

## Article

# Optimizing the Life Cycle of Physical Assets through an Integrated Life Cycle Assessment Method

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**Abstract:** The purpose of this study was to apply new methods of econometric models to the Life Cycle Assessment (LCA) of physical assets, by integrating investments such as maintenance, technology, sustainability, and technological upgrades, and to propose a means to evaluate the Life Cycle Investment (LCI), with emphasis on sustainability. Sustainability is a recurrent theme of existing studies and will be a concern in coming decades. As a result, equipment with a smaller environmental footprint is being continually developed. This paper presents a method to evaluate asset depreciation with an emphasis on the maintenance investment, technology depreciation, sustainability depreciation, and technological upgrade investment. To demonstrate the value added of the proposed model, it was compared with existing models that do not take the previously mentioned aspects into consideration. The econometric model is consistent with asset life cycle plans as part of the Strategic Asset Management Plan of the Asset Management System. It is clearly demonstrated that the proposed approach is new and the results are conclusive, as demonstrated by the presented models and their results. This research aims to introduce new methods that integrate the factors of technology upgrades and sustainability for the evaluation of assets' LCA and replacement time. Despite the increase in investment in technology upgrades and sustainability, the results of the Integrated Life Cycle Assessment First Method (ILCAM1), which represents an improved approach for the analyzed data, show that the asset life is extended, thus increasing sustainability and promoting the circular economy. By comparison, the Integrated Life Cycle Investment Assessment Method (ILCIAM) shows improved results due to the investment in technology upgrades and sustainability. Therefore, this study presents an integrated approach that may offer a valid tool for decision makers.

**Keywords:** ISO 5500X; asset management; physical assets; life cycle assessment; optimization; econometric model; sustainability; circular economy



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## 1. Introduction

### 1.1. Framework

A relevant current question regards the kind of planet we wish to leave for our posterity. According to Scopus [1], from 2011 to 2020 137,982 studies were published under the sustainability topic in three major areas, namely, environmental sciences, engineering, and energy. Keeble [2] defines sustainable development as “the progress to meet our needs and ambitions on our days without ruining the resources that future generations will need”. The author divides it into two concepts: first, meeting the needs of the world's poor, through a more reasonable sharing of opportunities and resources; and second, limitations

of growth and resource reduction, and the capacity of the environment to meet the needs of future generations.

Sustainability has been a popular topic in recent decades [3], and is typically explained based on three areas, i.e., society, the economy, and the environment [4]. More recently, energy has been introduced as an additional topic within the concept of sustainability [5–7]. The main concern is translating sustainability into sustainable development [8].

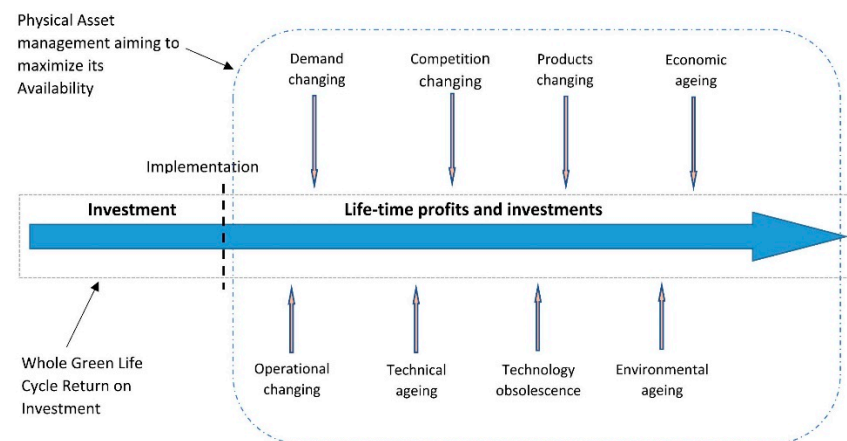
At present, development relies on technological growth [9]. This growth is the result of people's needs and is supported by economic and social progress. However, sustainable development must be sustained by environmental, sociopolitical, cultural, and economic factors [10]. As a result, there is a need to find an equilibrium to ensure sustainable development [11]. As an example, the use of clean energy is not sufficient [12]; energy reduction is also needed to achieve sustainable development. To achieve this, technological progress must occur [13] so that energy consumption can be reduced.

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” [14]

In the context of achieving sustainable development, the circular economy has become a popular research topic [15]. The advent of the circular economy has occurred when the reduction, reuse, recovery, and recycling of materials and energy has become a priority [16], and the transition from the linear economy to the circular economy needs to be consolidated. The circular economy is inspired by biological cycles in which nothing is wasted. Previous authors [17–20] have defended the importance of the circular economy to attain sustainable development, despite some misunderstandings about the concept of the circular economy. The Ellen MacArthur Foundation is deeply involved in educating the public about the circular economy, and has published several related documents [21–26]. Countries such as China [27] have understood the need for this transformation, which clearly depends on political engagement.

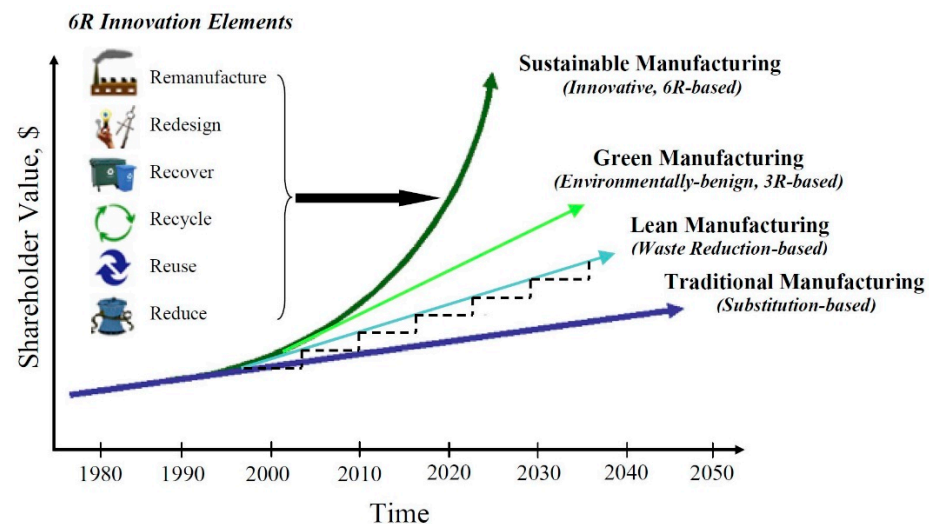
According to Goodland [28], the environment is a major constraint on human progress. Sustainable progress must be connected with social, environmental, and economic sustainability, and the need to use each of these factors to ensure sustainable evolution. Farinha [29] highlights the need to change from an economic paradigm to an ecologic economy paradigm, and notes that the costs of this change represent the cost of survival. Franciosi et al. [30] consider sustainable manufacturing to be one of the most important matters in the pursuit of sustainable progress. The authors note that sustainable manufacturing implies the migration from the linear economy to the circular economy, and the application of tools for a better use of resources, thus reducing waste through recycling, reuse, remanufacturing, and recovery of materials.

Asset management focuses on the changes undergone by assets (Figure 1). A large number of changes occur during a physical assets' lifetime, both internal and external. Thus, it is important to establish strategies to support decision making. Although some changes may be beyond the forecast range, others, such as legislation changes, environmental impacts, and production demand, must be forecast earlier. However, asset management is based on a holistic view, which provides the capability to prevent events that are the most difficult to predict.



**Figure 1.** The focus of asset management (adapted from: [31]).

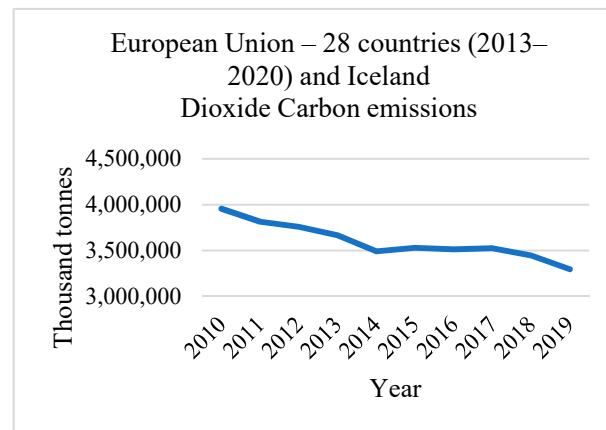
Although a major improvement has been implemented in the energy production sector, further progress remains to be made [24]. To achieve a circular economy, it is necessary to, among other actions, increase the life of the assets. This increase cannot rely only on economic factors because, as shown, factors such as technology and sustainability must be taken in consideration. Although the value earned from production is clearly highly important, what is the cost associated with this production? Are we willing to leave this cost to future generations? Bilge et al. [32] presents the 6Rs that promote closed loops in life cycles, in which the long-term objective is to preserve the environment by protecting resources and ensuring economic prosperity, while considering social problems and, at the same time, shrinking pollution and waste. The 6R methodologies are reduce; reuse; recycle; recover; redesign; and remanufacture (Figure 2). The major objective is to realize and create value from the assets, increase the life cycle, and maintain the assets' value and sustainability, via the appropriate maintenance.



