

Article

Quantifying Circularity Through Product Lifetime Extension (PLE) Using Life Cycle Assessment (LCA)

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Abstract

This study quantified environmental impacts of circularity strategies in the manufacturing industry, focusing on maintenance-driven product lifetime extension (PLE) using Life Cycle Assessment (LCA). The analyzed case builds on earlier work, which showed that the product's lifetime was shorter than the industry average lifetime and that the use phase was the dominant contributor to overall environmental impacts, identifying it as a key area for improvement. A computational code was developed to model maintenance-driven lifetime extension scenarios and to calculate selected total and normalized environmental impacts for the studied industrial process equipment. The model assumes maintenance-related impacts are smaller than the impacts avoided through reduced new production. Results show that while total impacts increase with longer use, normalized impacts per unit of production and per year of service life decrease by 58%, improving resource efficiency. Maintenance-driven PLE supports circular economy (CE) strategies by slowing material flows and extending product use. The findings highlight the importance of incorporating maintenance into circularity frameworks and life cycle-based decision-making.

Keywords: product lifetime extension (PLE); maintenance; life cycle assessment (LCA); circular economy (CE); circularity indicator; ISO 59020; sustainable manufacturing

1. Introduction

The manufacturing industry is a significant contributor to climate change impacts, responsible for 20–30% of overall global greenhouse gas (GHG) emissions and nearly 40% of the world's energy consumption [1,2]. Within this industry, steel production is responsible for 7–9% of global GHG emissions and around 11% of total industrial carbon dioxide equivalent emissions [3]. Improving environmental sustainability in this sector requires strategies that reduce resource use and extend product use across the life cycle [4].

CE principles are categorized into slowing, closing, and narrowing resource loops [5–8]. Slowing focuses on extending the product service life through reuse, repair and maintenance; closing involves recycling and material recovery; and narrowing aims to reduce resource use altogether through prevention. While recycling (“closing the loop”) has been widely studied in the literature, maintenance-driven product lifetime extension (“slowing the loop”) remains less explored in quantitative environmental terms [7,9,10]. Studies on lifetime modelling in LCA and repair in CE systems rarely combine LCA results with computational scenario modelling to quantify maintenance-driven PLE impacts [9,11,12].

In this framework, maintenance refers to the activities carried out using predictive methods—such as component replacements at different intervals and condition



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monitoring—that preserve a product’s original function through repair and upkeep, thereby extending the service life of both the product and its components. In contrast, recycling focuses on processing materials at end-of-life to close loops and maintain material quality [8]. This study uses the product lifetime circularity indicator defined in the ISO 59020:2024 standard, which provides a standardized framework for measuring and assessing circularity performance across different levels [13].

Although ISO 59020:2024 does not include explicit maintenance indicators, maintenance still plays an important role in circularity by improving equipment efficiency, reducing resource use, and supporting circularity strategies such as reuse, repair, and refurbishing [13–15]. Maintenance affects operational aspects such as availability, performance, and quality, which are central to frameworks such as Overall Equipment Effectiveness (OEE) [16,17]. Understanding these operational aspects positions maintenance not only as a way of extending service life but also as a relevant circularity strategy that sustains operational functionality and improves overall resource efficiency [18].

Circularity is typically quantified using circularity indicators [19] such as the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation, dynamic Material Flow Analysis (MFA) [20], or the ISO 59020:2024 standard which offers a unified framework for measuring and assessing circularity at different levels [13]. This study assesses the environmental impacts of circular strategies, with a focus on maintenance-driven PLE [11,21,22]. LCA is applied alongside circularity assessment to identify hotspots in resource use, emissions, and energy consumption across all life cycle stages—from raw material extraction through manufacturing, use, and end-of-life [20,21,23,24].

It builds on LCA results from previous work, which identified use phase as the dominant environmental impact contributor, and found that the product’s lifetime was 83% of the industry average lifetime [25]. These findings motivated the current focus on maintenance-driven PLE. Since use phase impacts originate from both operation and maintenance, this work targets the maintenance-related component to mitigate use phase impacts and improve circularity performance. The study is guided by the following research questions:

RQ1: How can computational scenario modelling quantify the environmental impacts of PLE through maintenance using existing LCA results?

RQ2: What are the trade-offs between increased maintenance-related impacts and reduced normalized impacts per unit of production and per year of service life?

2. Materials and Methods

This section outlines the methods used to assess and model impacts of PLE.

2.1. Extending Previously Published Method

The method was implemented for the studied industrial process equipment from cradle-to-grave system boundaries, with a specific focus on maintenance, including the replacement of main components and other maintenance services, as shown in Figure 1. A 100:0 cut-off allocation approach was applied, assigning recycling benefits to subsequent product systems (i.e., second and later product lives) and excluding them from the first-life system boundary. All LCA results were calculated using this cut-off method to avoid double counting, across multiple component life cycles in maintenance-driven PLE modelling [26].

