

Circularity Protocols for Extending the Useful Lifetime of Obsolete Large Industrial Equipment and Assets

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Abstract— The ‘take-make-dispose’ consumption model that remains shackled to the global economy, is also affecting production assets. Industry is promoting the transition to a circular economy (CE). Deployment of the evolving digital technologies and realisation of Industry 4.0 (I4.0) enhance machines automation, connectivity and provide large amounts of data that can be interpreted in a way that were not possible before. It offers to companies the opportunity to retrofit their legacy equipment that cannot meet the constantly increasing market demands. This helps to extend the useful lifetime of this equipment and accelerate the transition to a CE. However, Industry is still lacking an efficient systemic multi-level approach that enables a cost-effective, holistic, and integrated application of CE principles to the digital uplifting of factory 4.0 capital investments. Companies and particularly SMEs face diverse challenges for implementing I4.0 systems in their businesses due to lack of knowledge, expertise and investment. The translation of CE strategies into concrete actions will help professionals to consider circularity measures in a broad sense.

This paper introduces the 10 Circularity Protocols for extending the useful life of large industrial equipment, addressing issues at product, machine, and process level. With guidance on the application of I4.0 technologies, the Protocols help to digitally re-engineer outdated machines to be more productive and energy-efficient, to decrease maintenance downtime, spare-parts storage and off-spec pieces. The Protocols also support on the End-of-Life (EoL) management of the different machine components that are not technically, economically and environmentally feasible to be reused or repaired. As a final step, the future research line and methodology focusing on the digital implementation of the Circularity Protocols guidelines for their deployment and validation in real industrial cases is introduced.

Keywords—Circular Economy, Guidelines, Industry 4.0, Protocols, Retrofitting, Strategies

I. INTRODUCTION

For the past 200 years at least, the hallmark of global consumption and resource use can be aptly described as ‘take-make-waste’: a linear economy, bringing the planet health to an irreversible position which is not longer sustainable. Population growth, material usage and overconsumption has led us to a permanent situation of exponentially increasing greenhouse gas (GHGs) emissions, biodiversity loss, resource depletion and soil erosion among others, and consequently, to a terrible climate crisis. The reality is that the fastest route for mitigation hinges on substantial reductions in our overall use of materials [1] and here is where CE plays the role as the optimal solution for the planet good health and the global economy.

In linear economy, the material extraction and processing with their correspondent GHGs emissions not only affects the industrial processes and goods manufactured to satisfy societal needs and wants, but also the industrial equipment and machinery needed for that purpose. In the last decades, with the increasing approval of environmental regulations, manufacturing industries have put efforts in enhancing sustainable production and consumption in a linear supply

chain that involved only the decisions of vertically integrated systems. But the truth is that the implementation of such sustainable networks was never been fruitful for the industries [2].

With increasing CO₂ emissions allowance prices and scarcity of key materials, the economics of manufacturing and materials use and reuse will change. The substantial economic and environmental costs of buying, transporting, and installing new and more efficient machines in production lines, and consequently, the dismantling management of the replaced equipment, each time obsolescence materializes, make the option of acquiring new smart equipment unfavorable. This will cause a direct impact on manufacturing technologies, which will demand updated manufacturing equipment with gradual and modular advanced manufacturing capabilities to maintain the competitiveness of large legacy systems as the equipment ages. According to the 2018 World Manufacturing Forum after more than one century of traditional manufacturing, European factories and manufacturing assets are fully engaged in a significant transformation towards increasingly cognitive highly autonomous manufacturing models motivated by machines and factories connection through smart/Internet of Things (IoT) devices, data availability and declined costs. Introducing and deploying I4.0 technologies such as Intelligent systems, Predictive models, Simulation platforms and improved maintenance and management control systems, to capital equipment with no data collection nor interfacing options nor original hardware and software actualization for a decade or longer, requires strong orchestration of procedures. The definition of a common implementation framework packed with CE strategies including the technological and systemic transformations needed to adopt the I4.0 manufacturing capabilities and increase the value-retention of the assets, will demonstrate the transformative power of CE strategies to ensure sustainable resources use, tackle overconsumption and slash GHGs emissions.

Refuse, Rethink, Reduce, Reuse, Repair, Refurbishment, Reconditioning, Remanufacturing, Repurpose, Recycling, Recover[3], Reassembly, Recapture, Recreate, Redesign, Redistribute, Remarket, Renovate, Replacement, Reprocess, Reproduce, Resell, Restoration, Retrieve, Return, Revitalize [4], Cannibalization [5] are all individual CE strategies that have individually provided merits by themselves, but they show limited applicability for specific business types and fail to create a whole systemic framework that documents instruments to support the transition to CE [6]. For the machinery uplifting purpose, CE strategies need to be implemented through digitalisation to respond to the challenges imposed by the digital transformation of manufacturing. Companies and particularly SMEs face technical and economic challenges for implementing I4.0 systems in their businesses due to lack of knowledge and expertise, as well as investment requirements [2]. The

translation of CE strategies into concrete actions will help professionals to consider circularity measures in a broad sense.

