A Model for Optimizing the Life Cycle of Physical Assets based on a Circular Economy Approach

José Edmundo de Almeida e Pais

Tese para obtenção do Grau de Doutor em

Engenharia e Gestão Industrial

(3° Ciclo de Estudos)

Orientador: Professor Doutor António João Marques Cardoso
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Julho de 2024

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Dedication

This work, although challenging, made me grow on a personal, social, and academic level. I would like to recognize and thank my family for all their support, especially to my children for the time I took from them, to my mother for the example of strength she is for me and to my father who, although he is no longer with us, has always been an example of work and vision.

An exceptional recognition to Professor José Torres Farinha, my co-superviser, for believing in me and allowing me to pursue my PhD, with whom, through his example, I created a friendship relationship of which I am very proud.

It was surely an enormous honour to have him as my supervisor, and I want to thank Professor António Marques Cardoso for accepting to be my advisor on my PhD.

To my good friend Professor Hugo Raposo, who, despite not being my supervisor or co-supervisor, was always there helping me throughout this journey with suggestions and corrections to my work and always being by my side giving me encouragement.

To the Lusófona University in the person of Professor José Oliveira Santos for the support and trust in my work and to my colleagues at the Lusófona University.

To my friends who encouraged me and to the one even though away from me showed a full support, a special thank you to those who walked alongside me, my doctoral colleagues and friends, Alexandre Martins, Balduíno Mateus, and João Rodrigues.

Resumo

Nos últimos anos, a Gestão de Ativos (GA) era normalmente descrita como gestão de manutenção; o seu foco centrava-se em programas, procedimentos e outras tarefas para otimizar o tempo de atividade dos ativos da organização. Nos dias de hoje, quando se considera a gestão de ativos, deve ser tida em consideração uma gestão ativa do ciclo de vida dos principais ativos e componentes considerados, desde o berço até ao túmulo.

Por outro lado, ao realizar a gestão de ativos, alguns outros pontos devem ser levados em consideração. No passado, apenas alguns ativos eram considerados geridos; esta abordagem antiga traz alguns pontos fracos. Uma nova abordagem deve considerar todos os ativos como parte da organização. Mesmo que o seu papel após as análises não seja fulcral, é importante conhecê-los, devendo ser feitos planos para esses ativos, mesmo que não sejam complexos ou detalhados.

Ao considerar a GA, é necessário aplicar uma Avaliação do Ciclo de Vida (ACV). Ao fazê-lo, muitos fatores devem ser levados em consideração, com foco na redução de despesas e no aumento da sustentabilidade em diversos aspetos. Equipamentos com menor impacto ambiental devem sempre ser considerados e desenvolvidos, sendo igualmente necessário melhorar amplamente a sustentabilidade.

A gestão de ativos tem como principal função obter valor dos ativos, mas por onde começar? Para obter o seu maior valor, a ISO 55001 apresenta um conjunto de planos. Um deles é o Plano Estratégico de Gestão de Ativos (SAMP), que detalha os objetivos de gestão de ativos e explica sua relação com os objetivos organizacionais e a estrutura necessária para atingir os objetivos da gestão de ativos.

O SAMP precisa de ter um conjunto de processos para concretizar o valor esperado. A gestão de ativos lida com diferentes áreas. Deve ter uma forma clara de comunicação dentro e fora da organização porque cada setor desempenha um papel vital no todo.

Por outro lado, o SAMP deve fornecer ferramentas para gerir o ciclo de vida dos ativos físicos. Estas precisam de ser quantitativas para serem facilmente mensuráveis. Por outro lado, o SAMP deve estar alinhado com os objetivos da organização. Esse alinhamento é comunicado para garantir que as partes interessadas externas e as partes interessadas internas, em todos os níveis da organização, entendam por que as atividades do ciclo de vida dos ativos e as atividades de gestão de ativos são implementadas.

Ao construir um SAMP, é fundamental que ele possa ser medido com o uso de ferramentas como o *Balanced Scorecard* (BSC), com Indicadores Chave de Desempenho (KPIs) adequados que possam trazer uma abordagem quantitativa capaz de facilmente medir a qualidade do SAMP. Ao usar o BSC existem quatro perspetivas: Financeira, Cliente,

Processo interno e Aprendizagem e Crescimento, que atendem perfeitamente aos requisitos do SAMP.

Palavras-chave

ISO5500x; SAMP; Ativos físicos; Avaliação do ciclo de vida; Sustentabilidade; Economia circular; *Balanced scorecard*.

Resumo Alargado

A gestão de ativos físicos responde a uma evolução da gestão da manutenção, assente numa abordagem moderna, com uma visão holística há muito defendida por vários autores. Os ativos nas organizações cresceram de tal forma que a sua gestão baseada em novas abordagens se tornou indispensável por várias razões, nomeadamente de sustentabilidade, principalmente nos dias de hoje, onde as alterações atingem pontos de irreversibilidade, e o risco associado aos ativos, devido à sua cada vez maior complexidade e à nossa dependência dos mesmos, para assegurar as nossas necessidades. Assim, numa Terra com recursos finitos precisamos desenvolver técnicas e processos que aumentem o tempo de vida útil, conseguindo desta forma retirar o máximo de rentabilidade dos mesmos.

A economia circular é um perfeito parceiro da gestão de ativos, pois ambos se encontram perfeitamente alinhados nos seus objetivos de aumentar a vida útil de ativos e, noutros casos, dar-lhes uma nova vida sem que para isso sejam necessários consumos muito elevados de energia, como é o caso de fundição.

A presente tese apresenta esta necessidade como algo que deixou de ser uma opção nos dias de hoje, mas sim uma obrigação ou até mesmo a única opção. Não temos outro planeta para ocupar nem para explorar toda a matéria-prima e recursos de que necessitamos: recursos básicos como a água potável estão a tornar-se escassos e a sua utilização e gestão de todo o ciclo deve ser cuidada; o mesmo acontece com outros recursos. No desenvolvimento deste trabalho, o autor apresenta modelos para gestão de ciclos de vida dos ativos, considerando aspetos como a sua manutenção, disponibilidade, tecnologia e sustentabilidade.

O grande documento da gestão de ativos é o *Strategic Asset Management Plan* (SAMP), onde os objetivos da gestão dos ativos são alinhados com os objetivos gerais da organização. Desta forma, a organização é um todo e instiga-se uma cultura da organização acabando com silos, onde toda a organização converge para os objetivos da mesma e onde a comunicação é bidirecional e clara; é ainda lá que encontramos todos os planos e critérios de decisão relativos aos diversos processos e ativos da organização, entre os quais aqueles relacionados com a gestão do ciclo de vida.

Com o objetivo de apoio aos gestores na tomada de decisão, esta tese apresenta modelos econométricos que visam a análise do ciclo de vida dos ativos onde, através de decisões relacionadas com a manutenção, tecnologia e sustentabilidade, podemos analisar os resultados no ciclo de vida do ativo, nomeadamente qual é o momento em que devemos proceder à substituição do mesmo e de que forma os investimentos em manutenção, tecnologia e sustentabilidade aumentam ou reduzem a vida útil de um ativo; claramente estas decisões devem estar focadas nos objetivos da organização.

Sendo o SAMP um documento fundamental na gestão de ativos, é fundamental conhecê-lo e ter as ferramentas necessárias para medir o seu desempenho. Esta tese apresenta ferramentas simples, apoiadas em *softwares* disponíveis com grande facilidade para todos os utilizadores para as quais a maioria tem conhecimentos e facilidade em trabalhar. Nesta perspetiva, a ferramenta apresentada nesta tese permite aos gestores avaliar o desempenho de todo o sistema quando se focam apenas no SAMP. Esta ferramenta teve como base o *Balanced Scorecard* (BSC), que é uma ferramenta de gestão estratégica amplamente divulgada e usada por gestores, baseando-se na medição de aspetos principais como: financeiro, cliente, processo interno, aprendizagem e crescimento.

A criação do modelo de avaliação apresentado nesta tese, suportando-se num BSC, cria um alinhamento entre os requisitos da norma ISO 55001 e os aspetos apresentados pelo BSC. Desta forma, foram usados Indicadores Chave de Desempenho (KPI - *Key Performance Indicators*) que permitem o alinhamento e possibilitam o enquadramento dos requisitos em cada um dos aspetos do BSC. O resultado é um quadro onde é possível identificar o desempenho da organização em cada área, permitindo assim aos gestores identificar claramente os pontos de melhoria a implementar.

Assim, o trabalho apresentado enquadra-se nas necessidades dos dias de hoje, procurando colmatar modelos e ferramentas que respondam àquelas de uma forma ampla, de fácil utilização e sem necessidade de investimento de forma a implementar estas ferramentas. Os resultados apresentam uma capacidade de tornar as nossas organizações mais sustentáveis, algo que é fundamental nos nossos dias - afinal que planeta pretendemos deixar para os nossos descendentes?

Palavras-chave

ISO5500x; SAMP; Ativos físicos; Avaliação do ciclo de vida; Sustentabilidade; Economia circular; *Balanced scorecard*.

Abstract

In the past years, Asset Management (AM) was normally described as maintenance management; their focus was on programs, procedures, and other tasks to optimize the organization's assets uptime. Nowadays, when considering asset management, an active life cycle management of the major assets must be taken in consideration and components considered from the cradle to the grave.

On the other side, some other points must be taken into consideration when performing asset management. In the past, only a few assets were considered to be managed; this old approach brings a few weaknesses. A new approach must consider all the assets as part of the organization. Even if their role after analyses is not pivotal, it is important to know them, and plans must be made for those assets, even if they are not complex or detailed.

When considering AM, there is a need to apply a Life Cycle Assessment (LCA). While doing so, many factors must be taken into consideration, focusing on reducing expenses and increasing sustainability in several aspects. Equipment with less environmental impact must always be considered and developed, while improving sustainability broadly.

The principal function of asset management is to realize value from assets, but where to start? To obtain their major value, the ISO 55001 presents a set of plans. One of them is the Strategic Asset Management Plan (SAMP), which details the asset management objectives and explains their relationship with the organizational objectives and the framework required to achieve the asset management objectives. The SAMP needs to have a set of processes to realize the expected value. Asset management deals with different areas. It must have a clear way to communicate inside and outside the organization because every sector plays a vital role in the whole. On the other hand, the SAMP must provide tools to manage physical assets' life cycle. Those tools need to be quantitative to be easily measured. On the other side, the SAMP must be aligned with the organization's objectives., This alignment is communicated to ensure that external and internal stakeholders, at all levels of the organization, understand why asset life cycle activities and asset management activities are implemented. While building a SAMP, it is fundamental that it can be measured with the use of tools such as Balanced Scorecard (BSC) with adequate Key Performance Indicators (KPIs) that can bring a quantitative approach that can easily measure the quality of the SAMP. While using BSC there are four perspectives: Financial, Customer, Internal Process, and Learning and Growth, which perfectly fit the SAMP requirements.

Keywords

ISO5500x; SAMP; Physical assets; Life cycle assessment; Sustainability; Circular economy; Balanced scorecard.

Contents

List of Figures

List of Tables

Acronyms

ALCM	Asset Life Cycle Management
AM	Asset Management
AMMF	Asset Management Modelling Framework
AMS	Asset Management System
BELCAM	Building Envelope Life Cycle Asset Management
BIM	Building Information Modelling
BP	Business Plan
BSC	Balanced Scorecard
CAPEX	Capital Expenses
EN	European Standard
FMEA	Failure Mode and Effect Analysis
ILCAM	Integrated Life Cycle Assessment Method
ILCIAM	Integrated Life Cycle Investment Assessment Method
IoT	Internet of Things
IS	Industrial Symbiosis
ISO	International Organization for Standardization
ISO/TS	International Organization for Standardization / Technical Specification
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Investment
LCM	Life Cost Management
LCSA	Life Cycle Sustainability Assessment
LCV	Life Cycle Valuation
OPEX	Operational Expenses
PAM	Physical Asset Management
PDCA	Plan, Do, Check and Act
RCM	Reliability Centred Maintenance
ROI	Return on Investment
RQ	Research Questions
SAMP	Strategic Asset Management Plan

SMART	Specific, Measurable, Achievable, Realistic and Timebound
SP	Sustainability Performance
TCO	Total Cost of Ownership
TLAM	Total Life-Cycle Asset Management
UK	United Kingdom
USA	United States of America

Chapter 1

Introduction

1.1. Sustainability

Nowadays, some questions arise, what planet do we wish to leave for our posterity? Topics like sustainability and circular economy became of extreme importance when the major number of countries in the world see their Earth Overshoot Day approaching earlier every year (Figure 1) [1]; it is unequivocally clear that linear economy is not an appropriated model for our days. Sustainability has been a popular topic in recent decades [2], and it is typically explained based on three areas, i.e., society, economy, and environment [3]. More recently, energy has been introduced as an additional topic within the concept of sustainability [4]–[6]. The main concern is translating sustainability into sustainable development [7].

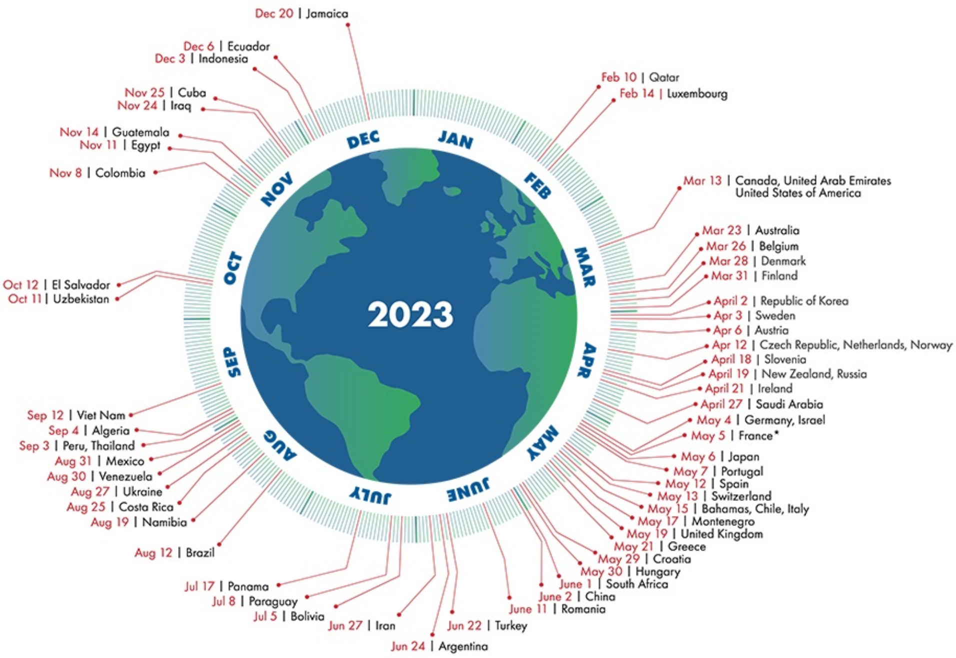

Figure 1 - Country's overshoot day.

Every year, Earth Overshoot Day has come early or has recovered just slightly from prior years. Nowadays, we are borrowing money from future generations, which is not feasible at the moment. We need to be able to live simply without putting the needs of the earth and future generations at risk. The Earth Overshoot Day shifted 145 days, from 25

December to 2 August, in slightly over 50 years, as seen in Table 1 [8]. The unanswered question is whether we are willing to pass on this debt to upcoming generations.

Table 1 - Earth Overshoot Day 1971–2023.

Year	Overshoot day	Year	Overshoot day	Year	Overshoot day
1971	25th December	1989	13th October	2007	15th August
1972	27th December	1990	18th October	2008	16th August
1973	3rd December	1991	20th October	2009	23rd August
1974	30th November	1992	30th October	2010	10th August
1975	27th November	1993	27th October	2011	6th August
1976	21st November	1994	16th October	2012	4th August
1977	17th November	1995	9th October	2013	3rd August
1978	12th November	1996	4th October	2014	5th August
1979	1st November	1997	6th October	2015	7th August
1980	16th November	1998	7th October	2016	9th August
1981	20th November	1999	26th September	2017	5th August
1982	1st December	2000	17th September	2018	1st August
1983	4th December	2001	13th September	2019	3rd August
1984	17th November	2002	19th September	2020	11th August
1985	7th November	2003	12th September	2021	3rd August
1986	5th November	2004	2nd September	2022	1st August
1987	30th October	2005	27th August	2023	2nd August
1988	16th October	2006	24th August		

[1] 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 emission of pollutant gases is the main reason for environmental problems; the emission of CO_2 and others pollutant gases create major problems on the ozone layer [8]–[10], also causing climate changes and environmental pollution of air, land and water, [11], [12]. The environmental pollution brings a major impact on health and life quality for all living beings. These take us to the need for a sustainable development, which has been a subject of major discussions on our days were governments, non-government institutions, academics and others are part.

The global water cycle is also becoming more intense due to climate change, with drier parts becoming drier and wetter parts typically becoming wetter. On the other hand, one of the sustainability concerns is related to global warming and rising sea levels [13]. While these changes increase vulnerability to climate disasters, they also increase the intensity of the global water cycle. Currently, nearly half of the world's 3.6 billion inhabitants live in areas where there may not be enough water for, at least, one month of the year [14]–[17].

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 [12]. From January 2022 to September 2022 [18], over 60% of Portugal's territory experienced extreme drought. On the other hand, in December 2022, Lisbon had precipitation with values of 17,1 mm/m2 in 10 minutes, resulting in flooding throughout the city (Figure 2) [19], [20].

