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Developing a Circular Business Model for Machinery Life Cycle Extension by Exploiting Tools for Digitalization

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Abstract: Digitalization technologies have been identified as enablers for the adoption of circular economy practices. The machinery-value chain addressed in this study is affected by the introduction of digital technologies that enable real-time monitoring of data on product condition and control optimization, the deployment of predictive analytics techniques, as well as offering circular-based services. Machinery-lifetime extension can be digitally enabled on both old and new machines. The research objectives were to investigate how digital technologies enable the adoption of circular economy-based business models by manufacturing companies and provide answers regarding (i) which Life Cycle Extension Strategy is suitable for digital circular-business model adoption and (ii) how digitalization of machines enables manufacturing companies to innovate their business models. The correlation matrix is the tool developed from the proposed approach and it aims to support manufacturers in their first contact with circular business models. In the European RECLAIM project context, two manufacturers have applied the approach. The next steps are expected to introduce quantitative indicators to define thresholds for the steps toward circularity without replacing the qualitative approach, as this guarantees its applicability in a context that has never considered circularity yet.

Keywords: circular business model; digitalization; circular transition; digital transformation; equipment life cycle extension

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1. Introduction

The concept of circular economy (CE) is receiving increasing attention worldwide as a way to overcome the issues of the current production and consumption model [1]. It requires companies to rethink their supply chains and business models (BM) [2].

The CE is a regenerative economic system that necessitates a paradigm shift to replace the end of life (EoL) concept with reducing, alternatively reusing, recycling, and recovering materials throughout the supply chain, with the aim of promoting value maintenance and sustainable development, creating environmental quality, economic development, and social equity, to the benefit of current and future generations [3].

The present work focuses on the machinery sector; to this sector belong all systems compliant with EU Directive 2006/42/EC [4]. The traditional machinery supply chain approach feels free of responsibility for EoL products. The reverse supply chain is slowly making headway and trying to account for EoL products in the most environmentally friendly manner possible [5]. Sustainable EoL management can be enabled by long-lasting design and the optimization of maintenance, repair, reuse, remanufacturing, refurbishing, and recycling strategies. Sustainable action must comply with, and account for, the complexity of socio-economic systems by encompassing economic, ecological, social, and political factors and addressing the hierarchical organization of nature [6].

Indeed, improving the EoL management of machinery can help reduce waste, minimize environmental impact, and save costs.

Digitalization, intended as the process of employing digital technologies and information to create value from firms' ordinary operations and inter-organizational relationships [7], has been identified as an enabler for the adoption of CE practices. Recent studies have demonstrated the potential of digital technologies to support companies' digital transformation, life cycle management, supply-chain management, and adoption of the circular business model (CBM), and product-service systems (PSS) [8]. While conventional BMs' value propositions are mainly geared towards sales of products, CBMs keep materials, components, and products at their highest utility and value [9]. CBMs gained popularity along with the spread of the CE, and involve recycling, extending, intensifying, and/or dematerializing products and energy loops to reduce the resource inputs into and the waste and emission leakage out of an organizational system [10].

A product is how the value proposition materializes in practice; a product encompasses both goods and services. Products are the economic output of production activities. Products are exchanged and used as inputs in the production of other goods and services, as final consumption, or for investment [11].

Using digital technologies embedded in machinery can improve EoL management by enabling predictive maintenance, monitoring of machinery conditions [12], and facilitating more effective recycling or disposal strategies [13]. Digitalization can (i) enable machine monitoring to predict when a machine is likely to fail or require maintenance; therefore, (ii) supports failure prevention and machine life cycle extension, which likewise can (iii) help improve EoL management of components by tracking their status, making it easier to identify materials for recycling or disposal and to make a decommissioning plan, or share data within the related supply chain on production processes and machines. Nevertheless, the application of digital technologies to machines already in use is still scarcely documented in the literature. Experiences from the field show limited applications of sensors to gather data on single machine components, difficulties in data transmission and elaboration, and the necessity for training operators to properly manage the EoL of components safely and in compliance with any regulations [14].

Machinery lifetime extension can be digitally enabled for both old and new machines, depending on the different relationships established by original equipment manufacturers (OEMs) with the other value-chain actors. A new product comprises parts that did not accomplish any function before; it may be composed of recycled materials, but all parts were bought (brand new) or produced for the product. All cases involve old products (i.e., the product was previously used, some parts were retrieved from other products, some parts were downcycled, etc.). Therefore, it is reasonable to affirm that an old product has already reached the used phase while the new one has not. In addition to the customer, three primary actors take the stage on the machinery value chain. OEMs are all the original producers; in traditional selling models they own the products until they are sold (to a retailer or the customer). Sometimes, they are remanufacturers themselves. Since they ran the process for the initial product to commercialization, they have the expertise and knowledge of the information valuable for remanufacturing. Moreover, they gain benefits out of remanufacturing, such as material, labor, and energy savings, while creating new market opportunities and a positive social image [15]. Outsourced remanufacturers are one kind of third-party remanufacturer; they carry out operations under contract from either the customer or the OEM (who continue to own the product). There might be close cooperation between outsourced remanufacturers and OEMs (for example, delivering information and training workers). The second type of third-party remanufacturer is the independent remanufacturer, who buys the used products from users and remanufactures and resells them. However, unlike the previous one, it has no cooperation with the OEM [16].

To this end, the research objectives were to investigate how digital technologies enable the adoption of circular economy-based BMs in manufacturing companies (OEMs). The present paper aims to answer two-fold research questions:

- What Life Cycle Extension Strategy (LCES) is suitable for digital CBM adoption?
- How does the digitalization of machines enable OEMs to innovate their BMs?

This study has been conducted in the context of the RECLAIM project (H2020 project, grant agreement no. 869884), which aims to develop solutions for extending machinery lifetimes and improving productivity and performance. In the project, several tools for the digitalization of machines have been developed to support predictive maintenance by detecting component failures; assessing the health of the machine in use (prognostic and health management toolkit); evaluating the cost of component maintenance, refurbishing, or remanufacturing of a machine (cost-modeling tool); guiding component maintenance (Augmented and Virtual Reality -AR/VR- for maintenance); support in the deciding the best LCES strategy to be adopted (decision support framework, life cycle assessment -LCA- tool and simulation and digital twin-pack); and enabling data transmission and monitoring (data repository and knowledge discovery). The developed tools have been used in this study for the selection of the LCES to be considered for circular transition by OEMs, analyzing how their value propositions change, and testing the methodology in two manufacturing companies.

2. Background

2.1. Digital CBMs for Machine Life-Cycle Extension

Traditional BMs can ease or obstruct products' circularity. Over the last decades, a multitude of innovative, sustainable BMs have arisen, and launching a product now requires identification of which BM most appropriately creates, delivers, and captures economic value while simultaneously contributing to environmental and/or social sustainability [17]. There are several methods to assess the circular performance of a system [18] and several frameworks and new practices have been developed to assist organizations in the implementation of circular products and processes [19]. ReSOLVE is one of the most frequently used [20].

In their review, Fontana et al. [21] summarize the field of CE and LCES through a revised taxonomy, drawing on relevant papers so that new strategies and methods can be implemented. In fact, there are many obstacles related to EoL management, such as product return via the reverse logistic, inspection and disassembly, and continuation of activities relating to cleaning, remanufacturing, reassembly and re-introduction to the market. There are multiple aspects to be considered, such as product and volume uncertainties, design constraints, brand reputation, and intellectual property [22]. Several technologies were created to specifically deal with goods at their EoL [23], especially relating to recycling and material treatment and breakdown [24]. Other products use the same technologies as manufacturing processes, also combining subtractive and additive ones [16].

Scholars widely agree that digital technologies (DTs) are crucial in facilitating the transition from the existing linear economy to a CE, as evidenced by numerous studies [13]. A digital CBM is a type of economic model that incorporates digital technology and data to support the principles of a CE. In a digital CBM, companies use digital tools and platforms to manage their resources and supply chains more efficiently and sustainably. This can include using sensors and tracking technology to monitor the use and movement of resources, as well as using data analytics to optimize production and distribution processes. By leveraging digital technology, companies can better understand their operations and make more informed decisions about how to use their resources in a way that reduces waste and promotes sustainability. On the other hand, digital technologies can support companies in waste minimization by adopting LCESs, such as recycling, reusing, remanufacturing, or even predictive maintenance.