This paper presents the actions and steps to be executed to implement the different CE strategies through Digitalisation, as a set of coordinated comprehensive and action-oriented guidelines, called the 10 Circularity Protocols, and defined considering their deployment in several industrial environments with different strategies and needs. Starting at Protocol Z-Modernise, and going through Protocols-Functional diagnosis, Inspection, Refurbishment, Disassembly, Repair, Remanufacturing, Upgrade, Recycling, to finally reach Protocol Ω - Re-assembly and Testing. Based on the protocol definition, the list of sequential actions and technologies that should be adopted by the Original Equipment Manufacturers (OEMs) or industrial machinery owners to retrofit and upgrade their machines, were defined. The adoption of the different actions is conditioned by the user needs, the business strategy and the machine condition. The main objective to be achieved through the application of the Circularity Protocols is the extension of the useful lifetime of the industrial equipment, maximizing their return on investment, and securing the sustainable and economical advantage of the manufacturing company in the market.

The additional goals of this paper derive from the intention of contextualizing and developing the knowledge needed to conceptualize the Circularity Protocols. This theoretical background is included in the State-of-Art (SoA) analysis. It synthesises the connection of I4.0 technologies and CE principles, introduces novel circular business models as Servitization, and presents the availability and usage of frameworks, guidelines and protocols for CE principles implementation, with a special focus on digitalisation and product life extension. The last part of the paper introduces the future research line and the methodology for improving the theoretical conceptualization of the actions and processes defined in the Circularity Protocols guidelines through their digital implementation and real validation in different industry case-studies.

II. STATE-OF-ART

This section is meant to present the literature review exploited in this work, built around the research analysis of the current relationship between CE and I4.0 topics, the I4.0 technologies influence on CE practices, new circular business models and the available strategies, guidelines and protocols focused on CE principles application and product lifetime extension. A qualitative reflection contextualizing and the knowledge needed to conceptualize the Circularity Protocols is provided.

A. CE principles and I4.0 relationship

Industry 4.0 and Circular Economy are undoubtedly two of the most debated topics of the last decades [7]. However, the scarcity of research papers and industrial applications, makes CE-I4.0 topics and synergies to be considered in its early phases of development [2]. A review of current research and future trends in [8] identifies the significant opportunity to apply circular approaches to our rapidly changing industrial system, including manufacturing processes and I4.0 which, with data availability, is enabling the latest advances in digitalization. However, little research proposes an integrative approach to these two emerging areas: CE and I4.0 [9].

In [10] the relationship and synergies between these two concepts are studied concluding on a one-way relationship- I4.0 enables, leads to and enhances CE- and a two-way relationship, indicating synergies between the two concepts. In [7] the hybrid categories of Circular I4.0 and Digital CE are introduced. Based on the one-way relationship, CE can improve repair, reuse, and reintegration of processes, machinery and products [11]. The emerging technologies in the Fourth Industrial Revolution context can contribute to the acquisition of the missing information and, consequently, can drive the diffusion and adoption of strategies, new products and business models based on CE concepts, measuring benefits and risks, and comparing different circular solutions [12]. The transition to a circular economy aimed at integrating sustainability into the company's business, has required a structural change in the traditional manufacturing model. This change is carried out through the digital transformation of the production system in an end-to-end digital integration [13].

However, as stated in [2], the implementation of I4.0 technologies is still in early stages and companies that are starting to introduce new technologies are doing it in a uneven manner. The diverse set of Industry 4.0 tools, impedes a clear indication of how to use these technologies at the industry level because they are very specific while industry is more general in terms of the factors hampering exemplifications [10].

B. Most prominent I4.0 technologies for CE practices

The number of technologies that I4.0 embraces is not rigorously defined and differs from different publications [2], based on the relevance the technologies have on the implementation of I4.0 ecosystems and the degree of innovation they introduce [2]. A straightforward description in [14], assumes that this new industry can be considered as Cyber-Physical Systems (CPS)- physical devices and processes that integrate computation and networking capabilities-, connected to an heterogeneous data and knowledge structure where the manufacturing process is integrated, optimized, adapted and service oriented, through the use of algorithms for Big Data (BD) and advanced technologies such as the IoT and Internet-of-Services (IoS), Industrial Automation, Cybersecurity (CS), Cloud Computing (CC) or autonomous Robots. In [10] it is stated that the most promising digitalisation tools of Industry 4.0 are the IoT and BD Analytics.