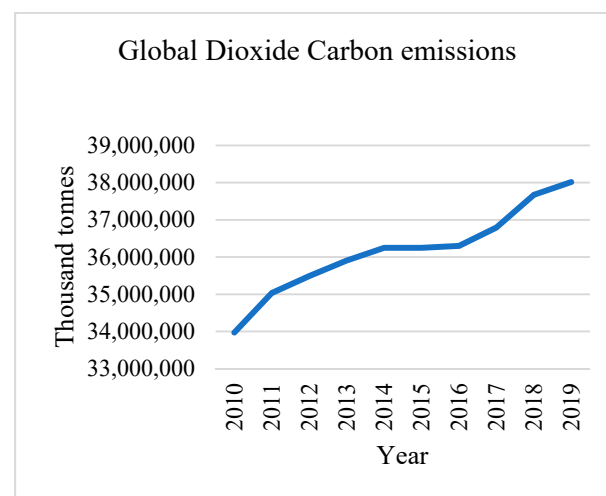
**Figure 2.** Sustainable manufacturing for the twenty-first century (Source: [33]).

CO<sub>2</sub> emissions in Europe have decreased (Figure 3). Those of the European Union—comprising 27 countries—and the UK have decreased in the past two decades; in 2019 they were 25.1% less than those in 1990, and 22.2% less than those in 2005. Europe's share of total global emissions also decreased from 9.6% to 8.7% between the years 2015 and 2019. In contrast, the global emissions of CO<sub>2</sub> from fossil fuel combustion and processes increased (Figure 4) by 0.9% in 2019, at about 50% of the previous annual growth rate (+1.9% in 2018), reaching a total of 38.0 Gt CO<sub>2</sub>. In 2019, China, the United States, India, EU27 + UK, Russia,

and Japan—the world’s biggest CO<sub>2</sub> emitters—were together responsible for 51% of the population, 62.5% of global Gross Domestic Product, and 62% of total global fossil fuel consumption, and emitted 67% of total global fossil CO<sub>2</sub>. Emissions from these countries showed different changes in 2019 compared to 2018: China and India grew +3.4% and +1.6%, respectively, and led the global growth in emissions. In contrast, other countries reduced their fossil CO<sub>2</sub> emissions: EU27 + UK (−3.8%), the United States (−2.6%), Japan (−2.1%), and Russia (−0.8%) [34].



**Figure 3.** European Union-28 countries (2013–2020) and Iceland Dioxide Carbon emissions, adapted from Greenhouse gas emissions by source sector [35].



**Figure 4.** Global Dioxide Carbon emissions, adapted from Fossil CO<sub>2</sub> emissions of all world countries—2020 Report [34].

“The Earth is one but the world is not. We all depend on the biosphere for sustaining our lives. Yet each community, each country, strives for survival and prosperity with little regard for its impact on others. Some consume the Earth’s resources at a rate that would leave little for future generations. Others, many more in number, consume far too little and live with prospect of hunger, squalor, disease, and early death.” [36]

As an example, the global use of steel has grown significantly; crude steel production increased more than 16% in the past 20 years (Figure 5).

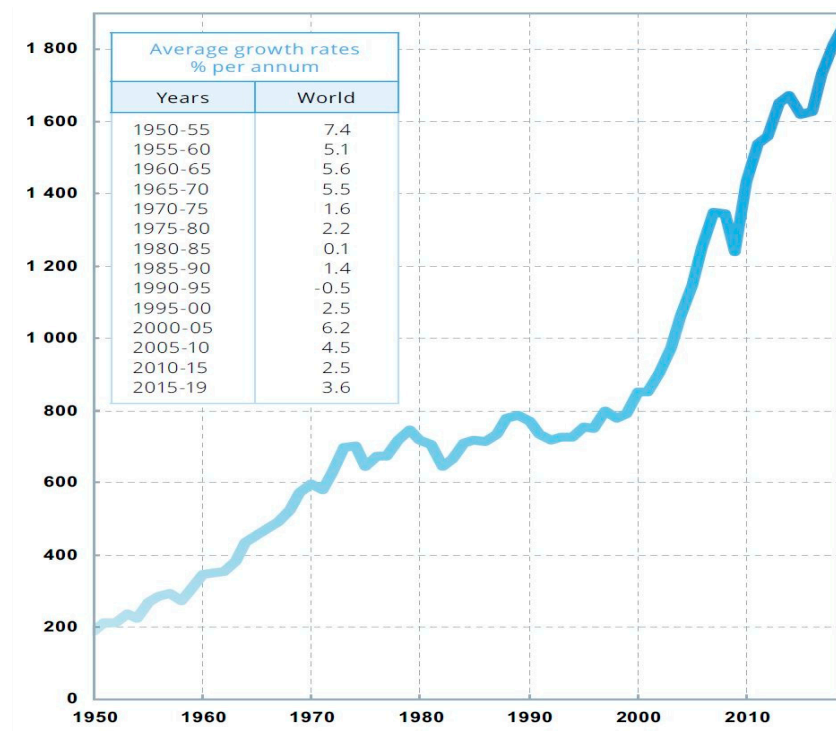


Figure 5. Crude steel production, million tonnes (Source: [37]).

The use of steel scrap reduces the emission of CO<sub>2</sub> into the atmosphere, diminishes environmental impacts, and reduces the depletion of natural resources. Thus, the use of scrap leads to a welfare gain, avoiding environmental stress and benefitting society, and leading to an improvement in the quality of life. The use of a ton of carbon steel scrap lowers greenhouse gas emissions by 1.67 t CO<sub>2</sub>, and the use of a ton of stainless steel reduces emissions by 4.3 t CO<sub>2</sub> [38].

In addition to significantly reducing CO<sub>2</sub> emissions, the use of scrap requires up to ten times less energy than that required for the production of crude steel. However, only 40% of steel production comes from scrap [39]. Due to the global demand for steel, the steel and iron industries are robust, and their goals include retaining the high quality of their products, increasing productivity, cutting business costs, decreasing energy consumption, and mitigating environmental emissions. Some of these objectives can be achieved through recycling [40].

Climate change is accepted to be happening: flooding in the summer in central Europe, a snowstorm in Brazil, and severe drought conditions in Madagascar are events that occurred during 2021. Previous studies have established a connection between climate change and the increase in the temperature due to CO<sub>2</sub> emissions [41–46].

Earth Overshoot Day has occurred earlier each year, or with only a minor recovery compared to previous years. In effect, we are borrowing from future generations, which is currently not sustainable. We must be able to live strictly with what we have, without compromising future generations and the planet. According to Table 1, in just over 50 years the Earth Overshoot Day moved from 30 December to 29 July, representing a shift of 154 days. The open question is whether are we willing to leave this debt for future generations to pay.

**Table 1.** Earth Overshoot Day 1970–2021, adapted from Past Earth Overshoot Days [47].

Year	Overshoot Day	Year	Overshoot Day	Year	Overshoot Day
1970	30 December	1988	14 October	2005	24 August
1971	20 December	1989	11 October	2006	18 August
1972	10 December	1990	10 October	2007	13 August
1973	26 November	1991	9 October	2008	13 August
1974	27 November	1992	11 October	2009	16 August
1975	30 November	1993	11 October	2010	6 August
1976	17 November	1994	9 October	2011	3 August
1977	11 November	1995	3 October	2012	2 August
1978	7 November	1996	30 September	2013	1 August
1979	29 October	1997	28 September	2014	2 August
1980	4 November	1998	28 September	2015	3 August
1981	11 November	1999	28 September	2016	3 August
1982	15 November	2000	22 September	2017	30 July
1983	14 November	2001	21 September	2018	25 July
1984	7 November	2002	18 September	2019	26 July
1985	4 November	2003	8 September	2020 <sup>1</sup>	22 August
1986	30 October	2004	30 August	2021	29 July
1987	23 October				

<sup>1</sup> The calculation of Earth Overshoot Day 2020 reflects the initial drop in resource use in the first half of the year due to pandemic-induced lockdowns. All other years assume a constant rate of resource use throughout the year.

The increase in global CO<sub>2</sub> emissions is a current concern. Previous research has examined the incorporation of technological upgrades, and technological and sustainability depreciation, to reduce the CO<sub>2</sub> emissions of assets used in different areas, such as transport, buildings, and industry. To date, studies have been conducted based on products [48–50] and assets in general [51]. However, none have presented methods that integrate technology and sustainability variables to calculate replacement time, and the implications for investment. The aim of this study was to fill this gap.

