), (Bauer et al., 2016), (Bocken et al., 2016), (Den Hollander & Bakker, 2012), (Paterson et al., 2017), (Gharfalkar et al., 2016), (Linton & Jayaraman, 2005)
Description and Implementation Guidelines	(Muztoba Ahmad Khan et al., 2018), (Reike et al., 2018), (Elia et al., 2017), (de Jonge & Scarf, 2020), (Muztoba Ahmad Khan & Wuest, 2018), (Um & Suh, 2015), (Morseletto, 2020), (Dehghanbaghi et al., 2016), (Thierry et al., 1995), (Go et al., 2015), (Bauer et al., 2016), (Bocken et al., 2016), (Den Hollander & Bakker, 2012), (Paterson et al., 2017), (Gharfalkar et al., 2016), (Linton & Jayaraman, 2005), (Ziout et al., 2014), (Mulders & Haarman, 2017), (Vermeulen et al., 2018), (Simons, 2017), (Coulon et al., 2019), (Mourtzis et al., 2018), (Y. Wang et al., 2014), (Muztoba A. Khan et al., 2020), (Guerra et al., 2016), (Abdi & Taghipour, 2019), (Zwolinski & Brissaud, 2008), (Zwolinski et al., 2006), (Favi et al., 2019), (Favi et al., 2017)
Metrics and Evaluation Methodologies	(Rossi et al., 2020), (Ding & Kamaruddin, 2014), (Elia et al., 2017), (Hu et al., 2015), (Tang et al., 2002), (Alamerew & Brissaud, 2019), (Paterson et al., 2017), (Gharfalkar et al., 2016), (Linton & Jayaraman, 2005), (Ziout et al., 2014), (Kobayashi, 2005), (Bakker, J D., H.J. van der Graaf, J.M. van Noortwijk, 1999), (Moraga et al., 2019), (Barberá et al., 2012), (F. Giudice, G. La Rosa, 2003), (March & Scudder, 2019), (Wu et al., 2020), (Yin et al., 2018), (J. Mesa et al., 2020), (Zwolinski & Brissaud, 2008), (Zwolinski et al., 2006), (Favi et al., 2019), (Favi et al., 2017), (HU et al., 2018)
Business Models	(Muztoba Ahmad Khan et al., 2018), (Ertz et al., 2019a), (Ertz et al., 2019b), (Muztoba Ahmad Khan & Wuest, 2018), (Bocken et al., 2016), (Den Hollander & Bakker, 2012), (Simons, 2017)
Digitalization and Lifetime Extension	(Neligan, 2018), (Bressanelli G., Adrodegari F., Perona M., Saccani N., 2018), (Ertz et al., 2019a), (Ertz et al., 2019b), (Bocken et al., 2016), (Alcayaga et al., 2019), (Ingemarsdotter et al., 2019), (Okorie et al., 2018), (Ghoreishi & Happonen, 2020), (Jose Ospina, John Gallagher, Paul Maher, Jose Ospina, John Gallagher, 2019), (Alcayaga & Hansen, 2017), (Kan & Anumba, 2019), (Hoffmann et al., 2020), (Ingemarsdotter et al., 2020), (Hickey & Fitzpatrick, 2007), (Jensen & Remmen, 2017), (Tygesen et al., 2018), (Klishin et al., 2020), (J. Wang et al., 2019), (Jane Marie Andrew, 2019), (Geerken et al., 2019)

2.1.2 Trend analysis

Paper and Patent Trend Analysis presented hereinafter are meant to provide an overview of how the CE and LCES topics were addressed in the last 10 years, both by academics and industries.

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2.1.2.1 *Paper Trend Analysis*

As a first step, an analysis in terms of number of publications and citations was performed in the Web of Science (WoS) online platform. Figure 3 depicts an exponentially growing trend in publications in the past 5 years, with close to 83% of all publications being between 2015 and 2019, with a total of 1262 publications. It can also be seen a slight growth between 2008 and 2010 but followed by a decrease in publications until 2015. As for the publications, the same trend can be observed in the last 5 years, with 95% of citations registered between 2015 and 2019, with a total of 9695 citations.

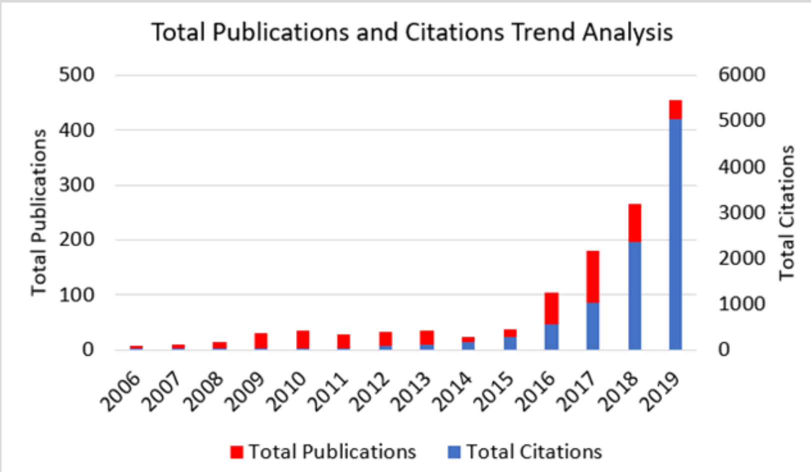

Figure 3. Trends of the CE publications and citations in manufacturing and industry-related topics

The current analysis was based on a search in WoS with the topic keyword of "circular economy" and the keywords having "manufacturing" or "industry", or both, in the topic as well. Although there are already some results from 2019, those were excluded being considered not closed and still increasing until the end of the year, making those not suitable to be included in the analysis.

An analysis based on the publication trend of life cycle extension strategies was carried out considering the following search engines: Science Direct and Web of Science, in the period 2010-2019. Figure 4 represents the results of research showing non-linear behavior: the number of publications relating to the life cycle extension strategies varies from year to year, maintaining an increasing trend over the last few years.

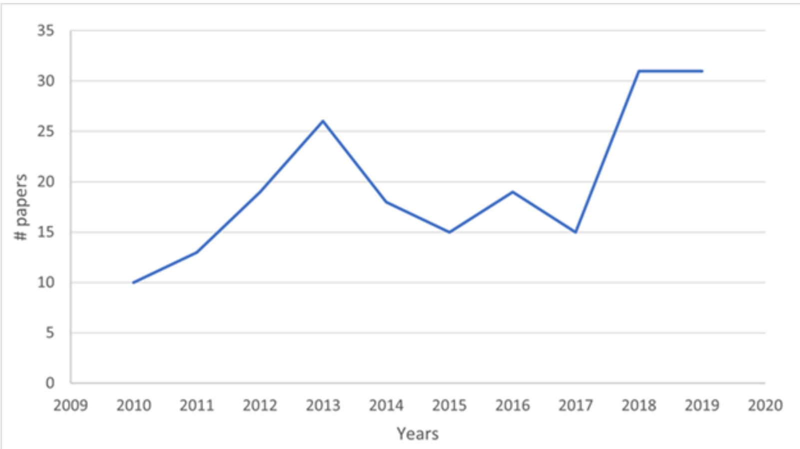

Figure 4. Trends of publications about Life Cycle Extension Strategies (LCES) (2010-2019)

A further analysis was performed focusing on the main trend of the papers related to how digitalization affects the product lifetime and the extension of machinery and equipment. The research was performed by using all the following search engines: Science Direct,

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Springer Link, Taylor Francis, Wiley Blackwell and Google Scholar. We selected the period from 2010 to 2019 considering the keywords related to “digitalization” and “lifetime extension” and their combination. Figure 5 and Table 4**Errore. L'origine riferimento non è stata trovata.** highlight the results of the research showing a moderate but constant increase in the number of publications in digitalization and lifetime extension topics, respectively, and a steep increase in the combination of the two topics for the last four years.

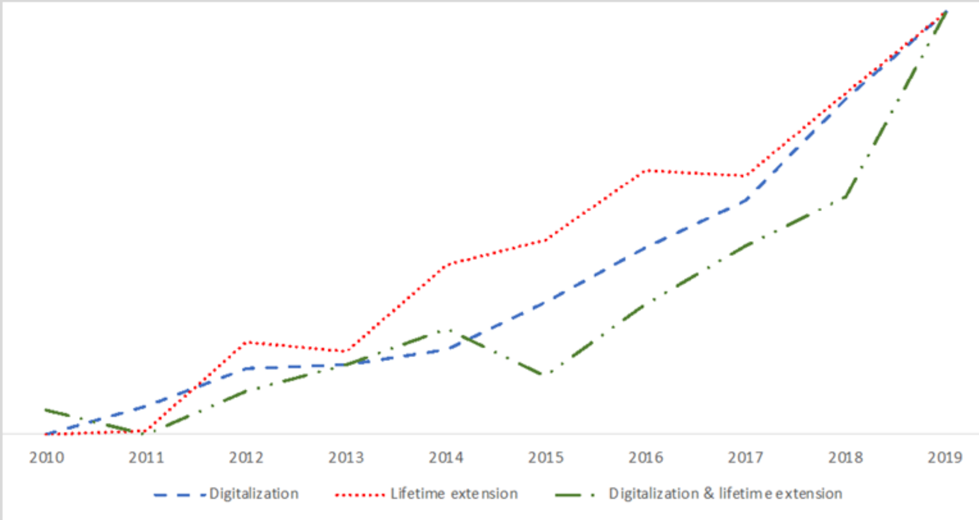

Figure 5. Trends of publications about “digitalization” and “lifetime extension” (2010-2019)

Table 4. Trends of publications about “digitalization” and “lifetime extension” (2010-2019)

TOTAL	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Digitalization	81,095	87,005	94,714	95,286	98,637	108,230	119,506	129,364	150,279	168,301
Lifetime extension	804	811	993	972	1,149	1,198	1,340	1,328	1,494	1,661
Digitalization & lifetime extension	12	3	19	29	42	25	51	73	91	160

2.1.2.2 *Patent Trend Analysis*

A patent analysis was carried out using Lens Patent as the main database for our purpose. The research on trends was based on patents over the last 10 years (from 2010 to 2019). A first analysis was conducted on the Life cycle extension topic for the industry and manufacturing sector with the following keywords: “Circular economy”, “Lifetime extension”, “Remanufacturing, Refurbishment” AND “equipment”, “Refurbishment” AND “machinery”, “Refurbishment” AND “industrial machine”, “Predictive maintenance”, “Predictive maintenance” AND “equipment”, “Predictive maintenance” AND “industrial machinery”, “Preventative maintenance”, “Preventative maintenance” AND “equipment”, “Preventative maintenance” AND “industrial machine”. These keywords are in line with the ones used for the analysis of trends in publications and citations and were selected with the aim to avoid too generic results, not pertinent to the purpose of this work. Our search strategy was related to the “granted” patent that is mentioned in the dataset under the following fields: title, abstract, full text and claims. We use a Boolean research strategy to get a representative sample excluding replication of patents. We obtained a final sample with 16,409 patents. Figure 6 highlights that the number of patents is clearly increasing over the years, with an increasing marginal number in the last 2 years. The figure also shows a high concentration of countries where the US (73% of the overall selected patents), Europe (16%) and Australia (5%) seem to have the most prominent role followed by China, South Korea, and Japan. The most prominent keywords in terms of the number we find in this

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analysis are "Preventative maintenance" (30.8%), "Preventative maintenance" AND equipment (20%), Refurbishment AND "industrial machine" (16.34%), Remanufacturing (11.6%), "Predictive maintenance" (8.34%), "Predictive maintenance" AND equipment (5.92%), Refurbishment AND equipment (3.79%), "Lifetime extension" (1.5%), "Circular Economy" (1.2%).

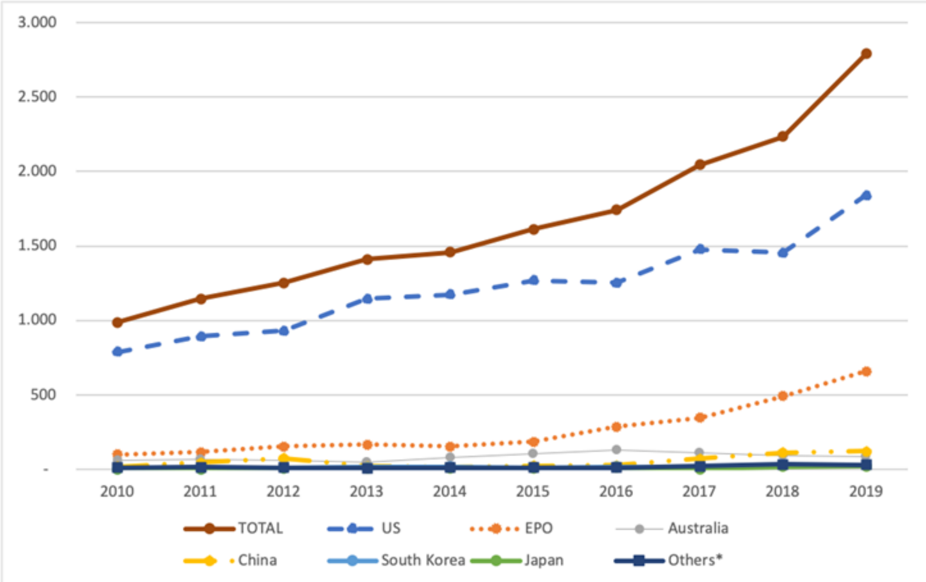

Figure 6. Annual and country trends of patents related to CE and Life Cycle Extension

Thereafter, we made a focus on the patents related to digitalization and lifetime extension collecting information from Lens Patent and Google Patent. We find an increasing trend as shown in Figure 7 confirming the higher interest on the topic not only for the academic sector but also for the market.

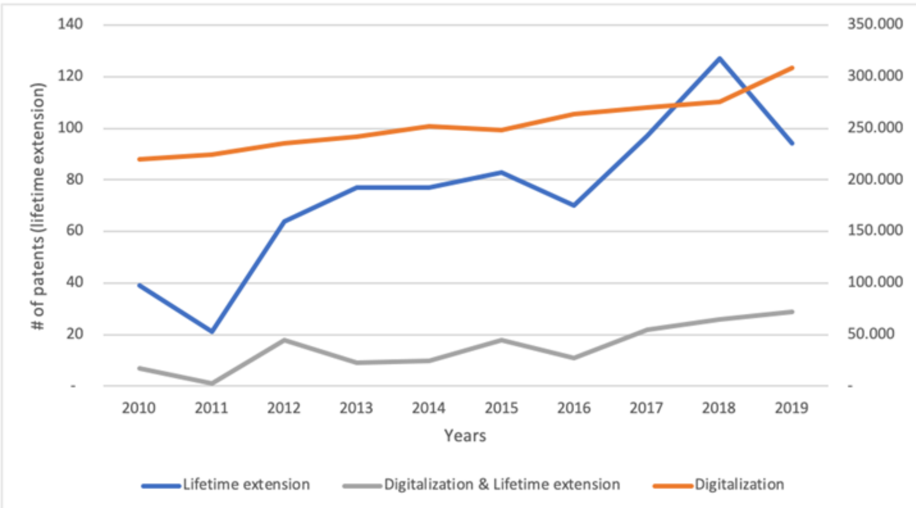

Figure 7. Annual trend of patents related to lifetime extension and digitalization

2.1.3 Literature analysis

This section is dedicated to the analysis of the gathered publications. The review of the papers was conducted by first analyzing them through the lenses offered by the taxonomy and presenting them in groups extracting the major contributions to the specific taxonomy element. Additionally, a bridge is established between this analysis and a set of standards to also highlight the regulatory initiatives being implemented.

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2.1.3.1 Analysis via the defined Taxonomy

The contribution of the most significant publications to the different facets of life cycle extension topic is hereinafter presented considering the taxonomy described in §2.1.1.3.

Literature review. In (J. A. Mesa et al., 2019), an analysis of literature reviews is performed regarding the design of Open Architecture Products (OAP) and their potential benefits to the CE concept, identifying at the same time the existing relations between product design approaches and product life extension. The major reviews in (Ding & Kamaruddin, 2014) specifically focus on maintenance, analyzing the methods used and the application areas in order to investigate the current standing of maintenance policy optimization issues and further explore possible improvement on a related topic. Ref. (Reike et al., 2018) deals on the historical development of the concept of circular economy and value retention options for products and materials. Three phases are distinguished in the evolution of the circular economy: Dealing with Waste, Connecting Input and Output in Strategies for Eco-Efficiency and Maximizing Value Retention in the Age of Resource Depletion, which is fully aligned with the concept of life cycle extension. The study presented in (Rossi et al., 2020) is an extensive review of the indicators exploited in CE. Focusing on product life extension, the literature review performed in (Chrisman et al., 1988) recognizes three current lacks of research: a systematic analysis of the structure which underlies organizational efforts, the role of two businesses and consumers and a systematic study of the product lifetime extension strategies. Eventually, Ref. (Muztoba Ahmad Khan et al., 2018) proposes divers key research theme to classify the upgradability concept literature re-view: General concept and definition, Issues of upgradability, Consumer value, Re-manufacturing with upgrades, Modular upgradability, Design methodology, Upgrade planning, Evaluation of upgradability, Upgradability in the context of PSS, Case studies. Ref. (Elia et al., 2017) analyses the current literature on CE assessment and the main existing environmental assessment methodologies based on indexes. Ref. (Saidani et al., 2019), through a systematic literature review considering both academic and grey literature, identified 55 sets of C-indicators, developed by scholars, consulting companies and governmental agencies, encompassing different purposes, scopes, and potential usages. Inspired by existing taxonomies of eco-design tools and sustainability indicators, and in line with the CE characteristics, a classification of indicators aiming to assess, improve, monitor and communicate on the CE performance is proposed. The paper (Ertz et al., 2019b) based its taxonomy on 150 organizations identified in the academic and managerial literature engaged in extending the life of the product. Ref. (de Jonge & Scarf, 2020) reviews more than two hundred papers on maintenance modelling and optimization that have appeared in the period 2001 to 2018, describes terms commonly used in the modelling process and distinguishes single-unit and multi-unit systems. The purpose of the paper (Muztoba Ahmad Khan & Wuest, 2018) is to identify key upgrade-enabling design features and provide a literature review on existing PSS design methodologies with a focus on their adoption towards an upgradable PSS design framework.

Life Cycle Extension. Within the taxonomy, publications that directly mention life cycle extension or indirectly consider the topic were distinguished. Directly mentioning Life cycle Extension: (Barberá et al., 2012; Dehghanbaghi et al., 2016; J. A. Mesa et al., 2019), the ancestor publication identified during this review, and (Bauer et al., 2016; Go et al., 2015; Linton & Jayaraman, 2005) present LCES and methodologies; (Den Hollander & Bakker, 2012; Ertz et al., 2019a; Simons, 2017) deal with product life cycle extension business models; (Paterson et al., 2017) proposes an end of life decision tool; (Gharfalkar et al., 2016; Moseichuk et al., 2010) address the R strategies (repair, recondition, refurbish and re-manufacture); (Rajput & Singh, 2019; Tasleem, M., Khan, N., Shah, S. T. H., Saleem, M., Nisar, 2017) present decision-making mechanism for EoL options; (Coulon et al., 2019) develops an approach to evaluate remaining life aiming to ensure asset durability and optimize operation to extend service life. Addressing the topic in an indirect way: (Alamerew & Brissaud, 2019; Reike et al., 2018; Vermeulen et al., 2018) more specifically deal with CE, but takes into account life cycle extension and its strategies as possible enablers; (Blomsma

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et al., 2018, 2019; Bocken et al., 2016; Morseletto, 2020) deal with product and business model innovation-oriented to CE; (Kobayashi, 2005; J. A. Mesa et al., 2019; Um & Suh, 2015) address product life cycle design and planning methodology; (Bakker, J D., H.J. van der Graaf, J.M. van Noortwijk, 1999) explicitly introduces the concept of maintenance as a life-extension enabler, (March & Scudder, 2019; Mulders & Haarman, 2017) focus on predictive maintenance, (Barberá et al., 2012; Ding & Kamaruddin, 2014) deal with maintenance model and policy; eventually, (Moraga et al., 2019; Rossi et al., 2020) provide a vision on CE indicators and (Mourtzis et al., 2018) develops a tool to improve B2B and internal communication that will enhance the maintenance life cycle.

Production Equipment. Just a few selected papers through the procedure mentioned are directly citing or ad-dressing production equipment. (Moseichuk et al., 2010) deals with the search of new sustainable solutions for the product lines and the improvement of products liability; (Abdi & Taghipour, 2019) develops an economic repair/replacement model related to the in-use equipment; (Mourtzis et al., 2018) studies a maintenance assistance tool of Engineering to Order manufacturing equipment.

Strategies. As suggested by (Ertz et al., 2019a), a part of the strategies extending production equipment life cycle is addressing the "starting loop" through the improved design of products: design for durability/reliability, design for ease of maintenance, repair, disassembly and reassembly, design for upgradability, design for modularity and part standardization, design for component recovery. A second list is related to the "slowing loop": Maintenance (including also Repair and several other kinds of maintenance activities such as the preventative and predictive), Resell–Reuse. Finally, some strategies fit in the "closing loop", involving Remanufacture, Recondition, Refurbish, Cannibalization, Recycle. The references related to the different loop areas are reported in Table 6. Within the papers classified in this field, there are some publications (e.g. (Blomsma et al., 2018; Ertz et al., 2019a; Ziout et al., 2014)), in which strategies are not the key topic of the work and are only mentioned for information purpose or as argumentation support. Among the papers that devoted attention to strategies, papers (Den Hollander & Bakker, 2012; Go et al., 2015; Muztoba Ahmad Khan et al., 2018) are the most significant and provide key elements for the analysis and characterization of "starting loop" and "slowing loop" strategies, while (Go et al., 2015; Thierry et al., 1995) are the ones more relevant for the "closing loop" strategies. It is moreover possible to mention paper (Antikainen et al., 2018) as the most dated document, since it dates back to 1995, but it fully illustrates the characteristics of the strategies considered in this study. Table 5 lists the strategies identified in this study.

Table 5. Identified strategies

#	Strategy
1	Design for durability/reliability
2	Design for modularity and part standardization
3	Design for ease of maintenance and repair
4	Design for upgradability
5	Design for disassembly and reassembly
6	Resell–Reuse
7	Pay per use
8	Repair or Corrective Maintenance
9	Preventive maintenance
10	Predictive maintenance (preventive)
11	Time-based maintenance (preventive)
12	Condition-based maintenance (preventive)
13	Remanufacture
14	Recondition
15	Refurbish
16	Cannibalization

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17	Recycle

Definition. Strategies definitions are a crucial element in order to understand how a strategy works, which are the action needed to implement it and which are the distinguishing features that allow differentiating between the diverse approaches to life cycle extension. A synopsis and a revision of the strategies definition to complete and clarify the existing one (when needed) together with the indication of the references related to the definitions is reported in Table 6.

Description and Implementation Guidelines. In total, there are 26 papers with descriptions and implementation guidelines that were further divided into three sub-categories: the ones providing the description of the strategy functioning, the ones providing implementation guidelines and finally the more complete ones, presenting both these elements.

Description. After the description of the different strategies (i.e., Repurpose, Remanufacture, Refurbish, Repair, Reuse, Refuse, Rethink, Reduce, Recycle and Recover), (Morseletto, 2020) presents a detailed analysis of them; (Bakker, J D., H.J. van der Graaf, J.M. van Noortwijk, 1999; Barberá et al., 2012) present in detail the global maintenance management and lifetime-extending maintenance model while (Simons, 2017) describes Upgrade business models. (Gharfalkar et al., 2016; Paterson et al., 2017) provide reuse options description; (Vermeulen et al., 2018) presents the stakeholder contribution in each strategy, while (Muztoba Ahmad Khan et al., 2018) provides a comprehensive over-view of product upgradability; (Bocken et al., 2016) focuses on product design strategies, while (Bauer et al., 2016; Den Hollander & Bakker, 2012) on Product Life Extension Strategies.