The creation of new technological solutions based on information and communication technology appears to be a promising facilitator for the introduction of CE to the business realm [10]. Depending on a dedicated area of CE, it is possible to see the prevalence of some I4.0 technologies, also referred as 'Digital Technologies', than others. However, the influence of I4.0 technologies on CE is always verified [7]. Based on review papers, a list of the most prominent I4.0 technologies for the digitalization of CE can be established. In the literature analysis carried out in [2],[7] Additive Manufacturing (AM) , Big Data Analytics (BDA) and IoT are the most frequently described technologies, followed by CPSs and Simulation. Other digital solutions mentioned in [15] are Artificial Intelligence (AI) and Blockchain.

The combination of these digital technologies and new business models could provide major opportunities towards more sustainable industrial value creation, value capture and circular economy practices facilitation [16], redefining production and consumption in the 21st century.

C. Digitalisation as enabler for CE and product lifetime extension

One general assertion shared among experts is that digital technologies can act as an enabler of circular economy. A company willing to become circular and integrate sustainability practices into its industrial activities cannot avoid considering I4.0 technologies. Two different perspectives on how digitalisation could help companies in their transition to a CE are presented in the literature review in [7] which declares that, on one side, digital technologies would support companies in improving their circular performance, and on the other side, digital technologies could enable circular business models (CBMs), involving customers, providers and stakeholders in general, within the industry value chain. Improving knowledge, connections and information sharing could be added as an additional approach for using digitalization in the transition to a CE [2].

Digitalisation enables new means to access process data and product utilization which allow companies to replace the EoL concept with concepts as maintenance, reuse, repair, and remanufacturing, which allows product lifetime extension, including circular loops [13], and minimizing transaction costs [16]. Smart and connected products allow producers to monitor, control and analyze products performance. Having knowledge of the product condition, from the information that sensors and similar devices provide about the status and performance of the asset, enables predictive maintenance, advances diagnosis and prognostics of the components function, increasing product reliability and extending their operational lifetime. The historical information of the product, such as component material, component use and previous repairability works, enables further repair, remanufacturing [16] and/or upgrade actions. Besides, access to this real-time information is unlocking new ways of value creation by enabling information gathering and analysis after products have left the production facility or distribution centre [13].

Data collection, interpretation and usage underpins a central aspect of value creation at the digital and circular era. The lack of data obstructs the acceleration towards CE. Data gathering typically should cover product lifecycle from design to final usage and EoL. The more data a business can acquire on all the processes, the easier it becomes to take the most value of the product or service use, improving the circularity of the model. A more efficient exploitation of field data could improve the overall circularity of a system and for that CPSs were considered by experts the most common method for gathering data from the field. The CPSs can be exploited for developing several types of smart services as, for example, cloud-based smart diagnostic services for manufacturing processes [7] or machine health forecasting. In this way, smart systems could adopt the characteristics of software products and be dynamically adapted or upgraded during the use phase according to new developments, user needs or the natural environment [13].

D. New circular business models- Servitization and PSS

Effective implementation of circular strategies requires not only innovation in product design, but also a focus on business models that incentivise companies to keep products and materials at their highest value for as long as possible, while ensuring minimal environmental impact [17]. Digitalization brings up the possibility of creating these new business models that can promote CE principles such as assets sharing and leasing, usage lifetime maintenance and aftersales

services, embracing consumer involvement in the product and service innovation processes too. As stated in [2], this will encourage maintenance and repair activities prolonging the operational phase of the product. Furthermore, it will become easier for the provider to get back products and parts after the use phase as they can be traced over the whole lifecycle and in consequence products are more easily reused, remanufactured or recycled by the provider that extends the responsibility over the product to the whole lifecycle.

In [18], innovative Circular Business Models include the concept of 'Servitization', which refers to the product transformation from a physical good to an integrated Product-Service System (PSS). In [19] the term PSS is also introduced, as a business model which equips manufacturers to capture customer values, and realize profits dispersed throughout the whole product life cycle. In [16], the PSS is also defined as a mix of tangible products and integrable services designed and combined so that they are jointly capable of fulfilling final customer needs. In PSS systems, digitalization enables to collect data that can be used in product innovation and in increasing the customer satisfaction. Integration of digital intelligence provides opportunities to distribute knowledge ownership and different levels of customization. This allows more connected and durable relationship with the OEMs and customers [18]. Another new term is utilized in [13]. This paper introduces the concept of smart-circular systems that reflects the interplay between the Internet of Things, the circular economy and service business models.

In the servitization model and the PSS, customer satisfaction is an important driver. In a service relationship, the customer experience feeds back strongly, raising consumers' awareness of their actual needs. Consumers can become prosumers who co- create or co-produce the products and services they need [2]. Customers are benefited from the improvement of communication along the product value chain. Change of real time requirements could be provided due to the high level of integration and communication about asset status, utilization parameters or instructions for anomalies detected, which will enhance the user experience.

