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Organizational Maturity and its impacts in Product Development

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Abstract

INTRODUCTION: Life-cycle extension strategies have become critical enablers of circularity in product development. By emphasizing product longevity, reusability, repairability, and recycling capacity, these strategies aim to minimize resource consumption and waste generation while fostering sustainable value creation.
OBJECTIVES: This research paper aims to explore approaches for extending product life cycles across all phases, from design through manufacturing, use, and end-of-life. For companies seeking to extend the longevity of their products, it is essential to understand the main principles in product life cycle extension (PLCE) but also to evaluate their maturity before implementing such strategies, in order to be sure that the best decision will be made. In this context, this work introduces an innovative methodology designed to support decision-making process by helping companies identify critical aspects that influence successful PLCE.
METHODS: The present study explores principles relevant to PLCE, including durability, modularity, repairability, reusability, and recyclability. In addition, the role of emerging technologies such as artificial intelligence and additive manufacturing in supporting PLCE strategies, particularly in applications such as predictive maintenance, is analysed. The PLCE maturity model was developed and an assessment was conducted using a structured questionnaire designed to capture and classify influencing factors across three domains: organizational, cultural, and technological. To validate the methodology, the assessment was applied to three manufacturing companies.
RESULTS: The three use cases provided specific answers to the questionnaire that were reflected into different maturity levels. These results highlight the relevance in developing a methodology that support decision-making in product development focused on life cycle extension. The implementation of this structured methodology allowed to release specific guidelines that enable the improvement of PLCE through strategies that targets company's needs.
CONCLUSION: Through a maturity assessment applied in three manufacturing companies, it was possible to characterize the readiness level for PLCE of each one and identify which issues should be worked on and what aspects are already mature in the company. With this knowledge in consideration, the companies can now make informed decisions of their next steps in innovation and management of their products' life cycle.

Keywords: Digitalization, Industry 4.0, Industrial Processes, Maturity, Life-Cycle Extension.

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1. Introduction

In recent decades, the limitations of the linear economy have become increasingly apparent, particularly in relation to sustainability, social equity, and economic resilience.

This traditional "take-make-dispose" model is fundamentally unsustainable, relying heavily on finite natural resources and generating significant waste, both of which contribute to the worsening climate crisis. As global awareness of these challenges grows, alternative models have emerged, with the Circular Economy (CE) gaining notable attention [1].

The CE model promotes the efficient use of resources by minimizing waste, maximizing the value extracted from materials, and closing the loop of product life cycles [2]. This approach is central to sustainable development, supporting socio-economic growth while preserving the environment.

However, despite its many advantages, CE still faces significant barriers. Grafström and Aasma [3] categorize these into four main areas: technological, market-based, institutional, and cultural. **Table 1** outlines these barriers in the global market, detailing their specific characteristics and impacts within each category.

Table 1. Circular economy barriers [4-10]

Category	Barrier's description	Mitigation
Technological	Recycled materials with poor quality; lack of infrastructure for adequate waste recycling management; lack of expertise in working with recycled materials.	Develop advanced recycling technologies; enhance material traceability; standardize material grades; increase research & development (R&D); adopt Internet-of-Things (IoT)-driven waste management systems; organize training and upskilling programs.
Market	Virgin raw materials cost less than recycled materials; products with low end-of-life (EoL); lack of a supply network/chain for dismantled products, components and recycled materials; high labor costs; lack of design tools for circular business models.	Promote CE and upcycling solutions among producers; promote platforms that connect the entire value chain; promote the interaction between financial managers to invest in circularity and the related benefits; award products and companies that stand out for their integration of CE principles.
Institutional	Lack of waste recovery policies; lack of support from public organizations; limited financial resources; poor environmental regulations and laws; complex and overlapping regulations.	Government's support; sanctions for non-compliance and incentives compliance; creation of CE laws; funding for CE research; subsidize technology for CE; reduced taxes and duties on green products; penalties for non-compliance; pressure governments to include part of the state budget for CE practices.
Cultural	Lack of consumer's interest and knowledge about CE models; Reluctance of companies in sharing materials with other companies and consumers; customer and public unawareness.	Awareness through social media; workshops and training on the importance of the CE; public education in sustainable practices; advertising that encourages CE.

A central strategy to addressing these challenges lies in enhancing product design and development processes, which serve as key enablers for embedding CE principles across industries and society at large [11]. One of the primary objectives in sustainable product design is extending product lifespan, which Bakker et al. [12] defines as the duration between a product's acquisition and its eventual disposal by the final user. Extending this lifespan contributes significantly to minimizing material waste and, in turn, reduces the demand for virgin raw materials and the environmental impacts associated with intensive production and processing activities [13].

Leube and Walcher [14] emphasize that the successful integration of CE principles into product design depends on several critical factors. These include the strategic selection of sustainable materials, the development of modular designs that facilitate disassembly, repair, and part reuse, and the adoption of open innovation and co-creation practices. Such practices promote collaboration between companies and end-users through shared knowledge and continuous feedback loops.

This vision aligns with the findings of Bocken et al. [15], who identify two primary design strategy groups essential to slowing and closing resource loops. The first group focuses on extending the use-phase of products by enhancing emotional durability, improving physical reliability, and enabling product maintenance, repair, upgrade, disassembly, and reassembly. The second group draws from the Cradle-to-Cradle design philosophy, as introduced by Braungart et al. [11]. This philosophy distinguishes between two cycles: the technological cycle, which encourages safe and continuous recycling of materials; and the biological cycle, which emphasizes the use of safe, biodegradable materials that nourish natural systems throughout their lifecycle.