Guidelines. (Mulders & Haarman, 2017) compares the maturity level of predictive maintenance 4.0 and another type of inspection and presents a list of implementation actions. The paper (Ziout et al., 2014) provides an accurate decision-making mechanism for ranking the recovery strategies while (Go et al., 2015) presents "Design for X" strategies and the related guidelines. Concerning the design approach towards remanufacturing, (Zwolinski et al., 2006; Zwolinski & Brissaud, 2008) present a methodology that, starting from the definition of remanufacturable product profiles, is meant to guide the design and the re-design of products in order to assure a higher level of reuse at their end of life stage. Again in the context of design, (Favi et al., 2017, 2019) outline an approach to support designers in improving the product eon of life performances in terms of disassemblability and recyclability. (Coulon et al., 2019) proposed and provided an approach to evaluate remaining life aiming to ensure asset durability based on coupled digital and experimental fatigue analysis and (Abdi & Taghipour, 2019) studies a repair-replacement decision model considering environmental impacts, maintenance quality, and risk. A corrective maintenance scheme for engineering equipment is developed by (Y. Wang et al., 2014) and the paper (Guerra et al., 2016) creates a flexible framework to support equipment life cycle management.

Description and Guidelines. (Reike et al., 2018) discusses the characteristics of some strategies such as Resell, Reuse, Re-manufacture, Repair, Refurbish and Recycle and some actions that make the implementation of the strategy possible. (Paterson et al., 2017) describes product recovery strategies together with an indication to direct a product towards the appropriate strategy based on the problem. In (Thierry et al., 1995), the product recovery strategies are described with the actions that must be implemented to extend products life cycle, while (Linton & Jayaraman, 2005) analyses the LCES and the product characteristics after the implementation of the strategy, the information related to the actions implemented and the characteristics that link the strategies and the production phases. (Elia et al., 2017) proposes a reference framework for the monitoring phase of a CE strategy and a systematic approach for the choice of the adequate methodology, (Mourtzis et al., 2018) develops an application that is moving towards digitalization, while the paper (Muztoba A. Khan et al., 2020) studies a replacement decision framework based on the influencing factors and motivations behind equipment replacement. (Muztoba Ahmad Khan

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& Wuest, 2018) is committed to elaborate a framework to design upgradable product-service systems.

Metrics and Evaluation Methodologies. In this area, literature findings were divided into two sub-groups: Methods and Tools for decision-making and Metrics. The investigated papers propose a plethora of evaluation methodologies, instruments and indicators for the analytical assessment of product performances that are pondered on different perspectives, ranging from the technical to the sustainability ones. Most of the publications indeed focus on the evaluation of economic and environmental performances, that, as also stated by (Matarrese et al., 2017), results as a crucial element in the decision-making process.
Methods and Tools for decision-making. (Zwolinski et al., 2006; Zwolinski & Brissaud, 2008) describe a tool to assess how much a product can be remanufactured starting from its design phase, while (Favi et al., 2017, 2019) outline a methodology composed of four indices and a tool to assess the possibilities to disassemble and recycle a product at the end of its life span in order to improve its performances concerning these aspects. (Alamerew & Brissaud, 2019) proposes a general product recovery multi-criteria decision tool to evaluate product circularity strategies under several, often-conflicting criteria, to assess the feasibility of recovery options with respect to relevant business, legal, environmental, social and economic factors and by taking into account the preferences of the decision-maker. Decision-making factors are also identified concerning technical, economic, business, environmental and societal aspects. Similarly, (Barberá et al., 2012) reports the development of a tool to aid designers in planning recovery cycles for a product at the end of its working life supported by a calculation model that calculates an indicator that translates the environmental effects of recovery cycles in terms of extension of the product's useful life. The product Life Cycle Planning (LCP) methodology accompanied by a design support tool is presented in (Kobayashi, 2005). The methodology clarifies the medium or long-term production and collection plan for the product family, then target values for the product and its life cycle are set to develop eco-solution ideas, realizing reasonable resource circulation by using various life cycle option analysis charts; eventually, the eco-design concept is evaluated at the beginning of the life of the product. Supporting the methodology, the design tool was conceived to efficiently planning product life cycles by using quality function deployment and life cycle assessment data. On the contrary, the study performed in (Paterson et al., 2017) presents a tool that starts from a different perspective: a method to quickly and accurately determine the status of a product that has already undergone an end-of-life recovery strategy. The tool assures to rapidly identify the status of a product, to quickly determine the best terminology for end-of-life products that have received a recovery treatment, a reliable method to check whether a re-manufactured product is wrongly labelled as "something else", a way to ensure compliance with legislation and standards, and the identification of only the essential characteristics of a re-manufactured product. The purpose of (Ziout et al., 2014) is to provide a decision-making method on selecting the most sustainable and suitable EoL product recovery option considering, unlike other available methodologies, all the interests of the stakeholder involved in the product life cycle. Eventually, considering nine different modes of product life extension, (Linton & Jayaraman, 2005) provides a framework and a qualitative evaluation methodology to determine what issues, resource requirements and management capabilities are required for specific life extension modes. This framework provides guidance to practitioners and academics on commonalities between different product life extension modes, thereby assisting practitioners in leveraging current internal skills and capabilities and researchers in determining the generalizability of research. The paper (Hu et al., 2015) introduces some trouble-shooting and life-predicting techniques and approaches, while (HU et al., 2018) paper proposes a new degradation modelling and RUL (Remaining Useful Life) estimation method taking the influence of imperfect maintenance activities on both the degradation level and the degradation rate into account. Ref. (Wu et al., 2020) builds a new data-driven model based on Long Short-Term Memory Recurrent Neural Networks algorithm used to detect the degradation of a manufacturing system and predict its future health

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condition. A risk-based maintenance tool able to reduce the probability of failure of equipment and the consequences of failure is developed by (Arunraj & Maiti, 2007) and some techniques and methodologies to adopt during the risk analysis phase are detailed and structured. The paper (Tang et al., 2002) presents recent methods for modelling and process planning in disassembly and the applications to industrial products.
Metrics. Concerning metrics, (Cherepanov, 2012) proposes a concept of methodological recommendations for estimating service life for designing, fabricating, and appraising safety of industrial equipment. The concept solves the problem of estimating the full residual calculated service life of industrial equipment. Focusing on two specific strategies (maintenance and predictive maintenance), (March & Scudder, 2019) provides a model to determine the economic cost and benefits to introduce IoT in predictive maintenance, testing the model on different scenarios, while (Ding & Kamaruddin, 2014) provides an evaluation of maintenance policy optimization through different models (e.g., Mathematically based model, Simulation-based model, Artificial intelligence-based model). On the contrary, (Moraga et al., 2019) provides a wider vision on CE indicator, proposing a classification framework to categorize indicators on CE strategies, grouped according to their attempt to preserve functions, products, components, materials, or embodied energy and considering different measurement scopes on environmental, social, or economic dimensions. Again, concerning CE, Ref. (Rossi et al., 2020) aims to develop a set of indicators linking CE principles, Circular Business Model and the pillars of Sustainability, developing a group of indicators focused on the three dimensions of Sustainability (environmental —from the material perspective— economic and social), applied in Circular Business Models to capture the innovations brought by CE that conventional indicators do not measure. Eventually, (Gharfalkar et al., 2016) proposes a hierarchy of reuse options that allows evaluating the relationship between the life extension strategy and: warranty, work content, performance, energy and cost. This approach could suggest possible metrics to evaluate, in a qualitative way, the benefits and the required "engagement" in implementing a specific reuse option. (Yin et al., 2018) cites universalization, serialization and modularization as the three important metrics in the standardization of manufacturing. To evaluate and optimize the standardized procedures, some metrics were designed among with a quantitative analysis-based evaluation model of equipment system. (J. Mesa et al., 2020) proposes a single generic indicator based on durability and environmental footprint for material selection. This indicator integrates into a single calculation chemical and mechanical durability, together with environmental impacts associated with the material.

Business Models. (Simons, 2017) describes and compares four generic types of upgrade business models based on industrial cluster cases related to product life extension. Using a modified business model canvas approach, the four upgrade business models are compared concerning how they create value for the customers, how they organize their main activities and how they earn money. The study performed in (Ertz et al., 2019a) develops and empirically validates a methodology to classify product lifetime extension business models, involving organizations and consumers, to bring quantitative rigor to the conduct and presentation of taxonomy research in the field of the circular economy. (Muztoba Ahmad Khan et al., 2018) reviews a series of publications dealing with Business models for upgradable products, while (Ertz et al., 2019b) offers a framework and a taxonomy based on product lifetime extension business models and (Bocken et al., 2016) lists a series of circular business model strategies. Concerning life cycle extension, this publication describes Business model strategies for slowing loops such as Extending product value (Exploiting the residual value of products–from manufacture, to consumers, and then back to manufacturing or collection of products between distinct business entities), Classic long-life models (Business models focused on delivering long-product life, supported by design for durability and repair) and Encourage sufficiency (solutions that actively seek to reduce end-user consumption through principles such as durability, upgradability, service, warranties and reparability and a non-consumerist approach to marketing and sales). Specifically focusing on product life extension, (Den Hollander & Bakker, 2012) explores the topic in a

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business context and the associated consequences for product design. In this deliverable a starting point is provided for this exploration, by outlining the development of a business model framework for product life extension, using strategies for product life extension and mapping these against common elements of contemporary business model theory.

Digitalization and Lifetime Extension. From the analysis of the main trend about how digitalization affects the product lifetime and the extension of machinery and equipment, 21 papers were selected. The possible role of digitalization on the sustainability concept was already investigated by (Andrea Barni, Alessandro Fontana, Silvia Menato, Marzio Sorlini, Canetta, 2018), even though more focalizing on sustainability assessment and optimization of environmental performances. The literature review here presented is on the contrary more focused on its role for CE and life cycle extension. The papers were gathered according to the following goals: literature review, case studies, theoretical analysis, survey and taxonomy.

Literature review papers. A list of seven papers was retrieved from the literature that is meant to describe how digitalization can play a crucial role to enable a more sustainable circular economy taking into account smart manufacturing, product design and I4.0. In particular, (Alcayaga et al., 2019) takes into account how smart enablers that involve physical and digital components permits to add value to the products, extending the product lifetime. (Ingemarsdotter et al., 2019; Okorie et al., 2018) highlight the smart manufacturing issues, in particular, about how product's lifetime is extended by predictive, preventive or reactive maintenance. (Bocken et al., 2016; Ghoreishi & Happonen, 2020) focus on how digitalization affects lifetime extension, in particular, utilizing digital technologies such as AI, IoT or Blockchain enhances the ways in developing and improving transparency and traceability throughout the product lifetime. (Jose Ospina, John Gallagher, Paul Maher, Jose Ospina, John Gallagher, 2019) is related to the product design in combining localized smart design and manufacturing approach for manufacturing computer equipment. (Alcayaga & Hansen, 2017) describes how smart products and digital tools enable better performance monitoring, data-driven design, and an extension of the product life cycle. (Kan & Anumba, 2019) provides a literature review and critical analysis of existing research into DT applications, with a view to identifying the opportunities for research and applications in the construction domain. (Hoffmann et al., 2020) reviews the current state-of-the-art of all aspects of condition monitoring for medium voltage switchgear and presents an approach to develop a predictive maintenance system based on novel sensors and machine learning. The interest of operators of electrical equipment and machinery in condition monitoring and predictive maintenance is due to the avoidance of catastrophic failures, the reduction of operational cost, and the lifetime extension of the equipment.

Case study papers. (Ingemarsdotter et al., 2020) presents a case study of LED lighting where the role of IoT is relevant to enable monitoring and predictive maintenance, to improve the estimation of the remaining lifetime of used products and inform design decisions to improve the durability of products. (Hickey & Fitzpatrick, 2007),(Jensen & Remmen, 2017) are focused on lifecycle management where sustainable manufacturing, IoT and sensor information can be utilized to promote lifetime extension in the personal computer and for automobile, aircraft and ship manufacturers, respectively. The role of the digital twin for prediction, integration of the life cycle of a product and develop a model to extend the lifetime is described in the case study of existing marine structures (Tygesen et al., 2018), rotating machinery fault diagnosis (J. Wang et al., 2019) and wind turbine (Jane Marie Andrew, 2019). (Klishin et al., 2020) forecasts the residual life of an assembly unit or machinery making maintenance planning more effective and preventing the occurrence of emergency failures for the vibration-based diagnostic. Eventually, no specific case studies were retrieved on production equipment.

Theoretical papers. (Geerken et al., 2019) describes the benefits of increasing the product lifetime and how globalization trend is not technical and economically favorable if a country wants to promote lifetime extension of products. On the other side, (Saidani et al., 2019) investigates how digital technologies (e.g., IoT, BigData, analytics) functionalities affect CE

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value drivers increasing resource efficiency and extending lifespan; it moreover introduces an approach for highlighting the conceptual framework in table referring to some CE value drivers showing which references of the analysed literature are referred to the lifespan extension of a product.

Survey papers. (Antikainen et al., 2018) provides a survey about how digitalization can play a crucial role to enable more sustainability and enables more efficient processes in companies, helping minimize waste, promoting longer life for products.

Taxonomy papers. Finally, papers offering a taxonomy of product lifetime extension (PLE) as a field of study through the development of a framework of product life-time extension business models (PLEBM) are (Ertz et al., 2019a, 2019b). (Ertz et al., 2019b) shows product lifetime extension business models and strategies in the literature where the digital interactive platform and digital transactional provide information or live support on the extension of product lifetime and provide the opportunity to conduct or schedule the exchange of the product whose lifetime is to be extended. (Ertz et al., 2019a) develops and empirically validates a methodology to classify a specific type of circular business model, namely product lifetime extension business models, involving organizations and consumers, to bring quantitative rigor to conduct and presentation of taxonomy research in the field of the circular economy.

2.1.3.2 Maintenance and Remanufacturing Standards

As previously seen, with the introduction of digitalization and other important key strategies, the topic of lifetime extension framed into Circular Economy has gained relevance and impact in today’s manufacturing environments. However, not only academic publications and patents are responsible for this new impact, but also the end results that most of these have. One important outcome is the standardization procedures that help manufacturing companies to implement and maintain the best practices in terms of, e.g., safety and process optimization, both internally and also among companies. Standardization fosters the alignment of companies thought the value chain in terms of procedures, product specification and quality that increases the trustworthiness in both B2C and B2B commercial transactions. Taking again the example of Resell/Reuse in §1, performing a set of procedures for the collection of maintenance logs, machine parameters, product quality and degradation data enables the calculation of the machine’s current health and predict its performance in the future. This way, the trustworthiness is increased and the servitization (e.g., leasing) to-wards machine resell can be achieved because the end customer has all the information about the machine's lifetime. Based on this, there are a set of existing standards already targeting some of these procedures. The following presented standards focus on two main topics: (1) maintenance procedures and predictive maintenance, together with (2) specifications and de-sign for remanufacturing. As a sneak-peek of each topic, eight standards about maintenance and five about remanufacturing are presented.

Regarding maintenance, the “CWA 17492:2020-Predictive control and maintenance of data intensive industrial processes” is a standard focusing on predictive maintenance and defines machine learning / deep learning techniques for predicting process and equipment drifts, hence providing indications on when to perform maintenance and machines health state.

“EN 15341:2019-Maintenance-Maintenance Key Performance Indicators” defines a set of key performance indicators to quantify and increase the effectiveness, efficiency and sustainability in the process of maintenance actions for physical assets.

“prEN 17485-Maintenance-Maintenance within physical asset management-Framework for improving the value of the physical assets through their whole life cycle” and “EN 16646:2015-Maintenance-Maintenance within physical asset management” introduce the physical asset management and address the role and importance of maintenance within physical asset management system during the whole life cycle of an item.

“EN 17007:2018-Maintenance process and associated indicator” illustrates for the maintenance process all the characteristics and steps of the defined processes, together

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with the establishment of a maintenance model that gives guidelines for defining indicators. This is a key element in order to standardize the whole maintenance process and therefore make all the maintained equipment comparable among themselves and lifetime extension strategies can ultimately be more precise in their analysis.

“EN 13269:2016-Maintenance-Guideline on the preparation of maintenance contracts” and “EN 13306:2018-Maintenance-Maintenance terminology” and “EN 13460:2009-Maintenance-Documentation for maintenance” This set of three standards focus on the maintenance contracts to be established, the terminology used and documentation. This is particularly important because these standards define at a business level how maintenance is performed and is understood. Contracts are based on well-established terminology and documentation that govern the maintenance process and should include lifetime extension strategies based on maintenance actions, or even others like KPIs and databased analysis throughout its lifetime.

As for the remanufacturing standards, the “ANSI RIC001.1-2016-Specifications For The Process Of Remanufacturing” is a standard that works on the definition of remanufacturing and clearly separates it from other practices. It also provides a benchmark, specification and characterization for the process of remanufacturing.

“ISO 8887-1:2017-Technical product documentation-Design for manufacturing, assembling, disassembling and end-of-life processing – Part 1: General concepts and requirements” standard specifies the requirements for the preparation, content and structure of Technical Product Documentation (TPD) of design output for the cycles of manufacturing, assembling, disassembling and end-of-life processing of products. This is particularly interesting because lifetime extension strategies can be incorporated in TPD and make sure equipment is handled towards its extension.

There also some standards that can be oriented towards remanufacturing or extending equipment capabilities based on well-defined specifications and processes. Such an example is the “ISO 9409-1:2004-Manipulating industrial robots - Mechanical interfaces - Part 1: Plates” and “ISO 9409-2:2002-Manipulating industrial robots - Mechanical interfaces - Part 2: Shafts”, which focus on the mechanical aspects and remanufacturing procedures that can be proposed as an extension. By knowing how to manipulate such mechanical interfaces and considering that industrial robots are key in what concerns flexibility and process adaptability, it is possible to redesign such products for new purposes and promptly use them for new tasks.

“ISO/TR 16355-8:2020 – Applications of statistical and related methods to new technology and product development process - Part 8: Guidelines for commercialization and life cycle” describes after optimization of product design to address non-functional requirements, for example, test, produce, commercialize, deliver, support, and eventually retire a product from the market and provides guidance on the use of the applicable tools and methods. Based on these non-functional requirements, the concept of remanufacturing can be introduced in all of them. For example, the testing and commercialization of remanufacturing processes can be contemplated, since new technology can result from extending the capabilities in machines.

The analysis of the literature performed via the proposed taxonomy and the research carried out also on standard is providing several topics of discussion that could guide future literature investigations and provide useful hints for the actual integration of the life cycle extension concept in industrial practices. This dissertation is proposed in the following section of this work.

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2.2 Life Cycle Extension Strategies Definitions

Concerning the application of strategies in industries, the analysis of the selected literature performed in the previous section highlights some open issues to be treated both in the industrial and academic debates.

One of the literature evidences concerns the fact that strategy definitions are not well established or at least acknowledged, leading to an unclear application and paving the way to misunderstandings. For that reason, a part of T4.1 activities was dedicated to revise and update definitions obtained from literature. A certain confusion emerged from the work carried out on the strategies definitions since most of them are unclear, incomplete or even conflicting. In the case of design-related strategies ("starting loop"), some repetitions were detected together with the need to slightly revise the formulation of the descriptive sentences that, in general already had a proper state. Concerning the "slowing loop" area, the material available in literature on maintenance already was in a good shape, thus the revision analysis only focused on the identification of the maintenance activities related to product life extension. On the contrary, the work on the "closing loop" strategies revealed to be more challenging since the existence of several definitions for the same strategy that sometimes introduces overlaps and conflict. In this area, the revision activities thus focused on defining homogenized and coherent definitions in order to make them clear and unambiguous. This work has been carried out with the collaboration of UNI that, using standards in addition to literature findings, validated and further revised the strategies definitions. Table 6 reported hereinafter resumes the LCES definitions, presenting the related bibliographic references and the reference standards (where applicable or available).

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Table 6. Revised definition

Strategy	Revised Definition	References	Standard
Design for durability/reliability	The ability of a product to perform the function(s) it was designed and built for an extended period of time or a specified period without experiencing failure or excessive wear and tear, considering also its environmental performances.	(Ertz et al., 2019a), (Go et al., 2015), (Den Hollander & Bakker, 2012)	
Design for modularity and part standardization	Design approach that is meant to achieve the maximum level of simplification and standardization in product design with common product platform and more efficient use of resources. In manufacturing fields, universalization, serialization and modularization are the three most important metrics.	(Muztoba Ahmad Khan et al., 2018), (Go et al., 2015), (Yin et al., 2018)	
Design for ease of maintenance and repair	This approach allows the products and parts to be maintained and repaired easily in order to retain the functional capability of a product or restore the working condition of a damaged product.	(Muztoba Ahmad Khan et al., 2018), (Ertz et al., 2019b), (Elia et al., 2017), (Go et al., 2015), (Mourtzis et al., 2018)	
Design for upgradability	Approach to the design meant to facilitate the enhancement of a product's functional as well as physical fitness for ease of upgrade.	(Muztoba Ahmad Khan et al., 2018), (Muztoba Ahmad Khan & Wuest, 2018), (Go et al., 2015), (Den Hollander & Bakker, 2012)	
Design for disassembly and reassembly	The characteristics of this approach allow for the separation and reassembly of products and parts in the most efficient way, i.e., the most suitable sequence is determined with minimal removal of components, ensuring environmental safety and avoiding future costly environmental liabilities.	(Muztoba Ahmad Khan et al., 2018), (Tang et al., 2002), (Go et al., 2015)	ISO 20887:2020(en), 3.13
Design for component recovery	It includes design for refurbishment and design for remanufacture. The concept of recovery stems from the fact that a certain number of parts or subassemblies have a design life that exceeds the life of the product itself, making the idea of reuse practical.	(Go et al., 2015)	
Resell-Reuse	Reuse and resell can be defined as the activity of recovering components and materials (still in good condition) for further use without reprocessing, i.e. that does not require any correction or repair action. The resold or reused products in intended to be put into service for the same purpose for which it was conceived.	(Muztoba Ahmad Khan et al., 2018), (Morseletto, 2020), (Dehghanbaghi et al., 2016), (Thierry et al., 1995), (Bauer et al., 2016), (Den Hollander & Bakker, 2012), (Paterson et al., 2017), (Linton & Jayaraman, 2005), (Vermeulen et al., 2018), (Moseichuk et al., 2010)	ISO/IEC 29142-1:2013(en), 3.59; ISO 21070:2017(en), 3.1.6.
Pay per use	In a classic pay-per-use model, the user of an industrial equipment does not purchase and own the product. Instead,		

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	customers pay a fee that depends on usage and is measured according to clearly specified consumption, output, or other indicators, which nowadays are more easily controllable through sensors connected to the IoT.		
Repair or Corrective Maintenance	Set of activities performed after occurrence of a failure, or detection of a fault, of a product so it can be restored to a state in which it can perform the original and required function. Repair is also making a broken product operational again through fixing/repair/replacing failed parts. The objective of repair is “bringing back to working order”, “making it as good as new”, “recreating its original function after minor defects”, “replacing broken parts”, “maintenance carried out to effect restoration”, “eliminating the causes of failures”.	(Muztoba Ahmad Khan et al., 2018), (Reike et al., 2018), (Ertz et al., 2019b), (de Jonge & Scarf, 2020), (Morseletto, 2020), (Dehghanbaghi et al., 2016), (Thierry et al., 1995), (Den Hollander & Bakker, 2012), (Paterson et al., 2017), (Gharfalkar et al., 2016), (Linton & Jayaraman, 2005), (Vermeulen et al., 2018)	ISO/IEC 14764:2006(en), 3.2 ; ISO 23815-1:2007(en), 3.3; ISO 19659-1:2017(en), 3.9.2; IEC 60050-192:2015, 192-06-06, modified; ISO/TR 12489:2013; ISO 14224:2016(en), 3.8; ISO/IEC 20926:2009(en), 3.13; ISO/IEC 2382-14:1997; ISO/IEC 2382:2015(en), 2123038; IEEE 14764-2006 3.2, 3.13; ISO/IEC/IEEE 24765:2017(en), 3.891; IEC 60050-191-46-06; ISO/TR 12489:2013(en), 3.4.4; ISO 20815:2018(en), 3.1.7; ISO 6527:1982(en), 2.19.
Preventive maintenance	Preventive maintenance is the performance of inspection and/or servicing tasks that have been pre-planned for accomplishment at specific time schedule, and performed according to prescribed criteria, to retain the functional capabilities of operating equipment or systems and to reduce the probability of failure or prevent degradation of the functioning of a product. The activity precludes the maintenance of an object in a satisfactory operating condition, controlling degradation and failures to an acceptable level; in order to sustain or extend its useful life, it is often necessary to plan some corrective maintenance actions. Three type of preventive maintenance are recognized in literature: **Predictive maintenance**, **Time-based maintenance** and **Condition-based maintenance.**	(Muztoba Ahmad Khan et al., 2018), (Den Hollander & Bakker, 2012), (Linton & Jayaraman, 2005)	ISO/IEC 14764:2006(en), 3.8 ; IEC 60050-192:2015, 192-06-12, modified; ISO 14224:2016(en), 3.76; ISO/TR 12489:2013(en), 3.4.3; ISO/IWA 28:2018(en), 3.3.3; ISO 26870:2009(en), 3.15; ISO 2710-2:2019(en), 3.1.3.6; ISO 23815-1:2007(en), 3.2; ISO 6527:1982(en), 2.18; ISO 19659-1:2017(en), 3.9.3; ISO 12749-5:2018(en), 3.9.12.4; INTERNATIONAL ATOMIC ENERGY AGENCY. “IAEA Safety Glossary: Terminology used in nuclear safety