### 1.2. Aim and Research Methodology

The aim of this research was to address the limitations of the existing quantitative methods used to assess the life cycle of physical assets, by offering a new approach that includes the economic dimension of sustainability and technology, beginning with existing methods [52,53]. For this purpose, a three-stage exploratory research methodology was used:

1. Research of the existing methods, and their limitations, applied to technology and sustainability investment;
2. Design of the new methods to be introduced as decision-making tools in the Strategic Asset Management Plan (SAMP) as part of ISO 55001 requirements;
3. Quantitative validation of the methods with investment data.

The first research step was based on detailed research of the methods available to extend the life cycle and investment above the return on the assets.

The second research step was the construction of two econometric methods.

Finally, in the third research step, the model was validated, and the conclusions were drawn.

### 1.3. Paper Structure

This paper is structured as follows:

- Section 2 synthesizes relevant literature on asset life cycle models and methods;
- Section 3 presents the Integrated Life Cycle Assessment Method (ILCAM);
- Section 4 presents the Integrated Life Cycle Investment Assessment Method (ILCIAM);
- Section 5 presents a discussion;
- Section 6 offers the conclusions.

## 2. Literature Review

Approaches and methods have been previously presented with the aim of improving maintenance and, consequently, extending the life cycle of an asset. The international standard on asset management [54] and the Institute of Asset Management [55] emphasize the need to optimize the life cycle cost according to a certain level of service. The Institute of Asset Management also defines the target of asset management as “the optimum way of managing assets to achieve a desired and sustainable outcome” [56]. Jardine and Tsang [57] and Campbell, Jardine and McGlynn [58] provide cost optimization models for replacement and an overview of probabilistic maintenance, with the aim of achieving excellence in asset management. A balance is required between performance, cost, and risk, over the full life cycle of the assets. It is also necessary to integrate environment and social factors, in addition to the economic factor, and a balance is required to support decision making.

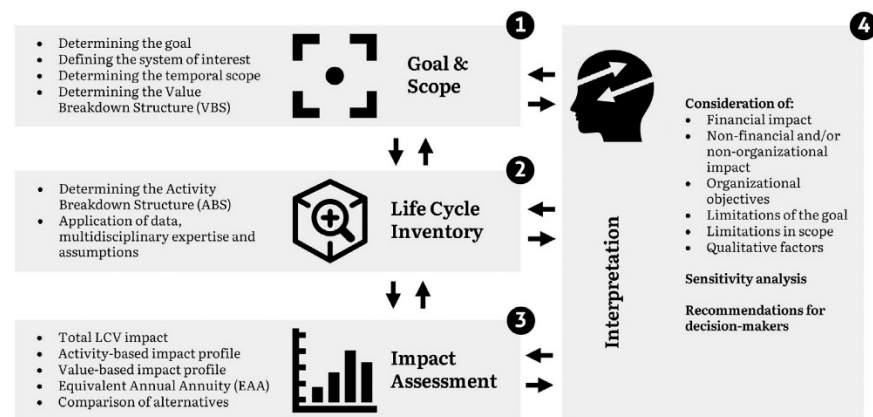
Pais et al. [51] present studies with models and approaches, including their advantages and disadvantages in terms of asset management, with a focus on the life cycle (Table 2).

**Table 2.** Models or approaches with advantages and disadvantages [51].

Model or Approach	Author	Year	Advantages	Disadvantages
Asset Management Process BELCAM	Campbell	1995	<ul style="list-style-type: none"> <li>• Nine step process</li> </ul>	<ul style="list-style-type: none"> <li>• Not a model</li> </ul>
Decision-support Tool	Vanier et al.	1996	<ul style="list-style-type: none"> <li>• Gathers information only in order to use in the analysis of life cycle</li> </ul>	<ul style="list-style-type: none"> <li>• Based on buildings</li> <li>• Don't introduce mathematical models</li> </ul>
Asset Management Program	Malano et al.	1999	<ul style="list-style-type: none"> <li>• Introduce elements of an asset management program</li> </ul>	<ul style="list-style-type: none"> <li>• Based on water utility</li> <li>• Don't introduce mathematical models</li> <li>• Not a model</li> </ul>
Asset Life Cycle Management	National Treasury guidelines	2004	<ul style="list-style-type: none"> <li>• Sets a framework for asset management</li> </ul>	<ul style="list-style-type: none"> <li>• Not a model</li> </ul>
Asset Management Modelling Framework	Malano et al.	2005	<ul style="list-style-type: none"> <li>• LCC model is proposed</li> <li>• Introduce mathematical models</li> </ul>	<ul style="list-style-type: none"> <li>• Requires lots of data that may not be available</li> </ul>
Asset Life Cycle Management	Schuman and Brent	2005	<ul style="list-style-type: none"> <li>• Introduce elements of an asset management program</li> <li>• Considers economic, environmental, social, and technical factors and performances;</li> </ul>	<ul style="list-style-type: none"> <li>• Don't introduce mathematical models</li> </ul>
Asset Life Cost Management	Haffejee and Brent	2008	<ul style="list-style-type: none"> <li>• Assets management from before acquisition to disposal;</li> </ul>	<ul style="list-style-type: none"> <li>• Based on water utility</li> <li>• Don't introduce mathematical models</li> </ul>

Different methodologies have been developed to assess the life cycle, of which some are presented here. The Total Cost of Ownership (TCO) is a complex approach, which requires that the buying company identifies the most significant costs during the acquisition, possession, use, and subsequent withdrawal or renewal. In addition to the price paid for the item, TCO may include elements such as order placement, research and qualification of suppliers, transportation, receipt, inspection, rejection, replacement, downtime caused by failure, and disposal costs [59]. Woodward [60] defines the Life Cycle Cost (LCC) of an item as the sum of all funds expended to support the item from its conception and fabrication through its operation to the end of its useful life. Norris [61] establishes a comparison between Life Cycle Assessment (LCA) and LCC, and identifies the difference between them: LCA evaluates the relative environmental performance of alternative product systems for providing the same function. This environmental performance is assessed as holistically as possible, aiming to consider all important causally connected processes, and all important resource and consumption flows, regardless of whether they eventually impact anyone. By comparison, LCC compares the cost effectiveness of alternative investments or business decisions from the perspective of an economic decision maker, such as a manufacturing

firm or a consumer. The differences in the purposes of the two approaches have resulted in differences in their scope and methods of implementation. Life Cycle Cost Analysis (LCCA) is used extensively to support project level decisions, and has started to be used as a network level analysis tool [62]. Life Cycle Sustainability Assessment (LCSA) mostly uses quantitative variables, such as measures of economic, environmental, and social impacts [63]. The Life Cycle Valuation (LCV) methodology consists of two main elements: (1) a four-phased framework (Figure 6) that guides the process of performing an LCV assessment, and (2) a combination of calculations [64].



**Figure 6.** Life Cycle Valuation (LCV) assessment framework (Source: [64]).

The presented models and methods aim to support sustainability and sustainable development, resulting in a reduction in costs during an asset's life cycle. This is also attained with the use of fewer natural resources which, in turn, results in a reduction in CO<sub>2</sub> emissions and a smaller impact on the population. In addition, new models and methods can create new markets and attract new business, which can result in social development.

Farinha et al. [52] present the concept of Life Cycle Investment (LCI). This represents a change in the concept of cost, which is traditionally assumed to be a loss. However, both the initial investment, which is a negative flow (cost), and the other variable “costs” occurring throughout the life cycle of assets, namely maintenance, must also be understood as being variable investment flows. These types of cost associated with an asset's life cycle must be seen as investments, because they originate a return that is indexed to the quality of the investment—initial and during the asset's life—and accrue value to the asset throughout its life cycle.

Models for replacement assets were presented by van den Boomen et al. [65], with a focus on the life cycles of civil infrastructure assets, which are often long. Other models were presented by Fox [66], Chen and Savits [67], Van Noortwijk [68], and Noortwijk and Frangopol [69]. Despite the differences in the mathematical expressions used in these models, their relationships are similar.

A model based on TCO derived by Roda et al. [70] is composed of three main phases: project setting, performance analysis, and economic analysis. It combines the concept of reliability engineering with economic and financial evaluations, and states that these are essential to strengthen the connection between technical asset management and profitability.

Maletič et al. [71] developed a model that links Physical Asset Management (PAM) and Sustainability Performance (SP). Although empirical, the model provides evidence that PAM significantly and positively contributes to SP.