The functional unit for LCA was defined as one industrial process equipment’s service life of 25 years to process a fixed amount of fibre stock [25]. The previous LCA was conducted using SimaPro 9.6 software and the Environmental Footprint 3.1 method, with background data obtained from Ecoinvent 3.10 and foreground data obtained from manu-

facturer and supplier information, in compliance with ISO 14040:2006 and ISO 14044:2006 guidelines [25,27,28]. Product Environment Footprint Category Rules (PEFCR) were applied to determine the most significant impact assessment categories for steel products [29]. ISO 59020:2024 was used as the framework for the circularity assessment [13], and the product lifetime circularity indicator ($CI_{lifetime}$) represents product lifetime relative to an industry average lifetime, as defined in Equation (1) [13].

$$CI_{lifetime} = \frac{L_S}{L_{avg}} \quad (1)$$

where L_S corresponds to the scenario lifetime and L_{avg} to the industry average lifetime, consistent with the ISO 59020:2024 circularity indicator 2.11. The use of an industry average lifetime (L_{avg}) reduces the effect of random variability, and thus partly reduces uncertainty, while systematic sources of uncertainty remain unaffected.

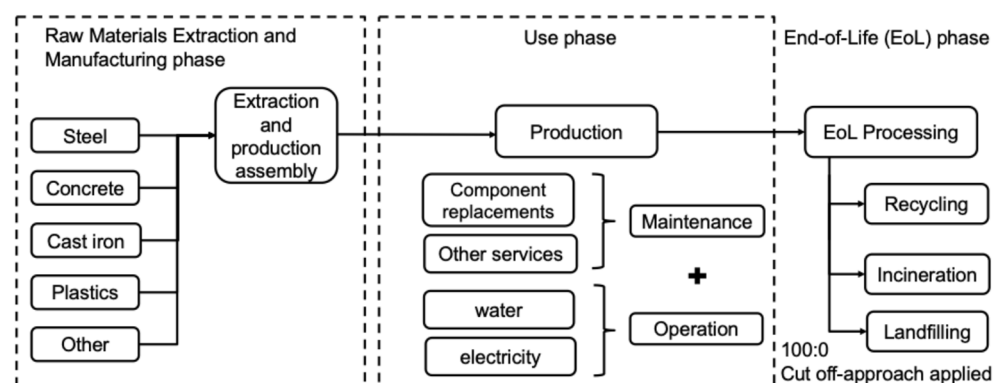


Figure 1. Conceptual life cycle stages of the studied system (based on the system boundary defined in [25]).

The overall scenario modelling approach implemented with MATLAB 2026a begins with baseline LCA results, extends these lifetime scenarios by adding annual maintenance increments, and calculates total and normalized impacts per unit of production and per year of service life. The selected six significant impact assessment categories for steel products were: (1) Climate Change (kg CO₂ eq), (2) Climate Change-Biogenic (kg CO₂ eq), (3) Climate Change-Fossil (kg CO₂ eq), (4) Resource Use (Minerals and Metals) (kg Sb eq), (5) Resource Use (Fossils) (MJ), and (6) Water Consumption (m³ world eq) [29].

2.2. Scenario Modelling for Lifetime Extension

To illustrate the rationale of the scenario modelling approach, a conceptual comparison of two maintenance strategies is presented in Figure 2. In this study, the term “lifetime production (kg)” is defined as the quantity of screened pulp processed by the industrial equipment during its use phase, not the mass of this equipment itself. In Figure 2, lifetime production doubles because extending the equipment’s service life allows twice as many use phase cycles to be completed.

To evaluate the effect of maintenance on impact intensity, product lifetime scenarios were defined as ranging from 25 to 60 years, as shown in Table 1.

Table 1. Scenario definitions.

Baseline Scenario	Extended Lifetime Scenarios
25-year (fixed) lifetime	26–60-year lifetime
lower maintenance with shorter lifetime	increased maintenance with longer lifetime