Nowadays, shop floors are pervaded with multiple tools intended for digitizing products and processes. Industry 4.0, with Key Enabling Technologies (KETs) such as Internet of Things (IoT), Big Data, Cloud technology, Artificial Intelligence (AI) and Machine Learning (ML), enhanced robotics, Data Analytics, 3D Printing, and Blockchain, is transforming industrial businesses on a vast scale [25], and is boosting the development of systems that monitor industrial processes and prevent machines' downtimes. The IoT refers to a network of physical devices embedded with sensors, software and network connectivity, which collect and share data. The IoT is characterized by a shared understanding of the situation of its users and their applications, a software architecture and pervasive communication networks and the analytics tools for autonomous and intelligent behavior [26].

The IoT can transform products into intelligent and interconnected ones, providing the ability to monitor the status and condition of products. As a result, companies can benefit from real-time remote monitoring of product usage and status [27]. Data collected through the IoT, combined with data analytics tools and data mining processes are necessary to unlock valuable insights, identify patterns, make predictions, and deliver advanced services like preventive and predictive maintenance. Consequently, in the literature, the combination of Big Data and appropriate analytics is widely acknowledged as an effective approach to facilitating better sustainability-oriented decision making [28].

In this context, the present work proposes and applies a framework to identify CBMs and exploit the functionality of digitalization tools. It is intended for companies still relying solely on linear BMs; in particular, the focus is on companies operating in the machinery value chain to promote resource lifetime extension-driven behaviors while adopting digital technologies.

2.2. Success Stories

Industrial scouting has been conducted to examine how CBMs are implemented in industrial contexts.

In the machinery sector, CBMs are spreading widely. Together with selling new machinery, Liebherr is now providing their customers' with fleets for hire too, together with the fleet management system—LiDAT. The benefits are multiple: Liebherr machinery may require high initial investments, but the OEM does not encounter the risk of cannibalization, since companies that often make use of specific machinery would buy them anyway. Furthermore, by letting the machinery be rented, Liebherr can reach all the construction companies that would not stand the investment. This allows the company to extend its market share, while also ensuring a greater management of resources. In addition, the OEM owns the machinery for the whole time and is responsible for maintenance, the product life cycle is elongated, and resources are saved. Liebherr has been extending the remanufacturing program over the last decades and can now offer different options for specific ranges of components, such as exchange, general overhaul, and repair [29]. Likewise, Liebherr is exploiting the potential of digitalization and product service systems (PSSs), while Hilti is similarly managing its portfolio, optimizing the repairing process, providing equipment at monthly fixed fees and guaranteeing full-time tools availability in case of damages or reduced effectiveness [30]. The threat for OEMs is that independent organizations provide a similar service independently. Many companies have realized that firms' environmental responsibility is not inconsistent with the creation of economic value and that remanufacturing generates higher environmental gain than recycling. Caterpillar perceives remanufacturing as a new era of profitability, and their Cat Reman is an independent remanufacturing division that generates up to 8% of the total revenue and has established a proper program—Cat Certified Rebuild—that guarantees the quality of re-manufactured products [31].

Nederman, with its Insight solution, addresses its customers' major difficulties with air filtration with sensors that monitor key performance parameters and functionalities, and deliver real-time data. Digitalization allows the new company division to sustain the customer and let him focus on his business activities [32]. Digitalization offers the opportunity to introduce, aside from the traditional selling–buying BM, additional services which improve the customer experience by providing alerts about product performances or monitoring its status. For example, EMTrack provides real-time reports that show tire performance. Tires can, thus, be tracked when they are currently in service or logged in inventory when they are removed from service. EMTrack also can help predict tire longevity in terms of hours, cost, and wear, which helps to enable more accurate forecasting and budgeting [33]. Those services come as additional maintenance or stand-alone services.

They are package(s) of services to address the customers' needs and willingness to pay, as in the case of Alstom transport [32].

When approaching the new paradigm of CE, each company evaluates which solution best combines environmental benefits with overall revenues. Some focus only on core elements or parts with high added value, while others put into practice extended producer responsibility (EPR) by (re)working the whole product. Bosch, with the program Bosch eXchange, is making repair shops for standard rail components more and more competitive, both in time and cost terms [34]. In its remanufacturing plan, Volvo trucks give a new lease of life to worn-out engines for heavy-duty trucks, bringing them to like-new condition by passing them through a process which has less impact on the environment [35]. French-based Schneider Electric employs 142,000 people, uses recycled content and recyclable materials in its products, prolongs product-lifespan through leasing and pay-per-use, and has introduced take-back schemes into its supply chain. Circular activities account for 12% of its revenues [36]. Valtra is one example of agricultural machinery that provides customers with spare parts, new and/or remanufactured, and who also rely on outsourced remanufacturers like SR Harvesting OY [37].

There are sectors in which customers, or people responsible for product functionality, are unwilling to give up on traditional design, or where products have such long phases of use that when they were designed sustainability was not considered. OEMs are willing to get as much value as possible out of them with proactive approaches. For example, in the latter case, the PAMELA and AFRA aircraft projects, responsible for studying the potential benefits of recyclable materials in aircraft, produced a de-manufacturing hangar. Tarmac Aerosave is now the company in charge of disassembling aircraft, and sorting and tracing the parts intended to be recovered [38]. Smartphones, tablets, and laptops are included in the former case. Here, design is too focused on functionality and aesthetics, and there are almost no cases of design for de-manufacturing. There are isolated exceptions, but they are not the standards yet. See in this regard the Fairphone case. In order to minimize resource exploitation, the phone is not sold with a charger or headphones, and the smartphone is made out of modules that make the product easily repairable even for non-experts [39]. Hyla Mobile remanufactures standard mobile phones, giving them new life (lives) [40]; similarly, Taitonetti finds new applications for old business computers, selling them to private individuals [41]. When reintroducing IT products onto the market, it is important to guarantee that all sensitive data from previous owners are destroyed and there are companies specialized in these activities, like CCL North [42]. To comply with regulations, organizations in this sector mainly address disassembly and recycling. Apple built two robotic cells, called Liam and Daisy [43], to disassemble specific models of smartphones and retrieve as many components out of them. The disassembly process is highly efficient, since a robot is designed for only specific products. Indeed, it is not an outstanding example of life-cycle thinking [44], but the first step toward more sustainable resource exploitation. Philips shortened the distance between OEMs and recyclers by suggesting that designers disassemble the products they design [45]. Over recent years, targets have been set [46], but the distance to circular systems in these sectors is still very far, despite the results achieved [47–49].

The office-printing sector has been a leader for a long time in remanufacturing and PSS practice, starting from the single-use, almost entirely remanufacturable and recyclable cameras of Kodak [50]. This was a starting point for the company that still today is engaged in finding new means to be more responsible, without compromising on quality [51]. Further examples, such as Xerox [52] and Canon [53], etc., describing the success of their take-back programs (with related remanufacturing of multifunction and recycling of consumables) are strewn all over the literature [54,55].

More examples of the implementation of CE are biofuels made out of waste [55], cases that involve making batteries [56] and their life cycles [57] good for the environment, and responsible packaging [58] that becomes returnable instead of being disposed [59]. Among them, the materials of tires and asphalt [60] are widely being revisited and replaced with greener ones, coming from products of extremely different supply chains, or the opposite direction, as is the case with Eldan Recycling [61], Lehigh Technologies [62] or Timberland shoes' soles [63].

An example of the inclusion of multiple stakeholders in the circular system is Kalundborg, the world's first industrial symbiosis, run by the main principle of a residue from one company, becoming a resource at another, benefiting both the environment and the economy. A local partnership allows attendees to share and reuse resources, save money, and minimize waste [64]. Clusters and networks ease the establishment of communities and ideas circulation, and a validated process for one company may become an inspiration for another.