Methods for physical depreciation of pavements, including the Straight-Line Method, the Sum of the Years Digits Method, the Declining Balance Method, the Double Declining Balance Method, and the Sigmoidal Method, are presented by Dojutrek et al. [72] Other methods, such as the Modified Method, the Renewal-Based Method, and the Condition-Based Method, are noted by Deng et al. [73].



Shokouhi et al. [74] aimed to help with the identification of the most appropriate model of the life cycle of physical assets, taking into consideration the LCC, risk, and Key Performance Indicators (KPIs).

Considering the need to manage costs with spare parts, Durán et al. [75] created a model in which economic sustainability was assumed to be one of the key elements. Life cycle sustainability assessment provides an interdisciplinary forum to discuss the main challenges in addressing sustainability from a long-term perspective.

Using a fuzzy logic-based LCCA model, Chen et al. [62] constructed a decision-making model for pavement deterioration (Figure 7).

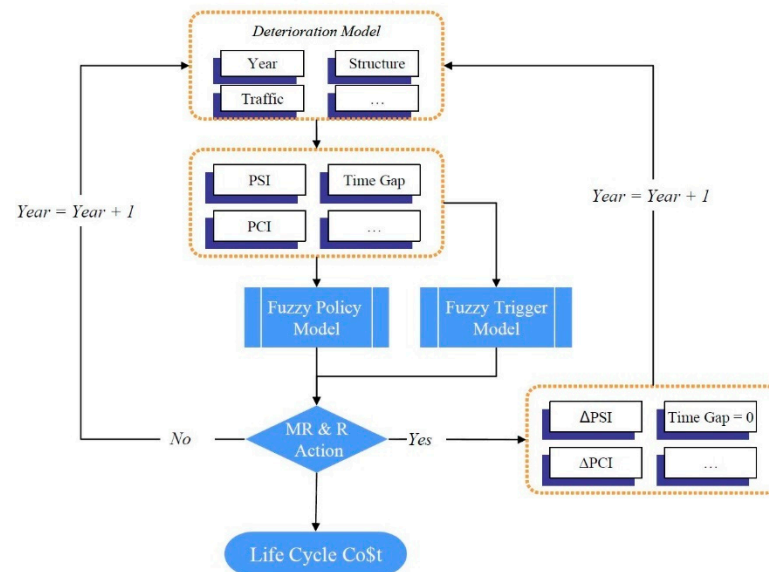


Figure 7. Fuzzy logic-based project selection algorithm (Source: [62]).

Methods to calculate the physical depreciation on general assets were presented by Farinha [76]. Three are well known, namely, the linear depreciation method, the sum of digits method, and the exponential method; these methods are based on the acquisition value, end of life (withdrawal or renewal), exploration costs (maintenance costs and running costs), inflation rate, and capitalization rate. This data needs to be collected throughout the asset's life and can be turned into information to support decisions on asset withdrawal or renewal. However, other decisions can be made during the asset's life, such as the decision relating to a technological upgrade, which consider not only production aspects but also the asset's environmental footprint.

The most common methods used to calculate the economic cycle of equipment replacement are the Uniform Annual Income Method (UAI), Minimizing the Total Average Cost method (MTAC), and MTAC with Reduction to the Present Value method (MTACMRPV) [77].

The Uniform Annual Income ( $U$ ) of the possession of equipment is given by:

$$U_n = \frac{i_A(1+i_A)^n}{(1+i_A)^n - 1} * \sum_{j=0}^n \frac{X_j}{(1+i_A)^j} \quad (1)$$

Minimizing the Total Average Cost ( $C$ ) of the possession of equipment is undertaken by:

$$\begin{aligned} C'_n &= \sum_{i=0}^n C_{Mi} \\ C''_n &= \frac{V_A - V_{Cn}}{n} \\ C_n &= C'_n + C''_n \end{aligned} \quad (2)$$

The MTAC with reduction to the present value (C) of the possession of equipment is given by:

$$\begin{aligned}
 C'_n &= \frac{1}{n} \sum_{i=1}^n \frac{C_{Mi}}{(1+i_A)^i} \\
 C''_n &= \frac{V_A - \frac{V_{Cn}}{(1+i_A)^n}}{n} \\
 C'''_n &= \frac{V_A - \frac{V_{Cn}}{(1+i_A)^n}}{n}
 \end{aligned}
 \tag{3}$$

The methods presented above differ and produce different results; for example, MTAC does not consider the capitalization and inflation rates, and should be avoided if an inflationary economy is being experienced.

Raposo et al. [53] present an econometric model that takes into consideration the Mean Time To Repair (MTTR); the model is based on the Uniform Annual Income Method:

$$\begin{cases}
 UAI_n = \frac{i_A(1+i_A)^n}{(1+i_A)^n - 1} * \left( CA + \sum_{j=0}^n \frac{(t * MTTR * \frac{CM_j}{d}) + CO_j}{(1+i_A)^j} - \frac{V_n}{(1+i_A)^n} \right) \\
 ROI = \sum_{j=1}^n \frac{CF_j}{(1+i_A)^j} - CA
 \end{cases}
 \tag{4}$$

where:

CA: Equipment Cost of Acquisition

CM<sub>j</sub>: Cost of Maintenance in year  $j = 1, 2, 3, \dots, n$

CO<sub>j</sub>: Cost of Operation in year  $j = 1, 2, 3, \dots, n$

$i_A$ : Apparent rate

$V_n$ : Value of the equipment over a period  $n = 1, 2, 3 \dots, n$

$t$ : Number of periods considered for MTTR

$d$ : Number of days per year MTTR Mean Time to Repair

The results of the Uniform Annual Income Method are interesting and have been shown to be adequate for application to a significant number of assets. This approach presents a new tool, as shown in Figure 8.

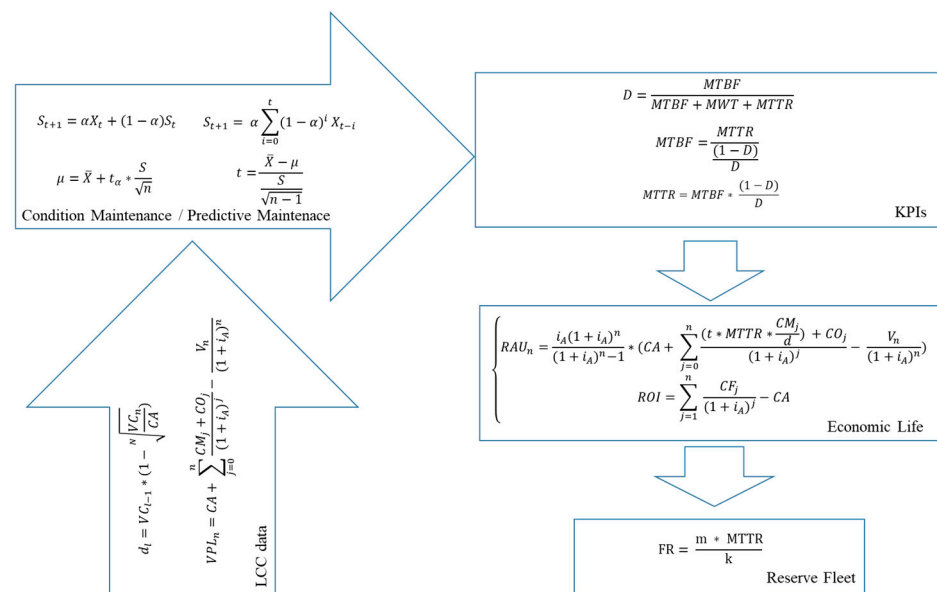


Figure 8. Model Integrated Reserve Fleet Assessment (MIAFRA) (Source: [53]).

### 3. Integrated Life Cycle Assessment Method (ILCAM)

This study investigated and addressed the question of when an asset should be replaced, among others. To replace an asset, several questions must be answered which,

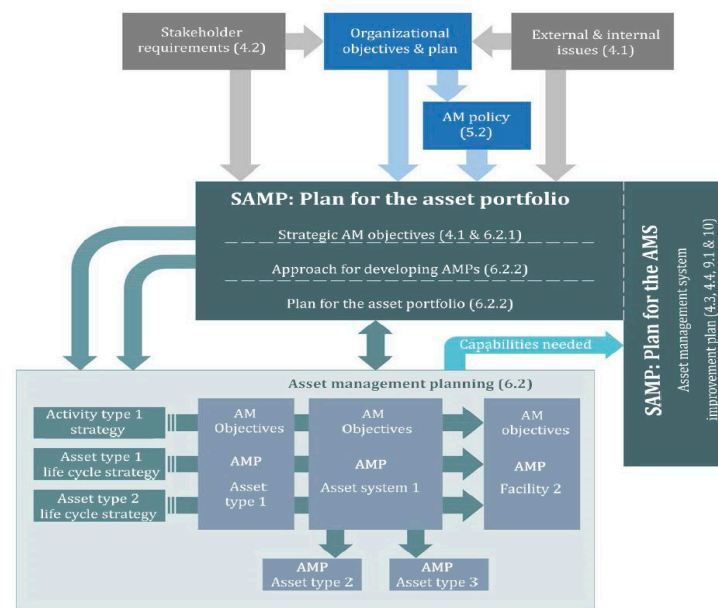
in turn, requires the collection of data from the asset during its life cycle. Thus, the basic requirement is the collection of data. There are a number of related questions: Does the asset bring value to the organization? How can we calculate the value of the asset? Farinha et al. [78] discuss Terology, considering the global life cycle of the assets. Emphasis is placed on the operation and maintenance, in addition to the importance of aligning the environment with the organization's goals. This may differ among organizations.