E. Frameworks, Protocols and Guidelines for product lifetime extension

Within the CE strategies, there are several well-known theoretical reference frameworks that boost CE principles application: the 3R (Ministry of Environment, Japan, 2004) [3][10][11][9], the 9R's (Netherlands environmental agency, 2017)[3][9], ReSOLVE (McKinsey, 2015)[6][10][12][16] [9] Cradle-to-Cradle™ (M.Braungart, W. McDonough, 2002) [3][6] [2][12] [18] [20] [21] [22] [23], the Waste Hierarchy (European Union's Waste Framework Directive, 1993) [3] [6] [2] [12] the Comet Circle™ (Ricoh, 1994) the Performance Economy (Walter R. Stahel, 2006) and the Seven Fronts of Mount Sustainability (Anderson, 1995). [6] Other referenced R-imperatives are the 4R, 5Rs, 6Rs, 7Rs, 8Rs, 10Rs [3][10][9][4]. However, there is an extensive variety and confusion found with the different R-imperatives. The problem lies in the scope definition and the interrelation of the CE strategies, but also in the implementation path, which could strongly vary depending on the sector or product in which the strategy is applied. The remanufacturing process - a process of returning used products to "as-new" condition with matching guarantee - do not follow the same steps for the remanufacturing of an automotive engine or the remanufacturing of a pair of jeans in the textile sector.

There is several literature analysing the standardization of these R- terms, but the reality shows that defining the theoretical concept (strategies/best practices) is simpler than creating their application plan (guidelines/ procedures/ protocols). This happens due to the fact that professionals without a background in CE often struggle with the implementation of circularity due to the high level of abstraction and ambiguity of the concept or because they are not aware of the full spectrum of circular approaches [24]. Despite the abundance of circular methods, principles and strategies provided in literature, this abstractionism makes difficult the translation of strategies into concrete actions towards circular practices. In this direction, the definition of protocols should help to bridge the knowledge gap between the conceptualization of circularity and their real application guiding professionals to get started with.

In the literature review of CE strategies implementation to real cases, the terms Guidelines and Framework are widely used, being the term Protocols less popular. The papers reviewed include Frameworks for manufacturing companies to support circular economy-oriented innovation [6]; for upgradability of PSS [19]; for circular design [21]; for product and business models design for CE [22]; for the identification of interfaces between CE and stakeholders in the infrastructure sector [24]; for product lifetime extension business models [25]; for CE strategies characterization [5]; for design for disassembly focused on mechatronic products [26] or for evaluating the sustainability content of a product in terms of economy, environment and society over its total life-cycle [27]. The Guidelines analyzed were defined for Design for X (DfX) [21]; for CE principles deployment for electric and electronic equipment [28]; for design for remanufacturing using AM [29], which provides a list of AM design rules relevant the for the remanufacturing strategy; for sustainable manufacturing [30], including the findings into design and manufacturing approaches to facilitate remanufacturing; and the Ellen MacArthur Foundation jeans redesign guidelines, establishing the minimum requirements for the durability, material health, recyclability, and traceability of denim jeans. Although some of the CE strategies activities definition may seem obvious in the eyes of a CE expert, professionals without CE expertise can use frameworks to arrive at the same outcome without having to first understand the multitude of circular principles and approaches that exist in literature [24]. Finally, the Protocols term is mentioned in [2], introducing the CircularID initiative from the EON company, whose protocols establishes the essential product and material data critical for identification and management of textile products; in [12], focusing on predictive maintenance activities; and in [31], in which a set of organized specific activities are provided for the inspection process for the remanufacturing of automotive engines.

Work reviewed for Frameworks, Guidelines and Protocols presented a same goal towards CE implementation facilitation and demonstrated that diagram workflows are widely used to comprehensively illustrate the theoretical action path or cycle that needs to be followed for this purpose. However, the level of the scope definition, the activities specifications and the availability of results and feedback from real CE adoption cases, differed among the three terms. On one side, Protocols share a common approach through the facilitation of CE strategies implementation to real use-cases, offering clear and concrete activities contributing to circularity for specific products or sectors, and being suitable to be used as an

independent tool for professionals who are not experts in the field of CE. On the other side, Guidelines and Frameworks, showed a higher degree of hypotheticals or generality respectively, lacking results from real implementation.

Focusing in the CE-I4.0 relationship, the reality is that there is still a lack of empirical evidence on how CE and I4.0 principles are applied in practice by companies [7]. As I4.0 contains a variety and growing number of sub-groups, domains, and technologies and the CE possesses a number of approaches (i.e., R-imperatives) it is important to refer to key concepts relating to I4.0 and CE in order to synthesize and build a consistent and integrative framework [9]. Furthermore, to convert the theoretical initiatives in tangible practices and be able to measure their effectiveness, a specific implementation plan, Protocols are needed in order to guide managers to choose their CE goals and accordingly identify the set of Industry 4.0 technologies that best support their strategy [10].