The comprehensive study of the literature and the successful business case is the basis of the approach proposed in the present work. Starting by clustering them, the correlation matrix aims at supporting companies approaching CBMs in exploiting the functionalities of digitalization tools.

3. Materials and Methods

The proposed method aims to identify suitable CBMs that may be implemented in the context of machinery life cycle extension. Therefore, it is suitable for all companies wishing to achieve more sustainable ways to conduct business. Most importantly, implementing CBMs allows the useful lifetime of the product to be extended and the resources required to make, use, and dispose of it to be optimized. This often paves the way to entering new markets and acquiring additional market segments. Given the multiple solutions, commercial or on-site developed [65], that are flourishing in enterprises with the advent of digitalization and the Industry 4.0 framework, the method rationalizes their potentialities and supports project managers in identifying how the tool may be the basis of CBMs. BM innovation capabilities can trigger a dynamic, sustainable competitive advantage for companies, increasing their importance for organizational strategy [66].

The approach has three main steps, as shown in Figure 1. Firstly, the correlation: the LCES and CBMs are classified and described through the correlation matrix; subsequently, the tools are attributed to the LCES; ultimately, prioritization is assigned and a roadmap toward CE is obtained.

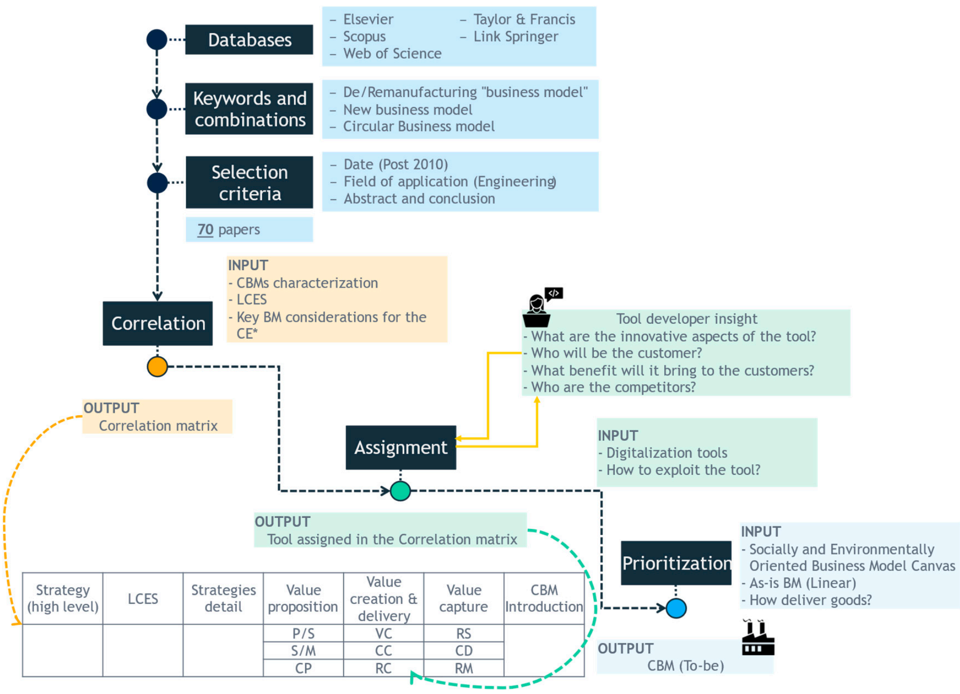

Figure 1. Method proposed to exploit digitalization tools' functionalities in the context of CBMs. * Key BM consideration for the CE adapted from [66,67].

Sections 3.1–3.3 describe in detail each step, starting from the CBMs' characterization, which is the main input of step 1, up to the ultimate phase, the prioritization. Boxes labeled with Databases, Keywords and combinations, and Selection criteria outline the methodology for reviewing the state of the art concerning CBMs. In accordance with the selection criteria (date and field of application, consistency of abstract and conclusions), 70 papers were analyzed in detail. In Figure 1, each step has its input (box on the right) and output (box below). The Correlation and Assignment phases contribute to obtaining the correlation matrix. The matrix obtained from the Correlation phase is generic, and for this reason, it is a tool provided to the future applicants of the proposed method. Industries or researchers provided with digitalization tools and looking for new CBMs can use the correlation matrix as a starting point. Subsequently, after having analyzed the tools, it is possible to attribute the tool to specific LCESs contained in the correlation matrix. The tool developer's insight is crucial to gaining an overview of the whole tool.

The input of the prioritization phase requires investigation of the present state of the company which is looking for new CBMs. This includes interviews, canvas sketching and similar actions aimed at describing their present way of conducting business (likely it is a linear model).

3.1. CBMs' Characterization

Figure 2 shows a characterization of CBMs. A BM can be considered as circular when: (i) it best manages all those resources already employed in products that reach their EoL or break and are not usable anymore, or (ii) it makes flows of resources (including whole products) circular. Alternatively, there are enterprises whose business is based on re-entering the resources into life cycle loops.

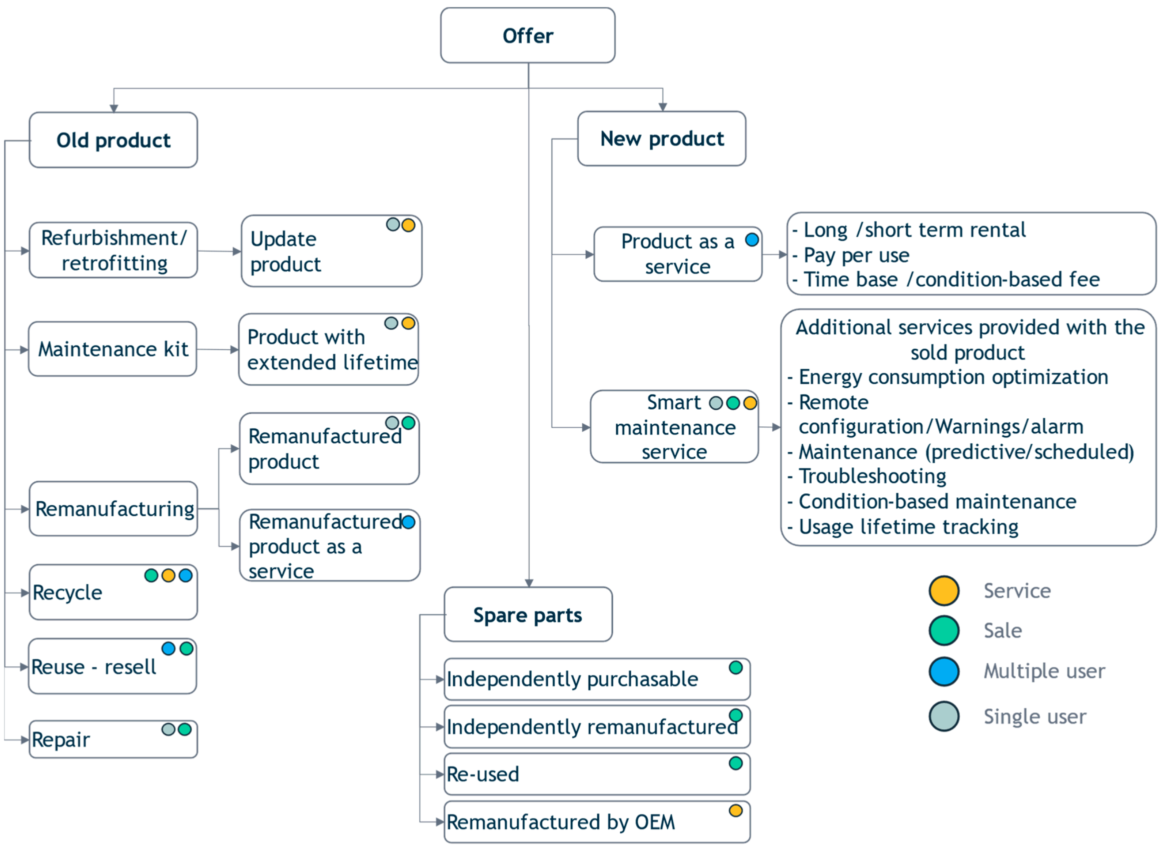

Figure 2. CBM characterization with a focus on the number of customers, novelty of products and offer type. Yellow bullet: A virtual/digital service that is offered to the client. Green bullets: A product is sold as in the traditional BM. Blue bullets: one stakeholder is involved in the product life cycle. Green bullets: multiple players use the product.