ISO 55000 [79] defines key concepts and presents tools to help with asset management. The standard presents a set of fundamentals, such as Value, Alignment, Leadership, and Assurance, under the topic of value life cycle management, which are included from a strategic perspective. There are a broad range of assets and, in order to maximize their value, it is important to manage their life cycle. In addition, it is necessary to implement decision-making processes, in which an econometric model can help stakeholders to support decisions related to the organization's assets. When outlining asset management plans, ISO 55001 [80] emphasizes the need to use processes and methods in the management of assets throughout their life cycles. Methods to conduct life cycle analysis include econometric models, which should be part of the Strategic Asset Management Plan (SAMP). According to ISO 55002 [54], the SAMP is "documented information that specifies how organizational objectives are to be converted into asset management objectives, the approach for developing asset management plans, and the role of the asset management system in supporting achievement of the asset management objectives". The SAMP can have a time span that is sufficiently long to address the complete life of the assets; this time span can be the organization's own business planning interval. In addition to the documentation of the SAMP, the decision-making criteria enable the definition of value realization and address the long-term financial sustainability of the assets.

The SAMP and its objectives must consider the entire asset portfolio, taking into consideration the asset management policy and the strategies of the life cycle of the different asset types, or generic activity types, which should be applied when developing the asset management plans. ISO 55002 [54] clearly states that the SAMP includes life cycle plans and "developing asset life cycle plans for an asset type or group of assets covering all life cycle activities (e.g., creation/acquisition, utilization/maintenance, renewal/disposal) and other functional plans (e.g., capital investment plan, energy management plan)".

Econometric models are included in the SAMP (Figure 9) to support the evaluation of the asset's replacement period. Additional considerations to aid their analysis are presented next.

To perform economic simulations and decide whether to replace an asset, different scenarios and considerations must be taken into account. It is extremely important to have reliable information and instruments for translating the condition of the asset [81]. Another means to avoid errors is the use of multivariate analyses [82], which can help to address problems that are difficult to detect, despite the need to apply several assumptions. Rodrigues et al. [83] also emphasize the importance of Artificial Intelligence (AI), which can produce reliable information, although good databases are required. Raposo et al. [53] note that deterioration is among the main reasons for replacing an asset. However, the authors also emphasize the need to choose an appropriate method to support a good decision regarding asset replacement, and highlight variables such as acquisition cost, value of withdrawal, operating costs, maintenance costs, operating costs, inflation rate, and discount rate.



**Figure 9.** SAMP concept diagram (Source: [54]). Labels: Refs—The clause numbers in Figure 9 relate to ISO 55001; AM—Asset Management; AMP—Asset Management Plan; SAMP—Strategic Asset Management Plan.

Information can be extracted from the historic data of each asset. Because information related to renewal or withdrawal may be difficult to acquire, in the case of a renewal the market can be consulted. Alternatively, in the case of a withdrawal, the asset devaluation can be simulated using one of the following methods, as presented by Oliveira [84], Farinha [76], and Farinha [77]:

1. Linear depreciation method—The annual decay of the equipment value is constant over time;
2. Sum of the digits method—The annual depreciation is not linear but less than that of the exponential method;
3. Exponential method—The annual depreciation is exponential over the equipment's life.

Farinha [76] applies several criteria for replacing an asset. From the financial perspective, the economic cycle is most often used to determine the optimal period that minimizes the average total costs of operation, maintenance, and capital immobilization. An additional commonly used method is the lifespan. In this approach, the life cycle of an asset ends when the operating costs are greater than the maintenance costs, plus the amortization of the capital cost of new and equivalent equipment.

To calculate the Uniform Annual Income (UAI) and determine the best time to replace an asset, the following data are necessary:

1. Equipment cost of acquisition;
2. Cession annual values (calculated according to the above methods or the market values);
3. Annual maintenance and operation costs;
4. Apparent rate.

To calculate the depreciation value, the exponential method is used. The formula evaluates the annual cost of depreciation during the equipment's life and is expressed as:

$$d_j = VC_{j-1} * \left( 1 - \sqrt[N]{\frac{VC_N}{II}} \right) \quad (5)$$

$$V_n = VC_{j-1} - d_j \quad (6)$$

where:

$d_j$ : Annual depreciation quota

$II$ : Initial Investment

$N$ : Time of life corresponding to  $VC_N$

$VC_N$ : Residual value of the equipment at the end of  $N$  time periods

$j$ :  $j = 1, 2, 3 \dots n$

$V_n$ : Equipment value in period  $n = 1, 2, 3 \dots n$

The Present Net Value in year  $n$  ( $PNV_n$ ) is given by:

$$PNV_n = II + \sum_{j=0}^n \frac{M_j + F_j}{(1 + i_A)^j} - \frac{V_n}{(1 + i_A)^j} \quad (7)$$

where:

$II$ : Initial Investment

$M_j$ : Maintenance in year  $j = 1, 2, 3, \dots n$

$F_j$ : Functioning in year  $j = 1, 2, 3, \dots n$

$i_A$ : Apparent rate

$V_n$ : Value of the equipment over a period  $n = 1, 2, 3 \dots n$

The Apparent rate ( $i_A$ ) is given by:

$$i_A = i_I + i_C + i_I \times i_C \quad (8)$$

where:

$i_A$ : Apparent rate

$i_I$ : Inflation rate

$i_C$ : Capitalization rate

The Annual ( $n$ ) Uniform Annual Income ( $UAI_n$ ) and Return Over Investment ( $ROI$ ) are given by:

$$UAI_n = \frac{i_A(1 + i_A)^j}{(1 + i_A)^j - 1} * PNV_n \quad (9)$$

$$ROI = \sum_{j=1}^n \frac{CF_j}{(1 + i_A)^j} - II \quad (10)$$

where:

$ROI$ : Return Over Investment

$II$ : Initial Investment

$CF_j$ : Cash Flow in year  $j = 1, 2, 3, \dots n$

$i_A$ : Apparent rate

$UAI_n$  represents the multi-year period in which the asset should be replaced; this value is equivalent to a minimum rent at which the equipment would need to be invested annually.

Based on the exponential depreciation method and Uniform Annual Income, a new approach was devised. In this approach, other investments, such as technological upgrades, technology depreciation, and sustainability depreciation, are taken into consideration to extend the life cycle of the asset. This approach is known as the Present Net Value Integrated in year  $n$  ( $PNVII_n$ ), given by:

$$PNVII_n = II + \sum_{j=0}^n \frac{IM_j + IF_j + TUI_j + TD_j + SD_j}{(1 + i_A)^j} - \frac{V_n + \sum_{j=0}^n R_j}{(1 + i_A)^j} \quad (11)$$

where:

$II$ : Initial Investment

- $IM_j$ : Integrated Maintenance in year  $j = 1, 2, 3, \dots n$
- $IF_j$ : Integrated Functioning in year  $j = 1, 2, 3, \dots n$
- $TUI_j$ : Technological Upgrade Investment in year  $j = 1, 2, 3, \dots n$
- $TD_j$ : Technology depreciation in year  $j = 1, 2, 3, \dots n$
- $SD_j$ : Sustainability depreciation in year  $j = 1, 2, 3, \dots n$
- $i_A$ : Apparent rate
- $V_n$ : Value of the equipment over a period  $n = 1, 2, 3 \dots n$
- $R_j$ : Residual value of the upgraded part  $n = 1, 2, 3 \dots n$

The Annual ( $n$ ) Integrated Life Cycle Assessment ( $ILCAM1_n$ ) and Integrated Return Over Investment ( $IROI$ ) are given by:

$$ILCAM1_n = \frac{i_A(1+i_A)^j}{(1+i_A)^j - 1} * PNVI_n \tag{12}$$

$$IROI = \sum_{j=1}^n \frac{CF_j}{(1+i_A)^j} - II \tag{13}$$

where:

- $IROI$ : Integrated Return Over Investment
- $II$ : Initial Investment
- $CF_j$ : Cash Flow in year  $j = 1, 2, 3, \dots n$
- $i_A$ : Apparent rate

The results are presented in Figure 10.