Figure 2 - Floods in Lisbon, December 2022.

When dealing with drought, some authors refer to massive economic collapse, enormous loss of life, destruction in housing and infrastructures, agriculture, and other activities [12], [13], [21]–[24]. However, when dealing with floods, authors refer to massive economic disruption, destruction in housing and infrastructures, agriculture, and other activities. Previous studies have established a connection between climate change and the increase in the temperature due to CO_2 emissions [25]–[30].

Earth Overshoot Day has occurred earlier each year, or with only a minor recovery compared to previous years. In fact, we are borrowing from future generations, what is currently not sustainable. We must be able to live strictly with what we have, without compromising future generations and the planet. The open question is whether we are willing to leave this debt for future generations to pay.

Keeble [31] 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.

Currently, technical advancement is necessary for progress [32]. The requirements of the populace drive this growth, which is supported by economic and social advancement. Nevertheless, environmental, social, cultural, and economic variables are necessary to maintain sustainable development [33]. Then, it is necessary to find a balance to guarantee sustainable development [34]; for instance, requiring energy reduction in addition to the use of clean energy [35]. To do this, technological development is required [36], so that energy use can be decreased.

In the European Council held in 2000 in Lisbon, the European Union decided to become a sustainable economy by 2010; this goal became more evident in the following years: in 2001 a Sustainable Development Strategy focused in four keys priorities was launched: limiting climate change and increasing the use of clean energy; addressing threats to public health; managing natural resources more responsibly; improving the transport system and land use [37]. In 2005 a review of Sustainable Development Strategy was published, which results were clear on the following years.

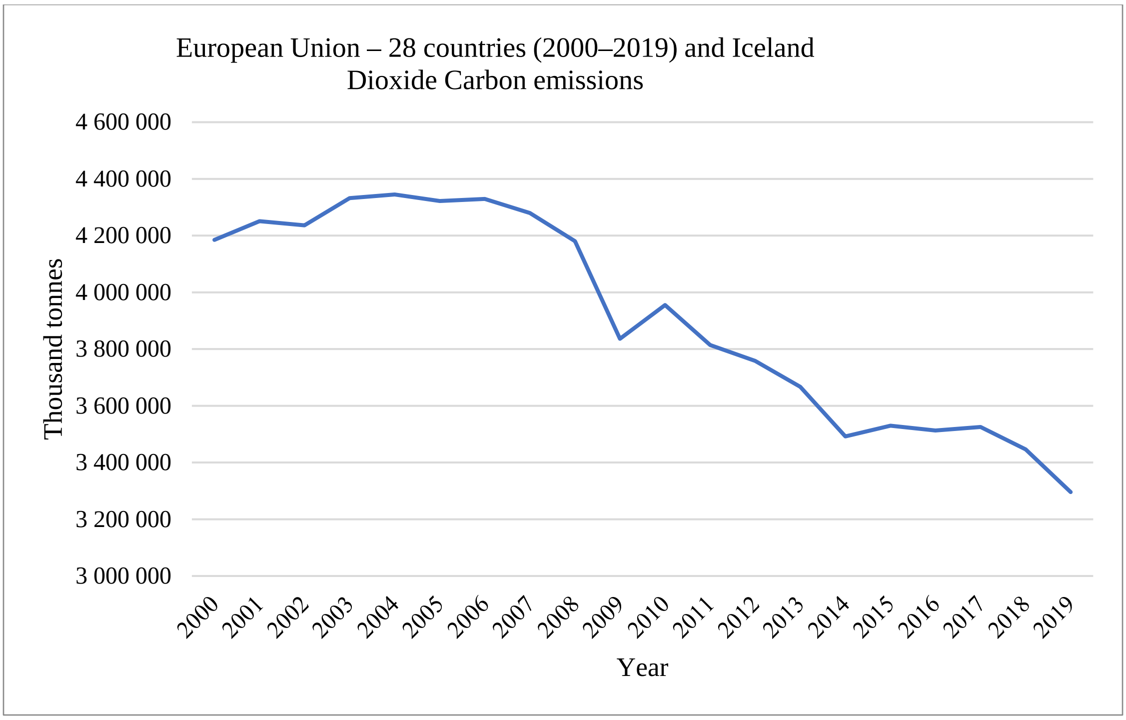

Figure 3 - European Union-28 countries (2000–2019) and Iceland Dioxide Carbon emissions.

In Figure 3 [38] the results of the Sustainable Development Strategy adapted by the European Union can be seen; without discussing the increase on the initial years, throughout the last two decades, those of the European Union, which consists of 27 nations plus the UK, have declined; in 2019 they were 25.1% and 22.2% lower than in 1990 and 2005, respectively. From 2015 and 2019, Europe's proportion of all emissions declined from 9.6% to 8.7%. In contrast, the worldwide CO_2 emissions from the combustion and production of fossil fuels rose by 0.9% in 2019 (Figure 4) [39], which is almost 50% slower than the previous year's growth rate (+1.9% in 2018) and reached a total of 38.0 Gt CO_2.

Together, the top CO_2 emitters, in 2019, China, the United States, India, the EU27 including the United Kingdom, Russia, and Japan were in charge of 51% of the world's population, 62.5% of the global gross domestic product, 62% of all fossil fuel consumption, and 67% of all fossil CO_2 emissions. China and India, which lead the world expansion in emissions, saw increases of +3.4% and +1.6%, respectively, in their emissions in 2019 compared to the previous year. Some nations, such as the EU27 + UK (3.8%), the US (2.6%), Japan (2.1%), and Russia (0.8%), cut their fossil CO_2 emissions [39].

According to United Nations World Commission on Environment and Development (UNWCED), "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" [40].

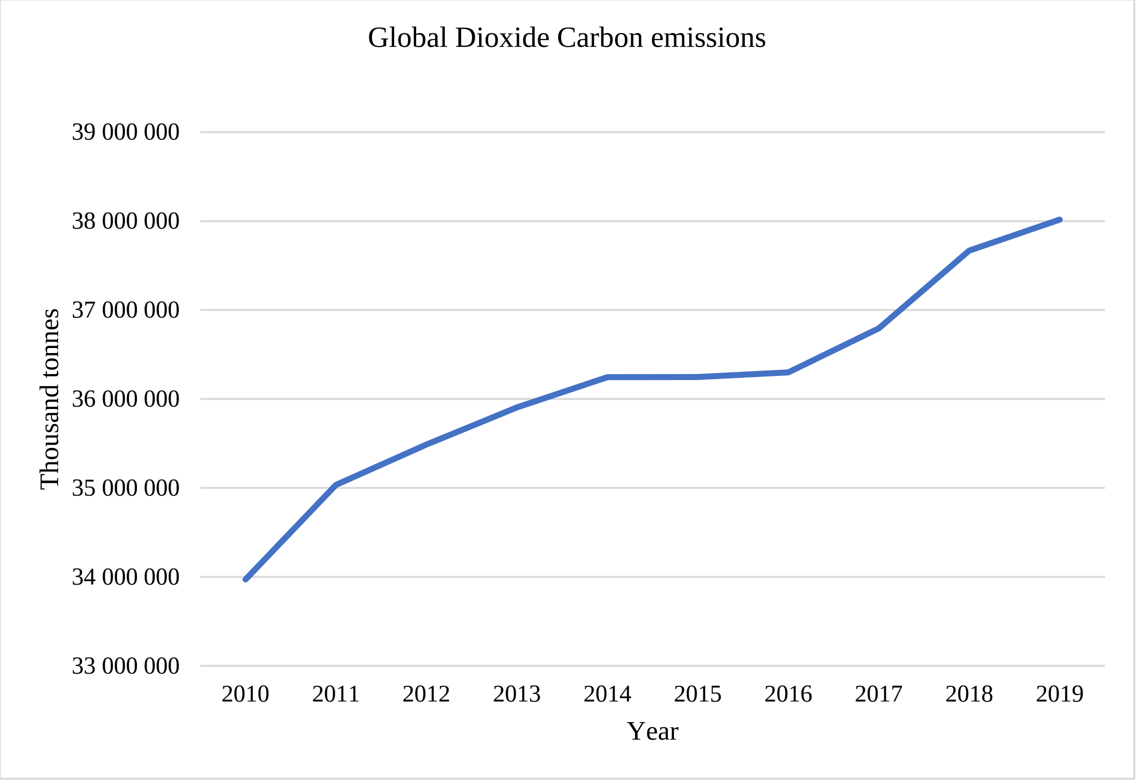

Figure 4 - Global Dioxide Carbon emissions, adapted from Fossil CO2 emissions of all world countries– 2020 Report.

On the other hand, the world emissions did not stabilize but, instead, they have increased; from 2010 to 2019 they grew about 12%, so, is this a real worldwide concern? An international treaty like Kyoto Protocol was adopted on December 11, 1997, having entered into force on February 16, 2005, its objective being to reduce the onset of global warming by decreasing the greenhouse gas concentrations in the atmosphere, namely Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulfur hexafluoride (SF_6) and, afterwards, Nitrogen trifluoride (NF_3) [41].

According to UNWCED, "Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs." [42].

According to Goodland [43], 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 [44] 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. [45] 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.

For instance, the consumption of steel worldwide has increased dramatically, and during the past 20 years, crude steel output has climbed by more than 16%. (Figure 5) [46].

Using steel scrap lessens environmental effects, it reduces the loss of natural resources, and lowers CO_2 emissions into the atmosphere. By reducing environmental stress, assisting society, and improving quality of life, the usage of scrap results in a welfare gain. Carbon steel scrap usage reduces greenhouse gas emissions by 1.67 t CO_2 per ton, and stainless steel use reduces emissions by 4.3 t CO_2 per ton [47].

The use of scrap also uses up to 10 times less energy than the manufacture of basic steel, which dramatically lowers CO_2 emissions. Just 40% of steel is produced from scrap, albeit [48]. The steel and iron industries are strong because of the great demand for steel around the world. Their objectives include maintaining the high quality of their goods, boosting productivity, lowering operating costs, consuming less energy, and reducing environmental pollutants. Recycling can help you reach some of these goals [49].

When considering sustainability there is a great demand regarding the growth; as an example, in Portugal, from 1995 till 2015, the urban area expanded 40,2% [50]. While the population between those years only increased 2,75%, the urban population grew 27,56%.

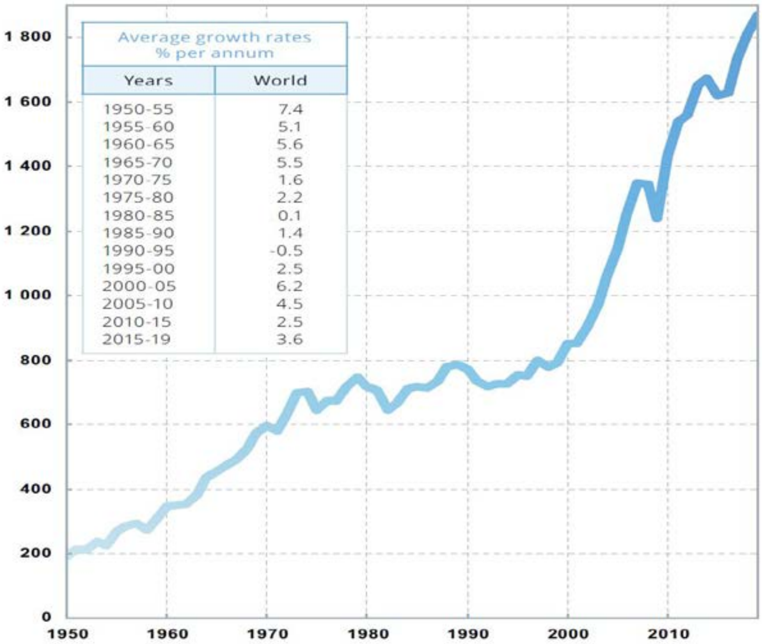

Figure 5 - Crude steel production, million tonnes.

Because the earth's natural resources are limited and finite [51]–[61], there is a need to manage them more effectively. Some authors contend that better utilization of natural resources leads to economic advancement [62]–[64], while other authors emphasize the necessity of reducing waste and reusing equipment after it has served its purpose [65]–[67]. The 6Rs, which encourage closed loops throughout life cycles, are presented by Bilge *et al.* [68]. The long-term goal is to maintain the environment by safeguarding resources and preserving economic prosperity while taking into account social issues and, at the same time, reducing pollution and waste. The relevance of 6R Approaches, including Reinforcing, Reduce, Reuse, Recycle, Recover, Redesign, and Remanufacture (Figure 6) [69], must be emphasized at this time. The fundamental objective is to extend the life cycle of the assets as much as possible, to recognize and produce value from them, and to sustain their value and sustainability through effective management [12].

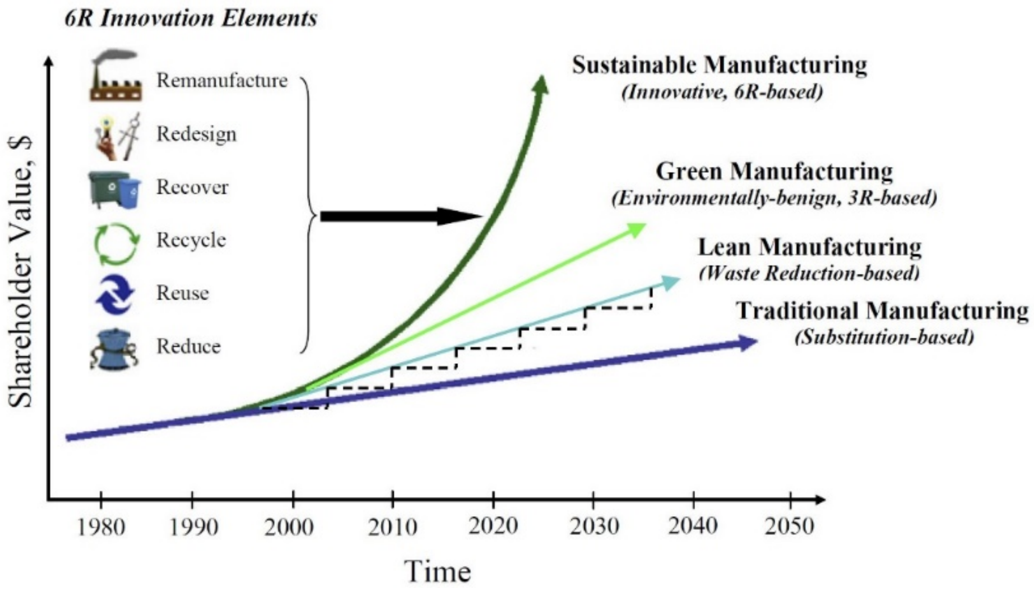

Figure 6 - Sustainable manufacturing for the twenty-first century.

1.2. Circular Economy

In the context of achieving sustainable development, the circular economy has become a popular research [70]. The advent of the circular economy has occurred when the reduction, reuse, recovery, and recycling of materials and energy has become a priority [71], 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 [72]–[75] have defended the importance of the circular economy to attain sustainable development, despite some misunderstandings about the concept of the circular economy.

In today's world, the circular economy is crucial to achieving sustainable development [70]. The move from the linear economy that began with the industrial revolution to the circular economy needs to be a priority, and the circular economy has played a significant part in achieving those aims [71], [76]. Previous authors [53], [54], [62]–[65], [77] have argued that the circular economy is essential to achieve sustainable development, despite certain misconceptions about the idea.

So, circular economy is much more than just recycling; circular economy aims to replicate biological cycles, basically nothing is lost, just entering in some other process; the energy used in this new process should not be high, thus promoting the sustainability that is promoted in circular economy.

The Ellen MacArthur Foundation is deeply involved in educating the public about the circular economy, and has published several related documents [78]–[83]. Countries such as China [84] have understood the need for this transformation, which clearly depends on political engagement. Although circular economy is a recent concept, concepts like Industrial Symbiosis (IS) were introduced in the early 70s [85], and is considered part of industrial ecology [86].

The principle of IS is based on the use of surplus resources generated by processes directed into a new process, by some or other industries, creating a symbiosis or mutual benefits among sectors, departments or company's; by doing this, there is a reduction of waste what brings economic, environmental, and social benefits. These items, like information, knowledge, expertise, political support, supply networks, and distribution markets, can also be shared, which brings some benefits mentioned before [87]. In most cases, these benefits might translate into a reduction in the operational costs, the reduction of greenhouse gas emissions, the increase in knowledge and skills, the job creation, the tax benefits, the economic profit [86] and the promotion of an industrial ecosystem compared to a natural ecosystem, where nothing is lost and is used by another being [88].

The IS gained a greater importance around the world due to concerns about climate change [89]. On these days, IS is part of initiatives to promote circular economy like European Circular Economy Action Plan and the European Green Deal [90], [91].

Most of the times, the economy growing is associated to the increase of pollution. In fact, statistics provided evidence that the US economy grew nine times as fast as carbon emissions, and the global economy grew 2.5% and 2.8%, respectively, while carbon emission dropped by 0.5% and 0.8%, during the years 1998 and 1999. This means that economic growth can be achieved without burning more fossil fuel or consuming more resources [92].

1.3. Energy

Even considering all of the current developments in order to achieve sustainable development, we must reduce energy consumption, look for renewable and low-carbon energy sources [93]–[98], and to develop low-consumption equipment and energy-efficient projects. By doing this, we will attract more investors [99] and promote economic growth [100].