Figure 2 shows how the main CBMs retrieved by the literature review are clustered according to what is provided to the client. Spare parts are duplicates to be replaced in lost, damaged, or outdated parts of products.

Green bullets are often associated with servitization and unvaried ownership, except for the reuse and resell case, where the number of users is expressed by the loops of the life cycle (how many times the product is sold).

3.2. Correlation

In the first step, the literature has been reviewed so that the approaches that have been validated can be associated with LCESs. The literature examined both academic results and success stories from enterprises that have already incorporated and introduced CBMs into their realities. As multiple BMs are appearing with the advent of CE, the inquiry aims at identifying possible examples to follow and strategies to exploit. The connection between sustainability, the manufacturing process, and digital innovation is strictly linked to disruptive business reconfiguration [68]. Therefore, circularity often couples with servitization, and attention must be paid to strategies that appeal to servitization and digitalization to pursue the goal of making a profit sustainably.

The correlation phase is partially based on the framework proposed by Geissdoerfer et al. [66]. It has been expanded and the LCESs were introduced as a lower level of the BM previously proposed (cycling, extending, intensifying, materializing). For example, predictive maintenance is a strategy that extends the product's useful time; by doing so, it is encompassed as a sub-group of the extension strategy. The additional information about the types of innovation has been located next to the information regarding the value proposition, the value creation and delivery, and the value capture. According to the literature review results, potential CBMs are described within the table; multiple BMs may refer to a single strategy.

At the end of this phase, the correlation matrix is structured. To fill all the cells, the guidelines are provided. As far as the value proposition is concerned, it may be as a physical product or a service (P/S); the customers and the market segment they belong to should be defined (S/M); and similarly, the problem the value proposition addresses, namely customers' difficulties, should be defined. This is the core point of the value proposition, because firstly, the customer detects the benefits that would be perceived from what is proposed, and only subsequently, further evaluations are made.

The further findings are related to value creation and delivery, which sums up the steps, for example, value and supply chain (VC), human resources (CC), and capabilities employed in building the P/S (RC). As the correlation referred to the LCESs, and general BMs, the data entered may be widely valid; however, multiple differences may arise from the correlation of the BM available.

Ultimately, the Value capture section investigates the potential cash flows (both expenditures—CD—and incomes—RS) associated with the current BM. What often distinguishes a CBM from a traditional BM is the revenue model (RM), as it may introduce additional strategies by which the P/S provider can be paid.

It is essential to define whether the proposed value, which the customer would pay through an (innovative) RM, transforms the business as usual or opens new paths to acquire customers.

The main outcome is the correlation matrix, whose headings are in Figure 1.

3.3. Assignment

In this second phase, the potentialities of available digitalization tools are exploited. The tools under consideration may be one or multiple, both commercial and developed in a specific industrial context. Therefore, the methodology may be integrated into the decision process when the development of certain tools must be prioritized against others. In this case, it is important to consider each tool's main functionalities and features. These may not be strictly related to the LCES; instead, the tools may be initially used for different purposes (i.e., process monitoring, quality control, defect detection, human error avoidance). However, they can be useful in extending the product's life cycle. Each analyzed tool must be allocated to the correct LCES, according to its features and functionalities. A single tool may be assigned to more than a single strategy. The tools are part of the core resources and capabilities of the CBM.

The OEM may play different roles when it comes to the use of tools. An enterprise may be the one developing a digitalizing tool but can also be the one who makes use of it; for this reason, the Assignment phase may be supported by the organizations who develop the tool and to verify or suggest the OEM's expectations.

Workshops, interviews, and questionnaires are helpful to support the tools' investigation and allocation.

3.4. Prioritization

The last point is about selecting which strategy best fits the company. There might be multiple chances to employ a single or a bundle of tools and make them the core of an innovative, eco-friendly way to commercialize goods or offer services. Nevertheless, it is necessary to schedule and prioritize the introduction of innovative aspects. Thus, a sorting of strategies is needed. This first consists of selecting those that best fit the OEM's case and then evaluating the urgency and feasibility of the implementation. In doing so, a comparison between the initial BM and the planned CBM is needed.

Most importantly, the full BM canvas, that also assesses the environmental and social benefits/impacts, should be used, which enables a wider overview of the starting state [69]. The introduction of a CBM has consequences not only on the revenue streams and customer relationship aspect; it also may influence multiple factors, such as key partners, key resources, channels, etc. Not ultimately, the actors in the supply chain and/or their role. For example, when a pay-per-use system is introduced, all players responsible for the RL acquire a proper, official position, confirmed and/or managed by the OEM. Without the pay-per-use system, this was a nonexistent role because, in the trade model, a product is discarded by the user and then treated as waste.

As each single tool may pave the way to very different CBMs, their comparison can lead to an implementation roadmap, where, little by little, the BM evolves or the innovative CBM is introduced. Introducing key performance indicators may help to evaluate when a certain roadmap step is successfully exploited and the organization is ready to step forward to the next one.

4. Results

4.1. Correlation Matrix

When multiple tools are available, and a rationale is needed to understand how they can be exploited for establishing CBMs, the first step is to correlate the results of the state of the art that enlightened the multiple CBMs and the LCESs.

It is important to note that a single, high-level strategy can be explicated in more than one LCES. Likewise, each of the latter can stand under multiple value propositions. Table 1 summarizes the outcoming correlation matrix, where only the value proposition for each BM is outlined. The CBM introduction column integrates information regarding how the corporation may introduce the innovative BM. The cases in Table 1 relate to acquisition and diversification. The first refers to innovative channels and ways to sell (additional) products or provide services that enter the business. Diversification instead consists of selling/offering a value different from the traditional selling/buying model, with the traditional business remaining in place. For example, the case of selling maintenance kit falls under diversification because the traditional trading system is maintained. However, additional products are added to the portfolio and are provided as a service. On the contrary, when a machine is remanufactured and provided for rent to new customers, this is a case of acquisition because the CBM is acquired and placed next to the existing one, not in its support. Transformation does not appear in the table because the identified CBM may be placed next to the traditional one.

Table 1. Circular value proposition and strategies correlation.

Strategy (High Level)	LCES	Value Proposition	CBM Introduction
Cycling	Resell–Reuse	Used machine take-back	Acquisition
	Pay per use	Machine as a service (rent- subscription/pay per use)	
		Remanufactured machine as a service	
	Recondition	Reconditioned machine	
	Refurbish	Machine refurbishment	
		Back in box spare parts	Diversification
	Cannibalization	Used machine take-back	Acquisition
	Recycle	Used machine take-back	
	Remanufacture	Remanufactured machines	
Extending	Repair or Corrective Maintenance	Remote/automatic troubleshooting AR maintenance	Diversification
		Spare parts/modules rent	
	Preventive Maintenance	- Remote configuration, statistics and alarms - AR for maintenance	Diversification
	Predictive Maintenance	- Remote configuration, statistics and alarms - AR for maintenance - Usage lifetime tracking	Diversification
	Time-based Maintenance	Maintenance kit	Diversification

The cycling strategy includes all those CBMs whose value proposition enables the establishment of (closed) loops of use of resources, both as they are (resell/reuse) and in a different state (i.e., reconditioned). The core of the value propositions accounted for by the strategy extends the use of resources to a longer timeframe through maintenance optimization, monitoring, and control of the machinery.

4.1.1. Reuse-Resell

The resell-reuse strategy has multiple elements in common with cannibalization, as both require a product to be disassembled, parts to be inspected and their selection to be re-employed, either for being resold or reintroduced in other products internally managed. The following tables describe the content of the correlation matrix in detail. The cells were filled considering the existing literature and the outcome of the literature search regarding the success stories of existing companies. Table 2 shows the part of the customization matrix, related to the resell–reuse strategy. This strategy can be carried out by industries or private businesses; however, in the current study only the first case is considered.