Effectively addressing these multifaceted challenges calls for a holistic approach—one that incorporates innovative design practices within the broader product development process. To reinforce the success of such initiatives, it is essential to adopt maturity models that assess an organization's preparedness and guide its alignment with supportive regulatory frameworks and collaborative business ecosystems.

The integration of maturity assessments plays a pivotal role in enhancing the implementation of Product Life Cycle Extension (PLCE) strategies, which are vital for advancing circularity, sustainable manufacturing, and long-term competitiveness. These assessments offer a structured methodology to evaluate an organization's existing capabilities, resource allocation, and overall readiness to implement circular practices, by identifying capability gaps and aligning PLCE strategies with broader sustainability goals [16].

Additionally, these assessments enable organizations to tailor PLCE initiatives to their specific industry context and operational constraints, avoiding the limitations of generalized, one-size-fits-all models [17]. They also foster a culture of innovation by encouraging the exploration of new design methods, alternative materials, and circular business models—key elements in extending product lifecycles [15]. Moreover, maturity models help mitigate risks related to change resistance and inefficiencies by enabling companies to anticipate obstacles, design mitigation strategies, and improve stakeholder engagement. This collaborative dynamic is especially critical when working across complex supply chains and with regulatory bodies, both of which are essential for a successful transition to a CE framework [18].

In this context, the present study investigates PLCE strategies through a focused literature review that bridges product design, life cycle thinking, and organizational maturity models. The objective is to develop a comprehensive assessment framework capable of evaluating the maturity levels of companies across various industrial sectors. By linking the adoption of PLCE strategies with organizational readiness and capability, the model aims to support more effective implementation and contribute to the achievement of broader sustainability objectives.

2. Literature review in life-cycle extension strategies in product development

2.1. Product life cycle in product development extension approach

The Product Life Cycle (PLC) comprises several sequential stages: raw material extraction, resource processing, manufacturing, distribution, usage, and EoL. At the EoL stage, products typically follow one of two primary pathways—recovery or disposal, with disposal usually involving landfilling. Recovery encompasses a range of circular strategies including reuse, repair, remanufacturing, and recycling, all aimed at minimizing waste generation and conserving resources [19]. Over time, the PLC concept has evolved to incorporate these sustainable strategies, supporting both the closure and extension of product life cycles in alignment with CE principles [20].

It is important to distinguish this sustainability-oriented view of PLC from the market-oriented PLC framework, which primarily tracks a product's commercial performance across its introduction, growth, maturity, and decline phases. Nonetheless, these frameworks are inherently interconnected. Embedding sustainable lifecycle strategies into product development not only extends physical longevity but also enhances a product's competitiveness and resilience in dynamic markets.

When a product enters the market, it represents the culmination of the design and development phases. A robust and forward-thinking design phase plays a pivotal role in determining the product's capacity to sustain prolonged growth and maturity phases. During the growth phase—characterized by rising consumer demand and market penetration—manufacturing processes must emphasize efficiency, scalability, and innovation to meet performance expectations and environmental targets. As the product transitions into maturity, the strategic focus shifts toward maintaining relevance and extending usability. This can be achieved through lifecycle management interventions, such as offering product upgrades, facilitating maintenance, and enhancing adaptability to evolving user needs.

The decline phase in the market-oriented PLC is often a result of stagnation in innovation or lack of strategic lifecycle planning. However, this decline can be delayed, or even mitigated, through design strategies that promote lifecycle extension. Incorporating features like modularity, reparability, upgradability, and recyclability ensures that products can be more easily adapted, maintained, or repurposed over time. These attributes not only enhance the product's functional longevity but also reinforce its market competitiveness.

By establishing a strong linkage between the physical stages of the product lifecycle and circular lifecycle extension strategies, companies can significantly prolong the maturity phase and delay obsolescence. This integrated approach supports CE objectives by ensuring that products retain value longer, reduce environmental impacts, and optimize resource efficiency. Ultimately, it fosters a product ecosystem where sustainability and market performance reinforce each other, advancing both economic resilience and environmental responsibility.

2.2. Product life cycle extension approaches

PLCE represents a set of strategies and actions to be implemented to increase the lifespan of a given product, machine or system, while ensuring its functionality, usefulness, and relevance, which results in a slowdown in the materials flow. These strategies are applied throughout the different PLC stages, starting with product design and ending with EoL. From this concept, several approaches can be implemented. In this study, a link between the most relevant strategies and the different stages of product life cycle was performed and summarized in **Figure 1**.

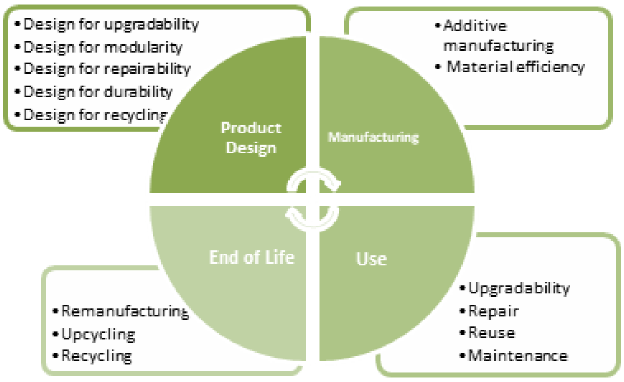

Figure 1. PLCE strategies through PLC.

Product design phase

The product design phase is crucial since the characteristics, functionalities, and structure of a given product are defined [21]. Under this phase, the term design for excellence (DfX) emerges as a product development approach that aims to optimize specific aspects represented by X. This X can correspond to the durability, modularity, repairability, upgradability, among others, depending on the priorities of the project [22]. **Table 2** provides an overview of the main DfX objectives related to PLCE.