The development of human society has always depended on the availability of energy sources. Since the industrial revolution [60], energy has been the main factor driving the growth of modern civilisation. The growth rate of the economy and energy consumption are correlated, although the population is growing less quickly each year.

According to some researches, the increasing of energy use and the physical assets promote economic growth at the expense of environmental sustainability [101]. Luciani [102] provides an example of how the pace of renewable energy transitions affects whether or not the economic growth supported; on the one hand, investing in physical assets makes it simpler to incorporate cutting-edge technologies into the production process, which will facilitate the necessary transition (Figure 7) [103]–[105] .

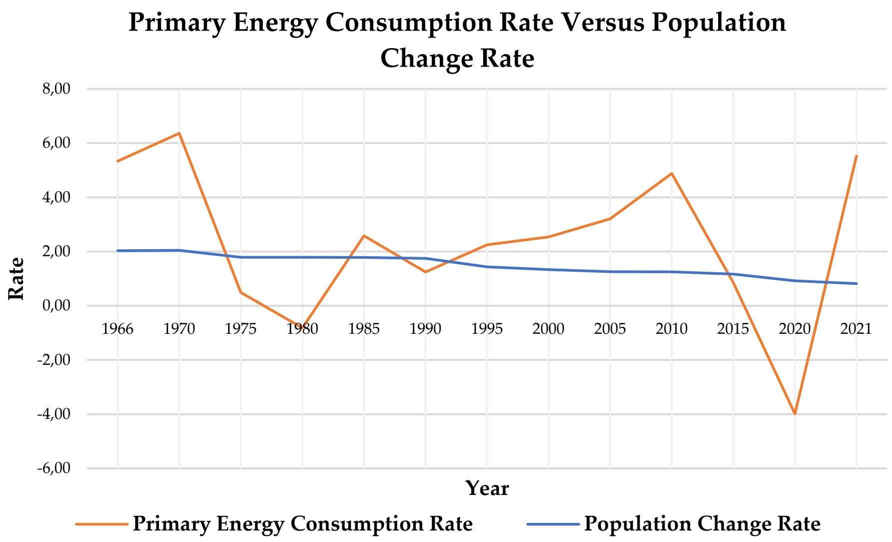

Figure 7 - Primary Energy consumption Rate Versus Population Change Rate.

Completing the required transition for Asset Management (AM), it will become a huge advantage because it makes it simpler to train skilled people, to increase knowledge transfers, to obtain top alternative management platforms, etc. [101]. This facilitates both the switch to renewable energy sources and the sustainable use of energy, which promotes economic growth [74], [75]. There are a few processes involved in building AM. The main document, the SAMP, outlines the asset management objectives, explains how they relate to organizational goals, and outlines the framework needed to achieve those goals [106]. Accurate data is required in order to develop a dependable SAMP [107].

1.4. Life Cycle Management

Asset Life Cycle Management (ALCM) is rapidly adopting industry 4.0 technologies and, in the manufacturing sector, companies expect to achieve sustainable outcomes through industry 4.0 technologies [108]. Industries are using industry 4.0 technologies to look for opportunities for sustainable manufacturing [109], [110]. In order to increase sustainability [111], technologies like Neural Networks are used to predict pavement performance. Basically, businesses hope to produce as much as possible, while using the fewest resources possible. Assets must have predictive maintenance procedures in place to increase their availability for this to occur [14]–[17], [112]–[116].

1.5. Asset Management

What is asset management? ISO 55000 defines asset management as a "coordinated activity of an organization to realize value from assets" [117].
Asset management involves balancing costs, opportunities, and risks with the desired performance of assets to achieve organizational goals. This balance may have to be considered in different periods. Asset management also allows an organization to examine the need and performance of assets and asset systems at different levels [118]. Furthermore, it allows the application of analytical approaches to manage an asset at different stages of its life cycle (which can start from the conception of the assets until their disposal and includes the management of any post-disposal obligation). Asset management is the art and science of making the right decisions and optimizing value delivery. A common objective is to minimize the cost of living on assets, but there may be other critical factors, such as risk or business continuity, to be objectively considered in this decision making [71].
When considering standards on asset management ISO 55000, sets the target audience as [117]:

- those considering how to improve the realization of value for their organization from their asset base;
- those involved in the establishment, implementation, maintenance and improvement of an asset management system;
- those involved in the planning, design, implementation and review of asset management activities, along with service providers.

When considering the benefits of asset management ISO 55000, this standard supports the realization of value while balancing financial, environmental and social costs, risk, quality of service and performance related to assets and sets the following benefits [117]:

- improved financial performance - improving the return on investments and reducing costs that can be achieved, while preserving asset value and without sacrificing the short or long-term realization of organizational objectives;
- informed asset investment decisions - enabling the organization to improve its decision making and effectively balancing costs, risks, opportunities and performance;
- managed risk - reducing financial losses, improving health and safety, goodwill and reputation, minimizing environmental and social impact, what can result in reduced liabilities such as insurance premiums, fines and penalties;
- improved services and outputs - assuring the performance of assets, it can lead to improved services or products that consistently meet or exceed the expectations of customers and stakeholders;

- demonstrated social responsibility - improving the organization's ability, for example, to reduce emissions, to maintain resources and to adapt to climate change, what enables it to demonstrate socially responsible and ethical business practices and stewardship;
- demonstrated compliance - transparently conforming with legal, statutory and regulatory requirements, as well as adhering to asset management standards, policies and processes, that can enable demonstration of compliance;
- enhanced reputation - through improved customer satisfaction, stakeholder awareness and confidence;
- improved organizational sustainability - effectively managing short and long-term effects, expenditures and performance, what can improve the sustainability of operations and the organization;
- improved efficiency and effectiveness - reviewing and improving processes, procedures, and asset performance, what can improve efficiency and effectiveness, and the achievement of organizational objectives.

What are these assets? ISO 55000 defines asset as a "thing or entity that has potential or actual value to an organization". This states that the asset life "does not necessarily coincide with the period over which any one organization holds responsibility for it; instead, an asset can provide potential or actual value to one or more organizations over its asset life, and the value of the asset to an organization can change over its asset life" [117] - this definition supports circular economy where assets may be considered waste or end-of-life by an organization, which can enter another organization and continue to create value, increasing the life-cycle of assets.

Asset management is a tool to help managing the organization (Figure 8) [117] that includes the asset management system and its assets.

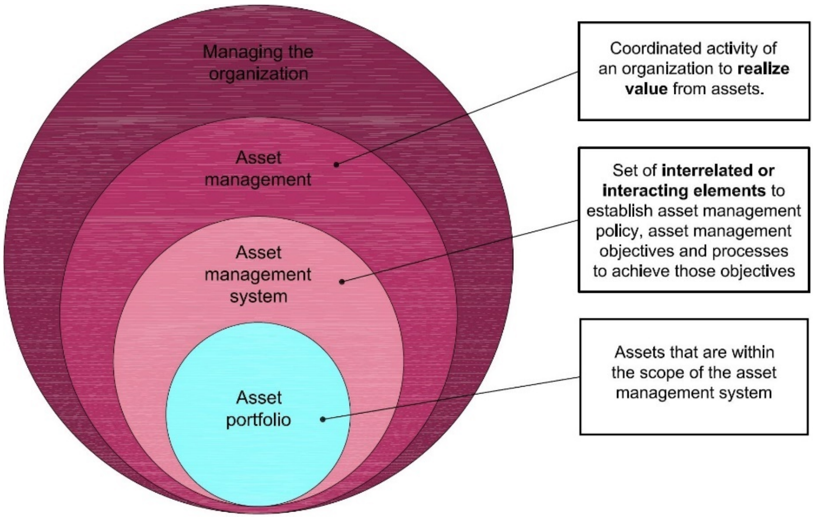

Figure 8 - Relationships between key terms.

Over the years maintenance was considered a necessary evil [119], having be seen only as a cost in the organisations. Nowadays, factors like cost, quality and reliability are taken into consideration [120]. On the other hand, assets well-kept bring great advantages to countries economy and organizations finance stability [121].

Over the last few decades, industry has been acquiring equipment with more and more technology and more and more complexity, in order to satisfy customers' needs [122]-[123]. This has increased the need of maintenance optimization. Asset management emerged to fill the need of managing complex systems to be able to increase productivity and quality.

With such complex systems, the organizations emerge in automation in order to improve competitiveness, productivity, and safety. To do that, they resort to digital technologies such as Building Information Modelling (BIM), Internet of Things (IoT), wearable devices and sensors [124], which are some of the tools that are commonly used in asset management that become handy to develop strategic plans.

Asset management focuses on the alterations that assets go through (Figure 9) [125]. Throughout the lifetime of a physical asset, several internal and external changes take place. Establishing ways to aid in decision-making is crucial. Others, such as legislation changes, environmental implications, and production demand, must be projected earlier even though some changes may be beyond the prediction range. Asset management, on the other hand, is founded on a comprehensive viewpoint, giving the potential to stop situations that are the hardest to foresee.

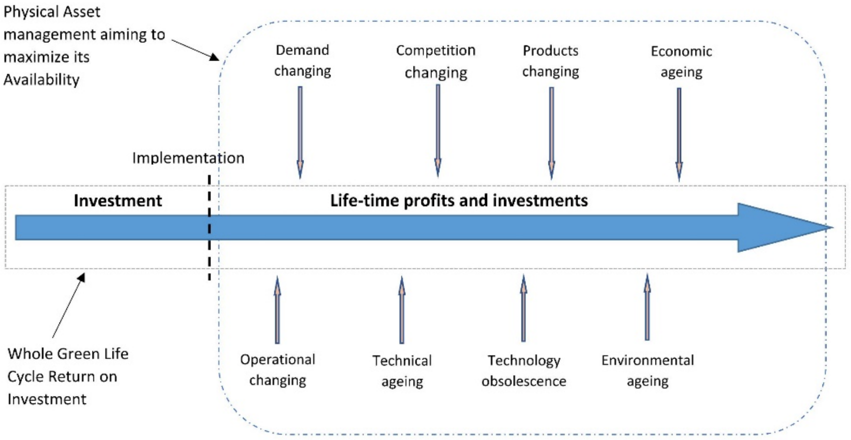

Figure 9 - The focus of asset management.

The use of assets is linked with sustainability [126], in order to develop sustainable economies; the advantages of these assets, in terms of innovation and knowledge-based technologies are used, linking innovation, knowledge, and the environment [127]. On the other hand, authors link economic sustainability with management of physical assets, while others claim that, in many industries, maintenance procedures can significantly contribute to the pursuit of sustainable development [128].

In order to successfully increase the sustainability of the environment, it is crucial to execute methods based on complementary assets [129]. The inability of decision-makers to design adequate maintenance plans or to maintain the assets make it difficult for them to sustain an asset's performance in accordance with reasonable repair techniques. Organizations are under pressure to ensure the longevity of their assets from all corners of the globe [130]. If necessary, installation maintenance is not adequately funded to ensure long-term viability, concerning sustainability and safety are raised [131].

1.6. Strategic Asset Management Plan

When planning about asset management, it is central to have a Strategic Asset Management Plan (SAMP). The SAMP must see the organization as a whole, and all the organizational plans - even the notes related with assets - must be integrated, ensuring that asset management is integrated with the organization's overall business planning processes. Besides this plan, it must be aligned with each other ensuring that concerns with one specific asset that doesn't interfere with other asset or group of assets.

The holistic view must always be present, meaning that plans must incorporate all actions to be taken on the assets, ensuring that plans cover it all, including life cycle analyses, which covers from cradle to grave. Recent authors, such as Sandy Dunn, bring old tools from other research areas such as the concept SMART (Specific, Measurable, Achievable, Realistic and Timebound) [132]-[133], reinforcing the need for asset management plans and objectives be clear and SMART (Figure 10) [133], bringing upwards the need to clearly identify and prioritize the actions to be included in plans. By the end, if you don't know where you are going, any road will get you there [134].

Figure 10 - SMART.

ISO 55002 [106] suggests that asset management objectives should be SMART, whereas ISO 55001 [135] only requires objectives to be measurable if applicable.

Figure 11 - Vertical alignment of objectives.

The SAMP is defined, by ISO 55000, as "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" (Figure 11) [117], [133].

According to ISO 55000, "a strategic asset management plan can be referred to by other names, e.g. an asset management strategy" and, ISO 55002 states that "a SAMP can be referred to by other names, e.g. 'asset management strategy'"; on the other hand, it includes the strategy and the strategic plan in the same document, what can become unwieldy - it will be hard to maintain and unlikely to be used, because, sometimes, it becomes to be a long document, with over 200 pages, that becomes part of a shelf and hardly anyone uses it, thus becoming worthless for the organization [117] [106].

1.7. Objectives and Purpose

The objectives of the research are to create tools that help managers manage their assets, and identify the status of their asset management system and improve it.

In order to achieve the objectives, extensive research was done to identify tools that could be used in order to fulfil the purpose.

The study's particular goals are as follows:

1. To study life cycle assessment methods, and in what ways they can fit in the SAMP requirements.
2. Create life cycle assessment methods that are easy to use and available with other tools, that managers have available in their daily lives, and that will help managers to make decisions on their assets identifying in what stage they are.

3. Create tools to help managers to build their asset management system, to measure and improve it.

1.8. Research Questions

How can an organization build a SAMP tool that be useful and will help the organization to bring value to their assets? The aim of this research is to bring a tool for the organizations that is quantitative, SMART, and at same time, simple and objective in order to support the decisions concerning life cycle of physical assets, since topics, such as total cost of ownership, return on capital employed, environmental impact, life cycle costs, lifetime expectancy, and asset energy performance [106] are part of asset management objectives.

Even if the ISO 55001 and ISO 55002 present a series of requirements and tools, it can be difficult for organizations to identify which ones to use and, in certain cases, the organization is not ready to have a structure which includes a heavy asset management department.

Based on the preceding, and what was referred in the preceding sections, the Research Questions (RQ) are the following ones:

RQ 1: How organizations may increase value from its Physical Assets?

RQ 2: How can Physical Assets' Life cycle be optimized according to the organization's needs?

RQ 3: Which are the econometric models that can best be conjugated to Physical Assets' Life Cycle Assessment (LCA)?

RQ 4: How can Strategic Asset Management Plan (SAMP) be designed to improve the Life Cycle of Physical Assets?

RQ 5: How can Strategic Asset Management Plan (SAMP) performance be measured?

The three attached papers address the five RQs, as shown in Table 2.

Table 2 - Relationship between RQs and appended papers

RQ	*Paper I (Appendix A)*	*Paper II (Appendix B)*	*Paper III (Appendix C)*
RQ 1	X	X	
RQ 2		X	
RQ 3		X	
RQ 4			X
RQ 5			X

1.9. Range and Restrictions

Research studies how asset management has evolved and identifies gaps that make it difficult for managers to work in their main activity of asset life cycle management, as well as to assess the state of the asset management system.

The focus of this research is the Strategic Asset Management Plan, which is the main operational tool to fulfil the objectives of the asset management system and, in short, the objectives of the organization.

The following are some limitations of the research:

- The number of organizations implementing asset management is low and organizations with ISO 55001 certification are practically non-existent.
- The difficulty that organizations have in recording and maintaining information on their assets from the moment their need was identified until the moment they decide to scrap them, convert them, upgrade them, or retrofit them.
- The lack of culture in organizations and the distrust of stakeholders when trying to make changes.

Future efforts will focus on overcoming these constraints.

1.10. Authorship of the Attached Papers

Table 3 summarizes each author's contribution to the attached articles. The contribution is divided in the following tasks:

1. Conception and design study;
2. Data collection;
3. Data analysis and interpretation;
4. Writing the article;
5. Critical analysis of the article.

Table 3 - Contribution of each author to the appended papers

Author	*Paper I*	*Paper II*	*Paper III*
Edmundo Pais	1,2,3,4	1,2,3,4	1,2,3,4
Hugo Raposo	1,2,3,5	1,2,3,5	1,2,3,5
José Torres Farinha	1,3,5	1,3,5	1,3,5
António João Marques Cardoso	5	5	5
Pedro Marques		5	
Svitlana Lyubchyk			5
Sergiy Lyubchyk			5

1.11. Overview of the Thesis

There are six chapters in the thesis. The need for asset management is described in the first chapter, which also sets the goals of the study. Finally, the papers mentioned in Chapter 1 are attached.

This thesis is structured as follows:

- Chapter 2 describes the State of the Art;
- Chapter 3 presents the Integrated Life Cycle Assessment Method (ILCAM) and Integrated Life Cycle Investment Assessment Method (ILCIAM);
- Section 4 presents a Strategic Asset Management Plan – A Quantitative Approach;
- Section 5 presents a discussion;
- Section 6 offers the conclusions.

Chapter 2

State-of-the-Art

The physical assets and its development have been a concern and a hallmark of the human activity from early times. Figure 12 [136] shows military wagons from the city of Ur dating from 2600 B.C. Clearly, the citizens of Ur were familiar with the wheel, but this means that there must also have been artisans who were familiar with the bearing, on which the wheel depends, with lubrication on which the bearing depends, and with the lathe and other woodworking and metalworking tools needed to build the wheels and the wagons.

Figure 12 - Military assets - city of Ur 2600 B.C.