III. METHODOLOGY

This paper is based on an explanatory research in the context of the EU-funded project LEVEL-UP, aimed at understanding the issues related to Circular Economy in the industrial environment with a focus on extending the lifetime of production equipment. For this reason, a qualitative methodology was adopted for the theoretical conceptualization and definition of the Circularity Protocols. A group of experts from manufacturing companies, digital technology providers, industrial equipment OEMs, a sustainability consulting firm, standardization bodies, research institutions and universities collaborated and agreed on the creation of the 10 Circularity Protocols guidelines.

The first stage consisted in the identification of the necessary actions for the total retrofitting and/or upgrade of large industrial machines, naming and delimiting the protocols. This distinguishment was made based, on one side, on an exhaustive review of CE strategies and digital solutions applied in the I4.0 paradigm, and, on the other side, on expert knowledge, criteria and field experience on retrofitting and machines actualization from the group of experts. The 7 pilot lines forming part of the LEVEL-UP project, including obsolete large machines from various sectors and with different technical issues and business strategies – a large vertical industrial lathe, a working centre for laminated-timber parts, a pultrusion line for rear crash beam, an extrusion line for plastic profiles, grinding equipment from a railway axle line, a transfer press for automotive parts and a CNC centre for aeronautic engine components – were taken as reference to understand the problems that industrial companies have and want to solve. The second stage involved the definition of the Protocols guidelines, including the scope, the purpose and the triggers, as well as the list of actions, describing the implementation steps, the I4.0 technologies to be adopted and the interconnection among them. Finally, to conclude the theoretical conceptualization of the Circularity Protocols, the guidelines were schematized in the form of a visual flowchart that can be easily followed by the Protocols users to successfully deploy them in the machines.

IV. LEVEL-UP CIRCULARITY PROTOCOLS

The 10 LEVEL-UP Circularity Protocols enable the adoption of CE strategies at theoretical level and the implementation of I4.0 technologies at practical level, extending the useful lifetime of large and obsolete industrial

assets thanks to the industrial and sustainable actualization. These Protocols are presented as a set of standardized guidelines, defining the trigger, scope and goal, and presenting the actions which include the integration of a physical or digital component and/or the adoption of a technological service offered by a dedicated third party. The flow diagram (see Fig 1) shows the interconnection among all the 10 Circularity Protocols as there is a particular sequence to implement them. Each Protocol is triggered by an action, which could be the initial action ‘Investigate machine’, the intermediate step ‘Decision making’ or an action included within a specific Protocol. A process diagram flow including all the actions for each individual Protocol (see Fig 2) was created as part of this set of action-oriented guidelines. However, the introduction of the in-depth analysis of each individual protocol is not the scope of this paper.

The process for deploying the Protocols starts with Protocol Zero, Modernise and the *CPSization* of the equipment allowing machine connection and data ingestion from the physical layer. Followed by Protocol 1, Functional diagnosis, which involves the processing and analysis of all the data gathered in the field, and Protocol 2, Inspection, which considers machine health monitoring and product quality inspection. Protocol 3, Refurbishment, embraces light repair activities, focusing on cleaning, painting activities and upgrading safety regulations. Protocol 4, Disassembly, contains the tests and evaluations that should be performed on damaged components separated from the machine. Protocol 5, Upgrade, differentiates between machine mechatronic upgrade or components and spare-parts with enhanced design and material functions. The next protocols are Protocol 6, Repair, and Protocol 7, Remanufacturing, aiming at restoring the original integrity and original functionality of the component. Laser-based technologies, such as cladding and metal AM, are respectively recommended for this. Protocol 8, Recycling, focuses on the recovery and valorisation of materials from components that cannot be repaired or reused in the previous protocols. Finally, Protocol 9, allows the reassembly of the machine and the validation of the processes ensuring that the machine will be put back into production with no flaws. The Protocols description, scope and activation are introduced.

A. Protocol Z-Modernise

Protocol Z starts after the ‘Investigate machine’ phase, in which it is required to perform a series of preliminary actions to evaluate the machine as-is condition and understand the end-user needs for retrofitting. Protocol Z is a prerequisite to apply any of the other Circularity Protocols. It includes the guidelines that involve the actions for the retrofitting of the old and legacy machinery with I4.0 technologies. The goal is to connect the physical layer with the digital world involving CPS, sensors, interfaces and gateways with IoT platforms and ERP, MES, and other IT Transactional data systems in a formalized manner. The protocol includes network integration, shop-floor integration and factory integration, but these actions do not follow a specific sequence, as there are activities that can be executed in parallel.

B. Protocol 1 – Functional diagnosis

It includes the guidelines that involve actions on machines where sensors and CPS are already in place. Protocol 1 is triggered when there is enough data to be analysed, in order to derive a diagnosis on the status of the equipment. It involves condition monitoring, simulations of virtual models, anomaly

detection, machine forecasting and prediction of failures. Data from the maintenance logs, repair protocols, PPS, ERP and any other relevant information stored in the enterprise systems may be used as reference. The goal is to evaluate Key Performance Indicators (KPIs) and to perform efficiency calculations. Upon finalisation of Protocol 1, the system will deduct and inform if there is an indication of malfunction.