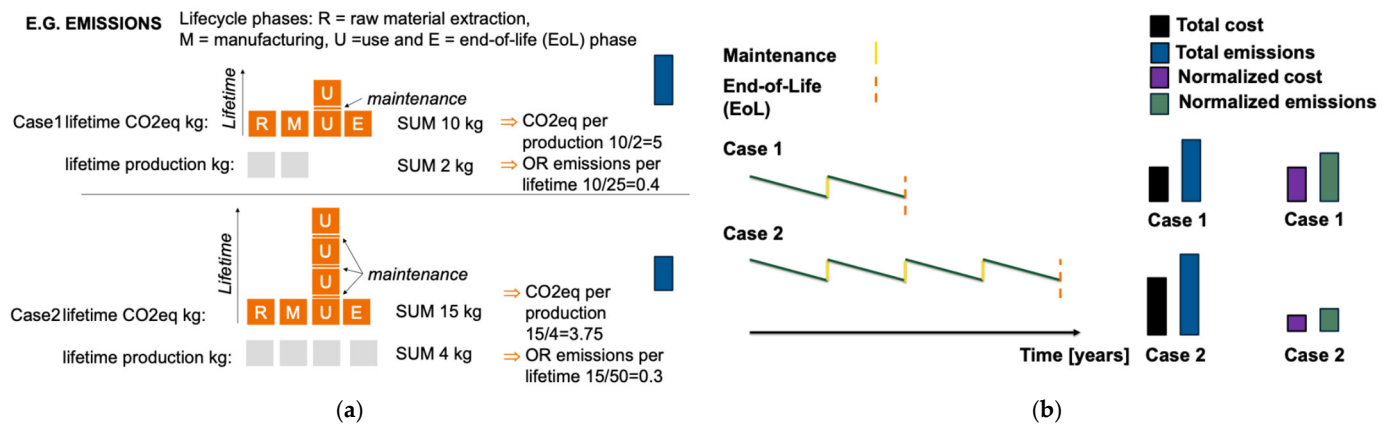


Figure 2. (a) Conceptual comparison of two maintenance scenarios: Case 1, lower maintenance with a shorter lifetime; Case 2, increased maintenance extending lifetime. (b) Illustrative breakdown of total and normalized life cycle costs and climate change impacts. Values are for demonstration only and used to explain modelling logic and associated trade-offs.

2.3. Normalized Impact Calculation

Normalized impacts were calculated after determining total life cycle impacts including maintenance, following the no-fixed-value modelling approach developed in [9] to compare lifetimes. A computational model was developed to implement these calculations using baseline impacts, maintenance impacts per year, and scenario-specific lifetimes as inputs to calculate the total impacts using Equation (2). Since predictive maintenance applied consists of multiple components such as component replacements at different intervals, and condition monitoring, aggregating these into a linear annual increment represents a practical modelling choice that allows systematic comparison across extended lifetime scenarios [9]. These assumptions introduce inherent uncertainties that are not explicitly quantified in the present analysis. In future work, Monte Carlo-based approaches will be explored to enable a more systematic and quantitative evaluation of uncertainty. For each selected impact assessment category, the total maintenance impact was calculated using Equation (3) and normalized by dividing total impacts by scenario lifetime and by production output separately, as illustrated in Equations (4) and (5).

Baseline impacts are derived from the LCA results of the circular scenario, in which the new industrial process equipment is produced from recycled steel [25]. The total environmental impact at baseline (25 years) is 2.32×10^7 kg CO₂ eq dominated by the use phase (2.3×10^7 kg CO₂ eq), with manufacturing contributing 4.7×10^4 kg CO₂ eq. EoL (1.6×10^3 kg CO₂ eq) impacts were excluded in compliance with the cut-off allocation method and reported separately [25]. Maintenance-related environmental impacts were modelled using annual increments for each impact category: 10^4 kg CO₂ eq/year for Climate Change, 5×10^2 kg CO₂ eq/year for Climate Change-Biogenic, 9×10^3 kg CO₂ eq/year for Climate Change-Fossil, 5×10^{-1} kg Sb eq/year for Resource Use (Metals), 10^5 MJ/year for Resource Use (Fossils), and 5×10^5 m³ world eq/year for Water Consumption [25].

$$I_{Ti} = I_{Bi} + I_{Mi} \quad (2)$$

where I_{Ti} is the total impact in relevant impact assessment category unit (i) for the industrial equipment, I_{Bi} is the baseline impact, and I_{Mi} is the maintenance impact.

$$I_{Mi} = y \times i_{\text{maint},i} \quad (3)$$

where y represents the number of extra years (y) beyond the 25-year baseline service life (e.g., $y = 15$ for 40-year scenario) multiplied by the maintenance impact per year $i_{maint,i}$ in the relevant category derived from empirical data in [25].

$$E_{norm_lifetime} = \frac{I_{Ti}}{L_S} \quad (4)$$

where $E_{norm_lifetime}$ is the normalized impacts per lifetime and L_S is the scenario lifetime. This normalizes the total environmental burden by scenario lifetime, allowing fair comparison of environmental intensity across scenarios of different lifetimes, following the no-fixed value approach in [9].

$$E_{norm_production} = \frac{I_{Ti}}{M_{prod}} \quad (5)$$

where $E_{norm_production}$ represents normalized impacts per production, and M_{prod} represents the produced material by this industrial equipment as explained in Section 2.2. Lifetime production is calculated dynamically using Equation (6):

$$M_{prod} = M_{base} \times \left(\frac{L_S}{L_i} \right) \quad (6)$$

Here, the baseline mass is the lifetime production at the baseline lifetime (100 kg), as explained in Section 2.2, L_i is the initial lifetime and L_S is the scenario lifetime.