2.1 Models

Prior approaches and techniques with the goal of enhancing maintenance and therefore extending the life cycle of an asset have been proposed. The Institute of Asset Management [137] and the worldwide standard on asset management [106] place emphasis on the requirement to optimize life cycle cost in accordance with a specific level of service. Asset management's goal is also described as "the best strategy to manage assets to achieve a desired and sustainable outcome" by The Institute of Asset Management [138]. To achieve excellence in asset management, Jardine & Tsang [139] and Campbell, Jardine & McGlynn [140] offer cost optimization models for replacement and a summary of probabilistic maintenance. Over the course of the assets' entire life cycle, performance, cost, and risk must be balanced. In addition to the economic component, integrating environmental and social considerations is also vital, and a balance is needed to support decision-making.

With an emphasis on the life cycle, Pais *et al.* [141] present studies using models and methodologies, along with their advantages and limitations in terms of asset management (Table 4 [141]).

Table 4 - Models or approaches with advantages and disadvantages.

Model / Approach	Author	Year	Advantages	Disavantages
Asset Management Process	Campbell	1995	• Nine steps process	• Not a model
BELCAM Decision-support Tool	Vanier *et al.*	1996	• Gathers information only in order to use in the analysis of life cycle	• Based on buildings • Don't introduce mathematical models
Asset Management Program	Malano *et al.*	1999	• Introduce elements of an asset management program	• Based on water utility • Don't introduce mathematical models • Not a Model
Asset Life Cycle Management	National Treasury guidelines	2004	• Sets a framework for asset management	• Not a Model
Asset Management Modelling Framework	Malano *et al.*	2005	• LCC model is proposed • Introduce mathematical models	• Requires lots of data that may not be available
Asset Management Techniques	J. Schneider *et al.*	2006	• Considers economic factores • Ageing model	• Don't introduce mathematical models • Based on electricity distribution networks
Asset Life Cycle Management	Schuman & Brent	2005	• Introduce elements of an asset management program	• Don't introduce mathematical models
Asset Life Cost Management	Haffejee & Brent	2008	• Considers economic, environmental, social and technical factors and performances • Assets management from before acquisition to disposal	• Based on water utility • Don't introduce mathematical models
Intelligent engineering asset management system	Trappey *et al.*	2015	• Fault prediction	• Based on Transformers • Not a Model
Integration of ISO 55001 with maintenance management	Parra *et al.*	2019	• Establishes a relationship of ISO 55001 requirements with maintenance management	• Don't introduce mathematical models

In 1996, Vanier *et al.* [142] used the Building Envelope Life Cycle Asset Management project (BELCAM) (Figure 13) [142], to provide models, methods and tools to meet these needs, and to assist building researchers and scientists in delivering their evaluation of the service life of building envelope components. This approach incorporates access to information technology such as: The Internet and the World Wide Web; Information technology tools, such as classification systems and product modelling; Life cycle economic principles; Service life and durability research; Risk analysis and reliability assessment; User functional requirement models; and Maintenance management strategies. This type of framework for managing data, information and knowledge could be used to predict the service life of other building or construction systems.

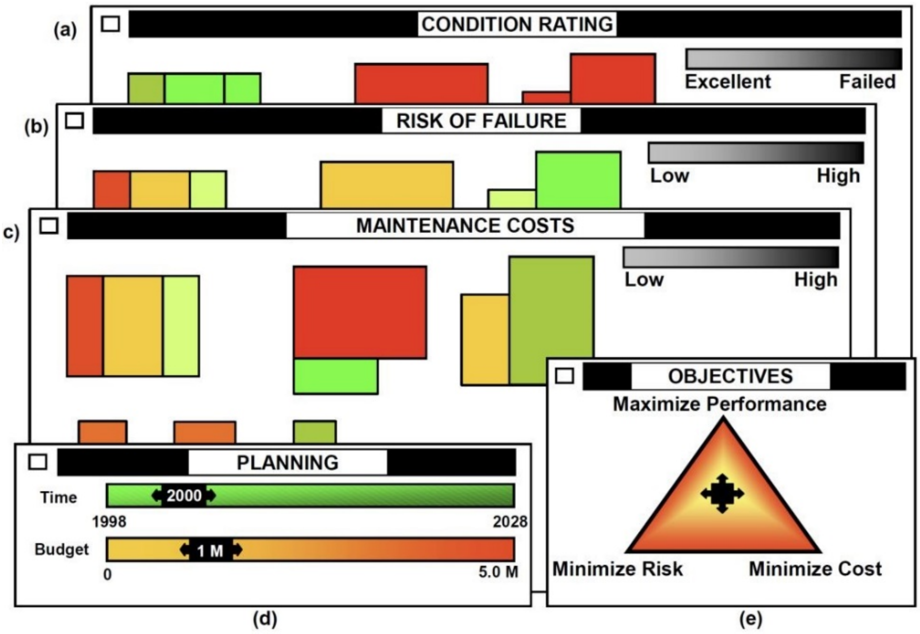

Figure 13 - BELCAM Decision-support Tool".

McElroy [143] defines asset management as a "systematic process of maintaining, operating and upgrading physical assets cost-effectively". Focusing on transportation systems states that asset management promises to provide a solid framework for optimizing the transportation system through cost-effective management, and programming and resource allocation decisions. Their focus is to develop, identify and advance analytical tools and organizational structures to make cost-effective engineering and investment decisions.

Asset Management links user-demands, technical analysis, engineering criteria and goals, and budgetary constraints. A generic description of the process follows: First - performance expectations (goals and policies), consistent with available budgets and user demands, are ascertained and used to control the decision-making framework; Second - condition information is collected and analysed, given stated performance expectations, to provide information on future system requirements; Third - the application of analytical tools and reproducible techniques indicate potential cost-effective strategies for allocating available budgets to satisfy user requirements, again using performance expectations as critical inputs. The program is then finalized and implemented. The entire process is continually evaluated through network-level performance monitoring.

Asset Management is a logical strategic decision-making framework that is made effective by organizational integration and technological support. Organizational integration refers to communication and inter-dependency across asset classes, across functions and from the executive level to the front-line, working level. The necessary technology includes the ability to collect, process, then evaluate the data and the analytical tools required and to select the most cost-effective alternative investment strategies [143].

Malano *et al.* [144], on their work in irrigation and drainage, show concern on the hydraulic infrastructure that fulfils most of the service; this infrastructure consists of many individual assets including dams, canals, control structures, pumps, etc., that are usually dispersed over very large areas. Their concerns rose as governments embrace economic reform policies that promote the transfer of operation and management functions to irrigators, proper accounting of the cost incurred in providing irrigation, and drainage services become more necessary. They state that asset management is a process that integrates all these life cycle events with the need to provide an agreed level of service. An asset management program considers all the events occurring over the life cycle of the infrastructure, and comprises a strategic and integrated analysis of the life cycle of the infrastructure as part of the continuous management review of the organisation. The ultimate outcome of an asset management program is to bring into focus the actual cost of owning and operating the infrastructure assets to provide a defined level of service. As such, it provides a clear picture for the organisation and customers of the financial implications of providing this level of service – Figure 14 [144].

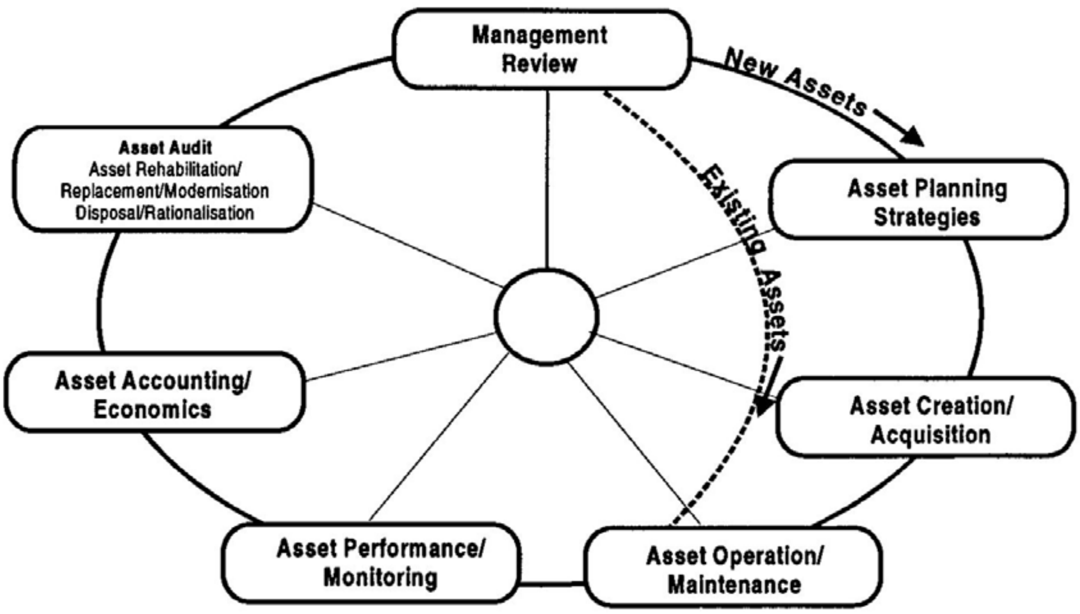

Figure 14 - Elements of an asset management program.

In 2005, Malano *et al.* [145] present an Asset Management Modelling Framework (AMMF) that enables the quantification of on-going ownership costs and operation costs. Additionally, it offers a life cycle cost (LCC) model for assessing various asset management techniques for drainage and irrigation. An asset management modelling framework consists of two main components:

1) A database of assets consisting of geographical location of assets, design features, maintenance records and asset condition and performance;
2) An analysis module which enables the modelling of future asset strategies including the calculation of future liabilities and life cycle asset costing associated with alternative courses of action.

Asset condition refers to the fitness of the asset to perform the function for which it was intended. The condition of assets is the result of several factors including wear and tear, quality of maintenance, age and quality of construction. It is a key measure necessary to determine the residual life of assets and therefore the future actions that may be required. It is also important to provide some idea of the overall reliability of the system to deliver the designed irrigation and drainage services. Aspects of reliability are related to the actual condition of the assets and their risk of failure [145].

Whilst concerned on electricity markets and in order to optimize the equipment utilization while focusing on cost-effectiveness and technological aspects Schneider *et al.* [146] present a study that focuses on electrical grids and their components, focused in economic factors such as CAPEX and OPEX, and maintenance factors such as cost and availability, and simulating ageing, thus predicting the moment of asset replacement, the model is applied only to this specific case.

Based on a component that is considered the main asset in the global power systems, the transformer is the focus of Trappey *et al.* [147] when bringing a tool very specific to be used only on transformers, while using artificial neural networks that has the capability to predict faults on the asset providing strategic data to enable maintenance decision-making.

Parra *et al.* [148] present a model that establishes a relationship between a maintenance management model with the asset management standard ISO 55001, establishing a model with eight phases in order to do the integration; in each phase requirements of ISO 55001 are identified. The authors reinforce that organisations can increase the value of their assets throughout their usable life cycles by implementing the maintenance management model in a sufficient manner that is coordinated with a thorough asset management procedure.

Vanier emphasis is placed on assessing decision-support tools for municipal infrastructure planning. He identifies the extent of the asset management market in North America, addresses the need for decision-support tools for municipal-type organizations, and identifies the challenges for maintenance, repair and renewal planning faced by asset owners and managers. Integration with existing systems such as computerized maintenance management systems, geographic information systems, and corporate legacy systems is seen as the largest challenge for developing and using decision-support tools in the area of asset management. It classifies various stages of implementation for asset management using the six "Whats" questions that asset managers should ask about the status of their portfolio:

- What do you own?
- What is it worth?
- What is the deferred maintenance?
- What is its condition?
- What is the remaining service life?
- What do you fix first?

Different approaches that have been developed to evaluate the life cycle are shown here. The buying firm must determine the most important expenses incurred during the acquisition, possession, use, and eventual withdrawal or renewal; this is required by the sophisticated Total Cost of Ownership (TCO) strategy. TCO may include costs for order placing, supplier qualification and research, delivery, receipt, inspection, rejection, replacement, failure-related downtime and disposal, in addition to the item's purchase price [149]. According to Woodward [150], the Life Cycle Cost (LCC) of a product is the total amount of money used to support the product from its conception and production through the use until the end of its useful life. Norris [151] compares Life Cycle Assessment (LCA) with Life Cycle Costing (LCC) and outlines their differences. LCA compares the environmental performance of several product systems that provide the same purpose.

Aiming to take into account all significant causally connected activities, as well as all significant resource and consumption flows, regardless of whether they ultimately have an impact on anyone, this environmental performance is analysed as holistically as feasible. From the viewpoint of an economic decision maker, such as a manufacturing company or a consumer, LCC contrasts the cost efficiency of various investments or business decisions. The scope and execution strategies of the two approaches vary as a result of their different goals. Life Cycle Cost Analysis (LCCA) has been increasingly popular as a method for network level analysis [152] and is frequently used to support project level choices. The Life Cycle Sustainability Assessment (LCSA) primarily employs quantitative factors, such as assessments of the implications on the economy, environment, and society [153]. Two key components make up the Life Cycle Valuation (LCV) methodology: (1) a four-phased framework (Figure 15) [144] that directs how to conduct an LCV assessment and (2) a combination of computations [154].

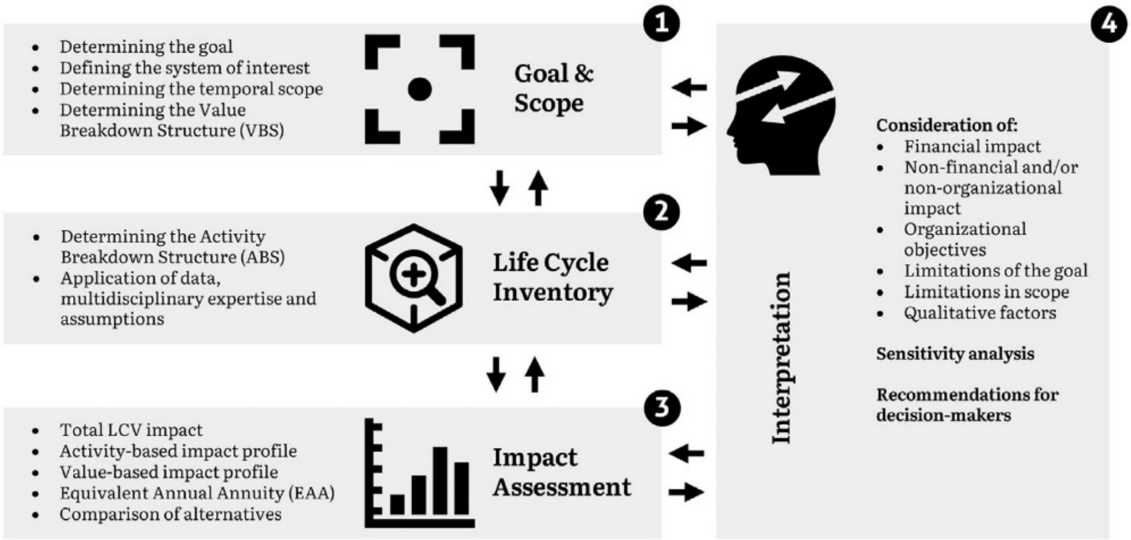

Figure 15 - Elements of an asset management program.

The provided models and techniques enhance sustainability and sustainable development by lowering costs throughout the life cycle of an asset. This is also accomplished by using fewer natural resources, which lowers CO_2 emissions and lessens the impact on the population. New models and techniques can also open up new marketplaces and draw in new clients, which can lead to the advancement of society.

Life Cycle Investment (LCI) is a concept that Farinha *et al.* [155] present; this signifies a shift from the conventional understanding of cost, which is seen as a loss. But it is also important to recognize that the original investment, which is a negative flow (cost), and the other variable "costs" that arise over the course of an asset's life cycle, such as upkeep, are actually variable investment flows. These costs connected with an asset's life cycle must be viewed as investments since they generate returns that are related to the quality of the investment, both at the time of the initial investment and over the asset's lifetime, and they add value to the asset over time.

Van den Boomen *et al.* [156] proposed models for replacement assets with an emphasis on the typically lengthy life cycles of civil infrastructure assets. Fox [157], Chen & Savits [158], Van Noortwijk [159], and Noortwijk & Frangopol [160] provided more models. Although these models' mathematical expressions change, their relationships are the same.

Project setting, performance analysis, and economic analysis are the three main phases of a model based on TCO developed by Roda *et al.* [161]. In order to increase the link between technical asset management and profitability, it blends the idea of reliability engineering with economic and financial evaluations.

A model linking Physical Asset Management (PAM) and Sustainability Performance (SP) was created by Maletič *et al.* [162]. Despite being empirical, the model shows that PAM considerably and favourably affects SP.

Dojutrek *et al.* propose various techniques for calculating the physical depreciation of pavements, such as the Straight-Line Method, the Sum of the Years Digits Method, the Declining Balance Method, the Double Declining Balance Method, and the Sigmoidal Way [163]. Deng *et al.* [164] mention more approaches, such as the Modified Approach, the Renewal-Based Approach, and the Condition-Based Approach.

Shokouhi *et al.* [165] goal was to assist in identifying the LCC, risk, and Key Performance Indicators (KPIs) based model of the life cycle of physical assets that was most appropriate.

Durán *et al.* [166] developed a model in which economic sustainability was believed to be one of the essential components, taking into account the requirement to manage costs with spare parts. A multidisciplinary platform to debate the key difficulties in tackling sustainability from a long-term viewpoint is provided by life cycle sustainability assessment.