When attributing a piece to reuse or resell, a defect must necessarily be classified, since the entities of the defects determine if a piece can be reused, remanufactured or must be discarded or employed in different sectors. Kin et al. [70] propose a criticality rank as an assessment of the defects. At the moment, the decision is mostly up to worker experience, and an extensive human intervention is required for feature recognition and knowledge interpretation [71]. This makes the classification costly and vulnerable to human error. In this field, AI can be a very powerful way to detect and cluster the status of components and make the process much more flexible [72].

Table 2. Correlation matrix, reuse–resell.

Value Proposition		Value Creation and Delivery		Value Capture	
P/S	Sell used full products or parts of it	VC	RSC management operations (take back)	RS	Revenue models based on used parts of product sale
S/M	Segment of existing or new customers	CC	Capacity management (demand and supply of products)	CD	- Machine disassembly/inspection/re-assembly - Logistics costs
CP	Need machine but with lower initial investments	RC	Machine experts or specific tools able to understand the state of the part/product	RM	Sale

Similar considerations about product inspection and defect classification are valid also for other strategies, such as pay per use, remanufacture, and refurbishment, as they all expect the product to be returned after the user discards it and has inspected it to evaluate which strategy better fits the component/product case.

4.1.2. Pay per Use

In the pay-per-use (Table 3) strategy, machines as a service and remanufactured machines as a service were included. The two value propositions are similar, except for the state of the machine that is provided. For more clarity, aspects that differ between the two CBMs are highlighted in different colors.

Table 3. Correlation matrix, Pay per use.

Value Proposition		Value Creation and Delivery		Value Capture	
P/S	Machine as a service Remanufactured machine as a service (grey)	VC	- Services operations - SC/RSC management operations	RS	- (Reman) machine is provided by time/activities - Lower cost of spare parts supply - Reimbursement from dismantlers
S/M	Segment of existing or new customers	CC	- Machine maintenance - Capacity management (grey:) - Machine maintenance - Capacity management - Machine remanufacturing	CD	- Maintenance - Machine disassembly/inspection/re-assembly - Logistics costs
CP	- Pay only when the machine is needed - Lower total cost of ownership and/or lower up-front investments - Have functionality or temporary availability of products, no ownership	RC	- Digital capabilities - Service network collaboration - Long-term customer relationship - Contract and customer relationship management (grey:) - Suppliers outsourcing and collaborations to close the loop - Disassembly, inspection, evaluation and assembly operations	RM	- Recurrent revenues from service temporary contracts - Pricing per unit of service (i.e., time, number of uses), rental or leasing rent

Grey background color marks characteristics of remanufactured machine as a service.

In the pay-per-use strategy the product is designed, materials are acquired and processed to obtain the finished product, then multiple customers use it.

The service may be provided under multiple revenue models, as a rent of the product, or under a subscription (time-based or cycle-based fee). Both are PSS, however, PSS was not born to support CBM specifically. Many organizations shift to PSS to reduce maintenance, remanufacturing, and up-grading issues, either from an economic or legal point of view [73]. The customers interested in renting a machine, or endorsing a subscription for it, may either be users who already know the product or new customers. They have in common the need to pay for the machine only when needed and face a lower total cost of ownership and/or lower up-front investments; they are not interested in owning the product, but rather to have it functioning when needed, even temporarily. As the product must be returned at the end of the subscription period, service and RL activities are crucial for the success of the pay-per-use strategy, where modules and components must be analyzed once returned. The inspection site may be the same or different from the OEM site. To make RL economically feasible many factors must be optimized: (i) the distance the product covers from the user to the facility to be reached; (ii) the means of transport it will travel by (road, rail, air transport or ship); (iii) the frequency of batch shipping; (iv) who is charged to pay (is the customer charged the purchase and the shipment costs or should these should be allocated to downstream products?); (v) stock management: taking into account the quantities of products aimed to be remanufactured and reused, will they be enough or will additional new spare parts be required? How to handle the floating availability of reworked modules/components (missing, late, defective, and non-available spare parts are a big challenge)? [74]; and (vi) the cost of core acquisition [75,76].

By service operations, all activities related to maintenance, and repair are included. In fact, when a customer gets a machine as a service instead of buying it, they implicitly expect the machine to always be well-functioning or whenever a failure occurs the user is not responsible for fixing it. When setting the fee, this is proportional to the guarantee ensured by the OEM and the limitations of roles and musts.

With running a PSS, the concept of delivery and Just in Time is partially modified. The service-provider must be careful when balancing the number of machines offered and the demand. In addition to that, the capacity demand does not only include the availability of machines for upcoming customers but also spare machines must be ready to be delivered to replace machines that face stops.

In contrast to the sale model, when a product is acquired by pay-per-use systems the user and the service provider may have multiple contacts; consequently, their relationship may last longer.

On a general basis, the EoL is a crucial phase, also because it requires high volumes to be optimized. The pay-per-use strategy gives an impressive advantage in this sense. The organization that offers the machines for rent has three main strengths: it may reach the high quantities that a single use may not fulfill, even with big machinery; secondly, it can gain considerable experience in treating goods at the EoL; ultimately, the big volumes may raise its profile to suppliers and all who may cooperate to close the loop, as gap exploiters, collectors, retailers.

4.1.3. Repair or Corrective Maintenance

Table 4 shows the part of the correlation matrix concerning the repair or corrective maintenance strategy. This is a well-known practice, widely applied also in linear economy contexts, since corrective maintenance is performed after a failure occurs, or detection of a fault. However, the advance of the Industrial Internet of Things (IIoT) and innovative practices can make this strategy more sustainable. First, organizations can be supported by companies that provide troubleshooting services, to release them from the burden of failure and faults. Remote troubleshooting may have multiple advantages because not only is time saved, but also transportation and the consequent impacts are lowered. AR and other KETs may be useful in easing maintenance demands. Corrective maintenance can be either adopted as an implicit service that comes together with a sold product or can also be apart from it and be offered as an additional service, whose extensions vary following the customer's preferences (customized/differentiated service packages). In the latter case, the customers who benefit from the packages may be both old and new. The size, the approach to maintenance, the location and multiple factors can influence the choice of adhering or not to the maintenance service. Nevertheless, a key point is the availability of data, connection, and sensors for those who take care of the maintenance and the machinery. The supply of maintenance is widely expected by the organizations, as they feel it is a non-core activity and do not wish to employ and increase expertise in secondary activities.

Table 4. Correlation matrix, repair or corrective maintenance.

	Value Proposition		Value Creation and Delivery		Value Capture
P/S	Troubleshooting AR maintenance Spare parts/modules rent	VC	Support maintenance phase/ service operations	RS	Revenue models based on service packages Revenues from storing services
S/M	- Existing/new customers - Segments of customers in need of expertise in certain non-core activities, convenience	CC	Knowledge of machine and failure cases	CD	Service maintenance costs Cost for warehousing and maintaining spare modules in good condition
CP	Willing to accelerate/make maintenance simpler	RC	- Digital capabilities - Service network cooperation Suppliers' management	RM	- Recurrent revenues from customized service packages - Platform fees

Grey background color marks characteristics of renting spare parts/modules for corrective maintenance.

When dealing with machines, downtimes are a major difficulty. The temporary unavailability of a machine can cause considerable losses. To avoid this inconvenience, enterprises resort to the stratagem of buying in advance (supposed) critical components, to store in their warehouses as spare parts. In addition to the costs incurred due to this attitude, problems can arise as spare parts need to be in the optimum state (i.e., electric motor). Being stored and not used can cause disorder (i.e., due to dirt and humidity) and missed functionality once the spare part is needed. The spare parts/module rent is a strategy that precisely tackles these issues. Instead of being bought and stored in the customer's warehouse, the OEM can offer the service of storing the spare parts, guaranteeing both their maintenance (also during the time they are not used) and rapid delivery when the module is needed. This practice has positive impacts both on the economy and the environment for two reasons: the OEM manages a higher number of parts, thus may have a convenient agreement for spare parts supply; secondly, the OEM arranges the required number of spare parts and customers avoid buying spare parts that may never be used and get damaged without being used (resources saving).