C. Protocol 2- Inspection

The main purpose of this Protocol is to measure, examine and test relevant parameters at three levels relying on three inspection systems respectively: Machine Level (ML), Product Level (PL) or Shop-floor Plant level (SPL). During the application of this protocol, data is compared with the specified requirements to check if targets are met. This protocol involves the visual inspection of the machine from the experts while it operates. If required, the use of non-destructive sensors and their correlation with the findings from the functional diagnosis will provide insights for a focused inspection while the machine is idle. In case of a suspected failure, this protocol will trigger the Refurbishment, Repair, Remanufacturing, or Disassembly Protocol, based on the degree of degradation or damage.

D. Protocol 3- Refurbishment

It includes the guidelines that involve light repair and cleaning actions of the equipment to bring it to its original status and integrity (as-new status). Old grimy machines, with corroded or rusted surfaces will be cleaned and treated to enhance their superficial appearance (painting) and improve their durability, easy cleaning or chemical resistance in harsh working environments (coating application). Furthermore, safety regulations will be upgraded to meet all appropriate health and safety requirements considering the necessary protective measures to mitigate or reduce those risks that cannot be totally eliminated.

E. Protocol 4- Dissassembly

It includes the methodology or series of steps to be applied each time a component from a machine is disassembled in a non-destructive manner (demanufactured). The general purpose of this protocol is to have a deeper knowledge of a specific component that is potentially defective, damaged or needs an improvement, by taking the part out of the machine to run some non-destructive tests. The identification of failed components and any degradation will lead to a 3D scanning to extract the component 3D shape. The design characteristics will be also analyzed and stored, such as the material identification, its sensitivity against contamination, wear, the tolerances against forces and the reaction to the environment under which it operates. The outcome analysis will consider the functional properties that have to serve in order to find the optimal substitute in case the component needs a replacement.

F. Protocol 5- Upgrade

The Upgrade Protocol is triggered in case there is a need to improve or add new equipment functionalities. It includes the guidelines that involve actions for improving functionalities, such as performance, reliability, connectivity, interoperability, durability, security, etc. Any hardware and software addition that provide advanced functionalities and properties to the equipment that were not installed in the original design can be considered within this protocol. Apart from that, old parts will be replaced by improved versions, considering the adoption of advanced materials and optimized designs, manufactured by new technologies as AM.

G. Protocol 6- Repair

The Repair Protocol is triggered in case a component is found worn out or damaged to bring it back to its original integrity. It can be executed while all components are in place or after disassembly. Once the sources of faults are identified, the damage located and characterize based on size and type, the suitable technology will be selected to be applied for the repair process. Surface cracks can be repaired using light machining and/or laser cladding; internal cracks can be repaired using electropulsing treatment and through-thickness cracks can be repaired using fusion welding methods including brazing, MIG/TIG welding and laser welding. Depending on the type of materials and repair method, the parts may need a subsequent heat treatment step (i.e., tempering/annealing) after the repair process to reduce the residual stress and maintain good metallurgical characteristics within the repaired areas, or a post-processing step (i.e.,

machining) depending on the tolerances or rugosity that are required for obtaining functional surfaces.

H. Protocol 7- Remanufacturing

The Remanufacturing Protocol is triggered in case a component is found worn out or damaged in a level that needs to be brought back to its original functionality for well-performing. This protocol is mostly suitable for parts that are non-repairable and thus, situations where there are clear technical, economic and environmental advantages for the remanufacturing instead of replacing the component. It includes the guidelines that specify the actions to allow the remanufacturing of missing parts as well as the recovery of the original design and/or material.

I. Protocol 8- Recycling

It includes the set of guidelines with actions for the recovery and valorisation of materials from components that