Table 2. An overview of DfX methods [22-24]

Domain (X)	Objective
Design for durability	The aim of this design is to choose durable materials that promote PLCE.
Design for modularity	The aim of this design is to simplify the product structure, while maintaining the original product value and functions, by creating independent and interchangeable modules. These independent parts, when combined, form a final product.
Design for repairability	The aim of this design is to simplify the repairing processes, by reducing disassembly times, reducing the cost of spare parts and increasing the availability of these parts.
Design for recycling	The aim of this design is to increase the use of recycled materials in the product development stage, as well as facilitating the recycling process at the end of its life cycle.
Design for upgradability	The aim of this design is to draw up an update plan for the various generations of a product during its use or reuse phase.

Manufacturing phase

Additive Manufacturing (AM), commonly known as 3D printing, has emerged as a transformative technology that enables companies to rethink and redesign products with an emphasis on dematerialization. By optimizing material usage and reducing waste, AM enhances efficiency across multiple life cycle phases, material consumption, energy use, production costs, and logistics, thereby supporting sustainable manufacturing goals. Moreover, AM serves as a powerful enabler of PLCE, particularly through facilitating repair, remanufacturing, and modularity. These capabilities support service-based business models and contribute to embedding CE principles into production and consumption systems [25]. AM introduces several key opportunities for innovation and PLCE implementation [26]:

i) Enhanced Product Design Flexibility: AM allows the rapid development of multiple iterations of a product design, enabling continuous refinement and customization to better meet user requirements. This adaptability not only shortens development cycles but also improves overall product performance by integrating reliability and durability from the design stage [27]. Additionally, it supports the creation of components that are easier to maintain, repair, and upgrade—critical strategies in prolonging product life [28].

ii) Localized and Decentralized Production: One of the most impactful benefits of AM is its capacity for localized manufacturing. By reducing dependency on extended supply chains, AM minimizes transportation needs, which translates to lower emissions, reduced logistical costs, and diminished risk of product damage during transit. This localized approach enhances responsiveness to local market demands and directly supports PLCE by enabling on-demand production and easier access to spare parts [29].

iii) Product Compatibility and Adaptability: AM promotes interoperability and compatibility by enabling the production of parts that can be adapted across various models or equipment types. This not only extends the service life of products but also fosters system-level sustainability by allowing components to be shared, replaced, or upgraded across product lines. Such design flexibility encourages collaborative maintenance practices and shared access to resources, reducing material redundancy and promoting circularity within product ecosystems [27].

These characteristics position AM as a key technological enabler in the transition to circular manufacturing. By aligning design innovation with circular objectives, AM supports the creation of products that are more adaptable, maintainable, and resource-efficient, ultimately extending their lifecycle and reducing environmental impacts. Furthermore, its integration into business models that prioritize service delivery over product ownership amplifies its potential to transform traditional manufacturing paradigms toward more sustainable, circular alternatives.

Use phase

The use phase is a crucial moment in the PLC, by fulfilling its function and being used, and it is characterized by different approaches, namely:

- Reuse: The European Parliament [30] defines reuse as the use of products or components that are not waste for the same purpose they were originally conceived. The best tool to assess if the product must be repaired, reconditioned, or reused is through intelligent maintenance. By analyzing historical and real-time data, this system provides an action plan that acts to correct or prevent failures, underlining causes and providing recommendations to prevent failures [31]. In addition, using statistical data and digital twin technology, it is possible to predict future failures or the remaining useful life (RUL) of the equipment. This prediction is very advantageous, as it optimizes decision-making processes when maintenance activities are required, thus avoiding shutting down machines when not necessary [32];
- Repair: It is the correction of one or more specific faults in a product or equipment to keep it functional. As a rule, the quality of the repaired products is inferior when compared to reconditioned and remanufactured products [33];
- Recondition: Reconditioning involves more effort than repair but less than remanufacturing. It often includes rebuilding or replacing the primary faulty components. However, because the product isn't fully restored to a like-new condition, it may still be susceptible to the same issues commonly found in repaired items [34].
- Upgradability: Even though consumers may be satisfied with the lifetime of their everyday products, several empirical studies suggest that the median lifetimes of consumer products are in decline [12]. Rapid technological cycles, frequently changing consumer preferences and increasing market competition, provide consumers with an opportunity to use products with more functions and better quality at a cheaper price [35]. Consequently, these products quickly become technologically (due to innovation through new knowledge), psychologically (due to changes in consumers' perceived need), or economically (due to high costs of repair and maintenance) obsolete [36], even before the end of their actual physical life/ economic value [37]. This functional depreciation ultimately results in shorter product life cycles [38]. To address these challenges, integrating upgradability into product design becomes critical. Upgradable products allow for incremental enhancements, extending their functional life and reducing the frequency of replacement. This approach aligns with CE principles by minimizing waste generation and conserving resources through reuse and refurbishment and fostering consumer trust and engagement by offering sustainable and cost-effective solutions.

EoL phase (upcycling, remanufacturing, recycling)

At the EoL of a certain product, several approaches can be considered to avoid disposal, such as remanufacturing, recycling, and even upcycling [39].

Upcycling consists of a process that transforms products that can no longer be used and are about to be discarded into more valuable products through repair and remanufacturing techniques. These products can even acquire new functionalities. In contrast to recycling, upcycling maintains the resource quality and increases the overall value of the product [40].

Remanufacturing is both a CE strategy and an industrial product recovery process. This approach consists of collecting used products and then sorting, cleaning, repairing, and finally combining them with new parts to sell them as new [41]. It restores products in their EoL so that they return to their original condition with the same quality and performance, minimising waste and resource consumption [42].