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	Predictive maintenance - A condition-driven preventative maintenance program based on forecasting made on mathematical models. It uses direct monitoring of the mechanical condition, system efficiency, and other indicators to model and calculate the actual mean time to failure or loss of efficiency.	(Muztoba Ahmad Khan et al., 2018), (Den Hollander & Bakker, 2012), (Linton & Jayaraman, 2005)	and radiation protection. 2016 Edition". IAEA, Vienna, 2016. (Retrieved: 11 August 2016). p. 219[1], modified.
	Time-based maintenance - A preventive maintenance consisting in restoring or replacing a component regardless of the condition of the product. This can happen based on time (predetermined time intervals) or based on the operating time of machines/components or on the remaining useful life (in this case a dedicated system is required to support data collection and maintenance planning).	(Muztoba Ahmad Khan et al., 2018), (Den Hollander & Bakker, 2012), (Linton & Jayaraman, 2005)	
	Condition-based maintenance - A strategy based on the component restoration or replacement, based on a measured condition compared to a defined standard (thresholds). Condition data can then be collected through non-invasive measurements, visual inspection, performance data, and scheduled testing.	(Muztoba Ahmad Khan et al., 2018), (Den Hollander & Bakker, 2012), (Linton & Jayaraman, 2005)	
Remanufacture	Remanufacture (or second-life production) is a strategy that implies using parts of discarded products in a new product with the same function. Used products are brought at least to original equipment manufacturer performance specification. Remanufactured products guarantee the same quality of original products. Remanufacture applies where the full structure of a multi-component product is disassembled, checked, cleaned and when necessary replaced or repaired in an industrial process.	(Muztoba Ahmad Khan et al., 2018), (Reike et al., 2018), (Ertz et al., 2019b), (Morseletto, 2020), (Dehghanbaghi et al., 2016), (Thierry et al., 1995), (Bauer et al., 2016), (Den Hollander & Bakker, 2012), (Paterson et al., 2017), (Gharfalkar et al., 2016), (Linton & Jayaraman, 2005), (Vermeulen et al., 2018), (Moseichuk et al., 2010)	ISO 13533:2001(en), 3.62.
Recondition	Reconditioning involves taking a product and restoring all critical modules that are inspected and upgrading it to specified quality level (with the same composition), typically correspond to approximate original design condition or less than virgin standard. Any warranties issued are typically less than a warranty given to a virgin product.	(Reike et al., 2018), (Paterson et al., 2017), (Gharfalkar et al., 2016)	ISO/TS 22002-4:2013(en), 3.16; ISO 3977-9:1999(en), 3.92; ISO 2710-2:2019(en), 3.3.9.
Refurbish	Refurbish means restoring an old product and bringing it up to date, in order to maintain reliability or extend service life. In general, refurbished products are upgraded and brought back to specified quality standards or satisfactory working and/or cosmetic conditions and have to fulfil	(Muztoba Ahmad Khan et al., 2018), (Reike et al., 2018), (Alamerew & Brissaud, 2019), (Morseletto, 2020), (Dehghanbaghi et al., 2016), (Thierry et al., 1995), (Gharfalkar	ISO 26871:2020(en), 3.1.49.

[1] http://www-ns.iaea.org/downloads/standards/glossary/iaea-safety-glossary-rev2016.pdf

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	extensive testing. Occasionally, refurbishing is combined with technology upgrading by replacing outdated modules and parts with technologically superior ones.	et al., 2016), (Vermeulen et al., 2018)	
Cannibalization	Cannibalization is the activity of recovering parts from returned products. Recovered parts are used in repair, refurbishing, reconditioning and remanufacturing of other products.	(Muztoba Ahmad Khan et al., 2018), (Alamerew & Brissaud, 2019), (Dehghanbaghi et al., 2016), (Thierry et al., 1995)	
Recycle	Recycling is activity of segregating and recovering components and materials for reprocessing. From the processing of materials, it is possible to obtain the same (high-grade) or lower (low-grade) quality of recycled materials. The purpose of recycling is to reuse or recover materials or waste materials from used products and components. These materials can be reused in production of original parts if the quality of materials is high, or else in production of other parts. Recycling begins when used products and components are disassembled into parts. These parts are separated into distinct material categories. These separated materials are subsequently reused in the production of new parts.	(Muztoba Ahmad Khan et al., 2018), (Reike et al., 2018), (Alamerew & Brissaud, 2019), (Morseletto, 2020), (Dehghanbaghi et al., 2016), (Thierry et al., 1995), (Paterson et al., 2017), (Linton & Jayaraman, 2005), (Vermeulen et al., 2018), (Moseichuk et al., 2010)	ISO 21070:2017(en), 3.1.5; ISO/TS 21929-2:2015(en), 3.33; ISO 8887-1:2017(en), 3.1.6.

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2.2.1 Validation with pilots

This section is meant to present the results of the workshop performed with the RECLAIM pilots. The workshop has been performed using interactive boards (conceptboard.com) that have been prepared before the workshop.

An example of the interactive board could be found at the link: https://app.conceptboard.com/board/nneq-cqbs-bmfc-76am-ag66. It is composed in three different parts, related to the three objectives addressed, discussed during a dedicated session and interaction with partner of about half an hour. In such a way to be able to provide additional time to the pilots for the completion and processing of the various tasks present, all the boards used in this activity remained available even after the conclusion of the planned work session.

In order for the pilots to arrive prepared and thus conclude the activities in the best possible way, preparation material was shared before each workshop. In particular, the following were shared: the list of LCES strategies and their definitions, the list of SCF fields with their definitions, an application example and an explanation with practical examples attached regarding the actions necessary in the implementation of a strategy

The goal of the workshop activity is therefore to validate some of the results obtained in Task 4.1. In particular, the workshop has been designed in order to meet the aforementioned three objectives:

- **Objective 1:** Identify the Life Cycle Extension Strategies (LCES) applied in RECLAIM and the possible strategies to be used in the future. The *guiding questions* used for the partner were: which are the LCES applicable in your pilot? Are you interested in other LCES for future applications? The results of the workshop related to Obj. 1 are addressed in this section.

- **Objective 2:** Considering the strategies applied in RECLAIM, validate the Strategy Characterization Framework (SCF), identifying which are the field considered as relevant, those considered not useful and giving the pilot partners to insert additional fields. The *guiding question* used for the partner was: What is the information you need to understand how a LCES works and to apply it? The results of the workshop related to Obj. 2 are addressed in §3.2.

- **Objective 3**: Identify the action needed within the pilots to activate extension strategies. The *guiding question* used for the partner was: Considering each phase of the equipment life cycle, which are the actions or the aspects to be considered to implement a LCES? The results of the workshop related to Obj. 3 are addressed in §5.

As for Objective 1, we have provided the definition of strategies and asked for position within the board created the strategies to be applied within the project and those interesting

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for the future (it was simply a matter of dragging the appropriate post-it in the relevant boards). An application example is show in Figure 8.

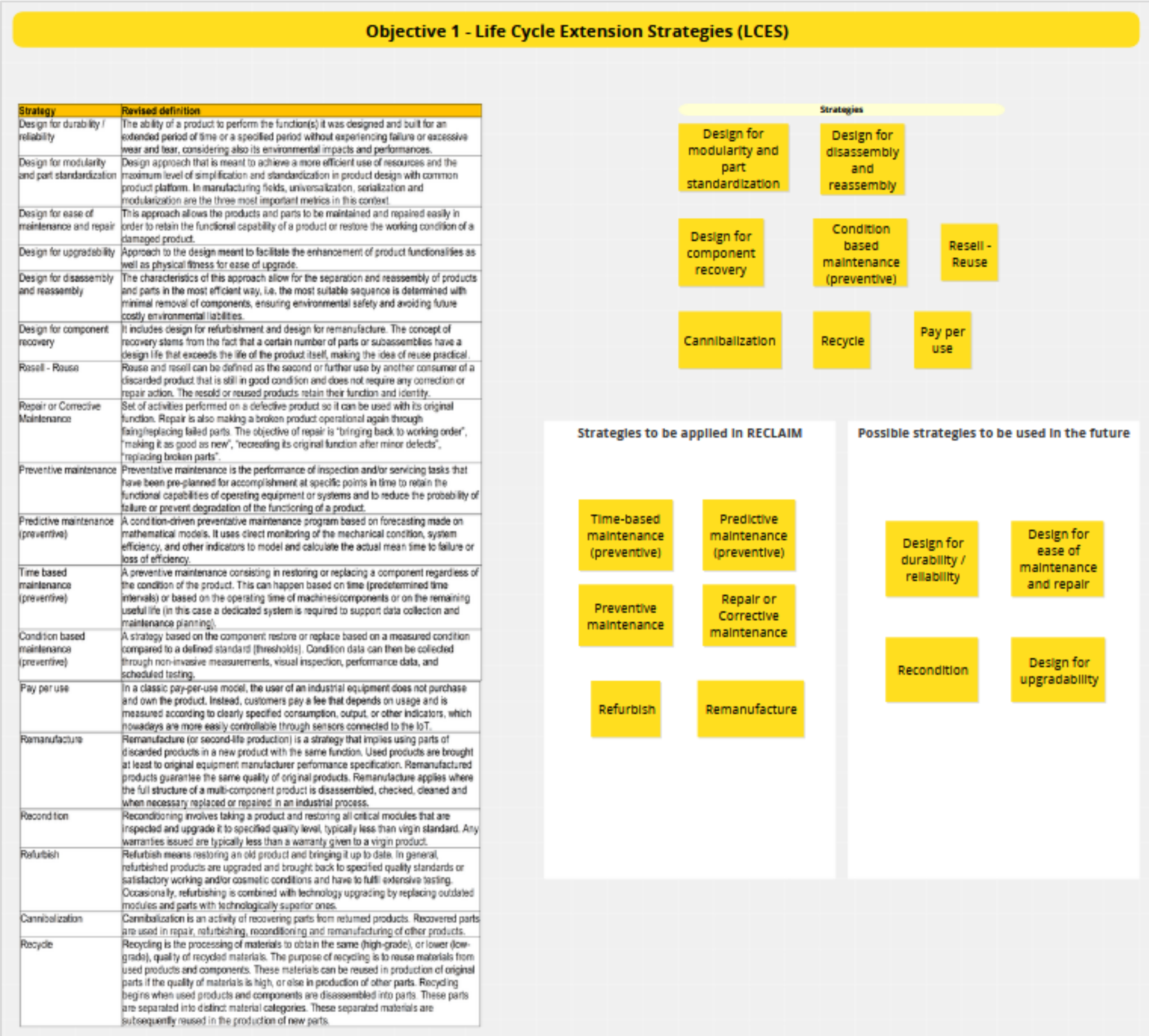

Figure 8. Example of workshop - objective 1 (interaction with Pilot 1A)

The summary of the first part of the workshop for all the pilots, mentioning the identified strategies for each pilot, is shown in Table 7.

Table 7. Pilots' adopted strategies in RECLAIM

Pilot	Adopted strategies in RECLAIM
Pilot 1 a - GORENJE (robot cells)	Preventive maintenance (time-based and predictive); Repair or Corrective maintenance; Refurbish; Remanufacture.
Pilot 1 b - GORENJE (white enameling line)	Preventive maintenance (time-based and predictive); Repair or Corrective maintenance; Refurbish; Cannibalization; Design for ease of maintenance and repair.
Pilot 2 - FLUCHOS	Preventive maintenance (predictive and condition-based); Repair or Corrective maintenance; Refurbish; Recondition.

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Pilot 3 – PODIUM	Preventive maintenance (predictive, time-based and condition-based); Refurbish.
Pilot 4 - Harms & Wende	Design for modularity and part standardization; Design for upgradability; Resell – Reuse; Refurbish; Recycling; Repair or Corrective maintenance; Preventive maintenance (predictive, time-based and condition-based).
Pilot 5 - ZORLUTEKS	Preventive maintenance (predictive); Refurbish; Remanufacture.

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3 Strategy Characterization Framework (SCF)

An additional focal point for the actual application in industries of product life cycle extension concept is the need for a framework that is meant to provide a deeper and structured analysis on strategies. The objective of the Strategy Characterization Framework (SCF) here presented is to better characterize the LCES, putting the basis for future works that will produce methodologies for the selection of the best strategy to be applied for production equipment life cycle extension on different specific industrial cases. As a consequence of the triplet analysis about scientific papers, patents and standards, an initial proposal for a possible future standardization procedure was an organic step. Industrial practice needs more detailed information about how a strategy works, how it can be put in place, which are the actors involved in its implementation and which are the costs and the benefits offered from the sustainability point of view, mainly focusing on economic and environmental aspects. In order to detect this information from the strategy analysis, the SCF was conceived as a possible solution for the detailed characterization of the LCES. The SCF is constituted by a list of fields that are meant to better typify the strategies used.

3.1 The SCF

The description of the fields is hereinafter reported.

- **Target**: it reports which is the focus of the strategy. Specifically, a strategy may concern the whole equipment or parts of it such as assemblies, components, or the materials constituting the product.

- **Life cycle phases involved**: it considers the possible life cycle phase of the production equipment that are affected/involved by the strategy. As already shown, LCES are not only affecting the EoL phase of the equipment but could require intervention in many other product life span moments, starting from the design phase.

- **Stakeholder involved**: it is meant to list the stakeholders mainly involved in the strategy implementation. This field of the SCF is meant to provide a view on the different actors that are actively or passively involved in the LCES, both in its implementation and during the functioning of the strategy.

- **Stakeholder contribution**: it describes for each stakeholder their contribution to the strategy implementation and functioning. After identifying the involved partners, their specific role, active or more passive, has to be precisely recognized so that the Original Equipment Manufacturers have a map to know how and when a stakeholder has to be activated or addressed.

- **Hierarchy**: it identifies the hierarchy distinguishing short loop (where product remains close to the user and its original function), medium-long loop (where products are upgraded and, at least a part of them, may be moved away from their first installation place) and long loop (where products lose their original function or components are mainly exploited as monitored sources of materials). This field offers a rapid, qualitative overview on how much the strategy is oriented to a strict application of the CE approach, where the short loop strategies are the ones aimed to prolong the life cycle of the equipment as a whole, with few interventions and new components needed.

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- **Ownership model**: it indicates the owner of the machinery after the execution of the actions related to a given strategy. The field is meant to distinguish strategies based on a more traditional business model, where the ownership is retained by the equipment user, to the ones that are promoting servitization, where the ownership of the machine is maintained by the OEM.

- **Equipment condition after the implementation of the strategy**: it indicates the state of the equipment after the application of a certain strategy. The condition of the product can correspond to: the original one, a decreased quality of the whole machine and their components, enhanced performances or even a completely different function for the machine subjected to the strategy implementation.

- **Enabling elements/technologies**: it shows the elements that enable the strategy deployment. Many LCES requires the deployment of technologies (IoT, augmented and virtual reality, recycling technologies...) and/or methodologies (design for re-manufacturing, pay-per-use approach) in order to actually put in place the strategy in a specific industrial application.

- **Closing loop management** model: it indicates the life cycle loop management approach promoted by the strategy. In the context of CE and LCES it is improper to talk about End of Life of the equipment or of its components, even though during life cycle extension some parts are discharged. The closing loop management model can thus assume a unique approach (100% reuse) or a blended one (70% reuse, 30% recycle for unrecovered parts).

- **Circular BM involved**: this field is meant to identify which are the possible Circular Business Models related to the strategy application. This is a focal point in order to make companies understand how life cycle extension can generate profit.

- **Strategy Implementation Actions**: it lists the action needed to implement a strategy starting from the blank page. This field of the SCF is meant to provide valuable support to companies interested in the actual implementation of LCES since they could exploit the list checking their as-is status, evaluating their maturity level in respect of a specific methodology and plan next steps and concrete activities in order to put in place the desired approach to equipment life cycle extension.

An example of the SCF application is reported in Table 8**Errore. L'origine riferimento non è stata trovata.**.

Table 8. Application of the Strategy Characterization Framework (SCF) to the Resell-Reuse strategy

Field	Resell-Reuse Strategy
Revised definition	Reuse and resell can be defined as the second or further use by another consumer of a discarded product that is still in good condition and does not require any correction or repair action. The resold or reused products retain their function and identity.
Typology of strategy	Closing loop
Target	Equipment
Stakeholder involved	1. Customer 2. Retailer 3. OEM or an alternative one 4. Reverse logistic partners
Stakeholder contribution	1. Customer:

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	• Buying second hand, or • Sell equipment that was not or hardly in use, after some cleaning or minor adaptations restoration. 2. Retailer: • Resell used equipment with quality inspections, cleaning and small repairs; • Resell of unsold returns or products with damaged packaging; • Multiple re-uses of (transport) packaging. 3. OEM or an alternative one: • Collect and resell used equipment. 4. Reverse logistic partners: • Collection of used equipment and delivery to the new owner.
Lifecycle phases involved	EoL/Retailing
Hierarchy	Short loop
Ownership model	OEM / Consumer (depending on the related BM)
Equipment condition after the implementation of the strategy	Original
Enabling elements / technologies	Sharing platforms (online consumer-to-consumer auctions for used products)
Closing loop management model	Oriented to extend original equipment lifecycle to Reuse 100%
Circular BM involved	Lifespan extension
Strategy implementation actions	*Design phase*: Modular design that allows the upgrade of critical components or assemblies or the replacement of components subject to wear; Plan to make some components available for a long time. *Manufacturing phase*: Flexible internal production process (to guarantee the spare parts production); Flexible purchasing process to guarantee the acquisition of the spare parts; Repair the damaged components and reuse them. *Logistic phase*: Organize reverse logistics of out of date or damaged components; Organize the distribution of the updated components or spare parts. *Equipment operation phase*: Introduction of IoT devices to monitor the working conditions of critical components; Introduction of monitoring systems and decision support tools (automated) related to the IoT devices. *Maintenance phase:* Introduction of maintenance services able to replace worn components and upgrade machinery; User of monitoring systems. It may decide to introduce IoT devices and create monitor systems. It may decide to change some pieces. *End of "first" Life phase*: See reverse logistic in the Logistic process phase; Repairable / Reusable Component: Repair and reuse in different equipment; Waste components: send them for recycling; Dispose of damaged spare parts.

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The SCF acts as a basis for the forthcoming research activities in this domain. The next steps could concern the refinement of this framework, with the addition or the modification of the proposed fields, together with its actual exploitation, that is, the completion of the field for each of the strategies interesting for the production equipment application.

The SCF applied to all the LCES can be found in the file “T41_Strategy Characterization Framework.xlsx”.

3.2 SCF structure validation with pilots

This section is meant to present the results of the workshop performed with the pilots that identified the most useful SCF fields and possible additional fields.

As mentioned in in §2.2.1, the goal of objective 2 of the workshop was to validate the Strategy Characterization Framework (SCF), identifying the fields which are considered as relevant and those considered not useful, as well as giving the pilot partners the option to insert additional fields.

To carry out this activity, before the workshop the structure of the SCF, the definition of the fields and the practical example were shared with each pilot.

Also for this activity, the task assigned to the pilots during the interaction on Conceptboard was to move the post-it notes that they considered most suitable on the related boards. An example of the interactive board and the execution of the “objective 2 exercise” is provided in Figure 9.

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Figure 9. Example of workshop - objective 2 (interaction with Pilot 3)

The results of the activity, i.e. the importance given to the various fields of the SCF by the pilots, are reported in Table 9 and Table 10.

Table 9. Useful fields identified by the pilots

Field	Pilot 1 a	Pilot 1 b	Pilot 2	Pilot 3	Pilot 4	Pilot 5
	Useful field					
Revised definition	✓		✓	✓	✓	✓

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Typology of strategy	✓	✓	✓	✓	✓	
Target	✓	✓	✓	✓	✓	✓
Stakeholder involved	✓	✓		✓	✓	
Stakeholder contribution	✓	✓		✓	✓	
Lifecycle phases involved	✓	✓	✓	✓	✓	
Hierarchy	✓		✓	✓		
Ownership model	✓			✓	✓	
Equipment condition after the implementation of the strategy	✓	✓	✓	✓	✓	✓
Enabling elements / technologies			✓	✓	✓	✓
Closing loop management model				✓	✓	
Circular BM involved				✓	✓	✓
Strategy implementation actions			✓	✓	✓	✓

Table 10. Not useful fields identified by the pilots

Field	Pilot 1 a	Pilot 1 b	Pilot 2	Pilot 3	Pilot 4	Pilot 5
	Not useful field					
Revised definition						
Typology of strategy						✓
Target						
Stakeholder involved			✓			✓
Stakeholder contribution			✓			✓
Lifecycle phases involved						✓
Hierarchy					✓	✓
Ownership model			✓			✓
Equipment condition after the implementation of the strategy						

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Enabling elements / technologies	✓	✓				
Closing loop management model	✓	✓	✓			✓
Circular BM involved	✓	✓	✓			
Strategy implementation actions	✓					

Pilot 3, PODIUM, identified also new possible fields:

- *Timeline of implementation actions*: the partners argue that having a sort of roadmap for the implementation of the studied actions is a useful factor both as regards the internal organization of the company and to have a complete picture of the situation.

- *Costs and benefits*: the field would indicate the costs of implementing the related circular strategy and the associated benefits.

- *Risks*: with the support of a brief risk analysis, this last field indicates the risks associated with implementing a strategy.

From the results, it is clear that, despite their difference, the pilots are aligned on identifying “Target” and “Equipment condition after the implementation of the strategy” fields as the most useful ones, while “Closing loop management model” is considered as not essential in the SCF context.

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4 Sustainability and Circularity LCES Evaluation Methodology

This section is meant to define a methodology supporting the identification of the LCES to be applied, especially into the RECLAIM context, to maximize environmental, economic and circularity benefits derived from the exploitation of equipment life extension in linear economy contexts. The methodology here presented represents the theoretical basis for the evaluation of the LCES effects evaluation that will be further developed in the project during the T7.4 activities, where LCA and LCC tools are developed in order to support the Decision Support Framework implemented in T4.4.

The T4.1 evaluation methodology is indeed constituted by the following main blocks:

- A list of indicators to be exploited in the LCES performance analysis, divided in three categories, such as environmental, economic and circular indicators;
- A calculation methodology for the circularity indicators;
- A calculation methodology, based on LCA and LCC approaches, for the economic and environmental indicators based on a “gap approach” that is meant to highlight the performances differences between the circular approach and the linear one by comparing the effects generated by the linear strategy with the ones created by the LCES analysed.

In this document, the gap methodology is specifically exploited to compare the linear approach with different possible circular ones (represented by the various LCES identified) since all the RECLAIM pilots are starting from a linear economy model. With few adaptations the gap analysis proposed could be also applied to the comparison between different LCSE so that the company could identify the more suitable to be applied in its specific case.