4.1.4. Predictive Maintenance

If machines are provided with sensors, data are analyzed and information about machine and process status is obtained, corrective maintenance may be anticipated, even in moments preceding failures. This is the case of predictive maintenance, whose matrix is shown in Table 5.

The BMs behind the different kinds of maintenance are very similar, however different are their value propositions and their objectives. While in corrective maintenance, failure may occur and no effort is put in to avoid it, in predictive maintenance pre-planned tasks are performed. The acquisition of data directly from the shop floor enables a huge range of activities, the tracking of usage lifetime among them. The phase of machine monitoring enables businesses to understand when and if a failure is about to occur. Sometimes the monitoring may also avoid the failure by anticipating the maintenance.

Table 5. Correlation matrix, predictive maintenance.

	Value Proposition		Value Creation and Delivery		Value Capture
P/S	- Remote configuration, statistics and alarms - AR for maintenance - Usage lifetime tracking	VC	Avoid physical interventions	RS	Revenues models based on service packages and/or tailored contracts
S/M	- Existing/new customers - Segments of customers in need of expertise in certain non-core activities, convenience	CC	Knowledge of machine and failure cases	CD	Service maintenance costs
CP	Need to avoid unexpected failures	RC	- Digital capabilities - Service network cooperation	RM	- Recurrent revenues from customized service packages - Platform fees

4.1.5. Time-Based Maintenance

Time-based maintenance is an additional, recognized type of preventive maintenance (Table 6). It consists of restoring or replacing a component regardless of the condition of the product. The scheduling and management of maintenance may result in annoyance and encroach onto secondary activities, even though they are crucial for the machine's safety. The supply of a maintenance kit may support enterprises. Through a subscription, the user can receive a maintenance kit based upon a set timeframe/number of cycles, so that it is known when to perform ordinary maintenance and what is necessary to substitute/repair.

Table 6. Correlation matrix, time-based maintenance.

Value Proposition		Value Creation and Delivery		Value Capture	
P/S	Maintenance kit	VC	Periodical shipment of maintenance kits to the customers	RS	Revenue models based on maintenance kit fee
S/M	- Segment of existing customers who wish to carry out maintenance autonomously - Segment of existing customers that did not buy original spare parts before	CC	- Machine/customer localization - Orchestration of suppliers - Capacity management (demand and supply of products)	CD	Maintenance kit logistics
CP	Need to avoid unexpected failures	RC	- Service network cooperation - Long-term customer relationship	RM	Revenue from providing maintenance kit (time-based)

Both the waste hierarchy and CE have evolved to emphasize the design and use of a product before it turns into waste. Therefore, they share a joint philosophy, aiming to manage waste by rethinking, redesigning, remanufacturing and repurposing in order to improve the resource effectiveness of a product and to reduce the generation and adverse impact of waste [77]. Depending on the status of the parts employed and the operated modules, the activities of taking old machines and restoring their conditions and functionalities or making new machines out of them refer to different LCESs and depend on the type and functionality of the products; for example, mechanical and electromechanical systems have to be separated from mechatronic systems [78].

4.1.6. Remanufacturing

The market of remanufactured products (Table 7) (as for reconditioned products, see Table 8) can be tricky for an enterprise. From the technical point of view, there are multiple barriers: firstly because the status that products come back in after the use phase is unknown and unpredictable, which directly affects inspection and disassembly times and costs. Disassembly automation can bring many advantages to disassembly tasks by applying the latest developments in I4.0 and cooperative and collaborative robots [72]. Some studies induced a physical phenomenon under controlled conditions to ease product de-manufacturing [24] or investigated eco-friendly approaches such as chemical ultrasonic treatment to separate all layers and components of electronic products [79]. The remanufacturing process may employ multiple technologies. Very often a winning strategy is the combination of additive (such as electroplating [80], welding [2,81], cold spray [82], and laser cladding [83,84]) and subtractive ones, i.e., Computer Numeric Control (CNC) operations, such as boring, turning, gross grinding, etc. [85].

All those strategies that expect partial action on the machine (i.e., remanufacture, refurbishment, recondition) also require an inspection that enables the go-not-go decision. In the specific case of remanufacturing, the parts or modules introduced come (if possible) from previously discarded machines (additional parts that enter the life cycle).

Table 7. Correlation matrix, remanufacturing.

Value Proposition		Value Creation and Delivery		Value Capture	
P/S	Remanufactured machines	VC	- RSC management (take-back) and remanufacturing operations - Acquire spare parts from discarded products	RS	- Remanufactured machine is sold - Lower cost of spare parts supply - Additional revenues from residual values of products/materials
S/M	Segment of existing or new customers	CC	- Machine remanufacturing - Capacity management (demand and supply of products)	CD	- Maintenance during guarantee - Machine disassembly/ inspection/re-assembly
CP	- Lower total cost of ownership and/or lower up-front investments - Need machine in good condition, but with lower initial investments	RC	- Suppliers outsourcing and collaborations to close the loop - Disassembly, inspection, evaluation, and assembly operations	RM	Revenue from high-quality products at lower prices

Table 8. Correlation matrix, recondition.

Value Proposition		Value Creation and Delivery		Value Capture	
P/S	Reconditioned machines	VC	RSC management (take back) and remanufacture operations	RS	- Reconditioned machine is sold - Lower cost of spare parts supply - Additional revenues from residual values of products/materials
S/M	Segment of existing or new customers	CC	- Machines are reconditioned - Capacity management (demand and supply of products)	CD	- Maintenance during guarantee - Machine disassembly/inspection/reassembly
CP	- Lower total cost of ownership and/or lower up-front investments, convenience - Need machine in good condition - Also not as new-, but with lower initial investments	RC	- Suppliers outsourcing and collaborations to close the loop - Disassembly, inspection, evaluation and assembly operations	RM	Revenue from reconditioned products sold at lower prices

4.1.7. Recondition

As well as the difficulties, the benefits are multiple. Among them, the customer faces lower initial investment, and resources are used more sustainably and efficiently. The lower price paves the way to the acquisition of new market shares, especially in the recondition strategy, because the requirements of the customer may be different from the traditional one (a reconditioned machine may not fulfill the overall functions of the new machine).

4.1.8. Refurbishment

The case of refurbishment is different (Table 9). In this case, especially in full machine refurbishment, the customer of the “old” and “refurbished” machine is the same. In addition to the benefits deriving from the machine update, the user can also obtain a smarter machine from the refurbishment. In fact, refurbishing a machine can provide it with a technological upgrade. Therefore, by incurring little expenditure, the user gets an old machine, that can be remotely monitored and switched on/off, connected to the industrial system.

Refurbishment provides similar contributions to the remanufacturing case, however, the customer along the whole supply chain remains the same.

The machine’s refurbishment may require the product to be moved to a specific facility for refurbishment. However, the strategy of returning the spare parts in the box employs refurbished components without moving the product. It consists of substituting certain damaged parts with refurbished ones. Those that are damaged are sent back to the manufacturer, instead of being thrown away, so that the OEM decides whether to refurbish or recycle them.

Table 9. Correlation matrix, refurbishment.

Value Proposition		Value Creation and Delivery		Value Capture	
P/S	Machine refurbishment	VC	Refurbish machines as in pilot cases	RS	Additional revenue through upgrade service
	Back-in-box spare parts		- Provided low-price spare parts - Reimburse the client for returning old part - Spare parts RSC management		Remanufactured spare part selling
S/M	Segment of existing customers that want their machines to be upgrade	CC	Supply chain management (if upgrades occur outside the shopfloor where the machine is installed)	CD	Refurbishment cost + machine analysis status costs (+ reverse supply chain cost)
	Segment of existing customers that did not buy original spare parts before		Spare parts refurbishment		- RSC, inspection, refurbishment costs - Cost for spare part residual value reimbursement
CP	Wish to have a keeping-up to times machine without investing a lot	RC	- Service network cooperation - Knowledge of machines + upgrading technologies	RM	Payment of refurbishment service
	Wish to pay less for maintenance but want guaranteed well-functioning spare parts		- Service network cooperation - Spare parts residue value estimation		Bosch Exchange—back in box

Grey background color marks characteristics of back in box spare parts.