Recycling involves the breakdown of the product into its basic raw materials, thereby taking away its original energy and value, and this needs the input of additional energy and resources to make it a usable new product [41].

2.3. Challenges and opportunities

While emerging technologies such as AM, Artificial Intelligence (AI), and the IoT offer significant promise for PLCE and CE strategies, several challenges must still be addressed to fully realize their transformative potential. These challenges span technical, organizational, and socio-economic dimensions, and their complexity often hinders the seamless integration of digital innovations into traditional manufacturing systems. **Table 3** summarizes some of the key challenges associated with the implementation of emerging technologies in the context of PLCE and CE, along with brief descriptions of their implications. Overcoming these challenges requires a comprehensive and collaborative approach that involves active participation from producers, consumers, technology providers, policymakers, and other stakeholders. Central to this approach is the development and deployment of robust digital infrastructures that can support data integration, secure information exchange, and real-time decision-making across product life cycles.

Moreover, the adoption of emerging technologies must be supported by targeted investments in workforce upskilling, cross-sector partnerships, and adaptive regulatory frameworks. Only through such systemic collaboration can organizations unlock the full value of digital transformation in promoting circularity. Once these barriers are effectively addressed, emerging technologies will become key enablers of digital transformation, accelerating CE-related initiatives and enhancing the implementation of PLCE practices. Their capacity to improve traceability, enable predictive maintenance, support decentralized production, and facilitate closed-loop systems positions them as foundational tools in the shift toward sustainable and circular industrial ecosystems [43].

Table 3. Potential challenges in emerging technologies integration for PLCE and CE [44-47]

Barriers	Examples
Cost of implementation	Implementing digital technologies often demands a substantial initial investment in areas such as hardware, software, training, and infrastructure. For many organizations, particularly small businesses, this can pose a significant challenge.
Complexity and integration issues	Integrating emerging technologies into existing processes and systems that support PLCE can be complex and demanding, as it requires a workforce skilled in IT and data management.
Data privacy and security concerns	Managing the collection, storage, and sharing of large volumes of data presents a major challenge when using digital technologies. This process raises important concerns about data privacy and security, especially when handling sensitive information related to PLC.
Data quality and reliability	Ensuring the accuracy, reliability, and integrity of data gathered through digital technologies is essential for making informed decisions about PLC. The key challenge lies in establishing robust processes for data validation and quality assurance.
Regulatory and policy frameworks	The continual evolution of regulations, data protection laws, and privacy standards poses a major challenge for organizations implementing emerging technologies in their PLC. Beyond legal compliance, organizations must also adopt practices that align with ethical standards.
Interoperability and Standardization	The absence of interoperability, standardized protocols in digital platforms, and effective communication between organizations represents an obstacle when it comes to exchanging information and collaboration. These challenges limit the potential of digital solutions and does not allow progress in PLCE.
Resistance to change and cultural barriers	Integrating emerging technologies into PLCE has some challenges, including resistance to change and cultural barriers. This inertia can compromise the adoption and implementation of these digital technologies by organizations. To overcome these challenges, it is essential to involve employees in transformation processes and create an environment that is favorable to the acceptance of new technologies.

Governance plays an important role in regulating certain industries by enabling and restricting various activities. The transition to a CE and, therefore, PLCE activities is also influenced by policies and incentives [48]. Barriers to product repair activities concerning governance influence include legislation and tax programs, unavailability of repair services, restricting or controlling of spare parts and lack of complete, and clear manuals provided by the companies [49]. It is up to the companies to adopt Circular Economy Business Models (CEBM). Good CEBM involve effective collection, reuse, and recycling systems of products [50], [51].

At the same time, once a product is purchased, the one responsible for its end life management is the customer. Once the product fulfils its purpose or gets broken, it is up to the customer to decide how to deal with it, either by reusing or repairing it instead of replacing it. It was concluded that, in electronic equipment, the repairer and the customer have a major influence on the decision so that they both act as the main decision-maker and main performer of the repair [52]. Repair may also present some barriers for consumers. According to a systematic review, these barriers can be either related to the customer's repair convenience or the user's willingness to repair [49]. Barriers, like a high cost of repair services along with insufficient quality of them and time wasting, make repairing less convenient than replacing the product to a customer. As for the user's willingness to repair, the lack of trust and knowledge about repair services and its impacts summarize the uncertainty users have towards repair services. The lack of attachment to a product and the desire for a new one are also common reasons users do not opt for repair services.

At last, the product's architecture dictates its reusability, repairability and remanufacturing ability, having a fundamental role in these practices when designed for it [53]. The technical possibility of repair and remanufacturing can be limited if the product architecture is inappropriate, generating a few challenges to repairing a product like: complex and long dis/re-assembly [54]; nonmodular and unopenable products [55], [56]; and impossibility of updates/upgrades [49]. Challenges for reuse can be summarized in planned obsolescence [57] and low-quality or fragile materials [58].

To fully unlock the potential of emerging technologies for PLCE and CE, it is crucial to address the outlined challenges. Overcoming these barriers demands a multi-faceted approach that emphasizes collaboration among producers, consumers, and stakeholders, alongside significant investment in digital infrastructure. However, achieving this transformation also requires organizations to assess their maturity levels. Maturity assessments help identify gaps in technological readiness, cultural adaptability, and process alignment, enabling tailored strategies for technology integration. By aligning maturity evaluation with the adoption of digital solutions, companies can systematically overcome challenges, fostering an environment conducive to innovation and sustainable practices [59], [60]. Ultimately, this alignment ensures that emerging technologies drive effective PLCE and CE initiatives, propelling organizations toward long-term resilience and sustainability.