Chen *et al.* [152] developed a decision-making model for pavement deterioration using a fuzzy logic-based LCCA model.

Farinha [167] provided methods for calculating the physical depreciation on general assets. 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. There are three that are well known: the linear depreciation method, the sum of digits method, and the exponential method. This information must be gathered during the course of the asset's life and can be used to influence decisions on asset renewal or withdrawal. However, other choices can be made throughout the asset's lifespan, such as the choice regarding a technical upgrade, which takes into account both the asset's production requirements and environmental impact.

The activities of a consortium in the area of strategic asset management are introduced. The limited number of decision-support applications, and none provides a comprehensive solution to address the current needs for planning the municipal infrastructure [168].

Woodhouse [169] sees asset management as making sure that the jigsaw puzzle is complete (Figure 16) [169], and the bits fit together. Asset management is the set of processes, tools, performance measures and shared understanding that glues the individual improvements or activities together. Or rather, since it is a very dynamic and self-adjusting set of techniques, it is the lubricant that keeps all the cogs from grinding against each other.

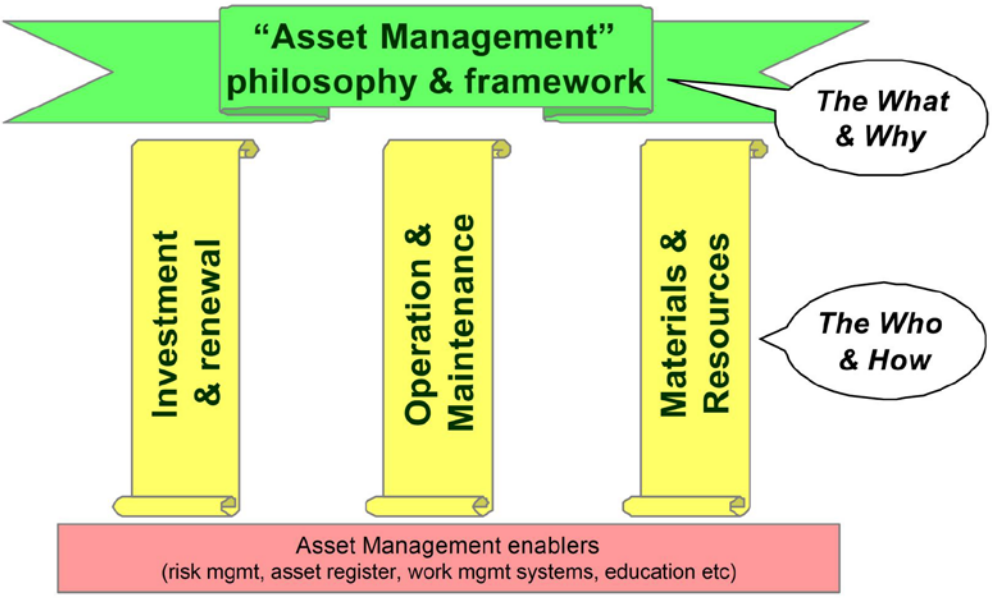

Figure 16 - Building a single structure, where all the bits fit together.

Of course, there are many types of assets – but the principles of best value-for-money are common to all of them. Physical asset management, knowledge management, financial responsibility and even the care of public reputation, customer impression and goodwill require good understanding of value, priorities, short-term versus long-term trade-off and risk exposures. The language varies a little, but the central concepts are constant. Woodhouse [169] defines physical assets as:

- "The set of disciplines, methods, procedures & tools to optimise the Whole Life Business Impact of costs, performance and risk exposures (associated with the availability, efficiency, quality, longevity and regulatory/safety/environmental compliance) of the company's physical assets."

It is clear that this affects all areas of the business – operations, projects, engineering, maintenance, safety, compliance, etc. It is only possible to achieve such "whole life optimal impact" if everyone pulls together. Key performance measures must be coordinated, not conflicting. A clear understanding of relative importance is needed. It is worth spending more to raise performance or reduce risks further. Most of the times, it is hard to have a clear answer and to know that the available evidence (data) is patchy and often speculative; risks and consequences are uncertain; attitudes and traditions sometimes get in the way; the impact of change can take time to emerge. Even the understanding of the language is a problem – getting everyone to agree on what "optimum" means - to Woodhouse the human factor is the weak link in all the procedures [169].

UK, Australia, and New Zealand are leading the world in such a holistic approach about asset management. Where the commercial or safety impact of failure is high, it is clearly vital to find the right combination of risk, performance, and cost. Airlines, oil & gas, power, and process industries have tended to develop, test and implement the most sophisticated reliability and performance optimisation tools.

However, asset management is mostly about people: shared understanding, cross-functional collaboration & teamwork, problem-solving instead of repeated firefighting.

The relevant asset management disciplines and procedures have generally emerged from the highly structured or regulated industries – initially the armed forces, airlines and nuclear sectors but now rapidly spreading to power, water and other utility sectors. Supply Chain initiatives, Quality Management, Total Productive Maintenance and Reliability Centred Maintenance are examples. Their industrial usage has sometimes suffered from poor adaption or implementation, but the underlying common sense (in properly managed introductions) is self-evident.

The first and crucial task in establishing an asset management regime is to make the objectives clear to everyone. There are many interests to satisfy and some of them are naturally conflicting. The regime must ensure that all business objectives are considered and minimise the inherent clashes among key performance indicators (Figure 17) [169].

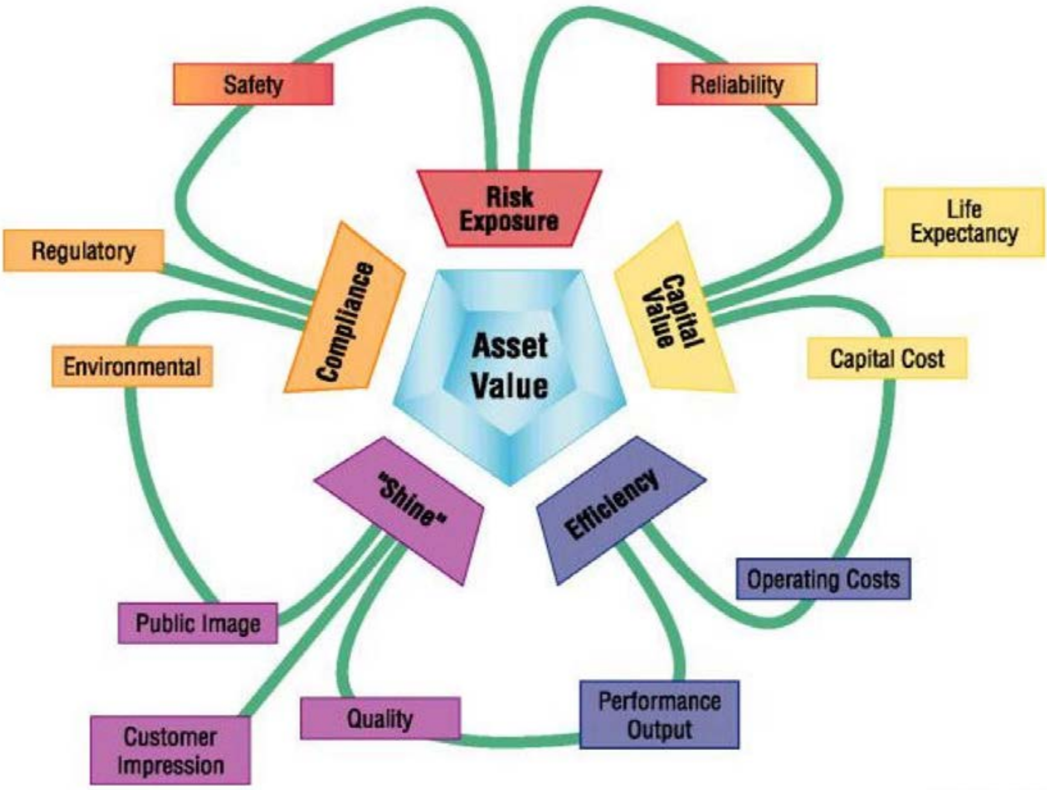

Figure 17 - Some of the links between competing objectives.

The overall map of asset management processes is very complex. Figure 18 [169] is just a view of the main links. Underpinning all of these activities are some vital "enablers", without which the individual activities grind together, and we would end up back where we started (lots of well-meaning, but silo-based and sometimes conflicting local interests).

Some of the asset management enablers are:

- Organisation alignment - agreed objectives, shared understanding, excellent leadership and communication;
- Integrated data, information and knowledge management - the right data collected, to the appropriate quality/detail, available to those who need it in a timely and appropriate form, based on the actual business (decision) needs for that information;
- Risk awareness and acceptance - building risk evaluation into normal decision-making;
- Long term-ism - taking account of long-term repercussions in short-term actions and decisions (e.g. Life Cycle Cost analysis).

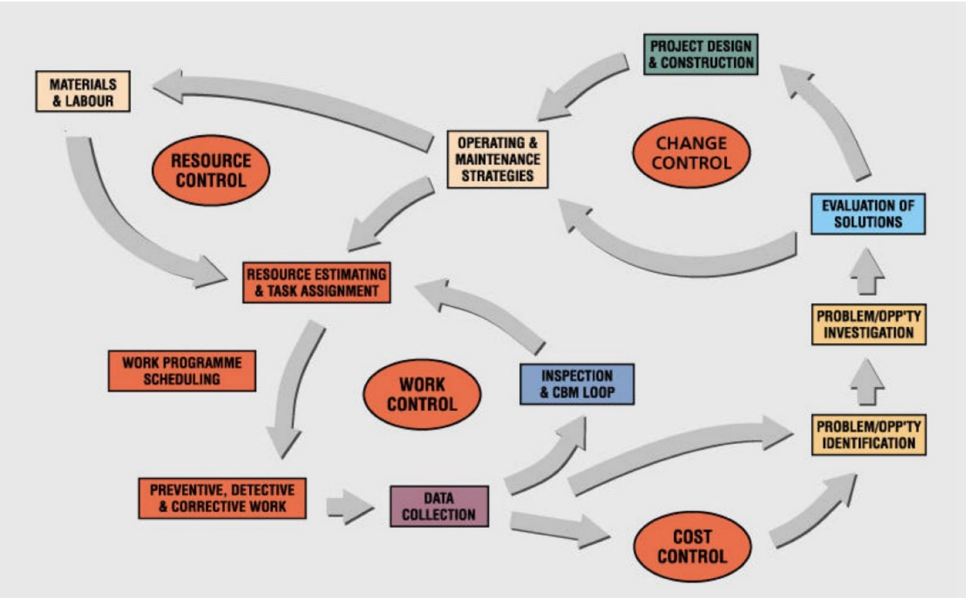

Figure 18 - Asset Management Processes

So, asset management is an umbrella for bringing a lot of existing good practices together, and for filling some of the remaining gaps. It aligns what we do to clear business goals and ensures that the component activities operate in harmony. It requires some sophisticated technical solutions but the most important element of all is the human one – shared understanding, motivation, trust, and collaboration to find the best combined outcome, rather than local and short-term self-interest. There is no real doubt that integrated "asset management", or whatever it may be called in the future, is becoming a vital business discipline. Yet there is a significant gap between those who "think they already do it", and those who realise the challenges and rewards of the

integration/alignment step (and are investing heavily in the merger of new technical solutions, management processes and the human factors).
Those companies that have had the vision and faith to adopt such an approach have universally recognised the tangible benefits – in some cases this has ensured continued company survival, in others it represents their key competitive edge in the next phase of global performance pressure [169].
Tsang [170] says that the contemporary business environment has raised the strategic importance of the maintenance function in organizations which have significant investment in physical assets. Four strategic dimensions of maintenance management are identified, namely service-delivery options, organization and work structuring, maintenance methodology and support systems. The two factors that permeate in these strategic dimensions are human factors and information flow.
According to Amadi-Echendu [171], physical asset management involves a wide range of disciplines and processes covering the life-cycle stages of creating, establishing, exploiting and divesting a physical asset in a balanced manner to satisfy the continuum of constraints imposed by business strategy, economy, ergonomics, technical and operational integrity, and regulatory compliance.
A developed system of manufacture, maintenance, and logistic support for these assets must have existed from a very early date. Despite these early beginnings, physical asset management has never been a well-understood activity within populations at large. The pattern of educational and professional specializations has generally by-passed the physical asset management field. Various technical areas, such as defence, aviation, and civil works, have evolved their own approaches to the topic, under such headings as logistics, systems engineering, public works engineering, infrastructure, and maintenance [172].
The conventional view of physical asset management is derived from maintenance; Amadi-Echendu states that physical asset management is much broader than the maintenance function; the author further adds that the management of physical assets refers to the creation of value, that is, it includes the life cycle processes of the creation, establishment, and exploitation, that is, the operation, maintenance and disposal of a physical asset, when it meets the constraints imposed by economy, ergonomics, technical integrity and business performance. The management of a physical asset should be in such a manner as to create and/or sustain value during each life-cycle stage, and throughout the asset's life. The value profile that physical asset management can provide will depend on what is desired by the stakeholders prevailing at the respective stage in the life of the asset [171].

On the other hand, Campbell did not profess an asset management speech itself; he describes asset management through a nine steps process as described in Figure 19 [173], and goes a step further in explaining the fundamentals of the asset management process [173].

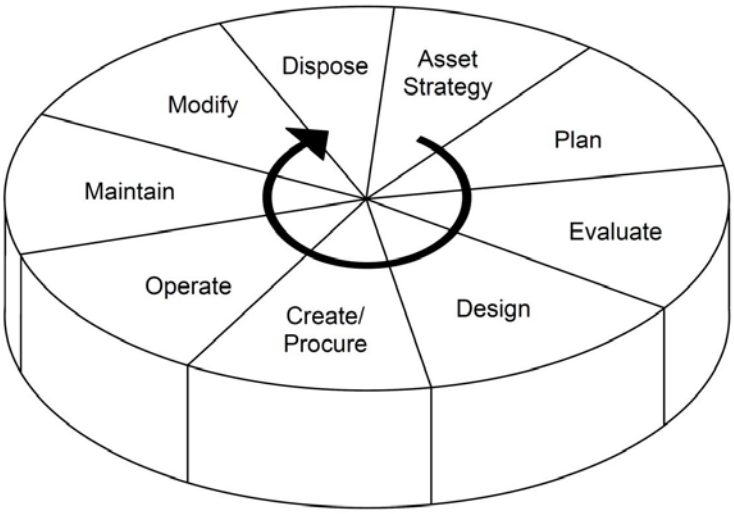

Figure 19 - Asset Management Process.

Kostic [174] cites the definition of asset management given by the Victoria government in Australia, namely public utilities, as “the process of guiding the acquisition, use and disposal of assets to make the most of their future economic benefits and to manage their assets, related risks and costs throughout the life cycle”.
From the South African perspective (Figure 20 [175]), the basic asset life cycle management model is described in the National Treasury guideline. An asset's life cycle can be defined as the period that an entity can predict by using an asset in an economically effective and efficient manner to promote the entity's provision of services or trade. The National Treasury guideline further states that the period covers all stages of an asset's life: acquisition; use and maintenance; and eventual alienation. This period is described as the useful life of the asset for the entity and may differ from the physical life of the asset [175].

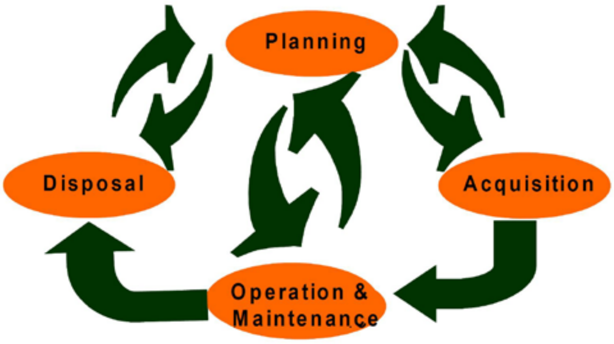

Figure 20 - Asset Life Cycle Management.

In 2008 Haffejee & Brent [175] proposed an integrated Asset Life Cost Management model (Figure 21 [175]), derived from an amalgamation of Life Cost Management (LCM) and asset management theories. This integrated Asset Life Cost Management refers to the management of assets over their complete life cycle, from before acquisition to disposal, taking into account economic, environmental, social and technical factors and performances.

They noted that strategic assets may include non-physical assets such as intellectual capital, but in terms of the model they proposed, only refers to physical assets.