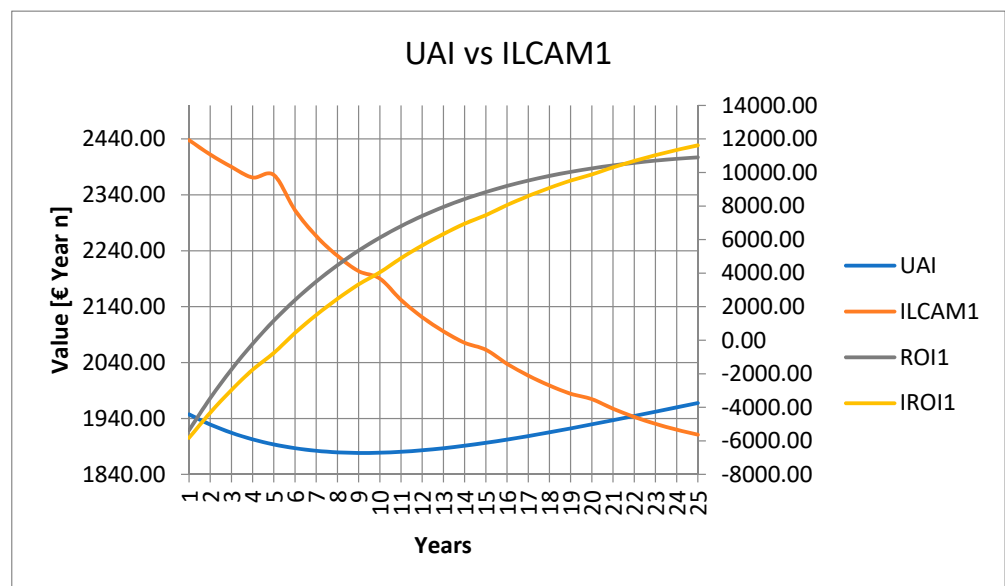


Figure 10. UAI vs. Integrated Life Cycle Assessment First Method (ILCAM1).

Based on the exponential depreciation method and the Minimization of Total Average Cost Method (MATC), a new approach ( $ILCAM2_n$ ) was tested:

$$\left\{ \begin{array}{l} ILCAM2_n = \frac{\sum_{j=1}^N IM_j + IF_j + TUI_j + TD_j + SD_j}{n} + \frac{II - (V_n + \sum_{j=0}^n R_j)}{n} \\ IROI2 = \sum_{j=1}^n \frac{CF_j}{(1+i_A)^j} - II \end{array} \right. \tag{14}$$

where:

- $II$ : Initial Investment

$IM_j$ : Integrated Maintenance in year  $j = 1, 2, 3, \dots, n$   
 $IF_j$ : Integrated Functioning in year  $j = 1, 2, 3, \dots, n$   
 $TUI_j$ : Technological Upgrade Investment in year  $j = 1, 2, 3, \dots, n$   
 $TD_j$ : Technology depreciation in year  $j = 1, 2, 3, \dots, n$   
 $SD_j$ : Sustainability depreciation in year  $j = 1, 2, 3, \dots, n$   
 $i_A$ : Apparent rate  
 $V_n$ : Value of the equipment over a period  $n = 1, 2, 3, \dots, n$   
 $R_j$ : Residual value of the upgraded part  $n = 1, 2, 3, \dots, n$   
 $CF_j$ : Cash Flow in year  $j = 1, 2, 3, \dots, n$   
 $IROI2$ : Integrated Return Over Investment

The results are presented in Figure 11.

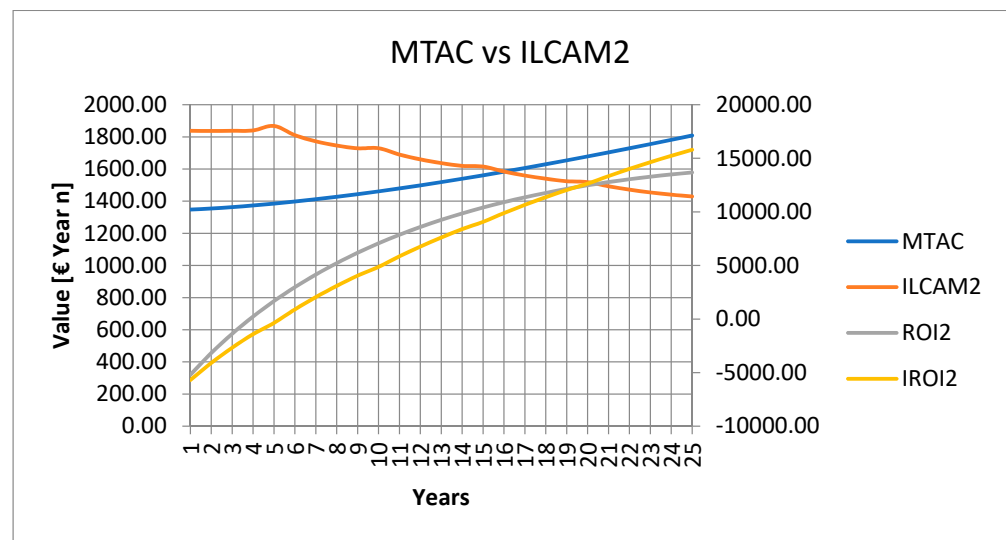


Figure 11. MTAC vs. Integrated Life Cycle Assessment Second Method (ILCAM2).

Based on the exponential depreciation method and the MMTAC Reduced to Present Value (MMTAC-RPV), a new approach ( $ILCAM3n$ ) was tested:

$$\begin{cases} ILCAM3n = \frac{1}{n} \sum_{j=1}^N \frac{(IM_j + IF_j + TUI_j + TD_j + SD_j)}{(1+i_A)^j} + \frac{II - \left( \frac{V_n + \sum_{j=0}^n R_j}{(1+i_A)^n} \right)}{n} \\ IROI3 = \sum_{j=1}^n \frac{CF_j}{(1+i_A)^j} - II \end{cases} \quad (15)$$

where:

$II$ : Initial Investment

$IM_j$ : Integrated Maintenance in year  $j = 1, 2, 3, \dots, n$

$IF_j$ : Integrated Functioning in year  $j = 1, 2, 3, \dots, n$

$TUI_j$ : Technological Upgrade Investment in year  $j = 1, 2, 3, \dots, n$

$TD_j$ : Technology depreciation in year  $j = 1, 2, 3, \dots, n$

$SD_j$ : Sustainability depreciation in year  $j = 1, 2, 3, \dots, n$

$i_A$ : Apparent rate

$V_n$ : Value of the equipment over a period  $n = 1, 2, 3, \dots, n$

$R_j$ : Residual value of the upgraded part  $n = 1, 2, 3, \dots, n$

$CF_j$ : Cash Flow in year  $j = 1, 2, 3, \dots, n$

$IROI3$ : Integrated Return Over Investment

The results are presented in Figure 12.

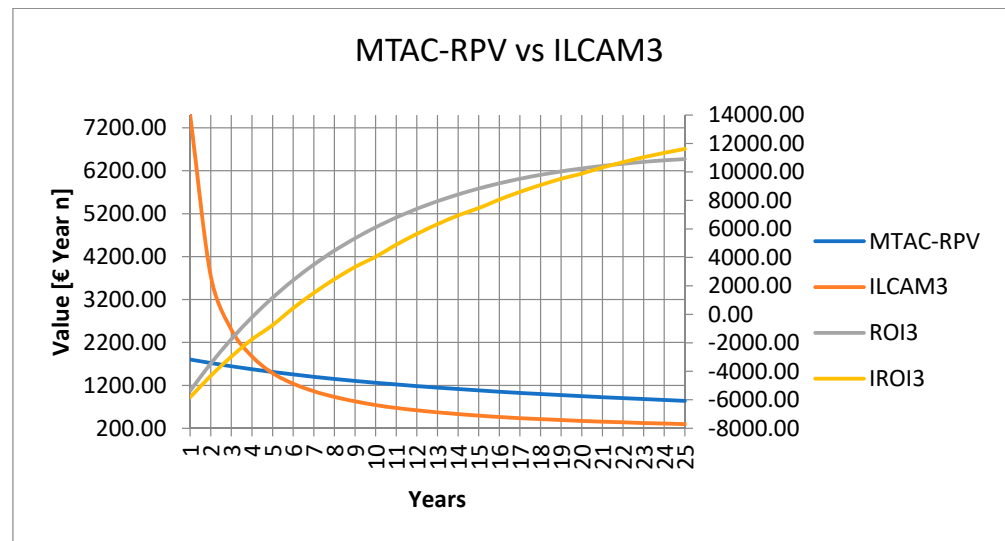


Figure 12. MTAC-RPV vs. Integrated Life Cycle Assessment Third Method (ILCAM3).