Different industries exhibit varying levels of readiness for PLCE. For example, the automotive industry products are already designed to be durable and easily repaired, whereas the electronic consumer industry, due to its fast technological advances and changing fashion, is less prone to lifecycle extension strategies [15], [50].

3. Maturity model

3.1. Maturity pillars

As discussed in the previous chapter, extending the life cycle of a certain product through reuse, repair, or any other strategy, depends on more than just the product itself. As such, three main key players in PLCE were identified as the pillars that should be focused on when assessing a product's maturity to PLCE:

(i) **Organizational** – It reflects the role of the company that manages the product and its life cycle. Product innovation, applying new and emerging technologies, comes from the company's motivation, capacity, and proactivity. Policies made by governments regarding environmental impact push companies to invest in CE practices. This pillar defends a clear and efficient interconnection between all the organizations to facilitate circularity in the product's ecosystem.

(ii) **Cultural** – It reflects the consumers' role and influence on PLCE. As awareness of sustainability and waste reduction keeps rising among consumers, they seek more durable and recyclable products. PLCE strategies should facilitate good consumer behavior, but ultimately it is the consumer's decision on how to deal with a product at the end of its use.

(iii) **Technology** – It addresses the actual product's capacity to be reused, repaired, remanufactured, and recycled. The product's design is a major factor if one wants to extend its life cycle, as properties like durability, upgradability, modularization, raw materials recyclability, among others, define the base possibilities of a product's future.

In every PLCE strategy, the three pillars always have a combined role.

3.2. PLCE maturity assessment methodology

After identifying the three main pillars of what it takes for a successful PLCE, the product's maturity is assessed through these same three criteria, in a structured and focused assessment. Through the maturity methodology, the assessor should be able to precisely pinpoint the weak points and therefore trace the correct strategies to improve a product's potential to extend its life cycle. The assessment of each maturity pillar can be made through several maturity factors, summarized in **Table 4**, which focus on specific key points that define the pillar's scope when gathered.

Table 4. Maturity factors for each pillar

Maturity pillar	Maturity factor
Organizational	Innovations strategy / planning
	Leadership involvement
	Corporate motivation and culture
	Interconnection between organizations
	Capital investments capacity
	Marketing
	Circularity implementation in design phase
	Employee training
	Eco-impact reduction programs
	Adaptable industrial processes
	Business models adaptation
Cultural	Company-stakeholder communication
	Customer integration
	Stakeholder awareness for product longevity
	Product attachment and trust
	Clear sustainable vision
	Ease of access to product repairability
	Openness to change
	Good consumer behavior
Technological	Technology implementation and availability to adapt
	Product modularity
	Ease of dismount and repairability
	Product Life Cycle Assessment

	Upgradability
	Product durability
	Usage of emerging technologies (ex: AM, AI, ML)
	Predictive maintenance
	Recyclable materials

Therefore, the assessor evaluates the product and company maturity by assessing each factor through a questionnaire to be completed by someone qualified and with in-depth knowledge of the company.

3.3. Maturity questionnaire

The questionnaire is structured according to the three key pillars of maturity: organizational, cultural, and technological. The questions asked have different answer formats. Some require a "yes" or "no" answer, others follow a scale between 1 and 5 (where 1 corresponds to "totally disagree" and 5 to "totally agree"). There are also multiple-choice questions, allowing more than one option to be selected, including the possibility to indicate an alternative that was not presented. In addition, each domain includes a final question where the interviewee can offer suggestions regarding PLCE.

Each type of question follows a normalization process resulting in an index, between 0 and 1. For yes and no questions, the scores would be 1 and 0, respectively. For multiple choice questions, the normalization process would either be cumulative alternatives (until maximum value of 1) or inverted cumulative alternatives (start with 1, decreases with each selected choice). For Likert scale questions, a simple mean was made for the index. At the end of the questionnaire, the average of these values is calculated, determining the maturity index of each pillar. Subsequently, an average is made between the three pillars, resulting in the overall level of maturity of the company where the questionnaire was applied. The normalization process could have taken into consideration a weighted criterion, giving more significance to certain questions or even pillars. However, the average criterion was deemed preferable as it provides more objectivity, better comparability and interpretability. Weighted scores can obscure meaning and introduce subjectivity [61].

For the organizational domain, 15 questions were made, for the cultural domain, 16, and for the technological domain, 19 questions were suggested. Overall, the questionnaire had 50 questions to assess the company's and product maturity.

The maturity factors are the inspiration for the questions, and at least one question was relative to each maturity factor, as seen in **Table 5**, in order to fully characterize the company and its product according to the methodology. This way, the results will tell which maturity factors are mature or lacking, simplifying the interpretation of the conclusions and the making of improvement guidelines for the company.

Table 5. Questions to each maturity factor

Maturity pillar	Maturity factor	Questions
Organizational (1-15)	Innovations strategy / planning	1,2
	Leadership involvement	3,13
	Corporate motivation and culture	4,14
	Interconnection between organizations	7
	Capital investments capacity	8
	Marketing	9
	Circularity implementation in design phase	10
	Employee training	5
	Eco-impact reduction programs	6
	Adaptable industrial processes	11
	Business models adaptation	12
Cultural (16-31)	Company-stakeholder communication	16,17
	Customer integration	18,19
	Stakeholder awareness for product longevity	18,28
	Product attachment and trust	19
	Clear sustainable vision	25,26,27,29,30
	Ease of access to product repairability	20,21,22
	Openness to change	23
	Good consumer behavior	21,24
Technological (32-50)	Technology implementation and availability to adapt	32,33,34,35
	Product modularity	37,39,40
	Ease of dismount and repairability	38
	Product Life Cycle Assessment	46,49
	Upgradability	42,43
	Product durability	44
	Usage of emerging technologies (ex: AM, AI, ML)	36
	Predictive maintenance	45
	Recyclable materials	47,48

4. Results and Discussion

After analyzing the various PLCE strategies, a maturity assessment methodology was suggested. When it comes to extending the PLC, there are several possibilities and phases when its producer and consumer can interfere. Due to the complexity of the scenario, the methodology is created to give simple answers to the assessor as to which steps should be taken. The maturity assessment is simplified by segregating the most important aspects of PLCE into three distinctive pillars. Then, each pillar is formed by various factors, which evaluate specific key aspects. Through these factors, the assessor can identify the readiness of its product, organization, or clients regarding circularity, and act accordingly.