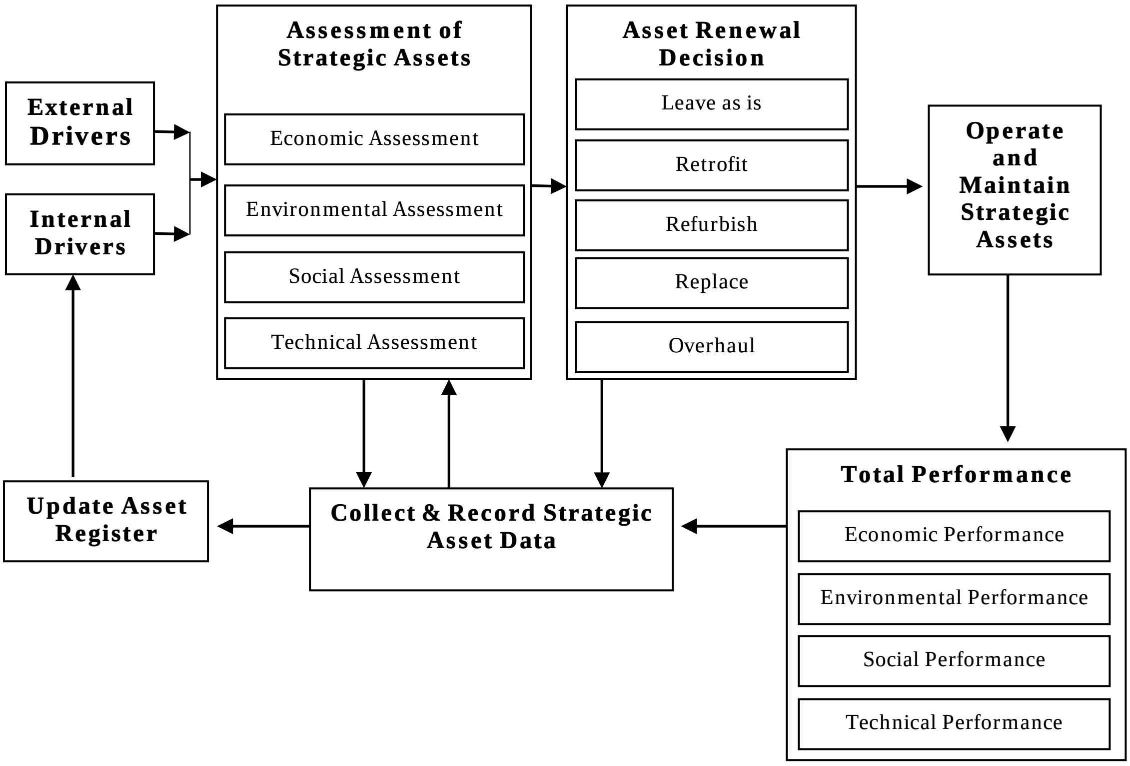

Figure 21 - Integrated Asset Life Cost Management Model.

The view is about creating and sustaining value, during each respective stage and, through all the life-cycle stages of an asset physical asset management; because of that, it involves a wide range of disciplines and processes covering the life-cycle stages of creating, establishing, exploiting and divesting a physical asset in a balanced manner to satisfy the continuum of constraints imposed by business strategy, economy, ergonomics, technical and operational integrity, and regulatory compliance. This wider scope for physical asset management not only embraces life cycle costing but, also, focuses on whether or not an asset is owned, managed and utilised in such a manner to create and/or sustain the value profile defined by its stakeholders. For physical asset management to enhance and sustain value requires a shift in thinking, approach, and practice beyond conventional cost policy of maintenance. He describes asset as an entity which has the capability to create and sustain value while in current use, or that appreciates its value because of perceived capability to create value in future use. Maintenance and terotechnology are among the core competencies that form the necessary capabilities for Physical Asset Management (PAM).

PAM faces a continuum of challenges arising from changing value-chain and life cycle stage characteristics.

Managing a physical asset based on a value-chain as it progresses through the life cycle stages requires a higher-level integration of the synergies between the traditional disciplines in accounting, economics, engineering, finance, and humanities, as well as logistics, process, and information systems technologies. It begs to question whether conventional ownership, management and utilisation policies along the traditional boundaries of disciplines will be effective in the future, in the sense that they, oftentimes, hinder alignment and integration of synergies required for effective physical asset management [171].

Effective physical asset management requires:

(i) Appropriate integration of the synergies between traditional disciplines and emerging technologies;

(ii) Application of the integrated synergies towards achieving the value profile desired at the respective life-cycle stage of the asset.

A first impetus for holistic approach arises from renewed emphasis on value-based performance measures. This makes it imperative for practitioners to demonstrate that physical asset management provides value to the associated business venture. Many decisions at the strategic level as to whether to acquire, buy, or sell a business venture depends on how effective the ownership, management and utilisation processes are at creating or, at least, sustaining the value profile as defined by the stakeholders. The primary objective for relevant due diligence studies is to establish to what extent prior or concurrent ownership, management and utilisation efforts have added, sustained, or destroyed value to the physical asset base.

A second impetus for the holistic approach to physical asset management stems from the wide range of capital funding and expenditure options applicable towards the initiation, development, acquisition, operation and maintenance, termination, and divestment of a physical asset. Several sources of capital can be used to fund tactical and operational choices during each stage in the life cycle of a physical asset. For instance, gearing, securitisation, and mutualisation are three funding models applicable to physical asset management. In some cases, it is imperative to have a mixture of models, such that the choice of any particular capital funding model; in principle, it optimises a defined value profile or minimises prevailing opportunity costs. At least, the preference must be to sustain economic profit during each life-cycle stage.

A third impetus for the holistic approach to physical asset management is outsourcing. Asset-intensive businesses need to mutate both organisational structures and core competencies in order to provide the value profile desired by stakeholders. One outcome of mutation is outsourcing, especially when it is applied towards effective physical asset management in terms of the value chain and life-cycle stages. Most business process re-engineering exercises of the recent past have emphasised outsourcing as a means to "offload" non-core competencies and processes. Some definitions of core/non-core have been weirdly, and as such, outsourcing has been viewed and applied as a cost cutting measure by many practitioners who tend to rely on conventional wisdom. In the holistic approach, outsourcing provides a means to unlock value. This is consistent with "unbundling", an approach that is being used extensively in prevailing times, primarily to unlock triple bottom line values embedded in major asset-intensive public establishments and private ventures.

A fourth impetus for holistic thinking and approach arises from the rapid changes in underpinning technologies applicable to support the value-chain in physical asset management. Technological innovation and evolution in physical equipment characteristics, information systems, methodologies, and the attendant physical processes are creating new application domains and situations. Innovative and evolutionary techniques are, in turn, forcing changes in the physical asset management value-chain and impacting the period of each life-cycle stage, thus creating opportunities for improvements in utilisation, management, and ownership.

A fifth and most profound impetus for a holistic approach to physical asset management is the evolution in the functional capabilities of information systems. These systems enable the collection, collation, and manipulation of a wide range of data sources. They also facilitate analysis of data and information for the purposes of decision-making. Data, information, and knowledge can be readily transferred along the value chain and between the life-cycle stages as necessary for effective physical asset management. For instance, the advent of integrated communication of data and information between the plant floor and the business management level during the exploit stage creates the opportunity to evolve control rooms into operational competency centres. This will further eliminate legacy distinctions between core competencies required for effective physical asset management.

The management of a physical asset as an entity capable of creating, enhancing and/or sustaining triple bottom line and corporate governance values requires a paradigm shift much wider than the scope of maintenance and terotechnology. Innovative systems-of-work that integrate the synergies well beyond the installation of information systems are necessary, and conventional metrics for measuring performance may no longer be adequate to achieve the value-adding objectives for physical asset management. One ramification for this is that during the exploitation stage of the asset life, conventional process control rooms may need to be converted into ownership, management and utilisation centres [171].

In 2010 Amadi-Echendu *et al.* [176] said that the field of asset management requires an interdisciplinary approach in order to ensure that an appropriate mix of skills can be brought to bear on resolving the vexed issue of asset management. The new orientation has been on developing a range of strategic responses to safeguard the large public and private investments in assets. In this context, however, definitions of what is asset management, engineering or otherwise, tend to be broad in scope. Approach is interdisciplinary and we include notions from commerce and business as well as engineering. The framework also draws on a broader set of considerations, emphasising the life cycle of the asset rather than just focusing on the maintenance aspects.

Until quite recently, definitions of engineering asset management focussed on two distinct but important aspects of the management of assets. The first concentrated on the information and communication technology required in the management of data relating to assets. The second focused on the way in which engineering asset management systems can be integrated and managed to inform decision-making about those assets [176].

Schuman & Brent [177] stated that a comprehensive life cycle management approach assures that the processes used across projects are consistent and that there is effective sharing and coordination of resources, information and technologies. All life cycles within a system must be considered, which spans the conception of ideas through to the retirement of the entire system. Within the process industry environment, LCM defines the processes for acquiring and supplying system products and services that are configured from the system components of hardware and humans. In addition, LCM provides for the assessment and improvement of the life cycles:

- The development cycle of a system, production plant or facility is initiated with the identification of a need (Figure 22 [177]);
- The system, production plant or facility requires maintenance and support during its operational lifetime in order to continue to fulfil the identified need;
- A life cycle approach is, therefore, required to reduce operating and maintenance costs and optimise the productivity of the plant and maintenance and support design should be engineered concurrently to the design of the system;

- The requirements with regard to system effectiveness in terms of reliability, availability and maintainability are of equal importance to the functional requirements of throughput, quality, capital cost, schedule, etc. It is critical that the first-mentioned requirements should also be defined during the conceptual phase.

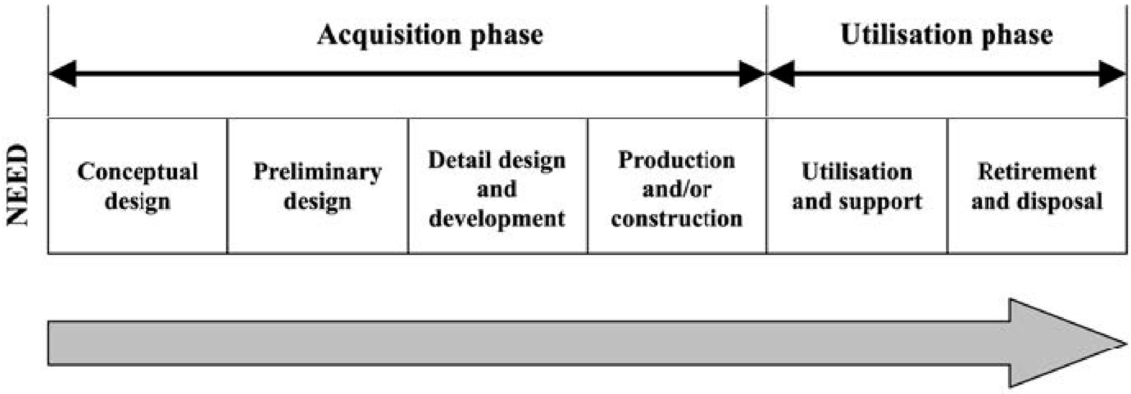

Figure 22 - Life cycle phases of process asset systems.

These fundamental concepts must be viewed as part of an effective asset management strategy, which has become a focus area of many companies to acquire and sustain a competitive advantage within a global economy.

Schuman & Brent [177] proposed ALCM model for the process industry integrates the different frameworks that have been discussed above and is illustrated in Figure 23 [177]. Thereby, the model consists of three levels the project management framework, the asset life cycle and operational reliability. The model is further described based on the different components of the asset life cycle level.

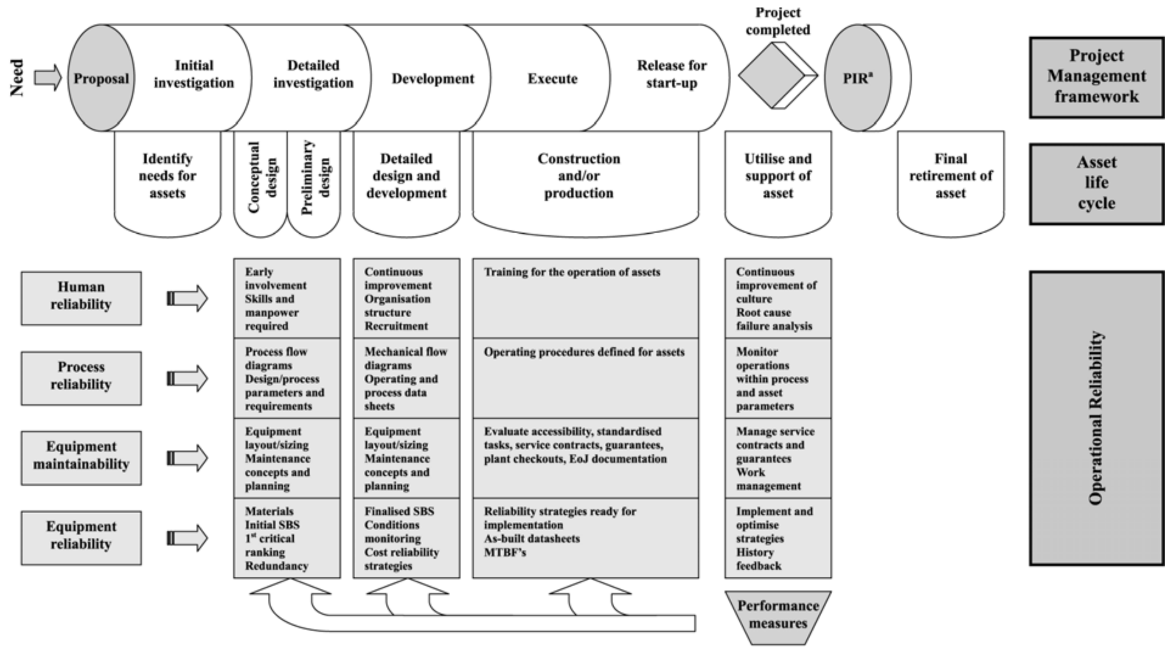

Figure 23 - The proposed asset life cycle management.

According to Campbell *et al.* [140], asset management excellence is many things, done well. It is when a plant performs up to its design standards and equipment operates smoothly when needed. It is maintenance costs tracking on budget, with reasonable capital investment. It is high service levels and fast inventory turnover. It is motivated, competent trades. Most of all, asset management excellence is the balance of performance, risk, and cost to achieve an optimal solution.

Companies, increasingly, face a competitive environment, requiring the development of more efficient and cost-effective operations than ever before. Many assets in heavy organizations are under intense pressures such as globalization, shifting markets, outsourcing, and external regulation. All these factors drive organizations to increase productivity, reduce costs, and improve product quality. A 1% improvement in performance can be worth millions of dollars annually for a manufacturer. In addition, service rates are often regulated, making business survival dependent on efficient management of capital assets using best practices and standards. Organizations are now looking for ways to extend the capabilities of their existing systems.

In the past, asset management was most often described in terms of maintenance management with an exclusive focus on the programs, procedures, and tasks necessary to optimize uptime of an organization’s equipment. Today, it requires active life-cycle management of the major assets and components from design and inception to disposal to achieve an edge against competition. A strategic view of asset management first requires new consideration of which assets are to be managed [140].

Balzer & Schorn [178] stated that a good infrastructure is one of the basic requirements for the growth of country’s economic strength as it facilitates investments from various industries and increases prosperity of the population, thus resulting in higher living standard.

The choice of strategy at the beginning of the total asset management process has the greatest influence on the financial success and optimized development of the network technology. This includes the long-term strategic asset planning and system development, project planning, implementation planning, commissioning, and the operation or the renewal. Technical conditions, such as voltage stability, reliability of supply, emission values, and current capabilities/ratings of components, must be kept in mind during the consideration of the planning. This forms the basis for deciding on the most economical way to deal with considered asset groups or systems.

Considering the importance of the infrastructures the author defines a set of four steps to manage the overall process:

- Step 1: Determining the overall strategy for all pieces of equipment

The overall system costs are calculated with the help of a long-term analysis so, both investment and operation costs can be derived for a longer period (e.g., 10 years). This happens taking into account different maintenance strategies on one hand, and other conditions on the other, such as the total energy not supplied or the number of disturbances at certain system nodes, but also issues such as economic development, customer cogeneration, electric mobility, and general political boundary conditions (renewable energy law, financial support for home ownership, etc.). Due to the unpredictability of particular developments, it is useful to apply a framework of scenarios with appropriately defined premises. Results of this process are the long-term needs of the network and the derived annual budget for the development, renewal and maintenance of assets, tasks which fall under the responsibility of the asset manager.

- Step 2: Implementation of the overall strategy and derivation of particular asset decisions on equipment level

Based on the results of the financial environment, which are determined in the first step, there is a selection of assets that have to undergo a maintenance or renewal activity. The determination is based on the condition of the equipment and the importance for the entire system.

In this context, the Reliability Centred Maintenance (RCM) strategy is often used in practice.

- Step 3: Selection of the appropriate maintenance activity

After the selection of the unit, which has to be maintained, a decision has to be taken in this step which maintenance activity (e.g., replacement or revision) should be applied taking into account the consequences that are caused by a potential outage of the unit. Here, risk assessment may be helpful.

- Step 4: Optimal maintenance activity of the asset

While the first three steps are related to the assets in the overall system, in this step, the decision is exclusively related to the equipment level. Using the FMEA (Failure Mode and Effect Analysis), the optimal maintenance of the equipment can be determined taking into account failure statistics and the consequences of failure for the entire unit.

In practice, the processing of various strategies in the area of asset management will be carried out under consideration of pre-defined Key Performance Indicators (KPIs) based on the benchmark results from internal and external service providers. The different superior asset management strategies can be divided into different areas with the associated individual tasks:

  - System development
    - Preparation of the strategic planning concept by continual adaptation;

        - Definitions of system planning assumptions;
        - Determination of the limitation in power flow capacity;
        - Consideration of customer needs during the planning stage;
        - Consideration of decentralized active components (generation, storage, etc.);
        - Identification and commissioning (specifications) of particular projects.
    - Maintenance
        - Definition of maintenance cycles;
        - Condition assessment of assets;
        - Decision regarding the procedure in case of outage of equipment;
        - Definition of the scope of work for maintenance;
        - Allocation of resources (material, finance);
        - Commissioning of the implementation (asset service).
    - Renewal
        - Definition of strategies;
        - Determination of the renewal time of assets including the volume of assets;
        - Decision regarding the used technology;
        - Provision of resources (finance, specifications, suppliers);
        - Commissioning of the implementation.