The “gap evaluation” described in detail in §4.2 is not only meant to present a methodological framework, but is also proposing some qualitative considerations on the possible differences of performances generated. In order to assess actual advantages (or disadvantages) in the LCES application, data from specific cases are needed to calculate precise gaps. It is in fact impossible to determine a general rule concerning the possible advantages offered by a life extension approach since the effect has to be evaluated case by case considering the equipment, the manufacturing and the logistic processes characteristics.

4.1 List of indicators

The identified indicators cover three main areas:

- Economic area, evaluated through a LCC indicator;
- Environmental area, evaluated through the LCA indicators;
- Circularity area.

The list of indicators for each area is shown in the following sections.

4.1.1 Economic indicators (LCC indicator)

T4.1 economic assessment methodology is based on the LCC approach, thus is meant to calculate the costs related to the equipment that are generated all along its lifecycle, guaranteeing an overall measurement of cost decrease (or increase) and avoiding cost

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shifting between the different life cycle phases. The **economic indicator** calculated by the T4.1 evaluation methodology is thus the total life cycle cost associated to a production equipment, evaluated starting from the extraction of the raw material constituting it, till the end of life of the equipment itself.

The total cost is calculated summing the costs associated to each life cycle phase. Within the single life cycle phase, cost contributions are identified in order to detail the single costs items. Most of the times these contributions are in common in the different life cycle phases. For instance, personnel cost is contributing both to the manufacturing phase and the disassembly one.

The cost related to a single life cycle phase is thus calculated summing the different contributions expected to affect that phase. Table 11 presents the involved life cycle phases and the related cost contributions adopted in the LCC methodology. Both life cycle phases and contributions are described in detail in the following sub-paragraphs. The first column of Table 11 is meant to identify the expected cost contributions, while the first row is listing life cycle stage. The table is showing the association phases and involved costs with a grey ticked cell.

Table 11. Phases and cost contributions of the LCC

COSTS	Design	Production		Distr.	Use phase			EoL								
		Procurement	*Manufacturing*		*Monitoring via IoT*	*Repair*	*Cons.*	*Disassembly*	*Inspection*		*Cleaning*	*Replace*	*Reassembly*	*Recycle*	*Reverse log.*	*Disposal*
									Control	*Test*						
Services	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Energy / fuel		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓
Hardware / components		✓			✓		✓			✓		✓				
Ancillary Materials / raw materials		✓	✓			✓	✓					✓		✓		
Personnel	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓		✓	✓
Downtime						✓		✓	✓	✓	✓	✓	✓			
Amortization of multi-year assets	✓		✓		✓		✓		✓							

The total cost related to the whole life cycle of the equipment is calculated as follow:

$$Total\ cost = \sum_i Cp_i$$

Eq. 1

where Cp_i is the total cost associated to the phase i.

The cost contributions identified in Table 13 **Errore. L'origine riferimento non è stata trovata.** are associated to life cycle phases in order to outline the economic impact of each stage. Indeed, for each life cycle phase in column of Table 11, the involved cost contributions are ticked.

The total cost contribution of each phase is given by:

$$Cp_i = \sum_j cc_{i,j}$$

Eq. 2

where $cc_{i,j}$ is the cost contribution related to phase i and cost item j.

For example, considering the Design phase, the related cost will be:

$$Cp_{Design} = Services\ cost + R\&D\ cost + Personnel\ cost + Amortization\ of\ multiyear\ assets$$

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4.1.1.1 Life cycle phases

Based on an LCC methodology, the phases of the product life cycle have to be considered. The life cycle of a machinery/equipment can be divided in the following phases: Design, Production, Distribution, Use, and End-Of-Life phases. Each phase can be further split into characteristic sub-phases that, together with the description, can be found in the following Table 12.

Table 12. Life Cycle phases description

Phase		Description
Design		Initial phase that has the aim of define the complete specification of the geometry, materials, and tolerances of all the parts through the provision of detail drawings, assembly drawings, and general assembly drawings[2].
Production	Procurement	The Procurement Phase is where the results of the detailed engineering effort are leveraged to acquire bids for equipment, materials, and construction services, technically and commercially evaluate those bids, and issue purchase orders and negotiate construction contracts[3] [4]. This phase includes also the transportations needed to acquire the items needed for the manufacturing phase.
	Manufacturing	The phase in which manufacturing activities can be carried out using tools, human labor, machinery, and chemical processing. In RECLAIM, the phase refers to the production of the production equipment in analysis.
Distribution		According to the agreements made by the parties, the distribution phase deals with the flow of products to customers, ensuring a timely placement of the product in the place, at the time, in the quantity and quality appropriate to the conditions[5]. Specifically, here the equipment is transported from the OEM to the equipment end user.
Use	Monitoring via IoT	In order to ensure that a function or service is performing as intended, the monitoring phase is exploited. The process is monitored using physical sensors and logical software-defined measuring devices[6].
	Repair	Process of replacing components following damage or failures, which determine a block of production, generating downtime costs and operator downtime. This phase includes also the transportations needed to acquire the items needed for the repair phase.
	Consumption	The consumption refers to the use phase of the equipment life cycle, in which the product is employed for the production process. This implies its deterioration and the use of resources such as energy, manpower, auxiliary materials, etc.

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[2] https://www.sciencedirect.com/topics/engineering/detail-design-phase
[3] https://www.amg-eng.com/what-we-do/lifecycle-phases/procurement-phase/#:~:text=The%20Procurement%20Phase%20is%20where,orders%20and%20negotiate%20construction%20contracts.
[4] https://www.midwestworld.com/the-7-key-steps-of-a-procurement-process/
[5] https://web.uniroma1.it/dip_management/sites/default/files/allegati/Lezione_Management_Produzione.pdf
[6] https://cloud.google.com/solutions/remote-monitoring-and-alerting-for-iot

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End-of-Life	Disassembly	Defined as "the systematic separation and extracting valuable entities for possible future re-usage", the disassembly is the first phase of the future strategy implementation, such as reuse, remanufacture or recycle[7].
	Inspection	Control - The control phase involves revision and verification of the component/components removed during the previous disassembly phase.
		Test – Performed as a quality control test, it is performed to ensure that the specifications are satisfied. Test consists in simulating the conditions in which a product should work, verifying its functionality.
	Cleaning	Action needed to remove dirt, marks, or stains from the removed pieces/assemblies and/or of the whole equipment.
	Replace	It refers to the action of replacing components following the disassembly phase. This phase includes also the transportations needed to acquire the items needed for the maintenance phase.
	Reassembly	The continuation of the disassembly phase, this is the operational phase of reconstruction of valuable entities, components or assemblies.
	Recycle	The process of converting waste materials into new materials and objects that aims at environmental sustainability by substituting raw material inputs into and redirecting waste outputs out of the economic system[8]. In this context, it involves the entire equipment or parts of it.
	Reverse Logistic	According to the strategy adopted, the used equipment can be moved from the final destination back in the distribution chain to the initial manufacturer (OEM) or to a new entity or place in the original chain, or another network (in case of reuse)[9].
	Disposal	As the phase at the end of the cycle, it refers to the action of discarding components / assemblies / entire equipment. Typical processes of the disposal phase are landfilling and incineration[10].

4.1.1.2 Cost contributions

The list of cost contributions considered in the current model is described in Table 13, and the evaluation of each contribution refers to the cost model proposed by T4.3 activities, discussed in §4.1.1.3. Cost contributions can be associated to life cycle phases in order to outline the economic impact of each stage. Considering the structure proposed by the "Standard for general use IEC 60300-3-3: 2017: Lifecycle costing for technological systems" and adopting a high-level view, the general cost items relating to the whole product life cycle were considered.

7 https://www.researchgate.net/publication/291068463_The_Disassembly_Line_Balancing_and_Modeling_-_Book_Review
8 https://en.wikipedia.org/wiki/Recycling
9 https://it.wikipedia.org/wiki/Logistica_di_ritorno
10 https://ec.europa.eu/environment/waste/index.htm

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Table 13. List of cost contributions

Contribution	Description	Calculation
Services	Costs related the purchase of non-material assets such as light, non-invasive maintenance actions, telephone, advertising, etc.	$C_{services} = C_{lights} + C_{telephone} + C_{adv} + C_{non-invasive\ maint.\ actions} + \cdots$
Energy / fuel	These costs account the expenditures on energy-related procurement. They are considered separately since often they represent a major impact on the overall costs of the equipment lifecycle.	$C_{energy} = c_{fuel} * l_{fuel} + P * t * c_{energy}$ Where: c_{fuel} is the fuel cost in (€/l), l_{fuel} is the amount of fuel needed (l), P in (kW) is the power absorbed by an equipment exploited in the considered phase, t (in h) is the functioning time of the equipment, and c_{energy} is the cost of energy in (€/kWh)
Hardware / components	They refer to the purchase of components and other hardware needed (excluding multi years assets).	$C_{hw/components} = \sum C_{component}$
Materials / raw materials	The costs refer to all the materials and auxiliary materials that the company needs for the production phase.	$C_{mat.} = c_{material} * m$ Where: $C_{material.}$is the materials costs in (€/kg) and m is the weight of the needed material in (kg)
Personnel	Personnel costs consider the total costs related to employee expenses: training programs, hiring expenses, termination benefits, taxes, workers' allowances, travel expenses, incentive programs and ancillary benefits for employees[11].	$C_{personnel} = R_p * t_p$ Where: $C_{personnel}$ is the personnel cost (€), R_p is the personnel cost rate (€/min) and t_p is the personnel labor time (min)
Downtime	It refers to the costs generated by the non-produced items when the equipment undergoes some shutdowns for maintenance, repair, replacement, etc.	$C_{downtime} = R_{downtime} * t_{downtime}$ Where: $C_{downtime}$ is the cost of downtime, $R_{downtime}$ is the downtime cost rate in (€/min), and $t_{downtime}$ is the downtime duration in (min)
Amortization of multi-year assets	It refers to the depreciation of multi-year assets, such as software, machinery, vehicles, equipment, furniture, etc.	$C_{amm} = \frac{C_{multi-year\ assets}}{t_{amm}}$ where: C_{amm} is the amortization rate per year (€/y), $C_{multi-year\ assets}$ is the total cost of the multi-year assets in (€), and t_{am} is the amortization horizon in (y)

Depending on the specific cost contribution considered, adjustment factors could be introduced in order to take into account the effect of learning curve, technology aging, and

[11] https://www.lawinsider.com/dictionary/personnel-costs

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bank interests respectively on labor, hardware, and investment costs. These aspects will be deepened by the ongoing activities of T4.3.

4.1.1.3 ASTON - SUPSI cost modeling alignment

The scope of T4.1 economic evaluation, based on life cycle cost assessment, is the definition of a methodology supporting the identification of the better Life Cycle Extension Strategy (LCES) to be applied in a linear economy business model in order to maximize the possible economic benefits obtained by life cycle extension.

Beside this task, ASTON is carrying out T4.3 activities that are more focalized in developing a cost evaluation methodology to be exploited within the Decision Support Framework, in order to support decision-making process. As mentioned in the work carried out, an analysis for every selected life extension strategy of the industrial equipment is done, aimed at establishing a cost breakdown structure to represent all the cost elements (see Figure 10) and developing cost estimation relationship (CERs) based on identified cost drivers for each element. Based on current requirements, T4.3 focuses on estimating cost of life-extension strategy at usage level of equipment/component (physical life-extension).

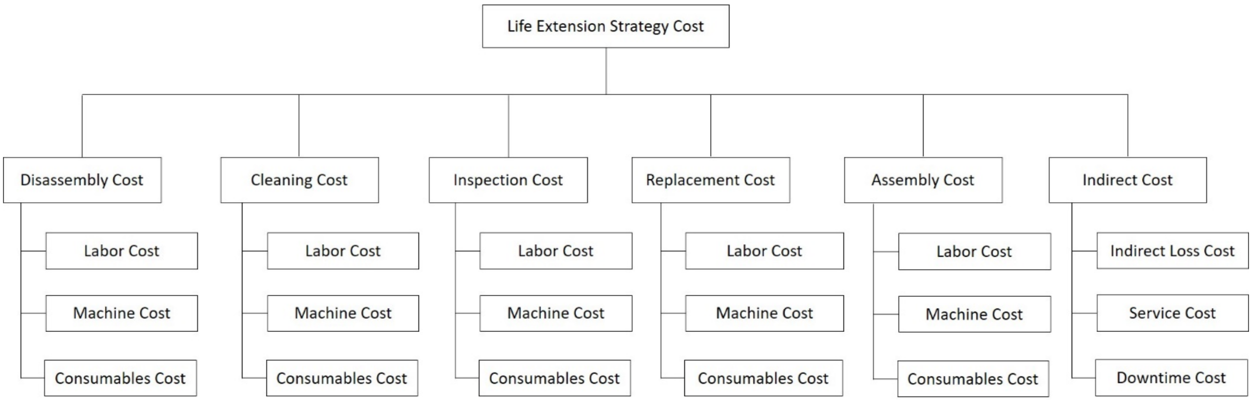

Figure 10. Proposed cost breakdown structure for life extension strategy (ASTON cost modelling)

Despite the different aim, both works will be the inputs for T7.4 (Life Cycle Assessment (LCA) – Life Cycle Cost (LCC)) in which an LCA/LCC tool will be developed. In order to integrate the two tasks' activities in the WP7 tool, an attempt is made to align the two models, both on the life cycle phases and the cost contributions. In particular:

- T4.1 cost modelling introduces the "inspection" phase, instead of keeping the test and control phases separated;
- T4.1 cost modelling enriches the model with the definition of the single contribution calculation formulas similarly to the T4.3 cost modelling (as can be seen in Table 13).

As a difference, T4.1 cost modelling considers the whole life cycle phases of the product, but this could be motivated for the different aim of the two cost models: T4.1 is meant to compare the costs related to the application of an extension strategy in respect to the linear one. It is thus crucial to be sure not to move cost impacts along the product lifecycle passing from a traditional strategy to a circular one, namely impacting on beginning of life phases (e.g. design and manufacturing). This point will be clearly addressed in the evaluation methodology developed in §4.2.

4.1.2 Environmental indicators (LCA indicators)

Similarly to the economic evaluation, also for the environmental assessment a life cycle approach has been adopted, in order to analyze and compare the indicators impact along all the entire life cycle of the equipment. According to the ISO 14040 standard, LCA studies the

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environmental aspects and potential impacts throughout a product's life cycle (i.e. cradle-to-grave) from raw materials acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences.

LCA is carried out, under the ISO LCA Standard guidelines, in four distinct phases, namely Goal & Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation phases, which are interconnected and interdependent:

- Goal & Scope Definition – the Goal sets out the context of the study and explains how and to whom the results are to be communicated. The scope describes the detail and depth of the analysis and should outline in particular the following: the Product System, the Functional Unit, the Reference Flow, the System Boundary, the allocation methodologies the Impact Assessment methodology and other possible elements needed to guide and regulate the other LCA phases.

- Inventory analysis – Life Cycle Inventory (LCI) analysis is meant to create an inventory of flows from and to nature (ecosphere) for a product system. It is the process of quantifying raw material and energy requirements, atmospheric emissions, land emissions, water emissions, resource uses, and other releases over the life cycle of a product or process. The output of an LCI is a compiled inventory of elementary flows from all of the processes in the studied product system (e.g. a production equipment). Figure 11 reports as an example the possible LCI data to be collected in order to characterize a generic process Pi from the LCA point of view.

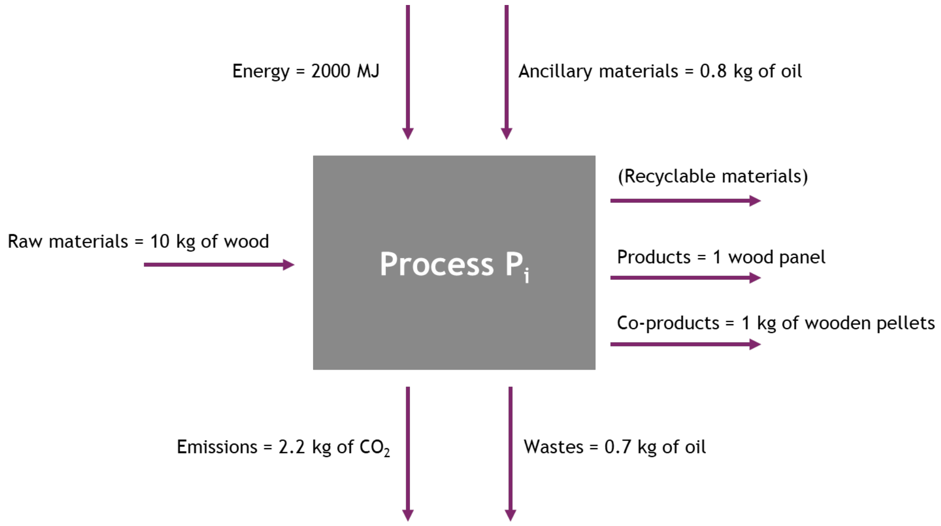

Figure 11. LCI of a generic process Pi

- Impact Assessment – Life Cycle Impact assessment is aimed at evaluating the potential environmental and human health impacts resulting from the elementary flows determined in the LCI. The ISO 14040 and 14044 standards require the following mandatory steps for completing an LCIA: selection of impact categories, category indicators, and characterization models; classification of inventory results, namely the LCI results are assigned to the chosen impact categories based on their known environmental effects; characterization, which quantitatively transforms the LCI results Ir_s for each elementary flow s within each impact category c via "characterization factors", $CF_{c,s}$, to create "impact category indicators", Ic, calculated as follows:

$$Ic = \sum_s CF_{c,s} * Ir_s$$

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Eq. 3

- Interpretation – the LCA phase dedicated to the preparation of the results and their analysis. The final aim of interpretation is twofold: extract all the possible information that could be exploited for product improvement; prepare a report for the communication of the results.

As reported in the Goal & Scope definition and in the Impact Assessment phases identified by the ISO 14040, one of the first steps needed to prepare an LCA is the selection of the impaction categories to be addressed together with the related category indicators and characterization methodologies.

To this end, a list of environmental indicators, reported in Table 14 has been identified considering the ones addressed by the Product Environmental Footprint (PEF[12]) initiative, a method proposed by the European Commission that is meant to standardize LCA realization in order to put the basis for a future ISO 14025-like product certification.

The list of indicators will be used as a reference also for the LCA assessment in the tool realized in T7.4.

Table 14. Environmental indicators

Indicator	Methodology
Global warming potential (kg CO_2 eq.)	Bern model
Acidification (mol H+ eq.)	Accumulated exceedance model
Eutrophication – terrestrial (mol N eq.)	Accumulated exceedance model
Eutrophication – aquatic (fresh water – kg P eq.; marine – kg N eq.)	EUTREND model
Photochemical oxidant formation potential (kg NMVOC eq.)	LOTOS – EUROS model
Ozone depletion potential (kg CFC-11 eq.)	EDIP model
Resource depletion – mineral, fossil (kg Sb eq.)	CML2002 model
Resource depletion – water (m^3 water use related to local scarcity of water)	Swiss Ecoscarcity
Land transformation (kg deficit)	Soil Organic Matter (SOM) model
Eco-toxicity for aquatic fresh water (CTUe)	USEtox model
Human toxicity – non cancer effects (CTUh)	USEtox model
Human toxicity – cancer effects (CTUh)	USEtox model
Particulate Matter/ Respiratory Inorganics (kg PM2.5 eq.)	RiskPoll model
Ionizing radiation – human health effects (kg U_{235} eq. to air)	Human Health effects model

With respect to the LCC methodology, life cycle phases are revised based on whether an impact is generated or not in the environmental dimension. Consequently, the Design phase is no more considered, and Monitoring, Disassembly, Inspection (both Control and Test), Replace, and Reassembly sub-phases are highlighted in orange as potential marginal contributors, since they are supposed to require more manual processing than resource consumption. The company, as well as for the LCC approach, has then the role of quantifying the environmental contribution of each phase for the strategy adopted, based on the provided model.

[12] https://ec.europa.eu/environment/eussd/pdf/footprint/PEF%20methodology%20final%20draft.pdf

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Obviously, the LCA method is no more comprehensive of the cost contributions, but the estimation of the impact is evaluated through the environmental indicators identified in Table 14. By way of an example, only the Global Warming Potential is reported in the Table 15, but the same can be repeated for all the other indicators. Making the comparison with the LCC method, for each process that is carried out in each phase it is necessary to carry out the LCI (as shown in Figure 11) and calculate the impacts through the characterization factors using Eq. 3.

Table 15. Phases and cost contributions of the LCA

Environmental indicator	*Design*	**Production**		**Distribution**	**Use phase**			**EoL**								
		Procurement	*Manufacturing*		*Monit. via IoT*	*Repair*	*Consumption*	*Disassembly*	*Inspection*		*Cleaning*	*Replace*	*Reassembly*	*Recycle*	*Reverse logistic*	*Disposal*
									Control	*Test*						
Global Warming Potential (GWP 100a)		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

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4.1.3 Circularity indicators

In addition to the evaluation of the environmental and economic performances suggested by the DoA of T4.1, the circularity assessment has been added in order to provide a measure of the circularity advantages offered by the LCES. Notwithstanding the evaluation of the circularity performances is at its early stage, a quite huge plethora of indicators has been conceived in order to address the performance evaluation at various levels: product, companies linked in industrial symbiosis environment, and regional.

The circular indicators have been retrieved from literature review, especially considering the recent work of De Pascale et al. (De Pascale et al., 2021) that proposed a wide analysis of the already available indexes. The literature findings have been revised to fit the contest of this task that is meant to provide an evaluation methodology addressing specifically the life cycle extension of production equipment.

Three different levels of application are provided: *macro*, as a city, region or nation, *meso*, as eco-industrial parks systems and industrial symbiosis, and *micro* level, as a single company or product. As the ones accounting for the circularity at products' application level, the micro level has been selected to proposed the most appropriate indicators to the case of RECLAIM. Those are presented and described in the following sections.

Amongst the 29 micro-level indicators, the selection has cut off the indicators that:

- belong to the "product", "components" and "materials" application level;
- are merely qualitative, without a mathematical formulation (as for example CE Toolkit or Circularity Calculator indicators);
- have a mathematical formulation, though the involved parameters are not defined clearly in their meaning and/or data sources, at least for the case in question;
- have a mathematical formulation, but the data collection results too complex and it is not possible to make an estimation, as issues are measured that are not necessarily already implemented (as for the Longevity Indicator).

The mentioned circularity indicators are described in the following sections.

4.1.3.1 Circularity Rate

The Circularity Rate (CR) measures the circularity of Recycle, Reuse and Remanufacture LCES focusing on the percentage of material reutilization for the system's components. It is given by:

$$CR = \left[\left(\frac{\sum_{i=1}^{p} m_i RCr_i}{m_{tot}}\right) + \left(\frac{\sum_{i=1}^{p} m_i}{m_{tot}}\right) + \left(\frac{\sum_{i=1}^{p} m_i\, REr_i}{m_{tot}}\right)\right] * 100\%$$

where:

- p is the number of components constituting the system;
- m_i is the mass of the recycled, reused or remanufactured component i;
- RCr_i is the percentage of recycled component i;
- REr_i is the percentage of remanufactured component i;
- m_{tot} is the total mass of the system.

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The indicator ranges from 0 to 100%, where 0% means all the system's material is landfilled at the end of life, while 100% means that all components are in some way recovered for a future use. Depending on the combination of applicable LCES adopted for the different components, a quantification of the circularity level is provided for the system.

Notice that there is a physical constraint to be respected in the application of the indicator: the total percentage of material recycled and remanufactured must be equal or less than 100%, assuming in addition that a component is reused at 100%. This translates for each component in:

$$RCr_i + REr_i + L_i = 100\%$$

where L_i is the percentage of component i that is landfilled.