As shown in Figure 10, the Integrated Life Cycle Assessment First Method better adapts to this asset, and provides clear results for replacement.

#### 4. Integrated Life Cycle Investment Assessment Method (ILCIAM)

The Present Net Value Integrated method proposes variable investment in maintenance, whereas investing more in sustainable and technological parts will increase the MTBF, reduce MTTR, and consequently increase availability.

Farinha et al. [41], while proposing the LCI, presents the Global Result in year  $n$  ( $GR_n$ ). The  $GR_n$  Formula (16) includes the initial investment and the annual variable maintenance investments throughout the asset's life; this yields the overall result that a company can expect from an asset's life cycle from an investment perspective. The results are presented in Figures 13 and 14.

$$GR_n = \sum_{j=0}^n \frac{B_j * \frac{MTBF_j}{MWT_j + MTTR_j + MTBF_j}}{(1+IRR_j)^j} + \sum_{j=0}^n \frac{F_j}{(1+IRR_j)^j} + \sum_{j=0}^n \frac{M_j}{(1+IRR_j)^j} + \sum_{j=0}^n \frac{B_j * \left(1 - \frac{MTBF_j}{MWT_j + MTTR_j + MTBF_j}\right)}{(1+IRR_j)^j} + \sum_{j=0}^n \frac{I_j}{(1+IRR_j)^j} \quad (16)$$

where:

$MTBF_j$ : Mean Time Between Failures

$MWT_j$ : Mean Waiting Time in year  $j = 1, 2, 3, \dots, n$

$MTTR_j$ : Mean Time to Repair

$F_j$ : Functioning in year  $j = 1, 2, 3, \dots, n$

$M_j$ : Maintenance in year  $j = 1, 2, 3, \dots, n$

$IRR_j$ : Internal Rate of Return in year  $j = 1, 2, 3, \dots, n$

$I_j$ : Physical Asset Value in year  $j = 1, 2, 3, \dots, n$

$B_j$ : Benefit in year  $j = 1, 2, 3, \dots, n$



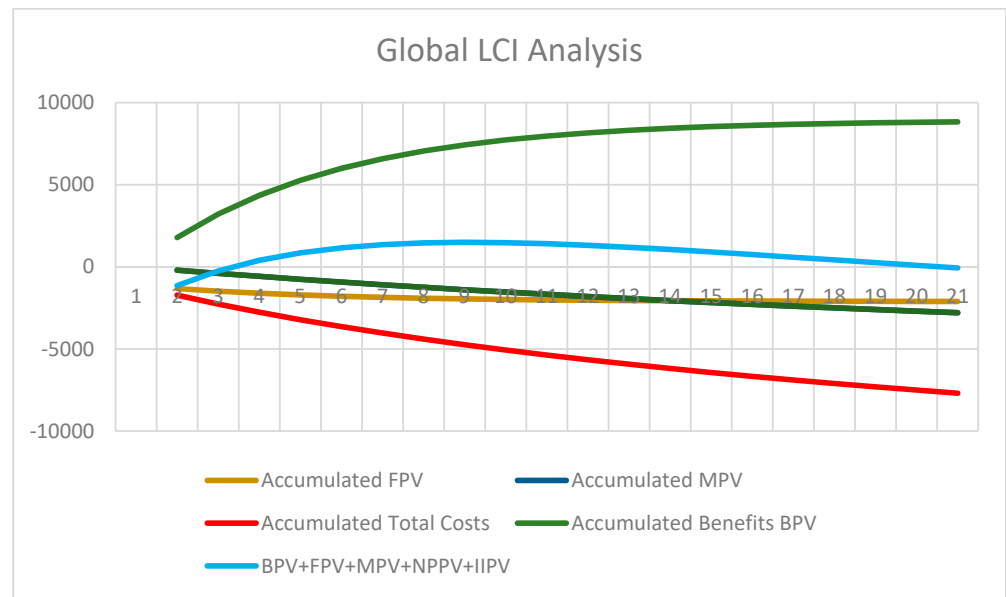


Figure 13. Values of investment, functioning, and benefits [41].

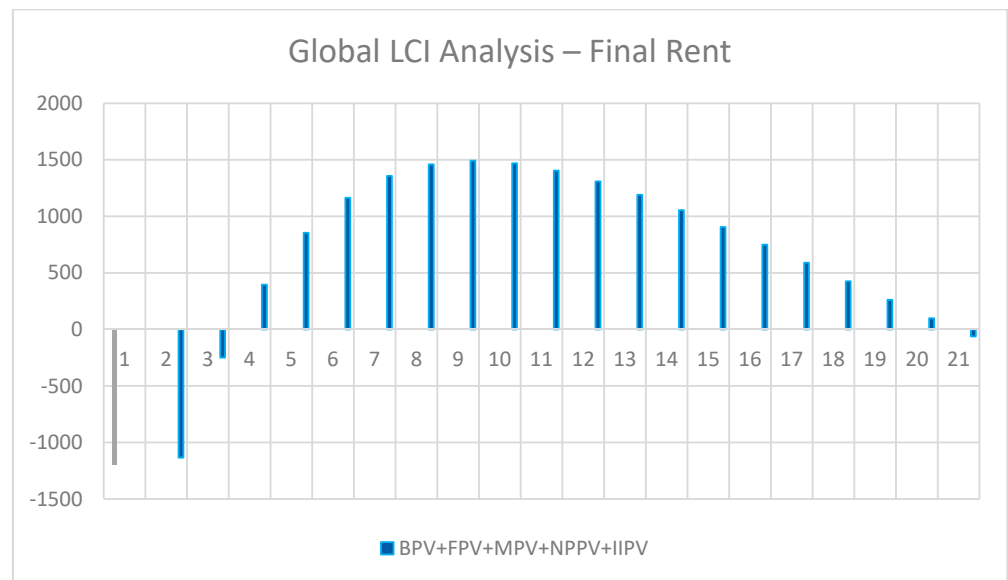


Figure 14. Annual financial results of the physical asset [41].

The comparison of ILCAM vs.  $GR_n$  shows that the two methods provide similar results. Furthermore, both are part of the SAMP.

Based on the  $GR_n$ , by integrating sustainability depreciation ( $SD$ ), technology depreciation ( $TD$ ), and technological upgrade investment ( $TUI$ ), we developed the Integrated Life Cycle Investment Assessment Method ( $ILCIAM$ ):

$$\begin{aligned}
 ILCIAM = & \sum_{j=0}^n \frac{B_j * \frac{MTBF_j}{MWT_j + MTTR_j + MTBF_j}}{(1+IRR_j)^j} + \sum_{j=0}^n \frac{IF_j}{(1+IRR_j)^j} + \sum_{j=0}^n \frac{IM_j}{(1+IRR_j)^j} + \\
 & \sum_{j=0}^n \frac{SD_j}{(1+IRR_j)^j} + \sum_{j=0}^n \frac{TD_j}{(1+IRR_j)^j} + \sum_{j=0}^n TUI_j \\
 & + \sum_{j=0}^n \frac{B_j * \left(1 - \frac{MTBF_j}{MWT_j + MTTR_j + MTBF_j}\right)}{(1+IRR_j)^j} + \sum_{j=0}^n \frac{I_j}{(1+IRR_j)^j}
 \end{aligned} \tag{17}$$

where:

$MTBF_j$ : Mean Time Between Failures

$MWT_j$ : Mean Waiting Time in year  $j = 1, 2, 3, \dots n$

$MTTR_j$ : Mean Time to Repair

$IF_j$ : Integrated Functioning in year  $j = 1, 2, 3, \dots n$

$IM_j$ : Integrated Maintenance in year  $j = 1, 2, 3, \dots n$

$IRR_j$ : Internal Rate Return in year  $j = 1, 2, 3, \dots n$

$SD_j$ : Sustainability depreciation in year  $j = 1, 2, 3, \dots n$

$TD_j$ : Technology depreciation in year  $j = 1, 2, 3, \dots n$

$TUI_j$ : Technological upgrade investment in year  $j = 1, 2, 3, \dots n$

$I_j$ : Physical Asset Value in year  $j = 1, 2, 3, \dots n$

$B_j$ : Benefit in year  $j = 1, 2, 3, \dots n$

When integrating sustainability depreciation and technology depreciation investment, the final rent increases. This occurs because the maintenance and functioning investments are reduced due to the technological upgrade, as shown in Figures 15 and 16.