With the results of above-mentioned activities, it is possible to fulfil the tasks of the asset management and to optimally operate infrastructure networks [178]. Even considering that the author relates is studies with infrastructure systems, it is perfectly clear that those steps are transverse to any other asset.

Yet in infrastructure asset management Van der Lei, Herder & Wijnia [179] refer the importance of infrastructure asset management that sets itself apart from asset management in many fully privately owned and operated industries. First, infrastructure assets for energy, roads, water, and telecom have a very long lifespan, when compared with other physical assets. The physical objects themselves often are designed to last more than 50-100 years. This means there is a high probability that the demands on the infrastructure will change during its lifespan. At the same token there is large uncertainty about what those demands will be at the outset during conceptualization and design of the infrastructure.

Second, infrastructure assets have no resale value, perhaps even not scrap value because these are offset against removal costs. Thus, if an asset is acquired, it remains technically in operation until failure. When the asset is taken out of service, eventually if at all, the physical infrastructure is hardly ever removed. Many infrastructure assets are passive elements, that require almost no attention to function. Their cost, performance and risk are almost exclusively determined in their design and a little bit in the maintenance. Given that assets will last very long and cannot be sold, the design has to be right for a very long time. This requires either flexible designs or, more likely, very robust designs. This is reflected in over dimensioned infrastructure systems, capable of handling more capacity than actually needed (e.g. electricity, gas, water). On the contrary, some infrastructures quickly grow out of their initial design capacity and need to be expanded (e.g. roads).

Another specific characteristic of infrastructures is the longevity of the equipment. Therefore, some construction and modification may have taken place in the past when other standards for asset administration and registration applied. Alternatively, data may simply have been lost over time. As a result, the precise content of the asset base may be uncertain to an infrastructure owner and asset manager.

More fundamentally, many infrastructure systems are evolutionary systems. They have not designed in a grand master plan, but have grown by many small add-ons over time, based on what already existed. Current decisions on the assets highly contains the decision space for future decisions. This is called path dependency and lock-in.

Infrastructure systems are networked systems. There may be some hierarchy in the importance of assets, but very rarely key elements exist that determine the performance of the system as a whole. This networked characteristic increases the robustness of an infrastructure system, as, typically, no one single failure will be able to bring the whole system down.

Infrastructure assets are not confined to a designated sector, business or area but are distributed widely, and often penetrate the public domain or even structure the public domain. This means that failures will be highly visible and are likely to put third parties at risk. Because of the widely distributed characteristics, it is virtually impossible to identify all third parties at risk, let alone get into a dialogue with them.

Infrastructure owners, decision makers and operators are, generally, not the users of the infrastructure. This means there is a large asymmetry in cost and benefits of decisions on infrastructure assets. If an investment is made, the owners will pay and the users will benefit, whereas on postponing maintenance the situation is, generally, the other way around. But if the decision maker is not the only one who will suffer harm if things go wrong it is difficult to take the right decisions.

Infrastructure users can be highly anonymous, which results in very little control on how the asset is used. Yet, some use may seriously damage the assets. Given the asymmetry in cost benefit the user is not likely to care.

In other words, managing infrastructure assets often faces complex uncertainties, often more complex and deeper that those found in other forms of asset management. Furthermore, these uncertainties are rooted in technical and social aspects and developments, making them difficult to address by means of technology alone. Uncertainty thus should be dealt with in a much more conscious way.

Van der Lei, *et al.*, [179] say that to overcome the challenges in different asset management, methods have been developed aimed to improve the asset life cycle. Smarter design can lead to improved operation. Likewise, improved operation and maintenance lead to lower replacement costs and may provide the basis for better design. Following this development, the design and operation and maintenance phases have seen a rise in methods and tools for engineering asset management.

Asset management stresses that it is key to consider the whole life cycle of the assets. This development is new as, traditionally, the improvement of the design, operation and maintenance phases have been separate management tracks. Engineering asset management is an interdisciplinary field that involves research fields like: life cycle costing; maintenance and reliability; risk assessment; change management.

Asset management is seen as a life cycle approach that covers the activities of the organization that undertakes to achieve its goals. This, in contrast to the assets, being something, an organization owns and must maintain. In the life cycle perspective, the management of the asset life cycle is central to the operational success of the organization [179].

Many times, asset management is described as maintenance, but asset management is an interdisciplinary field and involves research fields as: life cycle costing, maintenance & reliability, risk assessment, change management.

Hastings [136] describes asset management as a set of activities associated with:

- Identifying what assets are needed;
- Identifying funding requirements;
- Acquiring assets;
- Providing logistic and maintenance support systems for assets;
- Disposing or renewing assets.

So, as to effectively and efficiently meet the desired objective.

From this definition we see that asset management encompasses a broader and quite different set of activities from “maintenance”, which is primarily concerned with keeping existing equipment in operating condition.

So, the author states that asset management is needed to provide asset knowledge and the capacity for related management and decision support activities within the context of our business. In the area of capital planning and budgeting, or Capital Expenses (CAPEX), this involves:

- Asset (and associated capability) development planning and implementation;
- Asset continuity planning and implementation;
- Logistic support facilities development and management.

In the area of operating budget or Operational Expenses (OPEX) it involves:

- Procurement planning and management, e. g., for consumables and spares;
- Organization wide, asset related systems and procedures, e. g., computer systems applications in asset management and maintenance, shutdown / turnaround planning;
- Development and management of maintenance outsourcing;
- Awareness and management of regulatory compliance.

Despising the different activities on life cycle (Figure 24 [136]), Hastings sets the main steps the following:

- Identification of business opportunities or needs;
- Asset capability gap analysis and requirements analysis.

Hastings sets the importance of those with capability to forecast the stakeholders needs, that most of the times can be hard when considering the constant changes.

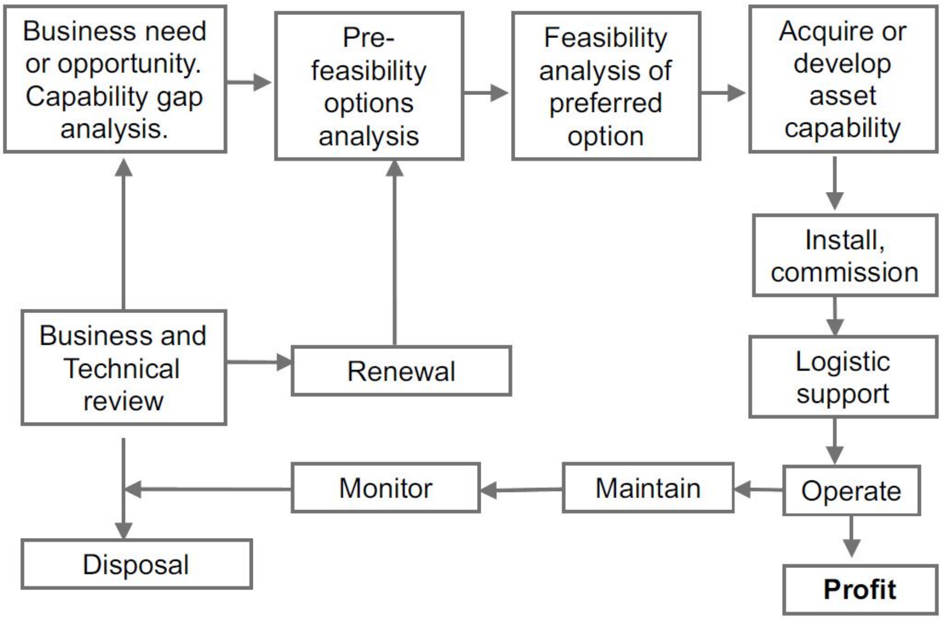

Figure 24 - The asset life cycle

Figure 24 illustrates the life cycle of a physical asset in outline. The main stages of the life cycle are:

- Identification of business opportunities or needs;
- Asset capability gap analysis and requirements analysis;
- Pre-feasibility analysis, physical and financial – options selection;
- Feasibility planning, physical and financial – for selected option;
- Acquisition, development and implementation;
- Operation, logistic support and maintenance;
- Monitor and review;
- Disposal.

When relating to asset operation activities, Hastings [180] sets a series of relevant actions in order to improve asset management (Table 5 [180]), and brings a relationship between assets and finance, aiming to meet the ISO/TS 55010:2019 requisites, giving an alignment between financial and non-financial (Table 6 [180]): the financial and non-financial activities, like asset acquisition, must be created and reviewed annually, having in consideration aspects as reliability and risk; the disruptions to business plans are minimized. On other hand, the author considers a set of changes such as, user requirements and expectations, technological change or changes to political sentiment, and those are important when considering Life Cycle Cost (LCC). Most of the times carrying out LCC happens after the acquisition is done or even after several years of service; on the other hand, the author considers a set of changes such as user requirements and expectations, technological change, or changes to political sentiment, so it is important to retain a flexible attitude to what the future may hold.

Table 5 - Asset operations related.

Asset knowledge
Management/monitoring of asset acquisition and/or development projects
Liaising with stakeholders on asset-related topics
Management of introduction into service
Change management
Equipment leasing policy and management
Applications of asset-related technology, e.g., new equipment developments, condition monitoring developments
Managing asset policies in regard to health, safety, environment, security requirements
Managing through life support provision, effectiveness and audit
Performance monitoring
Equipment disposal or redeployment for asset management reasons
Identifying and setting asset-related emergency response strategies
Risk analysis, risk mitigation

The Strategic Asset Management Plan (SAMP) is a top-level overview and is intertwined with the need to achieve organizational objectives, thus aligning business and finances goals of the organization.

Table 6 - Asset planning and finance related.

Input to asset-related aspects of business development at the concept planning stages
Input to pre-feasibility and feasibility analysis for asset developments including requirements analysis, input to financial analysis
Demand forecasting
Development of recommendations for acquisitions, process improvements, replacement, refurbishment
Level of service setting
Asset-related special studies
Preparation of asset-related input to capital budgets (CAPEX) and operating budgets (OPEX)
Life cycle planning and costing
Preparing business cases for asset-related activities can include preparing proposals, evaluating proposals and advising on the preparation of proposals
Cost–benefit analysis
Asset valuation
Asset renewal/replacement/overhaul policy assessment and decisions

According to Hastings [180], when preparing a SAMP, everything starts with a Business Plan (BP), being this a statement of the activities to be undertaken by the business, the resources required and timings expected over a planning period; when building the BP, it is important to estimate costs, revenues and profits, so the starting point for asset management is the BP.

The Strategic Asset Management Plan (SAMP) is a top-level overview and is intertwined with the need to achieve organizational objectives, thus aligning business and finances goals of the organization.

According to Hastings [180], when preparing a SAMP, everything starts with a Business Plan (BP), being this a statement of the activities to be undertaken by the business, the resources required and timings expected over a planning period; when building the BP, it is important to estimate costs, revenues and profits, so the starting point for asset management is the BP.

Yet from the same author, the SAMP is the process of developing, at a strategic level, a plan to provide the organization with asset capabilities, which match the needs of the organization's business plan, being consistent with the organization's financial plan and aligned with the business and finances goals of the organization; on other side, the SAMP is the tool to achieve and maintain that alignment, so, there is a need to plan to achieve the alignment.

In asset intensive businesses it is essential to structure the organization so that the development, acquisition, and operation of the assets are carried out effectively. Business functions, such as Sales, Operations, Finance and Human Resource Management may be clearly represented in the business structure, whereas asset management can be a "grey area", beneath the purview of senior management, but above the maintenance level. Figure 25 illustrates this [136].

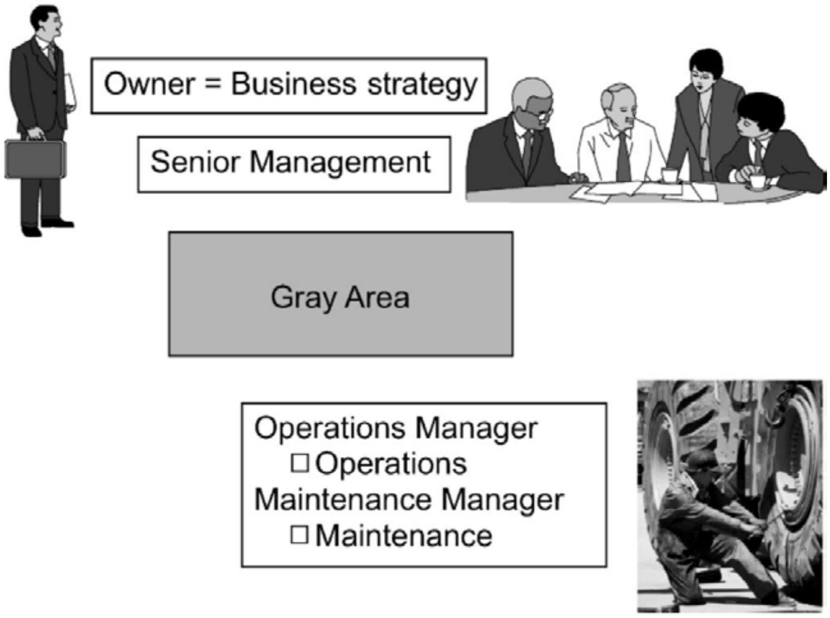

Figure 25 - Asset management – a grey area.

Successful asset management requires recognition and effective implementation of the functions indicated in as set of activities. The "grey area" of Figure 25 needs to be replaced by the functions shown in Figure 26 [136].

An essential step is to recognize asset management as an activity which requires representation at the Vice President or Chief Officer level. This is illustrated in Figure 26. The precise title may vary, and what we have referred to here as a Chief Asset Management Officer may have a title which refers to or includes engineering, planning or logistics. Representation at the Chief level allows asset management to play its role as a key asset related decisions and activities affecting the business. If asset management decisions fall between, on the one hand, senior managers whose background gives them little appreciation of the physical state of the company's assets in relation to needs, and, on the other hand, maintenance or engineering personnel who are too junior or too inarticulate in business terms to state their case, then financial and operational disasters can follow.

The existence of a Chief Asset Management Officer does not mean that all asset management activity must be concentrated at the top level. Operating divisions may have asset managers looking after their own assets, just as they have information technology and accounting staff looking after their own divisional activities in those areas (Figure 27 [136]).

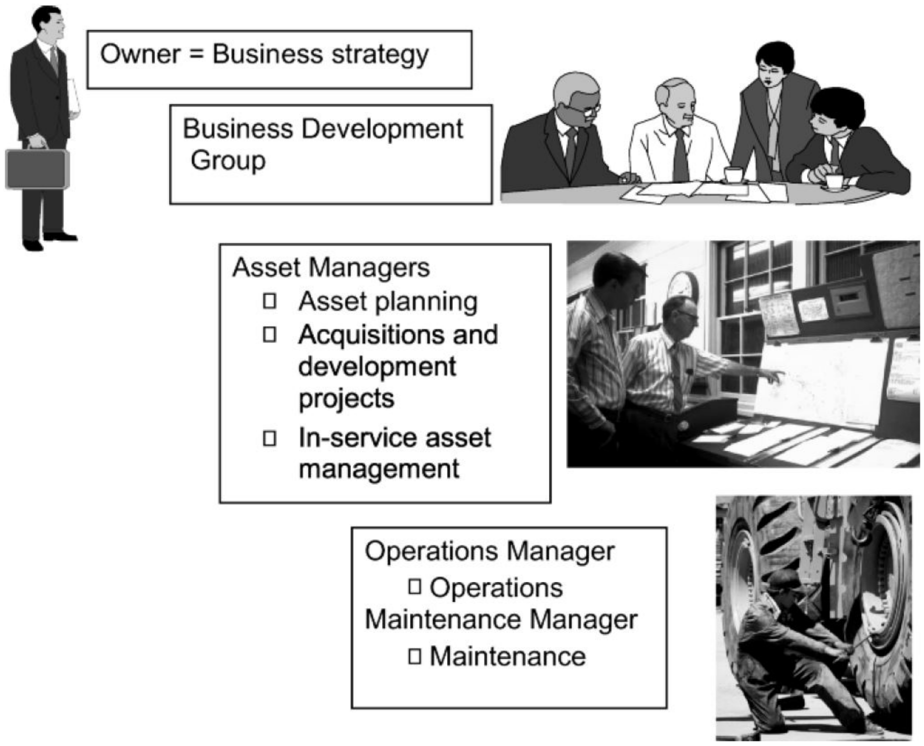

Figure 26 - Business activities and asset management.

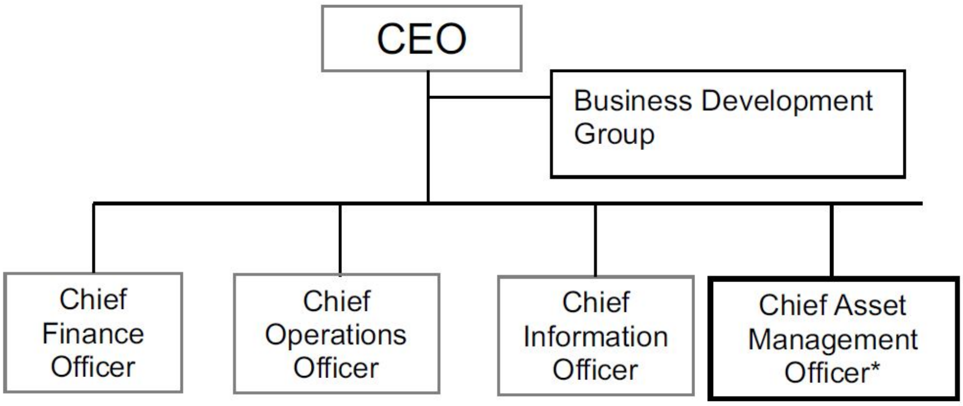

Figure 27 - Asset management in Organization.