4.1.9. Recycle and Cannibalization

CBMs can also support and push the recycling and recovery of parts from returned products (Table 10). What endangers recycling is the bad design of products (focused on functionality and manufacturing, not on EoL) and the lack of knowledge of the product.

The machine user may not be able to properly recycle the product because optimized recycling would require partial disassembly. Time, cost and inexperience make this ineffective and economically unsustainable. To gain increase convenience, disassembling a large number of machines is necessary. Dealing with high quantities of materials ensures higher refunds from recyclers, which may bring consistent incomes. Thus, the value reported in the table expects the machines to be collected after the use phase, properly disassembled (by selective disassembly) and the materials sorted in flows to optimize recycling.

The potential revenues from conferring the properly differentiated materials should exceed the costs of disassembly and cover the refunding of the customers. Similarly, the cannibalization strategy aims to recover parts of the products before they are recycled.

Therefore, this CBM may be coupled with others, such as those involved in reuse–resell, refurbishment, and remanufacturing strategies, because they also require the machine to be re-collected after the use phase. So, first, the parts of the machines are allocated to other machines or reworked, and the remaining resources are sent to be recycled.

Table 10. Correlation matrix, recycle and cannibalization.

Value Proposition		Value Creation and Delivery		Value Capture	
P/S	Used machine take-back	VC	- RSC operation - Suppliers outsourcing and collaborations (i.e., collectors)	RS	- Additional revenues from residual values of products/materials - Savings with reduced costs for resource input
S/M	Segment of customers who bought machines years ago and are replacing/dismantling the machine	CC	- Machine/customer localization - Recycling flow management	CD	Costs related to machine taking back (RSC) and preparing for recycle
CP	- Need to get rid of old machine in a sustainable way - Need a turnkey solution for machine dismantling	RC	- Access to core/EoL products/Selective disassembly - RSC	RM	Revenue model based on direct sales or trade of resources

4.2. Business Cases

The methodology presented, supported by the correlation matrix that has been developed, found an application in two industrial cases. One organization is a small–medium

German enterprise, active in the machining sector, which designs, produces and commercializes welding machines. The second is a large Italian enterprise that designs, produces and commercializes machines for wood- and metal-working.

Both the German and the Italian companies are OEMs and belong to the machinery construction sector. For the sake of discretion, in the following, they will be referred to as Company A and Company B respectively. Table 11 summarizes the main steps of applying the correlation matrix in the industrial contexts.

Table 11. Correlation matrix used in industrial context, workflow and tools.

Step		Tools	Resources Involved
1.	Company analysis	Structured interviews	Innovation manager
2.	Digitalization tools analysis	BM canvas	R&D manager
3.	Tools assignment	Correlation matrix	R&D manager
4.	CBMs prioritization	Correlation matrix BM canvas	Innovation manager R&D manager

Company A's clients are mostly large companies (B2B market) and belong to a niche market (mostly limited to automotive/industrial plants). However, they are located worldwide. Though the company currently takes care of the machine whenever damage occurs, there is no EoL treatment, neither is it known what happens to the machine when it is discarded. Company A provides both machines and after-sales services and its value proposition may be summarized as follows: to provide a high quality, durable friction welding machine that meets the customer's needs in terms of welding application and has the right dimensions. Compared to its competitors, the small size of the company allows for a different cost structure and, therefore, a cheaper offer. Revenues are generated from selling the welding machines, spare parts for critical components (e.g., welding heads), machine maintenance (head, motor, spindle), and small-series production of welded components. Each machine requires many laboratory tests before production and is characterized by a high degree of customization.

As far as Company B is concerned, the value proposition can be stated as follows: to provide reliable woodworking machines, and support in the maintenance phase through after-sales service and the supply of spare parts. The customers of company B are located worldwide and can either be amateurs (B2C) or industries (B2B), ranging from small carpentry shops to large enterprises. They are offered the opportunity to configure their machines based on the proposals in the product portfolio, but they can also choose to upgrade or add customized options. The larger the machine, the more likely it is to be customized. Company B is part of a group, and several enterprises in the group are close partners. The highly customized solutions lead to the acquisition of several patents every year, which protects the acquired know-how and the technology. Unlike Company A, which develops direct customer relationships, Company B relies on dealers or a separate commercial entity (belonging to the group) to reach customers. Consequently, established relationships are mostly indirect, with a few exceptions. Nevertheless, long-term relationships are established.

In both cases, the companies did not manage the EoL of the machines, nor did they obtain environmental or social certification.

The two companies present different characteristics (size, machine-damage management, and relationship with customers). Both organizations rely on external and in-house resources to develop digital solutions. Several tools have been developed and exploited to get information about the status of a product and its components during its life cycle, and the remaining useful lifetime, in order to extend it while keeping any action economically sustainable. For each tool, the main functionalities have been first investigated. This paved the way to the assignment phase: every CE-driven LCES was retrieved, and the tools were identified as core resources and capabilities of the strategies. One tool might be useful for more than a single strategy, and it may also be the case that a strategy is not enabled by any tool. Figure 3 graphically summarizes the main outcomes of the assignment phase.

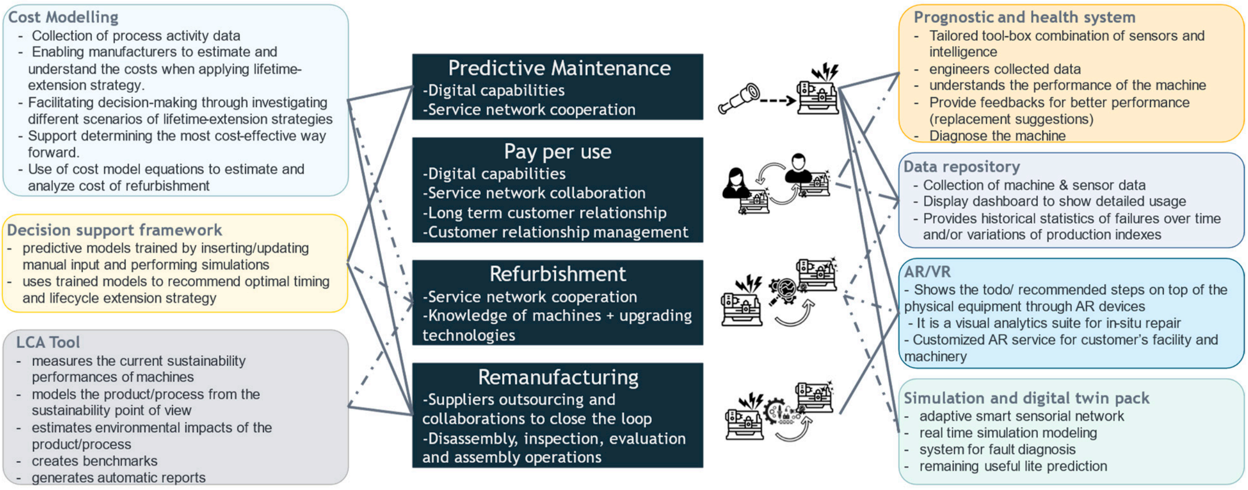

Figure 3. RECLAIM Tool assignment to the correlation matrix. Four LCESs were considered (pay-per-use, remanufacturing, refurbishment and predictive maintenance). For each tool, the main functionalities are summarized, while in the blue boxes, the resources and capabilities (RC) present in the correlation matrix are shown. As the functions of the tools are like those indicated for the CBMs, the link is established.

Both organizations were provided with multiple tools and the analysis of the current BM revealed that the businesses are closer to the traditional BM than the circular ones. In addition to some activities focused on digitalization, such as the machine connectivity of Company B, where digital services are provided through standard platforms and add-ons, maintenance, EoL management, and value offers are still bound to traditional schemas, when available. The roadmaps shown in Figure 4 were derived by prioritizing the implementation of CBMs according to the novelties they introduce; the more the CBM differs from the actual one, the later it is implemented.