3. Results

This section presents ISO 59020:2024 indicator results and the normalized environmental impacts derived from total impacts across extended lifetime scenarios.

3.1. Product Lifetime Circularity Indicator Results

The ISO 59020:2024 product lifetime circularity indicator ($CI_{lifetime}$) values were calculated and are shown in Table 2, where L_S represents scenario lifetime.

Table 2. ISO 59020:2024 circularity indicator results [13].

Ls	25	30	35	40	45	50	55	60
$CI_{lifetime}$	0.83	1	1.17	1.33	1.5	1.67	1.83	2.0

The ISO 59020:2024 product lifetime circularity indicator increases by 141% overall, from 0.83 at 25 years to 2.0 at 60 years, showing operation at twice the industry average lifetime ($CI_{lifetime} = 1.0$ at $L_{avg} = 30$ years) [13]. Values above 1.0 indicate extended use and improved circularity, whereas values below 1.0 indicate that the product lifetime is shorter than the industry average.

3.2. Normalized Impacts

Normalized impacts were calculated after determining total life cycle impacts, which were used as an intermediate result before normalization. Extending product lifetime reduces normalized climate change impacts per lifetime by 58%, with similar trends observed across other impact categories, as impacts are distributed over a longer service life as shown in Table 3. The baseline impact is 929.9×10^3 kg CO₂ eq/year. Extending the service life to 60 years reduces the normalized impacts by service life to 393.3×10^3 kg CO₂ eq/year—a 58% reduction—while maintenance contributes 10^4 kg CO₂ eq/year beyond the baseline lifetime.

Table 3. Normalized impacts with lifetime results.

Category	Unit	Baseline (25 Years)	Extended (60 Years)	Reduction (%)
Climate Change	kg CO ₂ eq	929.9×10^3	393.3×10^3	57.7
Climate Change-Biogenic	kg CO ₂ eq	2.2×10^3	1.2×10^3	44.9
Climate Change-Fossil	kg CO ₂ eq	917.8×10^3	387.7×10^3	57.8
Resource Use (Metals and Minerals)	kg Sb eq	1.5	0.7	49.7
Resource Use (Fossils)	MJ	$10,180.6 \times 10^3$	4300.2×10^3	57.8
Water Consumption	m ³ world eq	504.4×10^6	210.5×10^6	58.3

4. Discussion

This study quantifies normalized environmental impacts of maintenance-driven PLE through computational modelling using LCA results from previous work. For the equipment analyzed, the use phase energy consumption through operation and maintenance dominates overall impacts, accounting for 98–99% across all assessed impact categories. This large difference in magnitude implies that maintenance-related impacts remain comparatively small, and that even substantial variations or alternative (e.g., nonlinear) maintenance assumptions are likely to have a limited influence on the results. Therefore, although total impacts rise with longer use, extending service life through maintenance distributes initial manufacturing burdens over more years, reducing normalized impacts per year and per unit of production by up to 58%.

However, overall environmental benefits depend on equipment's use phase energy consumption. For consumer products or equipment with lower energy intensity, the extension–replacement trade-off may differ significantly [9,12], especially if newer equipment offers higher energy efficiency, making the extension–replacement decision case-specific. Under conditions where operational energy remains stable, and the electricity supply shifts toward renewable sources, maintenance-driven PLE can be an effective CE strategy.

Methodologically, scenario modelling assumes linear maintenance increments and applies LCA results from previous work to generate total and normalized impact trends. Notably, the baseline scenario reflects the circular scenario in which the equipment is produced from recycled steel [25], and the additional 58% reduction in normalized impacts through maintenance-driven PLE demonstrates that lifetime extension further enhances environmental performance beyond recycled material production alone.

These findings support inclusion of maintenance-driven PLE within CE strategies where maintenance can sustain availability and performance without significantly increasing impacts. However, they are specific to the studied industrial context and should not be generalized without further validation across different product types and operational contexts. Future work could integrate social and economic dimensions and explore additional CE strategies to align with regulations such as the Corporate Sustainability Reporting Directive (CSRD), moving toward a holistic Life Cycle Sustainability Assessment (LCSA) [30].

5. Conclusions

This study developed a computational scenario modelling approach to quantify the environmental impacts of PLE through maintenance using existing LCA results. The results showed that while total impacts rise with extended service life and accumulated maintenance, normalized impacts per unit of production and per year of service life decreased by 58% across climate change and other significant impact categories. The presented modelling

approach is a useful tool for analyzing PLE strategies within existing LCA frameworks, contributing to more sustainable and resource-efficient production systems.

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