The maturity assessment methodology also seeks to help the evaluator decide which phases of the product (conceptualization, manufacturing, use, EoL) need interference through the maturity factors. The selection of the correct strategies for PLCE should also be influenced by the information given by the maturity assessment. This methodology differs from sustainability-focused approaches [62] or other existing frameworks, like decision-making frameworks [63], by assessing the whole scenario around a product and not only the product's condition for LCE, and it is not as resource intensive as the Capability Maturity Model Integration (CMMI) models used for maturity assessments nor overlooks non-technical factors [64].

4.1. Use cases description

Three manufacturing companies served as use cases to implement the methodology and questionnaire, as they aim to apply PLCE in their products:

(i) Company A - a company that designs and constructs stone cutting machines
(ii) Company B – a company that manufactures bending machines, guillotines and other sheet metal forming processes
(iii) Company C – a company that designs and produces CNC machines

The PLCE actions that the companies are aiming for involve evolving their own products, without concrete knowledge of what the best strategies are. If the proposed actions focus only on the product itself to increase its value, they may introduce risks if other maturity pillars beyond the technological are overlooked. For example, if the organizational or cultural pillars score low, the changes to their products may prove ineffective. Companies might lack the financial flexibility to invest in new technologies or adapt their manufacturing processes. On the cultural side, customers may not possess the necessary skills or motivation to adapt to a newer version of the product.

In this context, a maturity assessment helps identify both potential risks and viable strategies for extending a product's life cycle. It is therefore recommended that any company looking to evolve its products through technological upgrades or new business models first assesses its overall maturity. This ensures that selected strategies are not only technically sound but also supported by the organization's readiness and capabilities.

4.2. Questionnaire results

Once all three companies had responded to the questionnaire, it was time to analyze the results. For company A, the overall score is 61%. Company B had a 62% average score and company C, with the highest maturity, scored 84% overall.

For easier analysis of the results, the scores were grouped together by maturity pillars, showcasing each company's performance.

Organizational

Figure 2 depicts the graphs with all the maturity factors of the organizational pillar of each company. According to the results expressed in the graphs, the companies differ their results in all factors, except for the "eco-impact reduction program", where all companies are excellent at it. For the organizational pillar, company A and B have similar scores, 0,63 and 0,61 respectively, whereas company C presents the highest score, with 0,74.

The factors that mostly undermine the organizational maturity of the companies are "interconnection between organizations" and "business models adaptation", whereas the factors that have good scores in general are "innovation strategy/planning", "leadership involvement", "capital investment capacity", "employee training", "eco-impact reduction program" and "adaptable industrial processes". Overall, company C has the best scores of the three companies in all factors, with the exception of "marketing", which is its worst result.

This analysis easily identifies which aspects of the organizational domain each company should improve in order to raise its receptibility for new changes.

Cultural

The graphs in **Figure 3** reveal the scores of the cultural maturity factors for the three companies. Once again, company C leads the results with a score of 0,88, followed by company B with 0,70 and, lastly, company A with 0,58.

"Stakeholder awareness for product longevity" appears to be the factor with the worst results for companies A and B. Company A also scored below average in "good consumer behavior". Overall, all companies score above average in the cultural factors, which means the companies' relationship with its customers and stakeholders is an advantageous one, and should be exploited to address the consumers and stakeholders about the new PLCE strategies implemented.

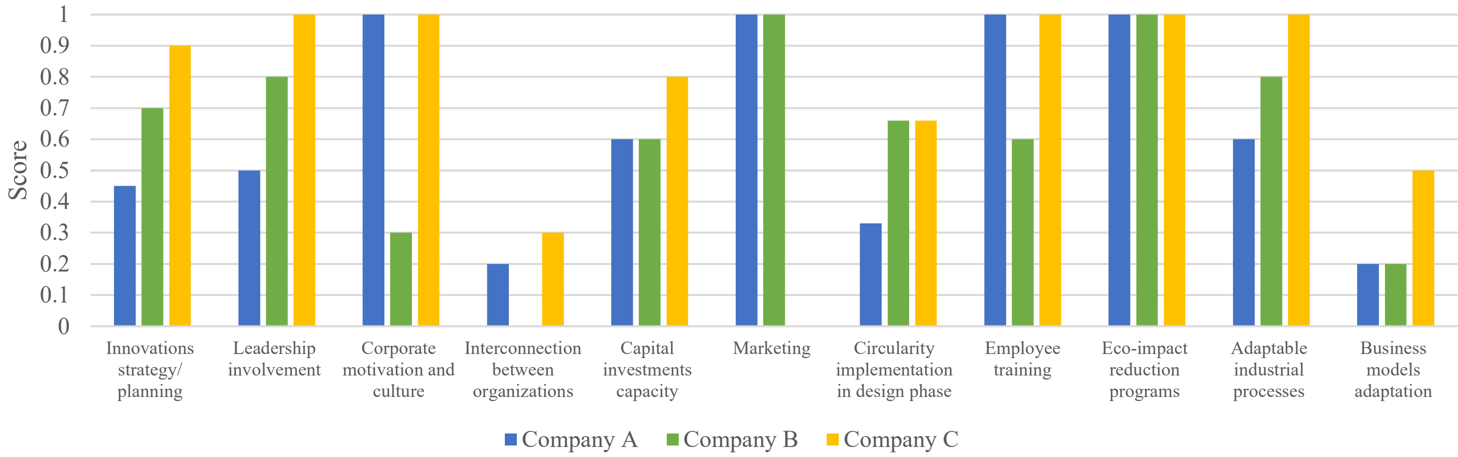

Figure 2. Organizational maturity results between the different companies.