The CR indicator is constituted by three terms, accounting respectively for the material recycling rate, $\left(\frac{\sum_{i=1}^{p} m_i \, RCR_i}{m_{tot}}\right)$, the material reuse rate, $\left(\frac{\sum_{i=1}^{p} m_i}{m_{tot}}\right)$, and the material remanufacturing rate, $\left(\frac{\sum_{i=1}^{p} m_i \, R_i}{m_{tot}}\right)$, coming from an adaptation of the Potential Reuse Index and Potential Recycle Index from (J. Mesa et al., 2018). As the design of the system is given, the system could be oriented towards one of the LCES, e.g. the percentage of material recyclable is higher than the percentage of material reusable. Therefore, it is possible to go into detail in the evaluation by looking at the three independent terms, in order to assess which scenario corresponds to a higher level of circularity, given the same CR value. For instance, considering that Recycle is less "circular" than Reuse strategy, between two systems with the same CR value, the one with less percentage of reusable material is the less circular one.

4.1.3.2 Material Circularity Indicator

The Material Circularity Indicator (MCI) measures the level of circularity of a product (or company) assessing how linear or restorative the flow of the materials for the product (or the company's products) and how long and intensely the product (or the company's products) is used compared to similar industry average products. Indeed, the Material Circularity Indicator of a product, MCI_p, is given by (Measuring Circularity, 2019):

$$MCI_p = \max(0, MCI'_p)$$

$$MCI'_p = 1 - LFI * F(X)$$

where:

- LFI is the Linear Flow Index, calculated as follows:

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}}$$

  It measures the proportion of material flowing in a linear fashion, with respect to the sum of the material flowing in a linear and a restorative fashion. Namely, it is the ratio of material sourced from virgin materials, V, and ending up as unrecoverable waste, W, over the total mass flow, $2M + \frac{W_F - W_C}{2}$, where M is the mass of the product, W_C is the mass of unrecoverable waste generated in the process of recycling parts of the product, and W_F is the mass of unrecoverable waste generated when producing recycled feedstock for the product);

- $F(X)$ is the Utility Factor, calculated as follows:

$$F(X) = \frac{0.9}{X}$$

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It is built as a function of the utility X of a product, accounting both for the length of the product's use phase with respect to industrial average lifetime (L/L_{avg}) and for the intensity of use with respect to an industrial-average product, in terms of functional units (U/U_{avg}).

The MCI assigns a score between 0 and 1, describing the circularity of products that, in practice, will sit somewhere between these two extremes. Indeed, MCI ranges from a fully 'linear' product, which is manufactured using only virgin feedstock and ends up in landfill at the end of its use phase (MCI = 0), to a fully 'circular' product, which contains no virgin feedstock, is completely collected for recycling or component reuse, and where the recycling efficiency is 100% (MCI = 1).

4.1.3.3 End-of-Life Index

The End-of-Life Index (IEOL) evaluates the impact on the circularity of a product of different End-of-Life strategies, in particular of Recycle, Reuse and Remanufacture. The original indicator is composed by a set of four indicators (Favi et al., 2017), which are arranged in the formulation hereafter:

$$IEOL = \frac{\sum_{i=1}^{p_{recycle}}(V-C)_i + \sum_{k=1}^{p_{reuse}}(V-C)_k + \sum_{z=1}^{p_{remanufacture}}(V-C)_z}{\sum_{i=1}^{p_{recycle}} V_i + \sum_{k=1}^{p_{reuse}} V_k + \sum_{z=1}^{p_{remanu}} V_z}$$

(Eq. 4)

where:

- $i = 1, \dots p_{recycle}$ is the number of recyclable components;
- $k = 1, \dots p_{reuse}$ is the number of reusable components;
- $z = 1, \dots p_{remanufacture}$ is the number of remanufacturable components;
- V is the actual value of the component;
- C is the cost of the component related to the applied LCES.

The assessment relies on the economic revenues and costs related to the strategies adoption, whose specific contributions are detailed in Table 16.

Table 16. End-of-Life Index contributions

Indicator	Revenues of $LCES_j$ (V_j)	Costs of $LCES_j$ (C_j)
Recycle	$V_{Rc} + V_{En}$ Where: $V_{Rc} = m * R_f * C_{Rc}$ $V_{En} = m * E_s * C_e$ Being: V_{Rc} value of the recycled material V_{En} energy saved by not producing virgin material m mass of the component[kg] R_f recycling factor [%] C_{Rc} recycled material cost [€/kg]	$C_{RL} + C_{dd} + C_C$ Being: C_{RL} reverse supply chain cost C_{dd} destructive disassembly operations cost C_C cleaning operations cost

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	E_s energy saved (difference between primary embodied energy and recycling energy) C_e energy cost (industrial) [€/MJ]	
Reuse	$V_{Re} + V_{Mat} + V_{Man}$ Where: $V_{Mat} = m * C_{Mat}$ $V_{Man} = C_{Man} + C_t$ Being: V_{Re} value of the reused part V_{Mat} value of the virgin material used to produce the part V_{Man} value of the manufacturing operations to build up the part m mass [kg] C_{Mat} virgin material cost [€/kg] C_{Man} manufacturing activities cost [€] C_t transport phases cost [€]	$C_{RL} + C_{Sd} + C_C$ Being: C_{RL} reverse supply chain cost C_{Sd} selective disassembly operations cost C_C cleaning operations cost
Remanufacture	$V_{Rem} + V_{Mat} + V_{Man\_s}$ Where: $V_{Mat} = m * C_{Mat}$ $V_{Man} = C_{Man} * C_t$ Being: V_{Rem} value of the remanufactured part V_{Mat} value of the virgin material used to produce the part V_{Man_s} value of original manufacturing operations to produce the part not necessary for remanufacture m mass of the component [kg] C_{Mat} virgin material cost [€/kg] C_{Man} manufacturing activities cost [€] C_t transport phases cost [€]	$C_{RL} + C_{Sd} + C_C + C_{Rem}$ Being: C_{RL} reverse supply chain cost C_{Sd} selective disassembly operations cost C_C cleaning operations cost C_{Rem} additional remanufacture operations cost

The IEOL is thought to be the economic dual of the CR indicator: it is indeed composed by three merged terms, accounting for Recycle, $\left(\frac{\sum_{i=1}^{p_{recycle}}(V-C)_i}{\sum_{i=1}^{p_{recycle}} V_i + \sum_{k=1}^{p_{reuse}} V_k + \sum_{z=1}^{p_{remanufacture}} V_z}\right)$, Reuse, $\left(\frac{\sum_{k=1}^{p_{reuse}}(V-C)_k}{\sum_{i=1}^{p_{recycle}} V_i + \sum_{k=1}^{p_{reuse}} V_k + \sum_{z=1}^{p_{remanufacture}} V_z}\right)$, and Remanufacture impacts on the system's costs, $\left(\frac{\sum_{z=1}^{p_{remanu}}(V-C)_z}{\sum_{i=1}^{p_{recycle}} V_i + \sum_{k=1}^{p_{reuse}} V_k + \sum_{z=1}^{p_{remanufacture}} V_z}\right)$.

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4.2 Environmental and economic "gap evaluation" methodology

The circular economy can drive sustainability: the consumption of resources and emission of waste is minimized by keeping materials in the loop as long as possible. It is therefore important for a company to select and implement circularity strategies; for that reason, it is necessary to know how to evaluate and compare the performance of these strategies based on their feasibility and potential results. However, evaluation methods for product-level circularity strategies are in their infancy (Alamerew et al., 2020).

Alamerew et al. (Alamerew et al., 2020) proposes a multi-criteria evaluation method of circularity strategies at the product level, which can be used by business decision-makers to evaluate and compare the initial business of the company, transformative and future circularity strategies. This multi-criteria evaluation method aims to assist business decision-makers to identify a preferred strategy by linking together a wide variety of criteria, i.e., environmental, economic, social, legislative, technical, and business, as well as by proposing relevant indicators that take into consideration, where possible, the life cycle perspective. It also allows for flexibility so that the business decision-makers can alter criteria, sub-criteria, and weighing factors to fit the needs of their specific case or product. The proposed method consists of five main steps: (I) description of the product and/or service under consideration, (II) identification of potential circularity strategies, (III) identification of evaluation criteria, sub-criteria and indicators, (IV) evaluation of circularity strategies, and (V) analysis and ranking of alternative circularity strategies.

Another example is the one discussed by Phuluwa et al. (Phuluwa et al., 2020), in which a sustainable decision framework for the selection and implementation of the EoL options is proposed for rail components' field. Using the railcar bogie as a case study, the EoL recovery processes identified, namely refurbishment, reuse, recycling, and remanufacturing were incorporated into the decision model. Mathematical models for the estimation of the cost relating to the identified EoL options were developed in order to project the cost-effectiveness and the profitability of the EoL identified options. Recommendations were also made to increase the level of awareness of the circular economy in order to promote economic, environmental sustainability and safe guide public health.

In order to highlight the advantages (or even the disadvantages) of the application of the circular economy model on the production equipment context, a comparison strategy has been developed based on these concepts retrieved from literature. The proposed evaluation methodology is based on a screening assessment that companies can exploit to measure the possible environmental and economic benefits offered by each single LCES in comparison with the linear way to produce, commercialize and consume a product.

The model essentially adopts and applies LCC and LCA approaches and aims to enable a high-level comparison in terms of environmental impacts and costs between a specific LCES and the linear economy approach. Through the high-level vision proposed the model has the objective to identify possible general trends of impacts gaps that could be generated by the life extension approach in each product life cycle phase. Despite that, the use of variables and parameters come into play in the evaluation of contributions in order to guarantee also a case-by-case evaluation. Indeed, it is not fully possible to determine that a certain LCES (e.g. resell) is always generating benefits for a company that currently bases its business on a liner model since the product and the company way to produce and commercialize it may influence the extension strategy efficacy from the economic and environmental point of view.

In order to present the conceived approach, a practical example is proposed. Being a comparison methodology oriented to the life cycle perspective, as indicated by the ISO 14040, the definition of a *Functional Unit* (FU) is a prerequisite to allow the gap analysis.

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The FU is a specific quantity of the function of the studied system and provides a reference to which the inputs and outputs flows can be related, enabling comparison of two essential different systems[13] but providing the same function. The FU is thus establishing a common quantity of the function provided. In the comparison of two products, the FU is a fixed parameter that regulates the comparison, while what could vary is the "amount" of the product needed to fulfill a specific function quantity. This second element is named *reference flow* (RF) and could vary passing from the different systems in analysis.

For instance, if a milling machine is considered as the system under investigation, a possible FU could be fixed at 300.000 kg of steel removed. Considering then a milling machine that is able to remove 100.000 kg of steel during its lifecycle, 3 machines are needed in order to accomplish the FU previously presented, where 3 is the RF of this specific analysis. This case could correspond to the case of the linear strategy since at the end of every life cycle the machinery is sent to landfill so a new one is needed in order to fulfil the FU. On the contrary, in this example, it is assumed that the reference flow associated to the application of a LCES is less than 3 since the strategy is meant to extend the machines lifecycle thus the number of machine needed is less than the linear case, but assuring the same quantity of the steel removed. In the case of the Reuse strategy, the RF could be equal to 1 since a single equipment could provide the 300.000 kg of steel removed. Generalizing, the parameter "y" is introduced into the evaluation model to represent the RF of the linear model.

This approach is shown in Figure 12 with a general approach. On the left side, the representation of the linear strategy which, considering "y" equals to *n*, completes *n* life cycles to remove a certain amount of steel (z). On the right side, the concept of circular strategies is addressed: in this case, since the circular strategies are designed specifically to extend the life cycle of the products, it is expected that the functional unit is reached with a number of equipment less than *n*.

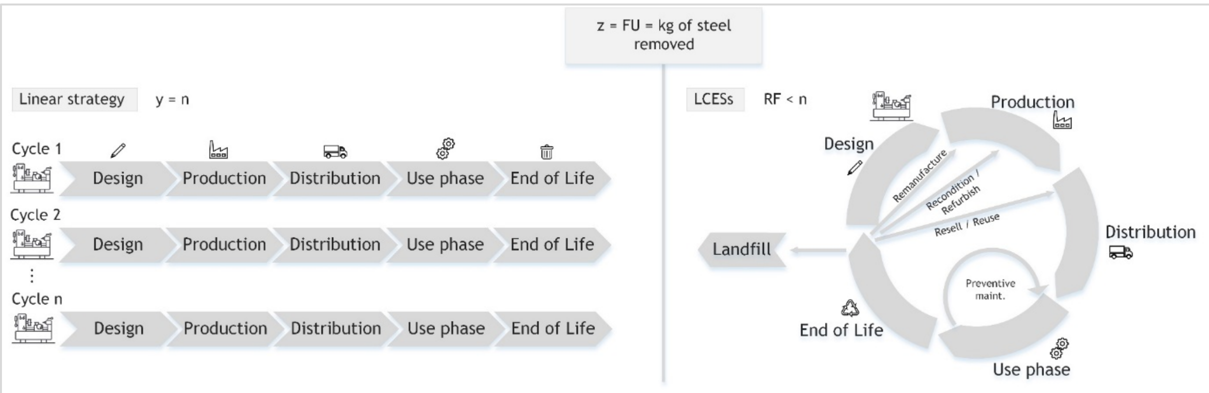

Figure 12. Linear strategy VS LCES

Taking in consideration a practical comparison example (Linear – Resell/Reuse), the related contributions can be the following, as shown in Figure 13.

[13]https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=ECOIL_Life_Cycle.pdf

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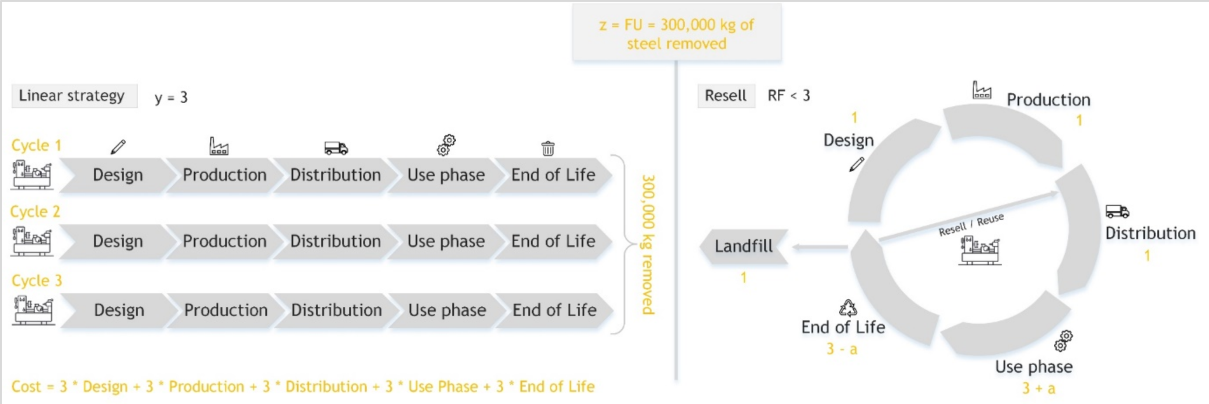

Figure 13. Linear strategy VS Resell/Reuse

The various phases that belong to the life cycle of the Linear strategy (on the right) will contribute to the total impacts (environmental and economic) with a factor of 3. On the other hand, the phases of the life cycle belonging to the Resell/Reuse strategy will contribute for the most part by a factor equal to 1 (see Design, Production, Distribution and Landfill phases), means that the execution of the relative phase is required only once until the functional unit is reached. The Use and End of Life phases instead contributing with a value of “3 + a” and “3 – a”, thus specifying that there is a delta with value “a” in the achievement of the functional unity. Therefore, the factor “a” has now been introduced to represent the effect of life cycle extension on the life cycle phases’ contribution. A more detailed description of “a” parameter’s meaning is provided in §4.2.1.

The following sections will address the practical explanation of the LCC and LCA methodologies applied to the RECLAIM project in the comparison between the linear economy model (the current approach of the RECLAIM pilots) and the ones offered by the application of the different LCES.

Among the LCES identified in §2.2, some of the strategies have been excluded from the evaluation methodology. In particular, Design-based strategies have been left out from the evaluation since their effect can be assessed directly in the related extension strategy promoted. For instance, Design for upgradability is meant to foster the refurbishment of an equipment, thus its effects in respect a linear approach is already investigated in the Linear vs Refurbish gap analysis. Concerning Recycle and Cannibalization strategies, they have not been considered since they are not extending the life of the equipment as a whole, but extending the life of the materials and components constituting it. Since the evaluation methodology has been conceived to allow a comparison between the strategies effects based on the same function and function quantity (the same FU), the focus of the analysis is the equipment and not a part of it (i.e. a recycled material or a reused single component) since they are not able to provide the identified FU and thus they cannot represent a RF. For what concerns Pay-per-use strategy, it promotes a service-based business model of the company that indeed could stimulate the deployment of different LCES, from 100% reuse to remanufacture or only involving predictive maintenance, depending on the characteristics of the specific case application (e.g. the kind of equipment, the market addressed…). For this reason, it is thus difficult to assess the environmental and economic gap provided by the application of the pay-per-use strategy since it could potentially mix different extension approaches.

Moreover, this evaluation methodology is prone to be further developed in order to allow also the gap evaluation between the various extension strategies applied.

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4.2.1 LCC and LCA gap assessment methodology

The proposed method, developed in Excel, consists of a General sheet and is presented as follows in Table 17 and Table 18.

Since the recycling strategy is not properly considered as a Life Cycle Extension strategy of the equipment, it was not involved in the implementation of the methodology. As a result, the gap between the linear and the recycling strategies will not be mentioned.

Table 17. LCC implementation

Cost		Production			Use phase			EoL								
	Design	*Procurement*	*Manufacturing*	Distribution	*Monit. via IoT*	*Repair*	*Consumption*	*Disassembly*	*Inspection*		*Cleaning*	*Replace*	*Reassembly*	*Recycle*	*Reverse logistic*	*Disposal*
									Control	*Test*						
Linear	y	y	y	y		ky	y							y		y
Resell / Reuse	1	1	1	1		ky + a	y + a		y - a	y - a	y - a			1	y ± a	1
Remanufacture	y - b	y - b	y - b	y - b		ky	y	y - b	y - b	y - b	y - b	y - b	y - b	y - b	y ± b	y - b
Recondition	1	y - c	y - c	1		ky + c	y + c	y - c	y - c	y - c	y - c	y - c	y - c	y - c	y ± c	y - c
Refurbish	y - d	y - d	y - d	y - d		ky - d	y - d	y - d	y - d	y - d	y - d	y - d	y - d	y - d	y ± d	y - d
Predictive maintenance	y - e	y - e	y - e	y - e	y	ky - e	y							y - e		y - e
Time-based maintenance	y - f	y - f	y - f	y - f	y	ky - f	y							y - f		y - f
Condition-based maintenance	y - g	y - g	y - g	y - g	y	ky - g	y							y - g		y - g

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Table 18. LCA implementation

Environmental indicator	Design	Production		Distribution	Use phase			EoL								
		Procurement	*Manufacturing*		*Monit. via IoT*	*Repair*	*Consumption*	*Disassembly*	*Inspection*		*Cleaning*	*Replace*	*Reassembly*	*Recycle*	*Reverse logistic*	*Disposal*
									Control	*Test*						
Linear		y	y	y		ky	y							y		y
Resell / Reuse		1	1	1		ky + a	y + a		y - a	y - a	y - a			1	y ± a	1
Remanufacture		y - b	y - b	y - b		ky	y	y - b	y - b	y - b	y - b	y - b	y - b	y - b	y ± b	y - b
Recondition		y - c	y - c	1		ky + c	y + c	y - c	y - c	y - c	y - c	y - c	y - c	y - c	y ± c	y - c
Refurbish		y - d	y - d	y - d		ky - d	y - d	y - d	y - d	y - d	y - d	y - d	y - d	y - d	y ± d	y - d
Predictive maintenance		y - e	y - e	y - e	y	ky - e	y							y - e		y - e
Time-based maintenance		y - f	y - f	y - f	y	ky - f	y							y - f		y - f
Condition-based maintenance		y - g	y - g	y - g	y	ky - g	y							y - g		y - g

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4.2.1.1 Strategy comparison methodology

In the evaluation of the different strategies implementation on the economic and environmental impact, the aim of providing a general gap assessment method is based on a parametric description of the strategies contribution to the single life cycle phases, and consequently on the related contributions.

Considering the linear strategy as the base case, it is supposed to fix the functional unit of the system, and to indicate with the parameter "y" the number of life cycles the machinery has to perform to fulfill the FU. Since we are facing the linear economy case, in order to fulfill the FU, we need to produce "y" machines, as at the end of life the whole system is sent to landfill (see the introduction of §4.2). As a consequence, every phase of the life cycle is exploited "y" times, and the associated cost contributions count themselves "y" times.

The same logic also applies to the analysis of the LCES. However, considering that LCES are designed specifically to extend the life cycle of the products, it is expected that the functional unit is reached with a number of cycles smaller than the one of the linear strategy adoption. Therefore, "a", "b", "c", "d", "e", "f", "g" parameters are introduced, one for each LCES. They are intended to represent the effect of life cycle extension on the life cycle phases contribution. The total cost associated to the phases of a specific LCES counts for "y" minus the related parameter.

It is important to notice that "y" is a fixed positive valued-parameter, it has the same value for all the strategies, while the other parameters are variable, and depend on the strategy under consideration; for this reason, as many variables as strategies are adopted. Moreover, the parameter related to a specific strategy (e.g. "a" in the case of Resell/Reuse strategy) always assumes positive values, but also within the same strategy assumes different values depending on the specific life cycle phases considered. The introduction of additional parameters to highlight this fact has been avoided for the sake of simplicity. The description of the introduced parameters and the boundaries concerning the possible values they can assume is reported in Table 19. A more detailed explanation of the parameter use is provided in the following sections where the comparisons between the single LCES and the linear strategy is performed.

As reported in Table 19, within the same LCES, the parameter assumes a different boundary in its values in the Use phase and Distribution/Reverse logistic sub-phase. Indeed, in these cases the parameter is intended to represent an additional positive contribution to the economic impact of the phase. In addition, a parameter "k" has been introduced in the case of "Repair" activities (corresponding to the corrective maintenance) for all the strategies analyzed. Indeed, "Repair" sub-phase reasonably is repeated more than "y" times in the time horizon considered fulfilling the functional unit, therefore being k > 0 always (this will have of course an impact on costs and environmental burden).

Table 19. Parameters description

Parameter	Description	Boundaries
y	Number of life cycles the machinery has to perform to fulfill the functional unit.	Fixed parameter for all the LCES and all phases. y can vary as follow: • It can assume value ≥ 0
k	Number of Repair actions during the time horizon considered to fulfil the functional unit.	k can vary as follow: • It can assume value > 0
a	Variable parameter for the Resell / Reuse strategy and its related phases.	a can vary as follow: • It can assume value from 0 to "y – 1" in case of Production, Distribution and EoL phases contributions, and in the case of Reverse

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		logistic phase when the contribution is equal to "y - a"; • It can assume values ≥ 0 in case of the use phase contribution and the Reverse logistic when the contribution is equal to "y + a".
b	Variable parameter for the Remanufacture strategy and its related phases.	b can vary as follow: • It can assume value from 0 to "y - 1" in case of design, production and EoL phases contributions, and in case of Reverse logistic contribution equal to "y - b"; • It can assume value ≥ 0 in case of Reverse logistic contribution is equal to "y + b".
c	Variable parameter for the Recondition strategy and its related phases.	c can vary as follow: • It can assume value from 0 to "y - 1" in case of production, distribution and EoL phases contributions, and in case of Reverse logistic contribution equal to "y - c"; • It can assume value ≥ 0 in case of use phase contribution and Reverse logistic contribution is equal to "y + c".
d	Variable parameter for the Refurbish strategy and its related phases.	d can vary as follow: • It can assume value from 0 and "y - 1" for all the phases contribution, apart when the Reverse logistic phase contribution is equal to "y - d"; in that case d can assume a value ≥ 0.
e	Variable parameter for the Predictive maintenance strategy and its related phases.	e can vary as follow: • It can assume value from 0 to "y - 1".
f	Variable parameter for the Time-based maintenance strategy and its related phases.	f can vary as follow: • It can assume value from 0 to "y - 1".
g	Variable parameter for the Condition-based maintenance strategy and its related phases.	g can vary as follow: • It can assume value from 0 to "y - 1".