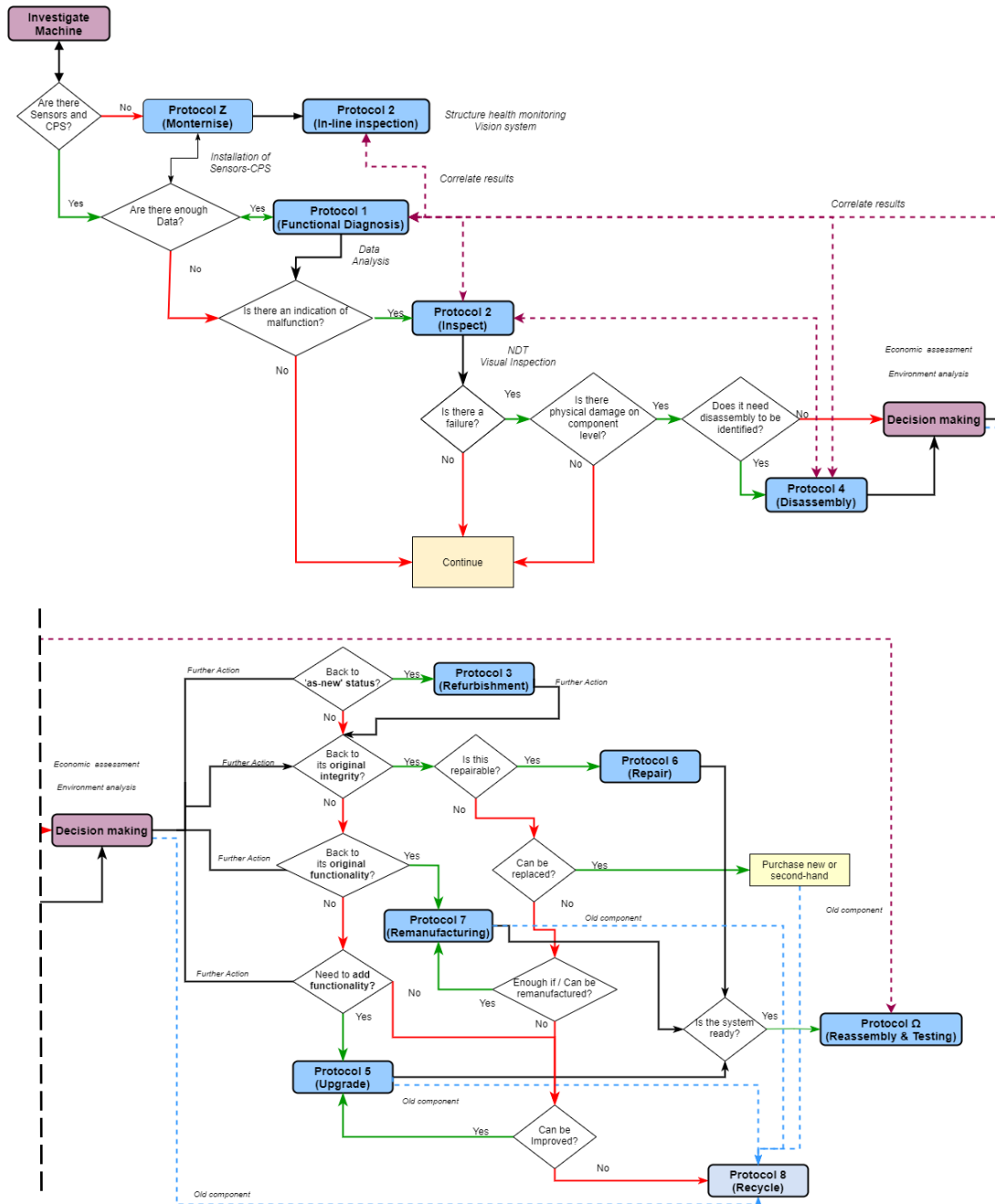


Figure 1. Circularity Protocols diagram flow.

cannot be repaired, remanufactured or reused, and valorisation of the waste generated in the industrial processes. The aim of the protocol is to determine how these materials can be treated and recycled to recover inherent value and minimize the impact on the environment. The protocol is triggered at different stages: at a decision-making step if a machine is deemed unrepairable for technical, economical and/or environmental reasons, at Refurbishment, Remanufacturing or Upgrade when old and dysfunctional components are replaced, and there is no reuse possibility, and at any process stage if waste material is generated.

J. Protocol Ω - Reassembly and testing

The protocol Ω is the last protocol aiming at setting the machine back in production without problems or flaws. The guidelines include tool adjustment and calibration actions. During this phase, validation of the processes will ensure that the machine will be put back into production effectively. The virtual scenarios will increase the efficiency avoiding possible risks during the previous processes. Testing results will be correlated with Protocol 1, Functional diagnosis.

V. RESEARCH PROGRESSION AND RECOMMENDATIONS FOR FUTURE INVESTIGATION

The next step after the theoretical stages presented in this paper- the identification of the necessary Protocols for retrofitting a machine, definition of the scope, listing of the actions, including processes and technologies to be adopted, and the creation of visual diagram workflows- consists in the deployment and validation of the Circularity Protocols in an industrial environment. To verify the suitability and the correct definition of each of the Protocols guidelines, these will be implemented and validated in 7 different industrial machine or production line scenarios. For the execution, and traceability of the Protocols, these will be digitally represented and implemented, allowing industrial users to plan and track the actions applied on their equipment. The data and information acquired from the different steps in each protocol will be digitally linked with an industrial Digital Thread,

which will facilitate the integration, interconnectivity and management of data, covering all the steps.