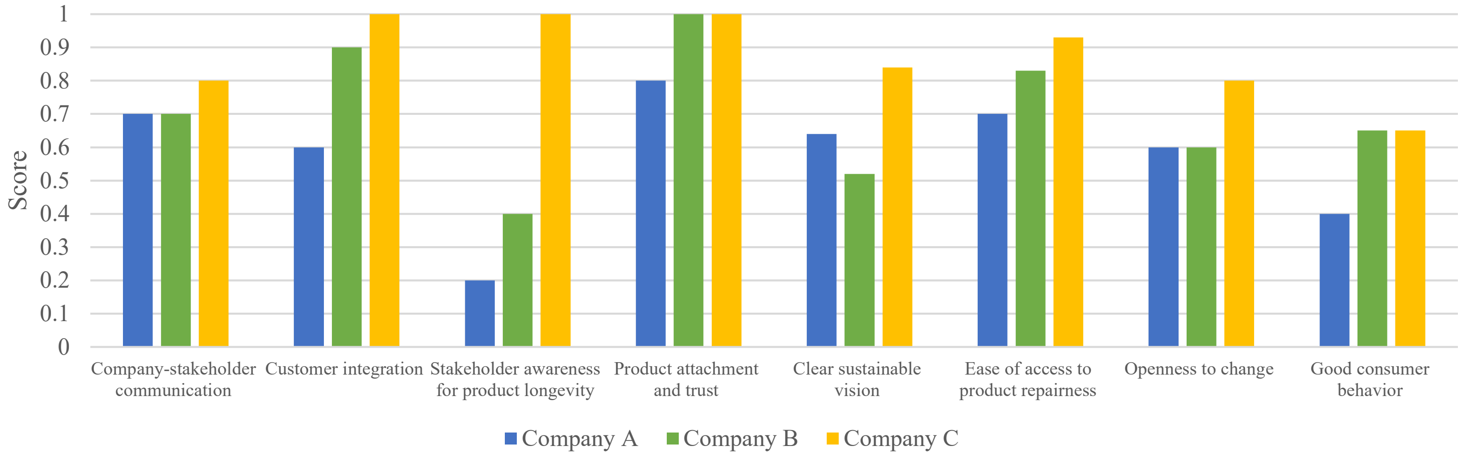

Figure 3. Cultural maturity results between the different companies.

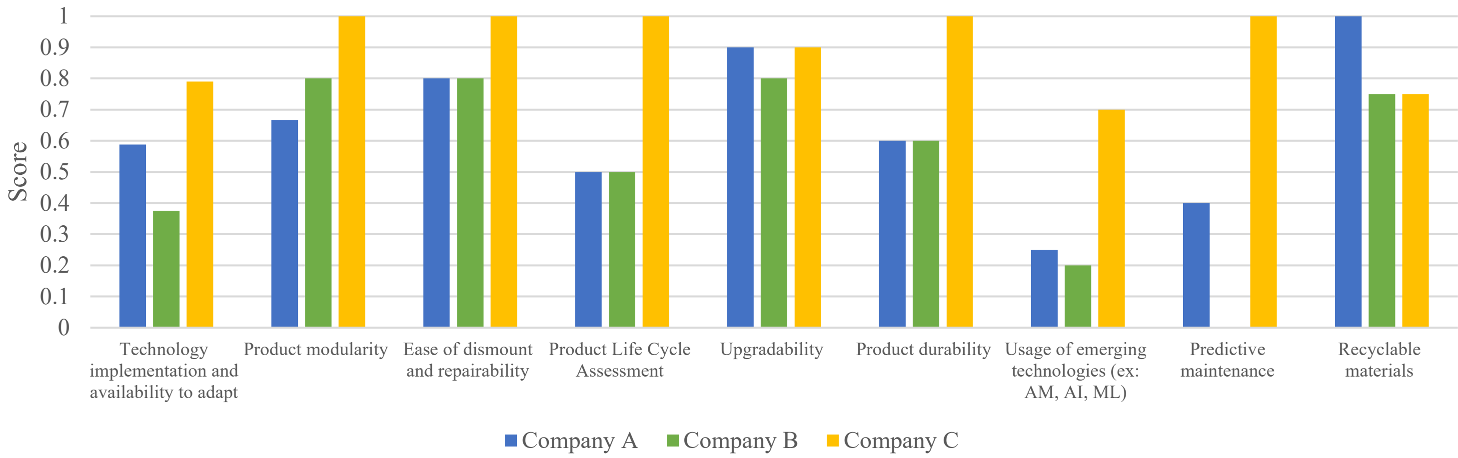

Figure 4. Technological maturity results between the different companies.

Technological

For the last pillar, company C once again leads with a 0,90 score, followed by company A with 0,63 and finally 0,54 for company B. From the technological point of view, **Figure 4** shows that the factors most lacking for company A and B are the “usage of emerging technologies” and “predictive maintenance”, which are correlated. Company B also lacks in “technology implementation and availability to adapt”. By investing in newer skills and technology, these factors’ scores will rise.