The calculation of the total life cycle cost/environmental impact for a strategy is performed via the following formulas:

$$Total\ cost_{strategy} = \sum_i F_i * Cp_i$$

Eq. 5

$$Total\ env.impact_{strategy} = \sum_i F_i * Ic_i$$

Eq. 6

where:

- Cp_i is the total cost associated to the phase i (see Eq. 2);
- Ic_i is the indicator of the impact category c for the phase i (see Eq. 3) ;

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- F_i is the correction factor for the phase i, which introduces the concept of RF (Reference Flow).

For instance, the total cost related to the *linear strategy* for Eq. 5 is:

$$Total\ cost_{linear} = y * Cp_{Design} + y * Cp_{Procurement} + y * Cp_{Manufacturing} + y * Cp_{Distribution} + ky * Cp_{Repair} + y * Cp_{Consumption} + y * Cp_{Recycle} + y * Cp_{Disposal}$$

and the total environmental impact for Eq. 6 is:

$$Total\ impact_{linear} = y * Ic_{Procurement} + y * Ic_{Manufacturing} + y * Ic_{Distribution} + ky * Ic_{Repair} + y * Ic_{Consumption} + y * Ic_{Recycle} + y * Ic_{Disposal}$$

Likewise, the total cost for the *Reuse strategy* is:

$$Total\ cost_{Resell} = 1 * Cp_{Design} + 1 * Cp_{Procurement} + 1 * Cp_{Manufacturing} + 1 * Cp_{Distribution} + (ky + a) * Cp_{Repair} + (y + a) * Cp_{Consumption} + (y - a) * Cp_{Control} + (y - a) * Cp_{Cleaning} + (y - a) * Cp_{Test} + 1 * Cp_{Recycle} + (y \pm a) * Cp_{Reverse\ logistic} + 1 * Cp_{Disposal}$$

and the total environmental impact is:

$$Total\ impact_{Resell} = 1 * Ic_{Procurement} + 1 * Ic_{Manufacturing} + 1 * Ic_{Distribution} + (ky + a) * Ic_{Repair} + (y + a) * Cp_{Consumption} + (y - a) * Ic_{Control} + (y - a) * Ic_{Cleaning} + (y - a) * Ic_{Test} + 1 * Ic_{Recycle} + (y \pm a) * Ic_{Reverse\ logistic} + 1 * Ic_{Disposal}$$

Once the contribution in terms of multiplying factor for each sub-phase of the life cycle is determined, the comparison between linear and each LCES is carried out as follow:

$$\Delta cost_{Linear-LCES_i} = Total\ cost_{Linear} - Total\ cost_{LCES_i}$$

Eq. 7

$$\Delta impact_{Linear-LCES_i} = Total\ impact_{Linear} - Total\ impact_{LCES_i}$$

Eq. 8

Considering the constraints imposed on the parameters, the differential cost/impact obtained from the previous formula may assume a positive or a negative value with the following meaning:

- A resulting negative Δ means that the LCES i adopted is less sustainable in terms of costs/environmental impacts than the linear one;

- A resulting positive Δ means that the LCES i adopted is more advantageous in terms of costs/environmental impacts than the linear one.

The indication provided by the methodology is both qualitative and quantitative. First of all, it aims to highlight the different impact on life cycle cost/environmental impact provided by LCES strategies with respect to the linear one. On the other hand, this methodology could

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be exploited as a theoretical basis for future precise evaluations to be carried out via the tools developed in T7.4 where the parameters and the cost contributions/environmental impacts will be substituted by calculated values and real data gathered from the field concerning specific equipment and actual industrial cases where LCES are applied. Starting from this method and taking into account its specific production system, the company can thus quantify the value of introduced parameters and the costs contributions/environmental impacts in order to carry out the economic/environmental comparison between its actual and its future production strategies.

In the following section, the detailed analyses of the single LCES phases contributions and the comparison with the linear strategy are described.

4.2.1.2 Comparison 1: Linear – Resell/Reuse

Starting from the definition of Resell-Reuse (see §272.2), the contributions are reported in Table 20 and Table 21, that is also meant to highlight the gap evaluation.

Table 20. Linear - Resell / Reuse comparison (LCC)

	Design	Production		Distr.	Use phase			EoL								
		Proc.	*Man.*		*Monit.*	*Repair*	*Cons.*	*Dis.*	*Control*	*Cleaning*	*Test*	*Replace*	*Reas.*	*Recycle*	*Reverse log.*	*Disposal*
Linear	y	y	y	y		ky	y							y		y
Resell / Reuse	1	1	1	1		ky + a	y + a		y - a	y - a	y - a			1	y ± a	1
Delta	y - 1	y - 1	y - 1	y - 1		- a	- a		a - y	a - y	a - y			y - 1	- y ∓ a	y - 1

Table 21. Linear - Resell / Reuse comparison (LCA)

	Design	Production		Distr.	Use phase			EoL								
		Proc.	*Man.*		*Monit.*	*Repair*	*Cons.*	*Dis.*	*Control*	*Cleaning*	*Test*	*Replace*	*Reas.*	*Recycle*	*Reverse log.*	*Disposal*
Linear		y	y	y		ky	y							y		y
Resell / Reuse		1	1	1		ky + a	y + a		y - a	y - a	y - a			1	y ± a	1
Delta		y - 1	y - 1	y - 1		- a	- a		a - y	a - y	a - y			y - 1	- y ∓ a	y - 1

For the Resell strategy, the Design, the Procurement, the Manufacturing and the Distribution phase is expected once in the comparison horizon, since the machinery is produced, designed and distributed only once (as already mentioned, for the LCA study the design phase is not contemplated). Following the same reasoning, also Recycle and Disposal phase contribute to the costs as 1. For what concerns the Control, Cleaning and Test phases, a parameter “a” is subtracted from “y” to indicate that to fulfill the functional unit less repetition of the processes related to these life cycles than the linear case are required even though a greater value of 1 is expected. However, longer life cycles mean older machineries: this implies that it is reasonable to suppose a greater exploitation of Repair phase and Consumption during the Use phase. For what concerns the Reverse logistic phase, it is assumed that it takes into account all the movement of the equipment needed after the first Distribution. The used machine can be fully reused by the same end user, thus the parameter could assume a value of 1, or moved within the supply chain and then returned to the OEM less times (“y - a”) or more times (“y + a”) in respect to the linear case.

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The last row in Table 20 and Table 21 represents the differential parametric contribution (addressed as “Delta”), calculated as the difference between correction factors of Linear and Resell/Reuse strategies (see Eq. 7 - Eq. 8):

$$\Delta\, cost_{\,Resell-Reuse} = (y-1)*Cp_{Design} + (y-1)*Cp_{Procurement} + (y-1)*Cp_{Manufacturing} + (y-1)*Cp_{Distribution} - a*Cp_{Repair} - a*Cp_{Consumption} + (a-y)*Cp_{Control} + (a-y)*Cp_{Cleaning} + (a-y)*Cp_{Test} + (y-1)*Cp_{Recycle} + (-y\mp a)*Cp_{Reverse\ logistic} + (y-1)*Cp_{Disposal}$$

$$\Delta\, impact_{\,Resell-Reuse} = (y-1)*Ic_{Procurement} + (y-1)*Ic_{Manufacturing} + (y-1)*Ic_{Repair} - a*Cp_{Consumption} + (a-y)*Ic_{Control} + (a-y)*Ic_{Cleaning} + (a-y)*Ic_{Test} + (y-1)*Ic_{Recycle} + (-y\mp a)*Ic_{Reverse\ logistic} + (y-1)*Ic_{Disposal}$$

The company has to further detailed the “y”, “a” and “k” values and the cost items related to each phase to find if globally the Delta is in favor of linear or circular strategy adoption.

4.2.1.3 Comparison 2: Linear - Remanufacture

The Linear – Remanufacture comparisons results are shown in Table 22 and Table 23.

Table 22. Linear - Remanufacture comparison (LCC)

	Design	Production		Distr.	Use phase			EoL								
		Proc.	*Man.*		*Monit.*	*Repair*	*Cons.*	*Dis.*	*Control*	*Cleaning*	*Test*	*Replace*	*Reas.*	*Recycle*	*Reverse log.*	*Disposal*
Linear	y	y	y	y		ky	y							y		y
Remanufacture	y - b	y - b	y - b	y - b		ky	y	y - b	y - b	y - b	y - b	y - b	y - b	y - b	y±b	y - b
Delta	b	b	b	b		0	0	b - y	b - y	b - y	b - y	b - y	b - y	b	- y∓b	b

Table 23. Linear - Remanufacture comparison (LCA)

	Design	Production		Distr.	Use phase			EoL								
		Proc.	*Man.*		*Monit.*	*Repair*	*Cons.*	*Dis.*	*Control*	*Cleaning*	*Test*	*Replace*	*Reas.*	*Recycle*	*Reverse log.*	*Disposal*
Linear		y	y	y		ky	y							y		y
Remanufacture		y - b	y - b	y - b		ky	y	y - b	y - b	y - b	y - b	y - b	y - b	y - b	y±b	y - b
Delta		b	b	b		0	0	b - y	b - y	b - y	b - y	b - y	b - y	b	- y∓b	b

Since the Remanufacture strategy implies using parts of discarded products in a new product with the same function (see §2.2), the Design phase is expected “y – b”. For the Production, Distribution and EoL phases, the variable “b” is subtracted from “y”, assuming that fewer life cycles than the linear case (i.e. less RF) are sufficient to satisfy the functional unit. With the same logic as above, the Repair phase considers the “k” factor.

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The economic and environmental gap assessment is calculated as the difference between the two strategies and can be expanded into the following formulations:

$$\Delta cost_{\ Remanufacture} = b * Cp_{Design} + b * Cp_{Procurement} + b * Cp_{Manufacturing} + b * Cp_{Distribution} + (b - y) * Cp_{Disassembly} + (b - y) * Cp_{Control} + (b - y) * Cp_{Cleaning} + (b - y) * Cp_{Replace} + (b - y) * Cp_{Test} + (b - y) * Cp_{Reassembly} + b * Cp_{Recycle} + (-y \mp b) * Cp_{Reverse\ logistic} + b * Cp_{Disposal}$$

$$\Delta impact_{\ Remanufacture} = b * Ic_{Procurement} + b * Ic_{Manufacturing} + b * Ic_{Distribution} + (b - y) * Ic_{Disassembly} + (b - y) * Ic_{Control} + (b - y) * Ic_{Cleaning} + (b - y) * Ic_{Replace} + (b - y) * Ic_{Test} + (b - y) * Ic_{Reassembly} + b * Ic_{Recycle} + (-y \mp b) * Ic_{Reverse\ logistic} + b * Ic_{Disposal}$$

4.2.1.4 Comparison 3: Linear - Recondition

The Linear - Recondition comparisons results are shown in Table 24 and Table 25Table 22.Table 23

Table 24. Linear - Recondition comparison (LCC)

	Design	Production		Distr.	Use phase			EoL								
		Proc.	*Man.*		*Monit.*	*Repair*	*Cons.*	*Dis.*	*Control*	*Cleaning*	*Test*	*Replace*	*Reas.*	*Recycle*	*Reverse log.*	*Disposal*
Linear	y	y	y	y		ky	y							y		y
Recondition	1	y - c	y - c	1		ky + c	y + c	y - c	y - c	y - c	y - c	y - c	y - c	y - c	y±c	y - c
Delta	y -1	c	c	y - 1		- c	- c	c - y	c - y	c - y	c - y	c - y	c - y	c	- y∓c	c

Table 25. Linear - Recondition comparison (LCA)

	Design	Production		Distr.	Use phase			EoL								
		Proc.	*Man.*		*Monit.*	*Repair*	*Cons.*	*Dis.*	*Control*	*Cleaning*	*Test*	*Replace*	*Reas.*	*Recycle*	*Reverse log.*	*Disposal*
Linear		y	y	y		ky	y							y		y
Recondition		y - c	y - c	1		ky + c	y + c	y - c	y - c	y - c	y - c	y - c	y - c	y - c	y±c	y - c
Delta		c	c	y - 1		- c	- c	c - y	c - y	c - y	c - y	c - y	c - y	c	- y∓c	c

The Design phase is expected once in the comparison horizon, since the machinery is designed only once (no design phase for LCA study). For what concerns the Production and EoL phases, a parameter “c” is subtracted from “y” to indicate that to fulfill the functional unit less RF is required than the linear case, while the Distribution phase weights for 1, means the machinery is entirely distributed only once during the time horizon. For Repair and Consumption in the Use phase, the variable “c” is added to the contribution on “y” means that it is assumed higher consumptions of the equipment since, according to the

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definition, the strategy does not imply a restoration to initial standard performance, but to a minor quality level that could include a lower efficiency during the use phase.

The gap assessment approach highlights that Recondition, as well as Remanufacture, is exploiting Design, Production and Distribution phases less than the linear strategy, but at the same time involves higher cost contribution for almost all Use and EoL sub-phases.

The economic and environmental gap assessment are:

$$\begin{aligned}\Delta cost_{\,Recondition} &= (y-1)*Cp_{Design} + c*Cp_{Procurement} + c*Cp_{Manufacturing} \\ &+ (y-1)*Cp_{Distribution} - c*Cp_{Repair} - c*Cp_{Consumption} \\ &+ (c-y)*Cp_{Disassembly} + (c-y)*Cp_{Control} + (c-y)*Cp_{Cleaning} \\ &+ (c-y)*Cp_{Replace} + (c-y)*Cp_{Test} + (c-y)*Cp_{Reassembly} + c*Cp_{Recycle} \\ &+ (-y \mp c)*Cp_{Reverse\ logistic} + c*Cp_{Disposal}\end{aligned}$$

$$\begin{aligned}\Delta impact_{\,Recondition} &= c*Ic_{Procurement} + c*Ic_{Manufacturing} \\ &+ (y-1)*Ic_{Distribution} - c*Ic_{Repair} - c*Ic_{Consumption} \\ &+ (c-y)*Ic_{Disassembly} + (c-y)*Ic_{Control} + (c-y)*Ic_{Cleaning} \\ &+ (c-y)*Ic_{Replace} + (c-y)*Ic_{Test} + (c-y)*Ic_{Reassembly} + c*Ic_{Recycle} \\ &+ (-y \mp c)*Ic_{Reverse\ logistic} + c*Ic_{Disposal}\end{aligned}$$

4.2.1.5 Comparison 4: Linear - Refurbish

The Linear – Refurbish comparisons results are shown in Table 26 and Table 27.

Table 26. Linear - Refurbish comparison (LCC)

	Design	Production		Distr.	Use phase			EoL								
		Proc.	*Man.*		*Monit.*	*Repair*	*Cons.*	*Dis.*	*Control*	*Cleaning*	*Test*	*Replace*	*Reas.*	*Recycle*	*Reverse log.*	*Disposal*
Linear	y	y	y	y		ky	y							y		y
Refurbish	y - d	y - d	y - d	y - d		ky - d	y - d	y - d	y - d	y - d	y - d	y - d	y - d	y - d	y±d	y - d
Delta	d	d	d	d		d	d	d - y	d - y	d - y	d - y	d - y	d - y	d	- y∓d	d

Table 27. Linear - Refurbish comparison (LCA)

	Design	Production		Distr.	Use phase			EoL								
		Proc.	*Man.*		*Monit.*	*Repair*	*Cons.*	*Dis.*	*Control*	*Cleaning*	*Test*	*Replace*	*Reas.*	*Recycle*	*Reverse log.*	*Disposal*
Linear		y	y	y		ky	y							y		y
Refurbish		y - d	y - d	y - d		ky - d	y - d	y - d	y - d	y - d	y - d	y - d	y - d	y - d	y±d	y - d
Delta		d	d	d		d	d	d - y	d - y	d - y	d - y	d - y	d - y	d	- y∓d	d

Refurbish is combined with technology upgrading, as defined in §2.2, and consequently the Design phase is expected to be repeated “y - d” times. In other words, it is assumed that sometimes, after life cycle end, some modifications, which involves a R&D phase, could be

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required. Therefore, it is assumed that, being the refurbished system a technologically superior one, the Use phase is less stressed in terms of number of repair actions and consumption during the total time horizon. For what concerns other life cycle phases, the same reasoning made for Remanufacture and Recondition strategies are valid.

The economic and environmental gap assessment are:

$$\begin{aligned}\Delta cost_{\ Refurbish} &= (y - d) * Cp_{Design} + d * Cp_{Procurement} + d * Cp_{Manufacturing} \\ &+ d * Cp_{Distribution} + d * Cp_{Consumption} + (d - y) * Cp_{Disassembly} \\ &+ (d - y) * Cp_{Control} + (d - y) * Cp_{Cleaning} + (d - y) * Cp_{Test} \\ &+ (d - y) * Cp_{Replace} + (d - y) * Cp_{Reassembly} + d * Cp_{Recycle} \\ &+ (-y \mp d) * Cp_{Reverse\ logistic} + d * Cp_{Disposal}\end{aligned}$$

$$\begin{aligned}\Delta impact_{\ Refurbish} &= d * Ic_{Procurement} + d * Ic_{Manufacturing} + d * Ic_{Distribution} \\ &+ d * Ic_{Consumption} + (d - y) * Ic_{Disassembly} + (d - y) * Ic_{Control} \\ &+ (d - y) * Ic_{Cleaning} + (d - y) * Ic_{Test} + (d - y) * Ic_{Replace} \\ &+ (d - y) * Ic_{Reassembly} + d * Ic_{Recycle} + (-y \mp d) * Ic_{Reverse\ logistic} \\ &+ d * Ic_{Disposal}\end{aligned}$$

4.2.1.6 Comparison 5: Linear - Preventive maintenance

Preventive maintenance involves extra costs during the Use phase of the machinery. The Monitoring phase, which takes place during the whole active life of the system, is carried out via IoT, thus implying costs related to sensors purchase, installation and management. All the three declinations/actuations of Preventive maintenance rely on data acquisition, even if the way data are elaborated and used in Predictive, Time-based and Condition-based is different. Thus, being irrelevant to the purpose of the analysis, the three strategies are collected into the same scheme under the Preventive maintenance strategy. Assuming to apply Preventive maintenance to the Linear approach, the main impact can be seen on the Use phase: it is supposed that constant monitoring helps in reducing the number of repair actions. Moreover, prompt actions on maintenance side lead to longer life cycles, reducing the impact of Production, Distribution and EoL phases.

The comparisons results are shown in Table 28 and Table 29.

Table 28. Linear - Preventive maintenance comparison (LCC)

	Design	Production		Distr.	Use phase			EoL								
		Proc.	*Man.*		*Monit.*	*Repair*	*Cons.*	*Dis.*	*Inspection*		*Cleaning*	*Replace*	*Reas.*	*Recycle*	*Reverse log.*	*Disposal*
									Control	*Test*						
Linear	y	y	y	y		ky	y							y		y
Preventive maint.	y - e	y - e	y - e	y - e	y	ky - e	y							y - e		y - e
Delta	e	e	e	e	- y	e	0							e		e

Table 29. Linear - Preventive maintenance comparison (LCA)

	Design	Production		Distr.	Use phase			EoL								
		Proc.	*Man.*				*Cons.*	*Dis.*	*Inspection*							

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					Monit.	Repair			Control	Test	Cleaning	Replace	Reas.	Recycle	Reverse log.	Disposal
Linear		y	y	y		ky	y							y		y
Preventive maint.		y - e	y - e	y - e	y	ky - e	y							y - e		y - e
Delta		e	e	e	- y	e	0							e		e

The economic and environmental gap assessment are:

$$\Delta cost_{\ Prev.\ maint.} = e * Cp_{Design} + e * Cp_{Procurement} + e * Cp_{Manufacturing} + e * Cp_{Distribution} - y * Cp_{Monitoring} + e * Cp_{Repair} + e * Cp_{Recycle} + e * Cp_{Disposal}$$

$$\Delta impact_{\ Prev.\ maint.} = e * Ic_{Procurement} + e * Ic_{Manufacturing} + e * Ic_{Distribution} - y * Ic_{Monitoring} + e * Ic_{Repair} + e * Ic_{Recycle} + e * Ic_{Disposal}$$

4.2.1.7 Summary of the comparisons

Table 30 shows the summary of the differential economic impacts resulting from the comparison of the linear strategy with all the LCES. The gap assessment is reported for every phase and is highlighted with different colors:

- Green color identifies phases in which the delta cost/environmental impact is in favor of LCES adoption;
- Red color means the delta cost/environmental impact in that phase is in favor of linear strategy adoption;
- Yellow color stands for delta not specified until the company applies the methodology to its specific case. Until then, the delta in that phase could assume both positive and negative values, being respectively in favor of LCES or linear strategy adoption;
- Grey color when the delta assumes 0 value, meaning that the cost/environmental impact of that phase is independent on the strategy adopted.

Table 30. Summary strategy comparisons' results for LCC

	Design	Production		Distr.	Use phase			EoL								
									Inspection							
		Proc.	*Man.*		*Monit.*	*Repair*	*Cons.*	*Dis.*	*Control*	*Test*	*Cleaning*	*Replace*	*Reas.*	*Recycle*	*Reverse log.*	*Disposal*
$\Delta F_{Lin - ResellReuse}$	y - 1	y - 1	y - 1	y-1		- a	- a		a - y	a - y	a - y			y - 1	- y∓a	y - 1
$\Delta F_{Lin - Remanuf.}$	b	b	b	b		0	0	b - y	b - y	b - y	b - y	b - y	b - y	b	- y∓b	b
$\Delta F_{Lin - Recondition}$	y -1	c	c	y-1		- c	- c	c - y	c - y	c - y	c - y	c - y	c - y	c	- y∓c	c
$\Delta F_{Lin - Refurbish}$	d	d	d	d		d	d	d - y	d - y	d - y	d - y	d - y	d - y	d	- y∓d	d
$\Delta F_{Lin - Prev.Maint.}$	e	e	e	e	- y	e	0							e		e

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Table 31 shows the summary of the differential impacts resulting from the comparison of the linear strategy with all the LCES.

Table 31. Summary strategy comparisons' results for LCA

	Design	Production		Distr.	Use phase			EoL								
		Proc.	*Man.*		*Monit.*	*Repair*	*Cons.*	*Dis.*	*Inspection*		*Cleaning*	*Replace*	*Reas.*	*Recycle*	*Reverse log.*	*Disposal*
									Control	*Test*						
$\Delta F_{Lin - ResellReuse}$		y - 1	y - 1	y-1		- a	- a		a - y	a - y	a - y			y - 1	- y∓a	y - 1
$\Delta F_{Lin - Remanuf.}$		b	b	b		0	0	b - y	b - y	b - y	b - y	b - y	b - y	b	- y∓b	b
$\Delta F_{Lin - Recondition}$		c	c	y-1		- c	- c	c - y	c - y	c - y	c - y	c - y	c - y	c	- y∓c	c
$\Delta F_{Lin - Refurbish}$		d	d	d		d	d	d - y	d - y	d - y	d - y	d - y	d - y	d	- y∓d	d
$\Delta F_{Lin - Prev.Maint.}$		e	e	e	- y	e	0							e		e

It is clear that the adoption of a LCES would imply the necessity of EoL operations needed to extent the product life cycle that are not part of the life cycle of a machine exploited with a linear strategy. This results in additional contributions in terms of environmental impacts in the EoL phases, as can be seen from where the majority of red cells are concentrated in Table 31. On the other hand, greater benefits are allowed by the adoption of LCES in the Production and Distribution phases, where presumably most of the environmental impact is focused.

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5 Strategy Implementation

This section is meant to identify the actions that, starting from a linear economy model, are needed to implement the life cycle extension approach. This work has been focalized on the LCES labelled by the pilots as most promising in the RECLAIM project (i.e. Reuse, Refurbish, Remanufacturing, Preventive Maintenance, see Table 7 and Table 32), and has been carried out with two different but complementary perspectives: the one offered by scientific literature and the one proposed by the demonstration partners extracted during the validation workshop presented in 2.2.1. This final section thus aims to put the basis to the creations of guidelines and methods to support companies in the transition towards a CE approach in the life cycle management of the equipment.