In parallel to the digital implementation, metrics to measure the Circularity Protocols' performance need to be formulated. The metrics will evaluate the understandability of the guidelines, their use level by CE non-experts and their adoption and validation process in a practical industrial context. Results from the validation phase will be compared to identify margin for improvement, level of compliance, relevance to OEMs, manufacturers and I4.0 technology providers, and also, pertinent blueprints, which will help to redesign the Protocols guidelines. The validation and redesign of the protocols are key stages that needs to be accomplished to work towards their standardization, allowing retrofitted equipment to be analogous and making lifetime extension strategies more precise. The ultimate goal of the Circularity Protocols is to become a standard for the factories of the future to adopt a conservative utilisation of their major capitals, minimising costs and increasing their return on investment, improving their maintenance practices and their optimal performance, also in a sustainable manner.

VI. CONCLUSIONS

The combination of I4.0 technologies, such as CPS, Big data, data mining, data analytics, IoT and the adoption of new circular business models as Servitization, could provide major opportunities towards more sustainable industrial value creation, value capture and CE. The definition of a common implementation framework packed with CE strategies including the technological and systemic transformations needed to adopt the I4.0 manufacturing capabilities and increase the value-retention of assets, will demonstrate the transformative power of CE strategies to ensure sustainable resources use and tackle overconsumption.

The LEVEL-UP Circularity Protocols are introduced in this paper as the set of action-oriented guidelines created to help non-experts in the area of CE to apply circular principles through digital solutions and I4.0 technologies

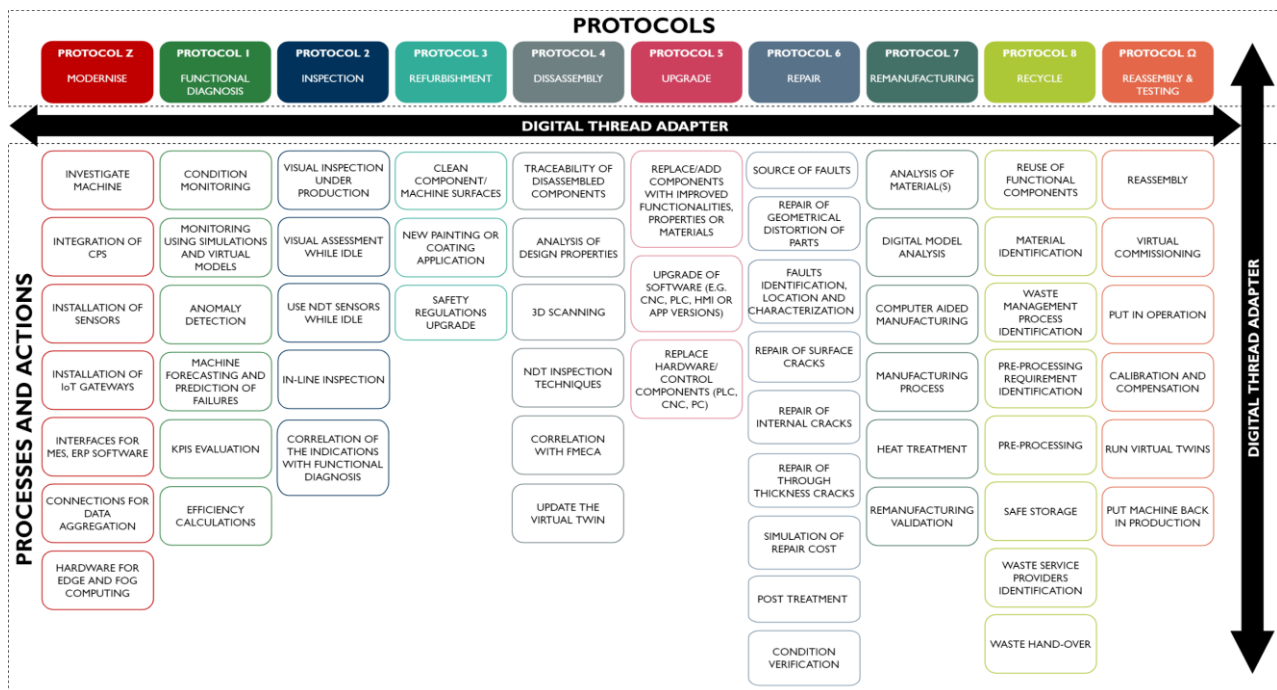


Figure 2. Circularity Protocols processes and actions.

implementation to extend the useful lifetime of large industrial equipment, making them competitive in the Industry 4.0 paradigm and avoiding the replacement of these machines. The aim of this work also derives from the intention of contextualizing and developing the knowledge needed to conceptualize the Circularity Protocols, synthesizing the connection of I4.0 technologies and CE principles and presenting the availability and usage of frameworks, guidelines and protocols for CE principles implementation, with a special focus on digitalisation and product lifetime extension. The Circularity Protocols will be digitally represented, deployed and validated in real industry scenarios. Data and information collected in the different steps will be linked through an Industrial Digital Thread, which will allow data integration, traceability and management.

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