As for the best technological maturity factors for the three companies in general, these are the “recyclable materials”, “upgradability” and “ease of dismount and repairability”, which show some regard for sustainability in their products.

The guidelines made to extend the PLC of their products should focus on the aspects that are lacking, and with the help of the questionnaire, these issues are precisely revealed.

4.3. Guidelines

After identifying the least mature aspects of the companies, some suggestions were presented to them in order to improve on those key points. The guidelines can also be separated by the maturity pillars.

Organizational

It is up to the company’s leadership to devise and plan PLCE strategies and apply them to the company. One of the possible ways to do that is by adopting circular business models. Some examples are:

- Product-as-a-Service (PaaS) – the company retains ownership of the equipment while providing ongoing maintenance, updating, and upgrading services. Customers purchase the equipment and retain ownership but can also subscribe to additional services from the company.
- Reverse logistics system - Create a collection programme that allows customers to return machines or components at the end of their useful life. After return, the company analyses the condition of the equipment and adopts the most appropriate circular strategy: reconditioning, reuse, remanufacturing, recycling, among others.

Another issue among the use-cases was the lack of interconnectivity between companies. This could be tackled by:

- Open innovation and collaborative development - Promote collaborative R&D initiatives with research centres, universities, other companies and entities, leveraging synergies in the sharing of knowledge, resources, etc. This collaborative model allows for the creation of innovative solutions that contribute to extending the life cycle of products;
- Marketplace - Assess the feasibility of utilizing an existing marketplace platform to commercialize spare parts currently in stock that are not expected to be used.
- Communication platforms - Integrate communication platforms that enable transparent, efficient, and two-way communication between the company and stakeholders.

Cultural

On the cultural side, companies A and B had some improvements to be made in stakeholder awareness of product longevity. In order to raise awareness of the importance of circularity and PLCE strategies among stakeholders, it is suggested to:

- Present the economic benefits to stakeholders – cost reduction of raw materials by reusing, remanufacturing and repairing components. By adopting PLCE strategies, and communicating them through marketing, the company also builds a very positive brand image valued for its sustainability, making it more competitive.
- Present the environmental benefits to stakeholders – PLCE strategies reduce water consumption, CO_2 emissions, toxic and non-degradable wastes.
- Present the productivity benefits to clients – fewer technical faults, reduction of unplanned downtime of equipment and optimisation of the repair process due to predictive maintenance.

Good consumer behavior is also one aspect that could improve the chances of a successful implementation of PLCE. It is important to encourage customers to adopt good practices regarding circularity. This could be done by offering incentives (example: discount on future purchases) when customers return used products for remanufacturing or recycling.

Technological

For this last pillar, there are a few suggestions of emerging technologies that could benefit the three companies and extend the life cycle of their products:

- Digital Twin (DT) – DT allows for the simulation of scenarios without stopping the machine and production. It also optimizes the equipment design process and maintenance planning.
- Augmented Reality (AR) - AR allows relevant information about the equipment to be overlay in real time and can be incorporated into a tablet, smartphone or AR glasses. This technology greatly helps in remote diagnosis and technical assistance.
- AM – the usage of AM is beneficial when dealing with complex geometries, high conventional manufacturing costs and low production volumes. AM provides advantages such as reduction in material

waste and production costs and time, and offers design freedom.
- Predictive maintenance with AI - integrating AI into predictive maintenance is a very significant addition and is recommended for all companies that want to make the monitoring of their equipment as efficient as possible. With it, it enables early fault detection, reduction in operating costs and intelligent maintenance planning.

These measures are more efficient and valuable if planned from the product conception. By implementing these technologies as early as in the product development phase, it would benefit the organizational pillar, "circularity implementation in design phase", as well as several maturity factors in the technological domain. These changes would greatly extend the life cycle of their products, thus improving circularity.

This maturity model distinguishes from others because of its easy implementation, straightforwardness and adaptability to other industries. Maturity models like CMMI can be can be too bureaucratic and high effort if used for smaller organizations. While CMMI defines five maturity level (from Initial to Optimizing) representing the stages of process standardization, measurement, and continuous improvement [65], the maturity model developed in this study takes a different approach, as it focuses on showcasing the company which aspects should be improved and how, instead of just appointing an overall score for the organization.

5. Conclusions

The present study summarized the PLC aspects and the various strategies to extend it, including reuse, repair, remanufacture, and recycle. Additionally, a maturity assessment methodology was developed and presented, showcasing the three main pillars that make PLCE viable and successful–organizational, cultural and technological. The three pillars represent the role of each consequential identity in extending the PLC, such as the companies and their governance policies, the clients' attachment to the product and consumer behavior, and lastly the own product's technological capacity to prolong its life cycle with features such as upgradability and durability.

The maturity assessment was done through a questionnaire with scores for each pillar, comprised of several maturity factors that inspired the questions made to the use cases. This way, it gives better insight as to what PLCE strategies should work best and what risks could be involved, as well as showcases the strengths and weaknesses of the use cases when analyzing the scores individually as demonstrated in this paper. Some guidelines resulted from this analysis, tackling the most critical issues identified previously. These guidelines serve as recommendations for the use cases to improve on their company's readiness level when dealing with changes in their products.

This approach allows for companies to efficiently work on improving their circular economy and adapt to the innovative and modern strategies that the manufacturing industry now demands, in a safe and effective way.

As future work, maturity assessment should be applied to other companies of different industries, to validate and demonstrate its effectiveness in multiple industrial contexts. It is also suggested turning the maturity assessment as automatic as possible, especially the technological pillar, which could gather information of the product through a CAD software.

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