Table 32. Occurrences of strategies identified by RECLAIM pilots.

Strategy	Pilot 1 A	Pilot 1 B	Pilot 2	Pilot 3	Pilot 4	Pilot 5	# of occurrences
Design for durability/reliability							0
Design for modularity and part standardization					✓		1
Design for ease of maintenance and repair		✓					1
Design for upgradability					✓		1
Design for disassembly and reassembly							0
Design for component recovery							0
Resell-Reuse					✓		1
Repair or Corrective Maintenance	✓	✓	✓		✓		4
Preventive maintenance	✓	✓	✓	✓	✓	✓	6
Remanufacture	✓					✓	2
Recondition			✓				1
Refurbish	✓	✓	✓	✓	✓	✓	6
Cannibalization		✓					1
Recycle					✓		1
Design for modularity and part standardization							0

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5.1 Identification of the actions from literature

The identification of the actions needed to implement LCES was carried out starting from the scientific literature review. A preliminary search shows that there are not many existing studies on the topic, thus the analysis exploits the already identified papers in §2.1.3.1, considering the papers that have been classified in the "Description and Implementation Guidelines" taxonomy field.

In (Thierry et al., 1995), the product recovery strategies, the so-called LCES in this context, are described with the actions that must be implemented to extend products life cycle. The importance of LCES management to the profitability of the company depends on the ability to reduce the environmental impact of used products, the capability to recover as much economic value as possible out of the used products, the ability to use LCES as a marketing tool.

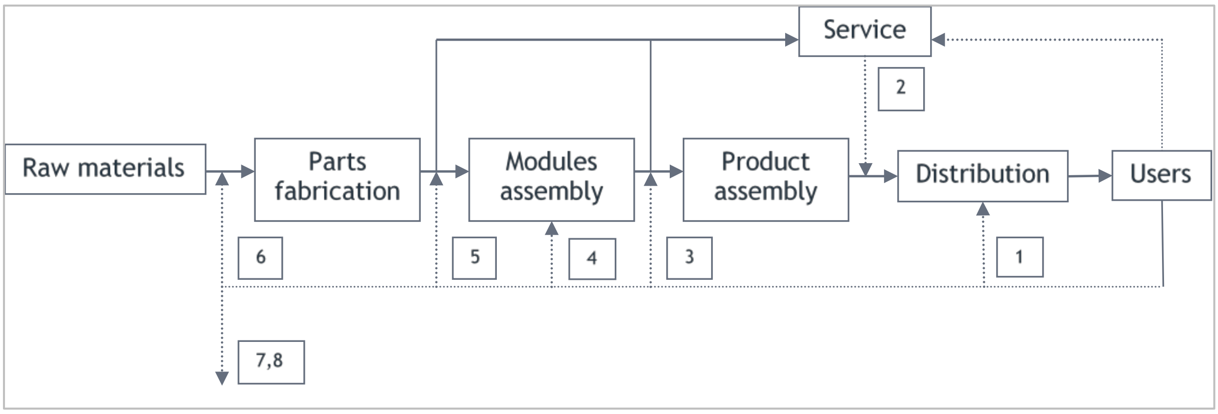

Figure 14. Integrated Supply Chain

forward flows

return flows

Figure 14 presents an integrated supply chain where service, product recovery, and waste management activities are included. Indeed, returned products and components can be:

- directly reused/resold (1);
- recovered, through repair (2), refurbishing (3), remanufacturing (4), cannibalization (5), or recycling (6) option, listed in order of the required degree of disassembly (teardown);
- disposed, through incineration (7) or landfilling (8).

Each of the product recovery options involves collection of used products and components, reprocessing, and redistribution. The main difference between the options is in reprocessing.

In the context of RECLAIM, the focus of the following analysis is set on reuse, refurbish and remanufacturing strategies that were identified from the pilot during the workshop as the most interesting LCES to be applied in their companies (see §2.2.1).

As remarked by (Thierry et al., 1995), LCES can have large influences on production, operations, and logistics management, and strategic changes may be required to deal with LCES. The changes concern the network structure as the company progressed with LCES. Companies could be forced to acquire new skills, e.g., to perform disassembly and repair operations, or to engage in new partnerships. New information systems must be established to monitor and control LCES activities. Transportation planning must take into account both forward and return flows. Warehouses must be designed to deal with two-way movements

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of products. Production control systems for remanufacturing must be able to deal with fundamental uncertainties in quantities, timing, and quality of used products. Inventory control systems must be adapted. Employees must be convinced of the significance of LCES to the company and be rewarded accordingly.

Thus, as stated by (Thierry et al., 1995), and confirmed also in following (more recent) studies by (Bressanelli et al., 2019), the ability of companies to successfully integrate LCES in existing systems depends especially on their ability to:

- Acquire information - required data are often scattered throughout the company or the business chain, or are not available at all. Nevertheless, companies have to be able to acquire essential information by collaborating with suppliers and waste management companies to implement successfully LCES. Basic information requirements deal with product characteristics, supply of used products, demand for reprocessed products, and the matching of demand and supply. Acquisition and processing of this information often require the development of new (company-wide or even business-wide) information systems;

- Redesign products and processes, if necessary;

- Cooperate with other companies - more cooperation for manufacturers with other organizations companies (including suppliers, and waste management for instance) in the business chain. Interesting cooperation opportunities arise in the areas of exchange of information, involvement in product redesign, and between companies that operate in the same market.

- Accurately predict and control supply of used products;

- Generate demand for reprocessed products;

- Control the LCES "production" process, e.g., ensure that remanufactured products are indeed as good as new.

In (Linton & Jayaraman, 2005), the LCES are examined from the perspective of the nature of complicating characteristics they introduce in the management of a company (see Figure 15), and the associated functional implications.

	Uncertain timing	Balance demand and supply	Need to disassemble returns	Uncertainty in materials recovered	Need for reverse logistics network	Material matching requirements	Stochastic routings for material repair and remanufacture
Recall	Moderate	NA	Moderate	Low	Yes	High	NA
Repair	Moderate	NA	Moderate	High	No	High	High
Preventative maintenance	Low	NA	Moderate	Low	No	High	Low
Predictive maintenance	Low	NA	Moderate	Low	No	High	Low
Upgrade	Moderate	NA	Moderate	Low	Yes/no	NA	Low
Product reuse	Low	High	None	Low	Yes/no	NA	NA
Remanufacture	High	High	High	High	Yes	High	High
Part reuse	High	High	High	High	Yes	Low	High
Recycle	High	Moderate	Low	Low	Yes	NA	NA

Figure 15. Complicating characteristics

The complicating characteristics (first row of **Errore. L'origine riferimento non è stata trovata.**) are a series of characteristics that are peculiar of the application of product LCES: they are additional issues to be taken into account, and different LCES are affected to different extents, which are investigate and described, by the complicating characteristics.

In general terms, it can be said that transformation ranges from none (in reuse) to complete (in recycling). The value added associated with the material is typically low. Exceptions to this are parts reuse and recycling in which the value is inherent in the material for both and the specific form in the case of parts reuse. Labor value added is low in the case of all modes

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of life extension, except remanufacturing. Consequently, remanufacturing is the mode where labor costs are likely to be of major importance. Information value added is high in recalls, repairs, preventative maintenance, predictive maintenance and upgrade. The involvement in these modes is very attractive for a firm if it is able to extract the value associated with the information.

Considering for instance product reuse strategy, critical issues are the policy for the acquisition, management and control of inventory to balance demand and supply, and the decisions to be made on the need and eventually on the nature of the reverse logistic network. On the other hand, the implementation of remanufacture strategy implies more complicating factors to be considered, which are mainly because remanufacture has the higher labor value added among the considered LCES. Indeed, the uncertain nature of the use and durability of a product requires firms to be able to design systems to manage the control of returns: failure to design the management of uncertainty into policies will result in at best poor operation of production planning and control. Another challenge for production planning and control is the need to know the degree and method of disassembly prior to the arrival of a product. Remanufacture has a high uncertainty in subassemblies, parts and materials recovered. Consequently, inventory, and purchasing systems must be managed differently from traditional materials planning approaches to accommodate for this complicating characteristic.

	Focus	Logistics	Production planning and control	Forecasting	Purchasing	Inventory control and management
Recall	Safety and extend life	Reverse flows, uncertainty in timing and quantity, supply driven flow	Certain	Supply	Uncertainty in purchasing of parts	Must take into account all parts new and used for a specific customer
Repair	Life extension	Forward/reverse flows, uncertainty in timing and quantity, supply driven flow	Stochastic routing and processing	Supply	Uncertainty in purchasing of parts	Must take into account all parts new and used for a specific customer
Preventative maintenance	Continuous use	Certain flow	Certain, more stable	Planned	Certain	Track and account for parts
Predictive maintenance	Life extension	More uncertainty than preventative maintenance, less than repair, supply driven flow	Stochastic routing and processing	Supply	Some certainty in purchasing of parts	Track and account for parts and time window for repair
Upgrade	Reduce cost and extend life	Reverse flows—sometimes, uncertainty in timing	Certainty in materials, fixed routing	Demand uncertainty	MRP	Must track and account for all parts. Product must be returned to the same customer
Product reuse	Life extension	Transfer from old user to new user	Routing, balance demand and return	Supply and demand uncertainty	Locating product at the best price	Track and account for all product

Figure 16. Functional implications - first part

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	Focus	Logistics	Production planning and control	Forecasting	Purchasing	Inventory control and management
Remanufacture	Life extension	Forward and reverse flows, uncertainty in timing and quantity, supply/demand driven flow	Balance demand and return, recovery uncertainty, stochastic routing and processing; disassemble, remanufacture and assemble	Supply and demand uncertainty	Old product and new parts	Must track and account for all parts—new, used and remanufactured
Part reuse	Reduction of materials and processing inputs	Forward and reverse flows, uncertainty in timing and quantity, supply driven flow	Recovery uncertainty, balance supply and demand, stochastic routing and processing; disassemble and test	Supply and demand uncertainty	Uncertain recovery	Track and account for all parts—new and used
Recycle	Reduce material and energy inputs	Reverse flows, supply driven flows, uncertainty in timing and quantity	Disassemble and sort, balance demand and return	Supply and demand issues	Spot market	JIT on spot market or inventory issues

Figure 17. Functional implications - second part

Having identified the factors that are unique to product life extension modes, the impact of complicating characteristics on the different functional areas of the firm are considered, which are focus, forecasting, purchasing, inventory control and management, production control and management, and logistics (see first row of Figure 16 and Figure 17). Considering logistic issues, in conventional manufacturing, logistics consider forward flows along the supply chain. These forward flows are demand driven based on the relation between demand forecasting, inventory and production policies. Product life extension modes are different due to uncertainty associated with not only the condition of the product and its components, but also the uncertainty of timing and quantity associated with the availability of these products. Reverse flows, for collection of goods from the field, are often required resulting in a logistics system that is supply driven in nature. The design, development and maintenance of a reverse flow network are considered by many to be the most obvious novel requirement of product life extension modes. Considering for instance product reuse, main functional implications concern the logistic and inventory & control management areas for transferring product between old and new user, while the uncertainty and the need of a balance between demand and supply have an impact on production planning & control and on forecasting areas.

In the following sections the discussion is focalized in the most promising LCES identified by the RECALIM pilots.

5.1.1 Reuse

(Reike et al., 2018) provides the consumer perspective on reuse/resell strategies. From consumer side, reuse implies buying second hand, and resell implies finding a buyer for a product that was not or hardly in use, possibly after some cleaning or minor adaptations for quality restoration by the consumer. In this context, online consumer-to-consumer actions for used products are increasingly important, like e-bay and national equivalents (Worrell and Reuter, 2014). Such ‘direct reuse’ (Agrawal et al., 2015; Loomba and Nakashima, 2012) can also take place as an economic activity via collectors and retailers. Literature suggests that quality inspections, cleaning and small repairs are common here (García-Rodríguez et al., 2013; Hazen et al., 2012; Stahel 2010).

However, it can be generally said that reuse/resell strategy implies little reprocessing to be implemented, but it is mainly around collection and redistribution. According to (Thierry et al., 1995) reverse logistics system incorporates a supply chain that has been redesigned to manage the flow of products or parts destined for reuse, and to use resources efficiently.

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The study presents some aspects to consider when dealing with the reverse distribution issues. Those are:

- Who will perform the reverse distribution, (original actors such as manufacturers, retailers etc. or secondary units)? This distinction puts crucial constraints to the very important issue of so-called, integration of forward and reverse distribution.

- Which functions to perform and where. Some related functions are collecting, testing, sorting and transporting. The location of performing these functions is also important. For example, early testing saves useless transportation, sorting requires the used parts to be sent to the relevant manufacturing area.

- The degree of integration of the forward and reverse distribution channel. This leads to a closed-loop transportation system. The difficulty here is not only managing two flows as opposed to one flow in traditional systems, but also managing two different, even contradicting flows together. Since, reverse distribution is not symmetric with the forward distribution.

(Bressanelli et al., 2019) involves the description of the supply chain management challenges:

- Transportation and infrastructure: due to the installed base geographical dispersion, CE drastically increases transportation activities and costs, since all the products have to be sent back to producers or specialized sites for refurbishing, remanufacturing, etc. In many CE schemes, products at end-of-use have to be collected from utilization places and sent back to specialized sites for renovation; then they are sent to where a new utilization cycle can take place. Thus, when a supply chain is redesigned for CE, transportation costs and the related environmental impacts increase (Bakker et al. 2014). For instance, Krikke (2011) describes a case where, following the implementation of a closed-loop supply chain in a printing company, the amount of transportation has tripled over ten years.

- Availability of suitable supply chain partners: companies which decide to move towards CE often experience difficulty in finding appropriate supply chain partners, with appropriate skills and a CE approach. The availability of suitable supply chain partners is another challenge widely recognized in the literature (Rauer and Kaufmann 2015). Companies which decide to move towards CE may not have access to partners with appropriate skills and the same CE commitment (Walker, Di Sisto, and McBain 2008). Coordination and information sharing CE requires a close collaboration and information exchange among the different tiers of the supply chain, which may not be achieved especially within global configurations. This can be due to several reasons such as competition among supply chain tiers, information sensitivity, IT system integration, poor planning of activities, etcetera. Even when companies can count on a set of suitable partners, coordination and information sharing is difficult to achieve (Govindan et al. 2014), especially because of competition among supply chain tiers, information sensitivity, poor IT system integration or planning of activities.

- Cultural issues (linear mind-set): internal resistance to change, especially given the prevailing linear mind-set and structures in industries (also referred to as the ‘Linear lock-in’), limited awareness and commitment (from both top management and employees).

- Internal resistance to change as well as limited awareness and commitment from both top management and employees (cultural issues) frequently prevent or make more difficult and troublesome the redesign of supply chain for CE (Wang et al. 2016).

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Even though this challenge may be caused by change as such (e.g. human inertia towards change), it is assumed that ad-hoc actions should be carried out to contrast with these cultural issues in CE contexts, so we consider this as a specific challenge of CE.

In summary, from the literature review of reuse strategy implementation what comes out is the fundamental importance of reverse logistic networks management challenges.

5.1.2 Refurbish

Restoring an old product and bringing it up to date, in order to maintain reliability or extend service life, required some implementation actions. Some observations and proposals retrieved form literature are presented below.

(Muztoba Ahmad Khan et al., 2018) provides a comprehensive overview of product upgradability. Decisions regarding upgrade planning involve trade-offs between product performance, operation and new component costs (Chung et al., 2010, 2017). After developing an appropriate upgrade plan, upgradable product design process is initiated: the process facilitates the designer in implementing Design for Upgradability (DfU) according to the upgrade plan (Aziz et al., 2016a). Goal of upgrade design is to maximize the ability of a product to adapt its functions according to changing consumer needs while maintaining minimal structural changes after the product is manufactured (Umeda et al., 2005b). Chierici and Copani (2016) mentioned modularity, standardization, compatibility and interoperability as key upgrade-enabling design features that are needed to design a robust upgradable product. The next step is to select the best upgradable product design based on different modeling and optimization tools.

Due to novelty, complexity and associated risks, upgradability feature changes the structure of the value proposition of a standard product (Pialot et al., 2017). Consequently, manufacturers need to rethink consumer relationships, key partners, channels, and revenue streams so that they are aligned with the new structure of value proposition. Additionally, compared to traditional supply chains, upgradability-oriented business models may require the key partners to exchange information and materials more intensively in the form of collaborative networks (Chierici and Copani, 2016).

The ability to upgrade a system during its future use phase by incorporating services and technologies that might not yet available, will provide additional value for the stakeholders throughout the extended lifecycle (Linton and Jayaraman, 2005). Upgrades can be introduced by several means that may lead to successive functional improvements. For example, upgrading the product by adding or exchanging modules, upgrading the service by adding new service element in the primary offering, or upgrading both product and associated services simultaneously.

Refurbish can involve the offer of additional services related to the product, thus promoting the passage to a Product Service Systems (PSS). Indeed, even if it is not easy to introduce new services that will add additional value to the existing system, the integration of multiple cycle upgrades, i.e. the “upgradability services” could be an opportunity for PSS providers to switch to offers with more services and thus facilitating the dissemination of PSS (Pialot and Millet, 2014). Moreover, the type of “service upgrades” (Pialot et al., 2017; Pialot and Millet, 2016) that can be offered based on software and exploitation of transmitted data from various sensors in the PSS may result in a whole range of potential new functionalities and a bundle of services. These services will require very little technological/ material changes to generate value and could be easily repeated by means of firmware upgrades. This in turn will allow PSS providers to discover new and repeatable ways of earning revenue via new modes of contracts.

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An upgradable system needs to be regulated by continuous interaction between the involved stakeholders, mainly the consumer and the manufacturer (Pialot and Millet, 2016). For instance, the Tata Motors case reported that customers are provided with reconditioned aggregates from manufacturer in exchange for old aggregates subject to simple acceptance norms[14].

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

- The importance of the design phase;
- The importance of the revision of the business model;
- The possibility to introduce new services;
- The possible need of technological and/or material changes to be taken into account.

5.1.3 Remanufacturing

(Zwolinski et al., 2006; Zwolinski & Brissaud, 2008) present a methodology that, starting from the definition of remanufacturable product profiles, is meant to guide the design and the re-design of products in order to assure a higher level of reuse at their end of life stage. (Zwolinski & Brissaud, 2008) has extracted the factors affecting the success of a remanufacturing operation from a wide range of products that have been successfully remanufactured. Encapsulated in 11 'remanufacturable product profiles', this knowledge is the core element of the design methodology developed and supported by the implemented software REPRO2. Among these factors, it is possible to highlight the following classification:

- Economic aspects – the profitability of the remanufacturable product; the level of the added value kept on products at their end-of-life; the savings achieved concerning the consumption of energy and raw materials.
- Technological aspects - the influence of new technologies on lifecycle and consequently on product definition during design phase.
- Market aspects – evaluation of consumers' interest orientation (on the service or on the acquirement of the product).
- Environmental aspects – evaluation of environmental profit, taking into account used resources and wastes generated all along the lifecycle of the product.

(Zwolinski et al., 2006) instead proposes an approach for the designers to integrate remanufacturing constraints throughout the design process, mainly in the earliest phases. The methodology assists designers in two steps: they are first helped in improving the reliability of a remanufacturing end-of-life strategy for that product on the bases of the analysis of the project context; then they are guided towards a product whose properties are adapted to remanufacturing.

WBCSD[15], the global and CEO-led organization of over 200 leading businesses working together to accelerate the transition to a sustainable world, proposes Circular Economy Practitioner Guide that cites remanufacturing as the process of recovering, disassembling, repairing and sanitizing components for resale at "new product" performance, quality and

[14] https://www.ceguide.org/Strategies-and-examples/Make/Refurbishing
[15] https://www.wbcsd.org/Overview/About-us

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specifications. It specifically states that remanufactured products or parts should be considered “like new”, as the typical process of remanufacturing is thorough to ensure “like new” quality[16]:

- Collection
- Identification and inspection
- Disassembly
- Reconditioning and replacement (when needed)
- Reassembly
- Quality assurance and testing

Considering a practical use case, Canon intends to apply this logic to its devices. Since 1992, Canon has been remanufacturing devices with more than one function. Its corporate ethos to optimize resource efficiency continues to shape Canon’s business strategy today. It uses cascading systems-thinking to capture resource value, and to prioritize product remanufacturing, component reuse and recycling. Canon also offers remanufactured multifunction devices as well as refurbished products. The company maximizes value from its manufactured capital by collecting used equipment from the market, remanufacturing it and re-selling it with the same high-quality guarantee as original products. In reusing at least 80% of the materials, Canon also reduces product greenhouse gas emissions associated with raw materials, parts and manufacturing by more than 80% compared to a newly manufactured product. By capturing the components and materials directly, Canon offers customers a high-quality product with and environmental impacts at a competitive price.

Once again, (Morseletto, 2020) gives some information about implementation of remanufacturing: used products are completely disassembled to the parts level and all parts are extensively tested. Worn-out or outdated parts are replaced with the new ones. Repairable parts are extensively tested. Approved parts are sub-assembled to the module level, and approved modules are sub-assembled to product.

(Muztoba Ahmad Khan et al., 2018), instead, described remanufacturing as an industrial process that transforms products that reached their EOL to a like-new functional state, or at least to current specifications while recuperating value from those products in mass production levels. It states that this is done by reprocessing, rebuilding, or replacing components parts, without deforming them to their material or chemical form. During this process, the retired products pass through a series of operations such as disassembly of the product into cores, cleaning of all parts, inspection and sorting of cores, reconditioning or repair of cores, and product reassembly (Kerr and Ryan, 2001) in order to ensure that they reach the desired state. Current trends of fast developing technology cycles, presence of product variety due to customization, changes in fashion trends and marketing may limit the effectiveness and expected benefits of remanufactured products. This is due to the rapid improvements in product design and changes in consumer requirements that often lead to higher consumer expectation in terms of product's functionality and quality. Thus, it becomes difficult for a remanufactured product, which has been rebuilt just as it was, to attract consumers in the market environment (Xing et al., 2006, 2007). Another issue that complicates the operation of the remanufacturing process is the reverse supply chain, which is required to retrieve EOL products from the end users. This is because, in a traditional setting, the remanufacturers lack information regarding the condition, quantity and timing of the returns, which is essential for an efficient remanufacturing process (Van Nunen and

[16] https://www.ceguide.org/Strategies-and-examples

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Zuidwijk, 2004; Guide, 2000). Another major challenge for remanufactured products is to target high-value consumers, who are primarily interested in state-of-the art products, in addition to pursuing only less demanding consumers such as the ones in the second-hand markets, who prefer convenient prices over new and improved functionalities (Kissling et al., 2012).

A possible solution to these issues relies on:

- a culture renovation and deeper knowledge from the consumer side not only on the economic benefit of effectively prolonging product's service life, but also on environmental performances;
- a clearer understanding of technological standard

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

- The importance of the economic, technological and environmental aspects of the remanufacturable product;
- The importance of integrate remanufacturing constraints throughout the design process;
- The importance to attract consumers in the market environment, not only less demanding consumer such as the ones in the second-hand markets, but also high-value consumers.

5.1.4 Predictive maintenance

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

(Mulders & Haarman, 2017) compares the maturity level of predictive maintenance 4.0 (PdM 4.0) and another type of inspection and presents a list of implementation actions. It also provides a framework for the step-by-step implementation of technical components in the PdM 4.0 model, in a manner that supports business strategy. The approach covers the technical infrastructure (data analytics platform, IoT infrastructure) needed to sustain PdM 4.0 and it is focused on two aspects: building skills and capabilities needed for PdM 4.0 and building a digital culture. The framework identifies four levels of maturity in predictive maintenance, with the related actions to be adopted:

- **Level 1** – visual inspections, to select the best time to shut down a piece of equipment so repairs can be carried out;
- **Level 2** and **Level 3** – instrument inspections and real-time condition monitoring, to provide more specific and objective information about the condition of the asset in question and send alert based on pre-established rules;
- **Level 4** - big data analytics starts, to drive decision-making where the digital revolution meets maintenance.