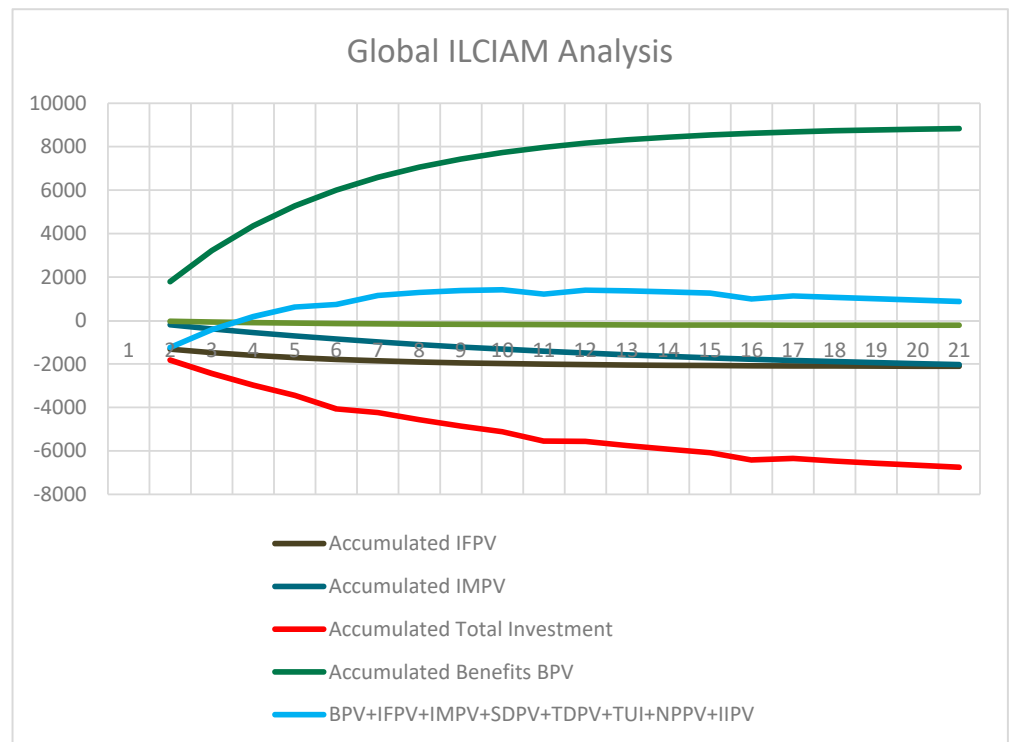
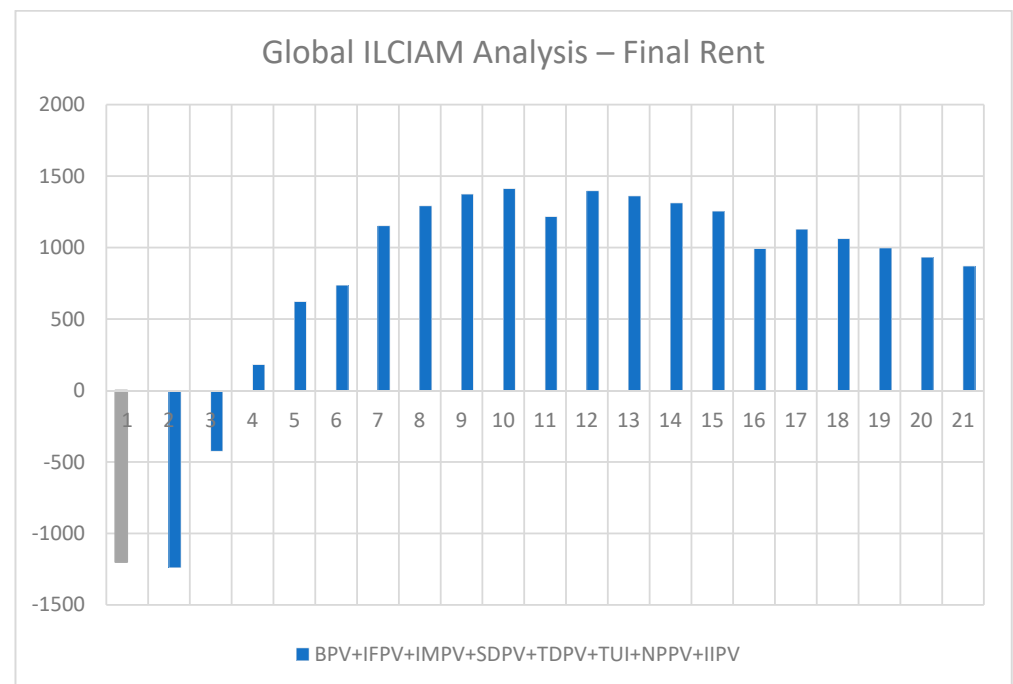


Figure 15. Values of investment, functioning, and benefits.



**Figure 16.** Annual financial results of the physical asset.

## 5. Discussion

The ILCAM shows the increase in the asset's value, and that the replacement of vital parts results in a more efficient, ecological, and sustainable asset with an extended life. However, the outcome is not only an extension; it is a sustainable extension of an asset that can reduce the cost of maintenance, be more reliable, and reduce CO<sub>2</sub> emissions. In certain types of asset, the CO<sub>2</sub> emissions may be reduced to the same level as that of a new asset.

A large share of energy consumption occurs in buildings [85,86]. Replacing parts on assets with lower CO<sub>2</sub> impacts results in an increase in overall sustainability.

Figure 10 shows that the Integrated Life Cycle Assessment First Method is better able to adapt to the asset. In the comparison of UAI with ILCAM1, year 9 is identified for replacement under UAI; in comparison, the life of the asset is extended to over year 25 with ILCAM1.

Comparing the results of Figures 13 and 15 shows that the accumulated total investment in ILCIAM decreases and, in Figures 14 and 16, the final rent is still positive in the 21st year under ILCIAM.

A key question is whether industry will be prepared for this new model. The design of assets can clearly be changed to accommodate the replacement of vital parts with a short life cycle with reference to sustainability. Thus, if this is considered in the design, the assets can facilitate the replacement of certain parts. As a result, the cost of replacement can be reduced.

The technological upgrade increases the life cycle of the asset and promotes reductions in waste, raw material use, and energy costs, in turn promoting the circular economy and sustainable development [15,16,87–92]. The upgraded parts in the asset can also be returned to assembly lines and refurbished to incorporate the latest technologies, and re-enter the market.

Can we estimate the worth of our planet? Does our planet have a price? Although these remain questions that we cannot fully answer, the major question is: how much are we willing to pay to live in a better world, in which we can be sure that our posterity will have a bright future?

We believe this challenge must be a win–win relationship between society and governments: society must be prepared to invest only in sustainable assets; and governments must support and incentivize society via fiscal incentives.

These challenges must be translated into the Strategic Asset Management Plan (SAMP) of each company, and ISO55001 may be a strategic tool to achieve those goals.

The presented models can be used in different assets. However, in the current case study, the Integrated Life Cycle Assessment First Method (ILCAM1) based on Uniform Annual Income (UAI) provided the better fit. For other assets with shorter or longer lives, or higher or lower initial investments, other models can be used after being tested.

Although the used model applies to the analyzed data, other assets may have different behaviours. Nonetheless, the presented approach is a robust and solid model that can be used for a broad range of assets.

The two introduced methods (ILCAM and ILCIAM) use different approaches to establish replacement periods. In the studied cases, the results were similar to the analyzed data, which reinforced the methods. In both methods, the replacement period increases, and the return and the initial curve slope are lower. However, the slope is steeper, which is translated as a significant return. The methods are robust and can be used in the SAMP as a decision-making tool.

## 6. Conclusions

The methods presented in this paper emphasize the need to increase sustainability in assets, in response to the climate emergency. Using these methods, asset managers can calculate the time at which an asset replacement or renewal should be made, in addition to the increase in the asset's value. Moreover, the methods stress the importance of creating value in assets according to ISO 55001, and represent a new approach for LCA. The methods promote the circular economy through parts replacement rather than replacement of the whole asset.

It is difficult to assign a value to sustainability. However, it is important to construct a method to calculate the worth of sustainability because numerous factors must be taken into consideration. Some are relatively obvious, such as greenhouse gases emissions, carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), nitrogen oxides (NO<sub>x</sub>), and fluorinated gases. In addition, respiratory diseases have been associated with some of these gases, and the degree of suffering induced by an illness can be determined.

Other important considerations in future research may include the addition of a coefficient of risk, as referred to in ISO 55001. The Standard requires that organizations ensure that asset management-related risks in the organization's risk management approach are included in the contingency plan. The risk factors when shortening or extending the life cycle of an asset must be considered.

Governments must pay more attention to the introduction of sustainability and technology depreciation benefits, and demonstrate the gains associated with the transition from a linear economy to a circular economy, and with the sustainable increase in assets' life cycles using standards such as ISO 55001.

In future research, new sustainable and technological factors will be included to evaluate new approaches and their influence on the sustainability of the circular economy.

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