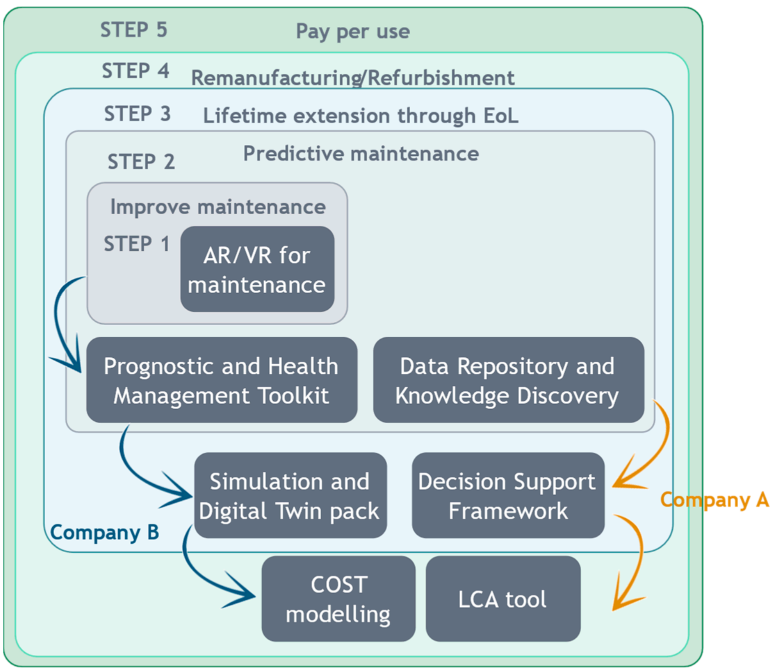

Figure 4. CBM roadmaps for Company A and Company B.

The roadmap is customized, according to the current status of the company. The very last strategy is the pay-per-use, however, several intermediate BMs were identified. The main potentialities of the roadmap exist in:

- Segmenting the complex metamorphosis process from linear to CBMs
- Simplifying the transformation by tackling difficulties and changes little by little.

By defining and respecting the roadmap, innovative and new approaches and activities can be introduced progressively without hampering the existing or new markets. In addition, a gradual change allows for a smoother and more seamless introduction of new roles and partners.

The roadmap supports the enterprises introducing digitalization tools and practicing the management of the used products they sell. First, the focus is on optimizing the maintenance of the operating machines. This can happen in situ, where the machine was produced, or where the machine was installed and the failure occurred. The main goal is to detect in advance potential failures and monitor the status of the machine so that the status of the components and modules is known. This first step requires the support of roles which were previously unnecessary, such as service providers, hardware suppliers, and data analysts.

Predictive maintenance can be investigated after managing traditional maintenance, which can be supported by innovative tools that decouple the physical machine and the maintenance operator's actions, so that then predictive maintenance can be explored. In doing so, it is necessary to be provided with a classification of the machine status, failure mode and causes so that off-standard events can be detected and unexpected failures avoided. Knowing the status of the machine and being able to handle and interpret unexpected behaviors paves the way to the modeling of a digital twin of the product to monitor its performance. Consequently, whenever the customer wants to discard it, the resources contained in the machine can be exploited most effectively (i.e., the best lifetime extension strategy exploited). This mastery leads to alternative models for providing goods as a service, rather than as a product.

5. Discussion and Conclusions

The transition from linear to CE is interesting for more and more enterprises. However, their management and direction departments, which have a leading role in guiding the company's transition towards the effective implementation of circular strategies, still need support, especially in the first steps of the transition [86]. There are several CBMs available to multiple genres of organizations, which are able to merge economic sustainability and its remaining pillars, the environmental one first.

However, each enterprise is characterized on its own. The present work proposes an approach to follow when an organization is figuring out which CBM best fits its practices. The main strengths of the proposed approach lay in the following:

- It supports the exploitation of digitalization tools; with the advent of the fourth and fifth industrial revolutions [87] companies equip their products and processes with innovative tools. Their potentialities can be exploited more deeply and enlarged to a wider perspective with the support of the proposed approach. The correlation matrix as it has been developed in its general form, stands as a base to be specified for the single organization, and thus digitalizing tools can be inserted between the core resources.
- It is based on qualitative evaluations, as it is designed to support the very first decision-making steps.
- It is widely applicable in enterprises of different sectors, as the correlation matrix can be customized according to the peculiar needs and features of the involved organization.

The transformation from linear to CE may require big changes in a company's organization, in its relationship with the customers, the roles and activities of key resources, and the revenue streams and modes. Consequently, existing realities need to, little by little, move towards the circular equilibrium. A precautionary strategy that prevents business from bumping into hazardous modes of business is to carry out a progressive change. Therefore, the importance of roadmaps that gradually open to new BMs is apparent.

Each step of the roadmap introduces new tools, which are likely to be used for their main purpose in advance. However, the step in which they appear is the one when the LCES and the CBM specifically require them. Once the digitalization tool's functionalities are exploited in a step, they likely will still be used in the subsequent step, even if they are not reported in Figure 4.

The present work contributes to filling the gap highlighted in the literature [14] that claims that the application of digital technologies to machines already in use still needs to be documented. The identified research questions find answers through the introduction of the correlation matrix. The correlation phase of the methodology determines the LCESs and their relationship with CBMs, while the latter steps, namely assignment and prioritization, supports OEMs who are approaching changes to their BMs for exploiting tools already in use to implement innovation in their operations. The business cases provide two examples: the prioritization allowed for scheduling actions toward CBMs, starting from those closer to the current BMs.

The methodology proposed offers a replicable approach and a tool, to support further application of the methodology, that is the correlation matrix.

Based on results from the business cases, guidelines for further application of the approach are provided:

- Clearly rationalize the tools available, focusing on their entire functionalities, not just the ones most used on a daily basis. This will help in having minor influences on daily routines and actions.
- Involve people with different roles in the company in the last phase, as they can contribute to building a more detailed description of the actual state.
- When defining roadmaps for new CBMs, prioritize the shift from actual (linear) to future (circular) business models, by picking those more like the present business model.

The companies were not provided with any validation procedure; however, they qualitatively provided feedback after following the proposed approach. The correlation matrix does not require specific resources to be used, although competencies with the know-how of the main operations of the company are needed. The acceptability of the framework is high as it consists of a simple tool (matrix) to reach the specific objective of being provided with a roadmap for new BMs. The implementation time varies depending on the choice of digitalization tools whose functionalities are investigated and whether they are new in the company. As far as effectiveness is concerned, the framework is a useful tool for the very first approach toward CBMs, otherwise is less of a strength.

As the approach is for the very first investigation of CBMS, the roadmap obtained as the output in the business cases is qualitative. Nevertheless, the definition of quantitative milestones for each CBM may help the roadmap to take a leap toward quantitative evaluations.

The current work investigates two industrial cases of companies producing machines with dissimilar functionalities and applications, and both companies come from the European manufacturing context. Future work may involve case studies coming from other geographical locations worldwide.

Future work should thus investigate and quantitatively set the boundaries of the ladders of the proposed roadmaps. For each step, Key Performance Indicators (KPI) should be defined to guide enterprises in running through the roadmap and reaching the final goal (pay-per-use CBMs in the case of two analyzed companies). KPIs should look at:

- The economic sphere: only when a new practice expected by the exploited step is well-established and economically advantageous can the company move to the following one; economical KPIs should not only observe the total revenues or incomes derived from a certain LCES, rather they might also evaluate the quantities of goods handled within that LCES. Specific KPIs should be defined for each LCES, as different strategies lay behind each LCES.

- The environmental and social sphere: each step of the roadmap should be sustainable within all the pillars of sustainability, and benefits involving proper management of the resources (i.e., materials, EoL processes, waste reduction) and the impact of the organization on its employees and the surrounding citizenship should be quantified and identified, prior to facing new challenges. For these two pillars of sustainability, the indicators should be defined as well for calculating methods for each.

The shift of BM involves a revision by stakeholders of the (re)production, disposal, and distribution phases. The changes may consist of a change of tasks and operations; additionally, roles and new actors that were not part of the traditional stakeholders may appear and become an active part of the product's life cycle. Therefore, a study focused on the resources involved in each LCES, for each life cycle phase, should be coupled with the above-presented approach.

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