Another aspect to be addressed in the approach is the digital culture: culture that embraces new, cross-functional ways of working, which allows companies to capitalize on the power

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of digital technologies. Companies with a robust digital culture possess the confidence and ambition to become increasingly data-driven in their decision-making.

(Ghoreishi & Happonen, 2020) focuses on how digitalization affects lifetime extension; in particular, utilizing digital technologies such as AI, IoT or Blockchain enhances the ways in developing and improving transparency and traceability throughout the product lifetime. Digitalization provides precise information such as location and availability of the products to help closing the material loops which facilitates companies in the transition towards a more circular sustainable model. New Industry 4.0 based technologies are enablers that will pave the way in integrating CE principles through tracking products post-consumption and recovering components (see Figure 18).

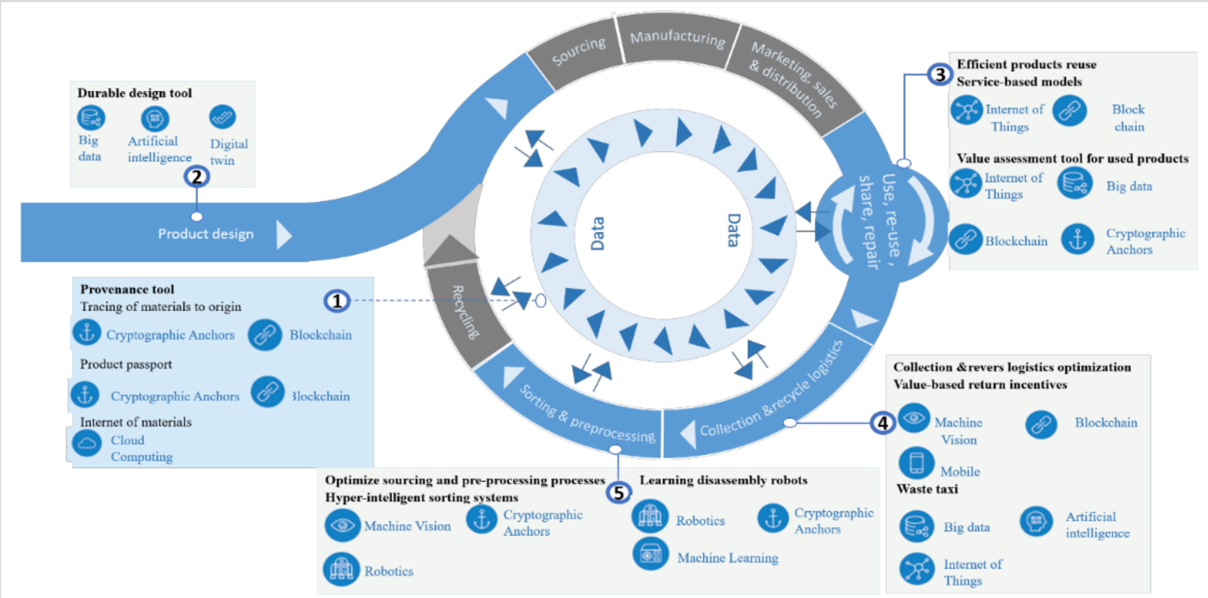

Figure 18. 4IR solutions for circularity

(Ghoreishi & Happonen, 2020) provides a roadmap towards an Industry 4.0-based CE business (see Figure 19) to provide a framework that gives basic guidance for companies that want to implement this strategy. The first step for organisations is to decide which business models are suitable to their production processes and purpose. The second step would be the identification of the Industry 4.0 technologies and resources that are viable for them, considering factors such as availability, costs and technical constraints. The third step for organisations would be the adaptation of sustainable operations management (SOM) decisions for the design, process, and logistics of products. The fourth step for organisations would be the development of integration between tiers in supply chains in order to connect technologies and resources and share information pertaining to demand, supply, deliveries, and customers' behaviour in real time. Finally, the fifth step for organisations would be the creation of indicators of performance in order to measure progress towards the CE. Predictive maintenance is one of the fundamental instruments that made the industry evolve into this new era.

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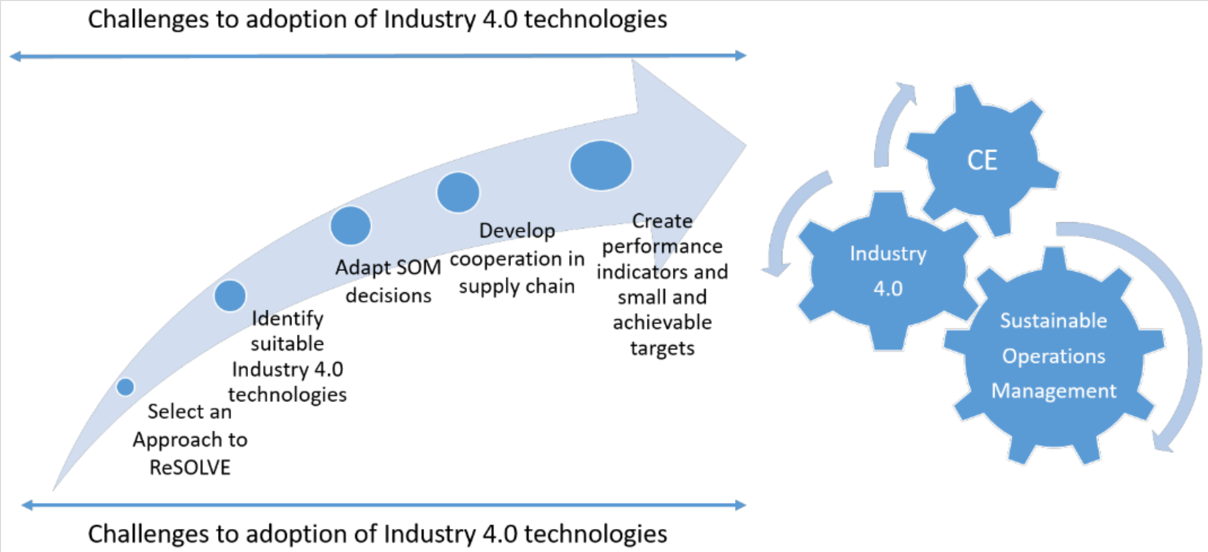

Figure 19. Roadmap towards Industry 4.0 and CE

The main challenges are the following: coordinating actions across different organisational areas; concerns about cybersecurity; lack of necessary talent; reliability of connectivity between machines, integrity of maintenance-related data, and/or available information. Moreover, organisations may face additional difficulties in following the proposed roadmap due to a lack of trust when integrating IT systems between supply chain partners and a lack of technical and technological knowledge of CE cycles and Industry 4.0 approaches (Jabbour et al., 2018).

(Hoffmann et al., 2020) provides a review of the current state-of-the-art of all aspects of condition monitoring for medium voltage switchgear as case study and presents an approach to develop a predictive maintenance system based on novel sensors and machine learning. Other alternatives to machine learning approach are *expert systems,* and *simulation-based systems,* however the cost of knowledge acquisition for both the cases can be quite high. The objective of predictive maintenance system integration is to minimize downtime while maximizing the lifespan of the equipment. The key to establishing predictive maintenance in the energy grid is the availability and analysis of appropriate data, enabled by the different sensors and monitoring techniques. These sensors data can then be used to make predictions about the health state of the system, or how much productive time is left until a failure occurs (RUL – remaining useful lifetime). This information can then be used to schedule maintenance in advance of the predicted failure. Practically, with predictive maintenance, the quality of the supply grid may be improved. At the same time, repair costs can be minimized, failures can be reduced, and the longevity of essential components can be extended —assuming that sufficient amounts of data are at hand and algorithms identify data patterns that precede incidents with sufficient predictive accuracy. In the specific case study, switchgear and other parts of the supply grid might be enabled to provide detailed condition data to an information system that predicts the failure of the component, avoiding unplanned downtimes, and results in a more effective usage of resources.

A fundamental implication of maintenance – it is valid for predictive maintenance, as well as for corrective one - is the implementation of repair actions. According to (Reike et al., 2018), repair operations can be performed by the customer or by third parts, at the customer's location, and through a repair company. More recently, peer-to-peer non-commercial repair workshops have become a trend (Ecoinnovators, 2015; Hultman and Corvellec, 2012). Businesses may send recollected products to their own repair centers, to manufacturer controlled (Thierry et al., 1995), or to third party repair centers (Sherwood et al., 2000).

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

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

5.2 Actions identified by pilots

As mentioned in §2.2.1, the goal of Objective 3 was to identify the action needed within the pilots to activate extension strategies. In fact, the work was structured to identify the necessary actions throughout the life cycle of the product, by maintaining two possible visions: the one of the user of the machinery (which corresponds to most of the pilots) and the one of the OEM.

Even in the case of users, the pilots had the option of using OEM post-its to signal the need to introduce greater interaction with the OEM. Figure 20**Errore. L'origine riferimento non è stata trovata.** provides an example of the board completed -it was possible to introduce as many "lines" as there were strategies selected by the pilots for the study.

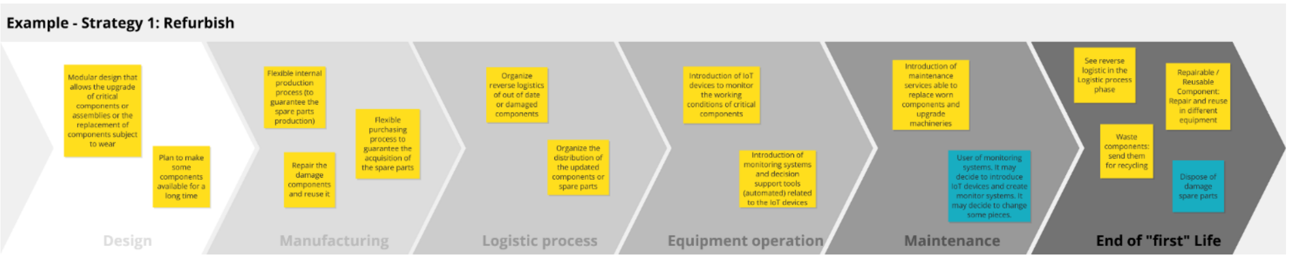

Figure 20. Example of activity implementation in Conceptboard

To carry out this activity, before the workshop a practical example applied to the refurbish strategy were shared with each pilot (see Figure 20). In particular, the example detailed the activities to be performed to implement the refurbish strategy:

- Design:
    - Modular design that allows the upgrade of critical components or assemblies or the replacement of components subject to wear;
    - Plan to make some components available for a long time.
- Manufacturing:
    - Flexible internal production process (to guarantee the spare parts production);
    - Flexible purchasing process to guarantee the acquisition of the spare parts;
    - Repair the damaged components and reuse them.
- Logistic process:

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

The results of the activity, i.e. the proposed actions to implement LCESs, are reported in the following tables (from Table 33 to Table 38), divided for each pilot.

Table 33. Identified actions by Pilot 1 A - GORENJE

Pilot 1 - GORENJE 1 A	
LCES	**Actions**
Time-based maintenance	Design: • Design of equipment follow customer demands for time based maintenance (sensor integration, modular design, easy to use and maintenance of machinery,…) Manufacturing: • Installation of sensors to monitor the process and operating of equipment • Modular assembling of components for later possible easy maintenance (standard parts if possible) Logistic: • Availability of short time deliverable spare parts • Low cost and safe logistic of machinery Equipment operation: • Monitoring of data for critical components

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	• Monitoring of process parameters and other working data friendly for end user • No manual data input, automatic support of data needed Maintenance • Maintenance Dep. carries out the planned interventions • Able to replace of worn components or parts of equipment • To predict failures of critical components • OEM Service carries out the planned interventions End of “first” Life: • Repair and reuse of components, parts of machinery
Predictive maintenance (preventive)	Design: • Design of equipment follows customer demands for time based maintenance (sensor integration, modular design, easy to use and maintenance of machinery,…) Manufacturing: • Installation of sensors to monitor the process and operating of equipment, algorithms or SW if needed • Modular assembling of components for later possible easy maintenance (standard parts if possible) Logistic: • Availability of short time deliverable spare parts • Low cost and safe logistic of machinery Equipment operation: • Monitoring of data for critical components, data processing, give signal for further actions • Monitoring of process parameters and other working data friendly for end user • No manual data input, automatic support of data needed, automatic information to responsible people. Maintenance • Maintenance Dep. carries out the interventions that come out from DSF • OEM Services carry out the interventions that come out from DSF • Able to replace of worn components or parts of equipment before failure End of “first” Life: • Repair and reuse of components, parts of machinery
Repair or Corrective maintenance	Design: • Design of equipment follow customer demands for time based maintenance (sensor integration, modular design, easy to use and maintenance of machinery,…) Manufacturing: • Modular assembling of components for later possible easy maintenance (standard parts if possible) Logistic: • Availability of short time deliverable spare parts • Low cost and safe logistic of machinery Equipment operation:

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	• Monitoring of failures, failed part or component is important Maintenance • Maintenance Dep. carries out the interventions as soon as possible • OEM Services carry out the interventions as soon as possible End of "first" Life: • Repair and reuse of components, parts of machinery
Refurbish	Design: • Design of equipment follows customer demands for refurbishment (sensor integration, modular design, ease to change of components and machineries) Manufacturing: • Modular assembling of components for later possible easy refurbishment (standard parts if possible) Logistic: • Low cost and safe logistic of parts and machinery for refurbishment Equipment operation: • Monitoring of important parameters for recognizing of worn out components or machines, robots, etc. in lifetime. Maintenance • Repairing the equipment in planned services is very cost efficient • OEM service for refurbishment of the equipment End of "first" Life: • Repair and reuse of components, parts of machinery
Remanufacture	Design: • Design of equipment follows customer demands for remanufacture (modular design, ease to change of components and machineries) Manufacturing: • Modular assembling of components for later possible easy remanufacture (standard parts if possible) Logistic: • Low cost and safe logistic of parts and machinery for remanufacturing Equipment operation: • Monitoring of important parameters for recognizing of worn out components or machines, robots, etc. in lifetime Maintenance • Repairing the equipment in planned services is very cost efficient • OEM service for remanufacturing the equipment End of "first" Life: • Repair and reuse of components, parts of machinery
Preventive maintenance	Design: • Design of equipment follows customer demands for preventive maintenance (ease to change of components and machineries) Manufacturing: • Modular assembling of components for later possible easy preventive maintenance (standard parts if possible) Logistic: • Low cost and safe logistic of parts and machinery for preventive maintenance Equipment operation:

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	• Very good plan for preventive maintenance • Automatic warning system for preventive maintenance Maintenance • Maintenance Dep. carries out the preventive maintenance services according to yearly plan End of "first" Life: • Remanufacturing of components, parts of machinery if possible

Table 34. Identified actions by Pilot 1 B - GORENJE

Pilot 1 - GORENJE 1 B	
LCES	**Actions**
Refurbish	Design: • Definition of parts that must be exchanged. Technical conditions of refurbished machine • Design and offer for refurbishment of machine Manufacturing: • Manufacturing of hanging arms and hangers • Manufacturing of parts needed for refurbishment Logistic: • Transport of parts for refurbishment Equipment operation: • Add sensors • Upgrade the machine • Update the software Maintenance • Time based predictive maintenance, predictive maintenance, repair, corrective maintenance End of "first" Life: • Refurbishment of components, parts of machine if possible
Preventive maintenance	Design: • Design of equipment follows customer demands for preventive maintenance (ease to change of components and machineries) Manufacturing: • Modular assembling of components for later possible easy preventive maintenance Logistic: • Available spare parts with short time delivery for quick repairs Equipment operation: • Automatic warning system for preventive maintenance Maintenance • Very good plan for preventive maintenance • Maintenance Dep. carries out the preventive maintenance services according to yearly plan End of "first" Life: • Remanufacturing of components, parts of machinery if possible
Repair or Corrective maintenance	Design: • Design of equipment follows customer's demands (quick exchange of parts)

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	Manufacturing: • Modular assembling of components for later possible easy maintenance Logistic: • Available spare parts with short time delivery for quick repairs Equipment operation: • Monitoring of failures Maintenance • Repair actions made as soon as possible End of "first" Life: • Repair and reuse of components, if possible

Table 35. Identified actions by Pilot 2 - FLUCHOS

Pilot 2 - FLUCHOS	
LCES	Actions
Predictive maintenance	Design: • Provide accurate information about components (CAD models if possible) • Manufacturer to take into account the needs of our production • Re-design elements based on data and experience Manufacturing: • Manufacturer to take into account the needs of our production Equipment operation: • Put sensors to measure several parameters • Train workers to understand the data thrown up by the machines • Increased operator knowledge of the machine's condition Maintenance: • Cleaning Inspection • Assembly and disassembly • Improved knowledge of the exact status of the machines • Visualize the data coming out of the project to make the best possible decision about the machine • Train workers to understand the data thrown up by the machines

Table 36. Identified actions by Pilot 3 - PODIUM

Pilot 3 - PODIUM	
LCES	Actions
Refurbish	Equipment operation: • To identify main issues on the equipment • Implementation of sensor • Upgrade some components • Change some components Maintenance • Define a maintenance schedule • Analysis of data from sensor • Define control and monitoring management plan End of "first" Life: • End of life removed components management

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Predictive maintenance	Equipment operation: • Define a mathematical model • Identify and collect main data • Test and control the mathematical model • Software/tool to collect and analyse data • Implementation of sensors Maintenance • Analyse results and identify some strategical actions • Define a schedule about predictive maintenance End of "first" Life: • End of life removed components management
Time-based maintenance	Equipment operation: • Define the time frame through historical data • Identify the components to manage • Test and control the time frame • Software/tool to collect and analyse data (e.g. sensor) • Change/upgrade components Maintenance • Analyse results and identify some strategical actions • Define a schedule about maintenance • Ensure the best "time frame" by analysing historical data End of "first" Life: • End of life removed components management
Condition-based maintenance	Equipment operation: • Define the condition • Test and control the strategies • Identify the components to manage • Change/upgrade components • Software/tool to collect and analyse data (e.g. sensor) Maintenance • Ensure the best "condition" by analysing historical data • Define a schedule about maintenance • Analyse results and identify some strategical actions End of "first" Life: • End of life removed components management
Preventive maintenance	Equipment operation: • Collect process, machineries and components data • Analyse data to identify preventive actions • Implementation of tool/software to collect data Maintenance • Implementation of preventive actions • Define a schedule about maintenance • Analyse results of software/tool to ensure the best preventive maintenance strategy • Control and monitor management plan End of "first" Life: • End of life removed components management

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Table 37. Identified actions by Pilot 4 - Harms & Wende

Pilot 4 - Harms & Wende	
LCES	**Actions**
Resell / Reuse	Design: • Implement condition monitoring capabilities in order to easily diagnose which of components must be replaced for refurbishment
Repair or Corrective maintenance	Design: • Modular design for easy repair Equipment operation: • Detect production failure Maintenance: • Identify damaged components and repair them on user request
Preventive maintenance (predictive, condition-based, time-based)	Design: • Implement condition monitoring capabilities in order to have possibility of condition based maintenance (with remote condition diagnosis possibilities) Equipment operation: • Monitor equipment condition and plan and organize maintenance operations (condition-based maintenance) • Monitor predictions of equipment condition and plan and organize maintenance operations based on prediction schedule (predictive maintenance) • Plan and monitor repair times of time-based worn components (time-based maintenance) Maintenance: • Perform maintenance on user request
Refurbish	Design: • Modular design for easy repair End of “Life” cycle: • Sell • Buy old equipment and refurbish
Design for modularity and part standardization	Design: • Implement modularity and standards

Table 38. Identified actions by Pilot 5 - ZORLUTEKS

Pilot 5 - ZORLUTEKS	
LCES	**Actions**
Predictive maintenance	Equipment operation: • Introduce new sensors • Store historical data Maintenance • Critical parts identification and use of predictive maintenance for these parts mainly • Forecasting algorithms End of “first” Life: • Recycling/repair of discharged parts
Preventive maintenance	Equipment operation: • Introduce new sensors • Analyse equipment effectiveness

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	• Store historical failure rate Maintenance • Set priorities for the different parts of the machine to implement preventive maintenance • Forecasting algorithms End of "first" Life: • Recycling/repair of discharged parts
Refurbish / Remanufacture	Equipment operation: • Implement cameras in bleaching machine to monitor whiteness degree • Store historical data Maintenance • Build A Data Set For Machine Learning (training data) • Forecasting algorithms

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6 Conclusion

D4.1 on Circular Economy-driven lifetime-extension strategies has the aim to identify effective strategies to pursue Circular Economy-driven machine lifetime extension and to provide indications, methodologies and tools to enable their actual implementation into the RECLAIM project and, more in general, to the production and commercialization of production equipment.

As one of the main results of this study, first, it was observed that the topic of CE is very wide and diverse, with a high number of research directions, from environmental impact to artificial intelligence techniques for a more informed and wise decision regarding existing equipment. A better characterization of all these research fronts is attempted in the present work, though the classification of literature results concerning life extension strategies via a taxonomy. The analysis is giving clear and objective definitions so it is possible to rely upon them when studying each strategy and better frame the research development or the actual life extension approach implementation. Concerning the strategies definitions, the activities carried out with RECLAIM pilots partners allow to identify the strategies to be considered as more interesting for the project and for the future company activities. Moreover, both paper and patent trends indicate strong growth in the last 5 years, representing an increasing awareness for this topic and ultimately the development of a large number of strategies and methods for this research area. It is often observed that a certain area that is rapidly growing becomes quickly inconsistent, with conflicting concepts due to the diverse amount of new innovative ideas that do not gain their own place. Thus, this review additionally serves to pack up this field of CE and LCES through a revised taxonomy, matching with relevant papers, so that new strategies and methods can be placed in their deserved place.

Secondly, the Strategy Characterization Framework is proposed in order to provide companies with a deepen view on the LCESs. The SCF fields are meant to describe how the strategy works, which are the value chain partners to be activated, which are the possible business model related and many other information that could provide a valuable support to companies to better understand a strategy, promoting its implementation. The SCF aims thus to provide a basis for the identification of the actions needed to put in place a strategy in many industrial contexts allowing to address different specific cases. Also in this case, the workshop carried out with RECLAIM industrial partners allows to validate the proposed characterization framework and evaluate the possibility to introduce new fields.

As a third result, the evaluation methodology conceived during the T4.1 activities can support both OEM and equipment users in the economic and environmental analysis of a shift from a linear economy scenario to a CE one, when the effects of different LCESs can be compared with the actual life cycle management of the equipment. In order to identify which strategy to pursue, a set of environmental indicators based on LCA together with a LCC methodology and circularity indicators have been pinpointed to evaluate the possible choices considering economic and environmental impacts in a life cycle perspective, together with the circularity level of the solution defined. The indicator set has been moreover completed with a gap analysis evaluation methodology, offering a theoretical approach that is meant to highlight the possible advantages/disadvantages offered by the LCESs along the equipment lifecycle comparing these effects with the linear case. The gap analysis provides a high-level vision where, for each LCES compared with the linear economy case and for each life cycle phase, a positive differential impact (impact of linear minus impact of LCES) detects a possible advantage of the CE approach. The trends identified will be then confirmed when real data concerning specific cases will be available. On the one hand, the evaluation methodology conceived represents the foundation of the LCC and LCA

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tools to be developed in T7.4, on the other hand these tools could be exploited to support this kind of high-level evaluation.

Eventually, the final part of this deliverable is again dedicated to provide RECLAIM pilots and, more in general, companies involved in the production or use of industrial equipment with practical indications for the deployment of LCES in the industrial reality. In this context, two different but synergic perspectives have been adopted since the actions needed to implement a LCES starting from a linear economy approach have been investigated in literature and directly with the RECLAIM pilot partners. The bibliographic analysis has been performed exploiting the literature classification via the taxonomy presented in the beginning of this work, thus selecting the papers classified in the “Description and Implementation Guidelines” taxonomy field. On the contrary, a collaborative board has been used so that pilot partners could identify the needed actions to be put in place in their specific use cases, considering both the vision of OEM and equipment user. The work carried out on the implementation action identification described in this last part of the deliverable could be exploited for the deployment of LCES in the RECLAIM pilots or as a basis for future research activities in this field.

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