** Title may vary to cover the Asset Management / Engineering / Logistics / Planning functions but representation at "Chief" level is important.*

Also, asset management is a functional activity which pervades many areas of the business. Asset management skills and awareness are needed in many roles, and not just by persons who are labelled "Asset Manager". At the risk of some ambiguity, we shall use the term Asset Manager to cover both a person employed primarily in asset management activities and a person who needs to use an asset management approach in tackling issues which are only part of their overall job. However, companywide issues, policies, strategies systems and procedures need to be coordinated from the higher level, and we shall assume the existence of a group which we shall refer to as the asset management group, recognising that other names may be used in various organizations.

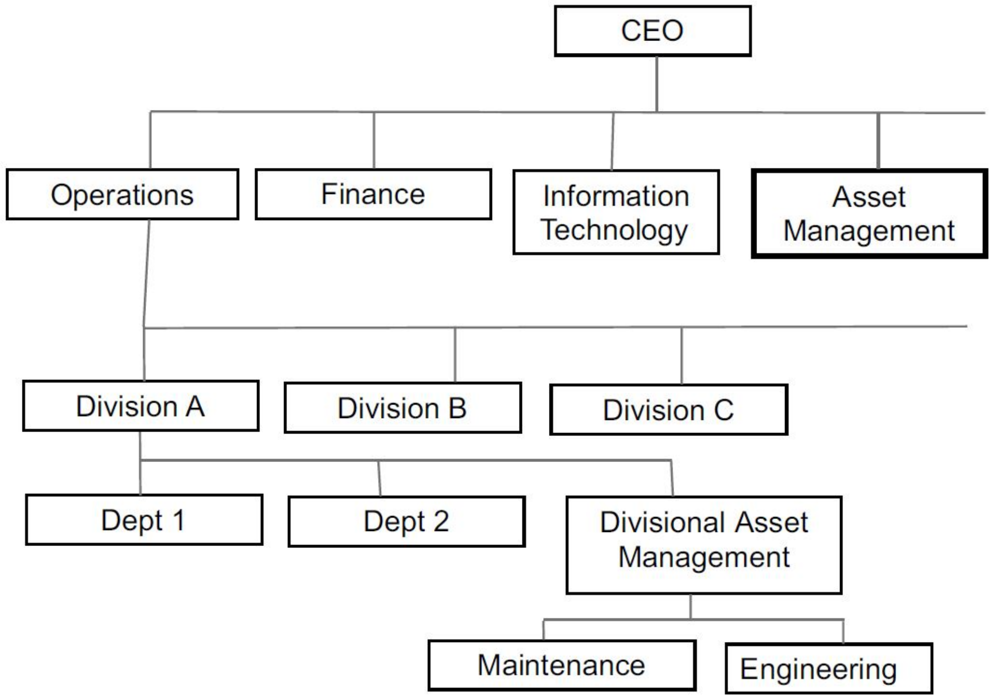

Figure 28 - Asset management in Organization (2).

Figure 28 [136] illustrates how asset management at the divisional level can combine with asset management at the chief officer level [136].

2.1. Data Quality

In order to achieve a good performance in asset management, it is strategic to rely on good and reliable information; according to Redman [181], the estimated total cost for poor data quality has been estimated as 8-12% of revenue range, and 40-60% of a service organization's expense that may be consumed as result of poor data; those ranges are considered a good working estimate of the cost of poor data quality, and, at the operational level, poor data qualify lowers employees job satisfaction. One simply cannot expect the sales manager dealing with customers whose productions have been delayed or whose comfort of an administrative staff dealing with buildings and equipment's problems to exhibit a high level of positive morale.

First, poor quality data compromises decision-making; it is a widely accepted maxim that decisions are no better than the data on which they are based, and since any decision of consequence depends on thousands of pieces of data, the chance that decision is based only on good data is extremely small; the slightest suspicion of poor data quality often hinders managers from reaching any decision, and, many times, the most relevant data may be simply unavailable. While all decisions involve some amount of uncertainty, decisions based on the most relevant, complete, accurate, and timely data have a better chance of advancing the organizations goals. Second, at the tactical level, poor data quality makes more difficult to reengineer; many reengineering projects aim to put the right data in the right place at the right time to better serve a customer, making difficult to serve a customer when data is not correct. Finally, just poor data decreases employee job satisfaction, and also increases the mistrust that internal organizations may have one to another; it is made clear that departments in the organizations have needs overlapped, but if each department keeps its own data, sometimes they will find out that they have different data concerning the same issue [181].

Increasingly, however, those who design databases must support managerial decision-making activities rather than traditional transaction-oriented systems; for a variety of reasons data in such systems may not be of ideal quality - decision makers often must utilize data that are inherently unverifiable, often referred to as soft data. Those charged with designing databases that support decision making, frequently are dealing with imperfect data, so managers must make decisions in spite of the imperfections of data found in databases; an effective decision-maker can compensate for various deficiencies the data may possess, especially if the decision-maker is acquainted with the data's idiosyncrasies. But this intuitive knowledge is lost, however, whenever data are used by various parties for purposes other than the original, which increasingly is the case, especially as data warehouses become more prevalent. Those potential users who do not possess an intuitive feel for the data may well be forced either to accept the data, which implicitly assumes that all data values are equally valid, or, at the other extreme, to avoid using data whose quality they cannot personally guarantee; these leads that many decision-support systems are not fully utilized for exactly this reason. The most effective format for presenting data-quality information could be a function of the decision-making process or strategy; conjunctive decision making assumes that the decision depends upon a known and specified set of criteria, and, for each of these criteria, a minimum acceptable level is established. The decision-maker must choose from among several possible options; in order to make the decision, each option must be evaluated on each of the criteria. An option is acceptable as long as the evaluation on each of the criteria is at least as large as the specific minimum for that criterion; if the evaluation is below the minimum for even one criterion, then that option is not acceptable [182].

According to Woodall et al. [183], maintaining a good quality of information is vital, yet keeping information is a difficult task, and many leading asset management organisations have difficulty in planning and executing successful information quality management practices. According to this approach, the asset management decisions, such as whether to replace or maintain an ageing underground water pipe, are critical to ensure that organisations maximise the performance of their assets. These decisions are only as good as the information which supports them; basing decisions on poor quality in formation can potentially result in great economic losses.

Baškarada [184] extends the information quality management theory by identifying a wide range of organisational, technical, and social information management as well information quality management maturity indicators, mapping them to a staged evolutionary capability maturity model (Figure 29 [184]). It has identified up to 50 major factors, which, when not managed appropriately, may have detrimental effects on the quality of information used in contemporary organisations; evolutionary model comprises five levels, representing a "best practice" maturity continuum for information quality management.

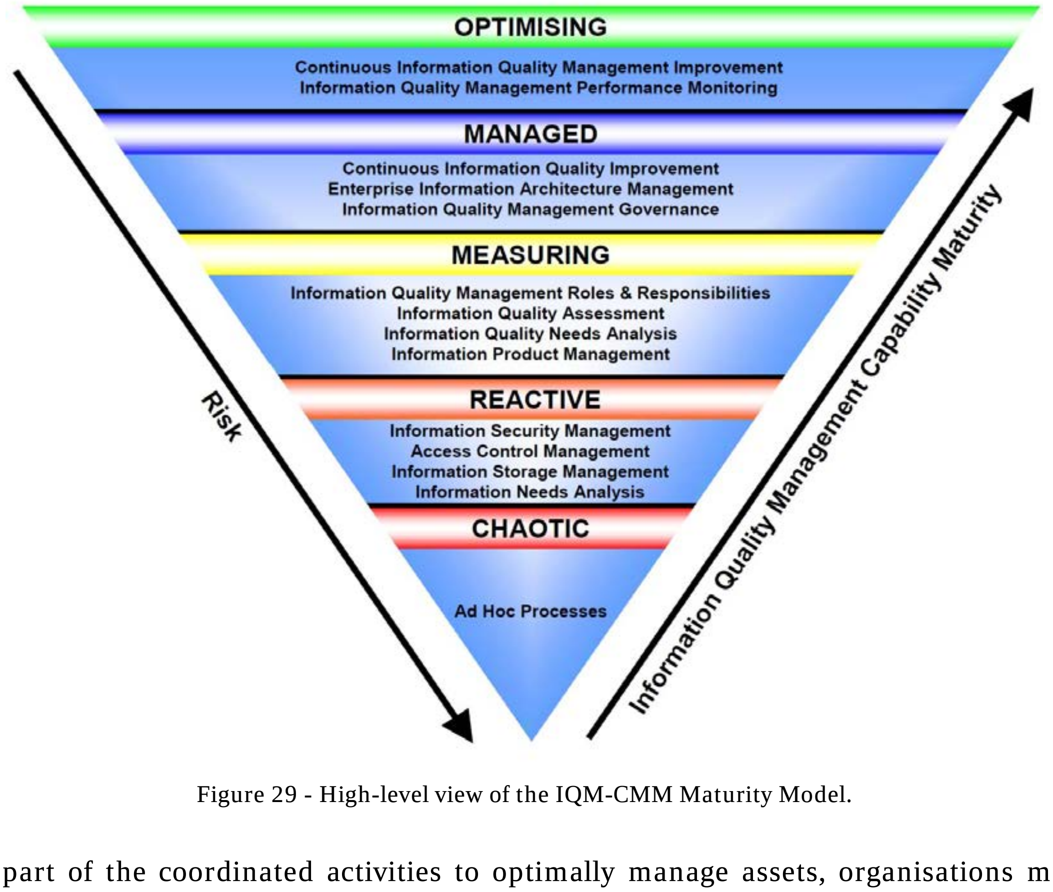

Figure 29 - High-level view of the IQM-CMM Maturity Model.

As part of the coordinated activities to optimally manage assets, organisations must make decisions which affect the state of their assets for each of the life cycle stages (Figure 30 [183]) while recognising that these decisions are not independent. Maintaining and providing good quality information is a difficult task, and many leading asset management organisations, therefore requiring guidance on how to plan and execute successful information quality management practices; typical practices include the identification of information quality management key performance indicators and the application of suitable in formation security procedures. In order to develop such guidelines and ensure that they are geared towards the current maturity and needs of the organisations, an understanding of the current state of information quality management performance (maturity) of asset management organisations is required [183].

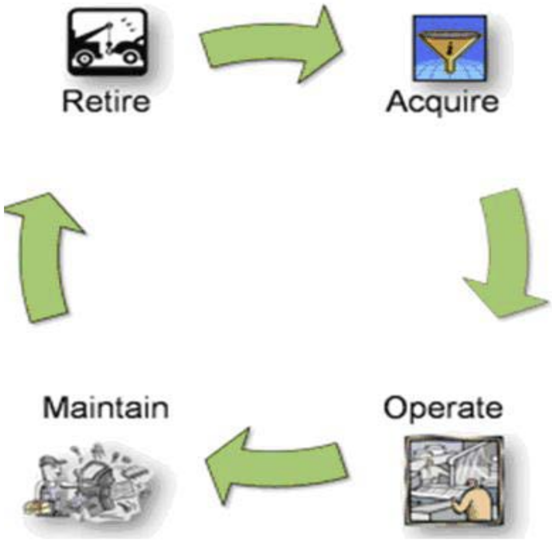

Figure 30 - The asset life cycle.

One of the most accepted definition of information quality is given is by Juran et al., [185]: “fitness for use”. This definition expresses the fact that information quality is something dependent on the context and high-quality information for a purpose that can be considered low quality for a different purpose.

The high-level view of the model is shown in Figure 29, which illustrates the maturity levels with brief descriptions of the characteristics at each level. For each maturity level, Process Areas (PAs) are defined, and these contain a set of Critical Success Areas (CSFs). The mapping of all PAs to CSFs is shown in the results section of Table 7, adapted of [183]. The aim of a maturity assessment using this model is, therefore, to determine the extent to which each CSF is satisfied within an organisation. The results for each CSF are then aggregated to determine the extent to which each PA is satisfied and then, aggregated once again to determine whether a maturity level is satisfied. The processes and systems being analysed were complex and determining whether these processes and systems meet the CSFs was not feasible beyond the scale used [183]. Assuring the quality of information is both important and difficult, but achieving high-quality information is a battle that is never really won, in part because what constitutes victory is not clear, as different parties have differing views to the definition of success. Yet all concerned agree that striving to achieve or acquire high quality information needs to be a high priority, as the consequences of not having it can be devastating. The very existence of the organization can be threatened by poor information quality [186].

Business executives should view data quality as a direct mean to reduce costs & impact revenue. Data quality should also be considered as a business issue in addition to a technological concept. Companies' survival depends on the information hidden under the piles of data.

Table 7 - CSFs satisfied by the organisations ('-'= Not Satisfied, P = Partially Satisfied, S = Fully Satisfied), A- Utility, B- Utility, C- Defence Support, D- Facility Management, E- Utility, F- Facility Management, G- Utility, H- Defence Support, I- Defence Support, J- Transport; cP- Partially Satisfied, cF- Fully Satisfied.

			Organisation											
Maturity Level	Process Area	CSF	A	B	C	D	E	F	G	H	I	J	cP	cF
5	IQ Firewall	IQ Firewall	-	-	-	-	-	-	-	-	-	-	0	0
5	IQ Management Performance Monitoring	IQ Management Metrics	-	-	-	-	-	-	-	-	-	-	0	0
		Analysis and reporting	-	-	-	-	-	-	-	-	-	-	0	0
		IQ Management Benchmarking	-	-	P	-	-	-	P	-	-	-	2	0
4	Continuous IQ Improvement	IQ Problem Root-Cause-Analysis	-	P	S	-	-	-	-	-	-	-	1	1
		IQ Risk Management and Impact Assessment	P	-	-	P	-	-	S	P	P	-	4	1
		IQ Management Cost-Benefit Analysis	-	-	S	-	P	-	-	S	-	-	1	2
		Business Process Reengineering for IQ Improvements	-	-	S	P	-	-	-	P	-	-	2	1
4	Enterprise Information Architecture Management	Enterprise Tier Management	P	P	S	P	P	P	S	S	P	P	7	3
		Information Tier Management	-	P	P	-	-	-	P	-	P	P	5	0
		Application Tier Management	-	S	S	P	P	-	P	P	P	-	5	2
		Physical Tier Management	P	P	S	P	P	P	P	-	S	P	7	2

If the data is bad, system is bound to fail. Data quality is often overlooked in trade-off between time, cost, and performance. It must be made sure that it is not ignored in the race for low cost and delivery before deadline. Organizations must realize that there is no point in being quick if information is poor. Reports from META[1] group indicate that 75% of companies in USA have yet to implement any Data Quality initiative. Businesspersons ignore data quality due to:

[1] http://www.meta-group.com/

- Very little attention dragged by technical persons to this issue;
- Cost and difficulty in implementing data quality initiative;
- Inability to measure ROI.

It is now easy for business executives to understand what the propounding effect data quality can play in business. Estimates show that 15-20% of the data in an organization can be erroneous [186].

Organizations are forced to manage larger volumes of data, strong push to gain business intelligence and competitive advantage has increased the number of different ways how data is analysed, and the variety and frequency of decision-tasks performed with it. The advent and widespread use of wireless technology/devices within the mobile-business arena promise to further increase it. Decision-makers are forced to become more responsive and make quicker and more dynamic decisions because of having access to data anywhere, anytime. A decision-maker uses the same data for different decision-tasks besides sharing the data and decision-outcomes with several others. This creates dynamic decision environments characterized by data at different levels of granularity, high frequency and a large variety of decision tasks, and multiple stakeholders (data providers, decision-makers, and data custodians). Supporting decision-making in such environments in the face of increasing data volumes demands efficient and proactive data quality management. The decision-maker has no control over these data sources. The number and distribution of such data sources makes it difficult to guarantee data quality. Efficient data quality management must include informing the decision-maker about the quality of the data being used and/or providing him/her with the ability to gauge it. The decision-maker can then decide if the quality is acceptable for the decision-task at hand and evaluate if alternate data and/or sources are more acceptable along with the associated risks/benefits [187].

The cost associated with making decisions based on poor-quality data is quite high, so, the management of data quality and the quality of associated data management processes have become critical for organizations. An important first step in managing data quality is the ability to measure the quality of information products (derived data) based on the quality of the source data and associated processes used to produce the information outputs. Information systems are critical to organizations for supporting strategic, tactical, and operational decisions. These systems present a view of the real world for decision making. When this view is not close to reality, the decisions made are inappropriate and can be very costly to the organization. The terms information quality and data quality have been used to characterize mismatches between the view of the world provided by an information system and the true state of the world. The importance of managing the quality of data and derived information has been widely documented in the information economy. Whereas there is little dispute regarding the importance of managing the quality of data and information systems, only a few organizations have implemented any kind of a process to manage and control data quality. There are two important factors for this: First, implementing such a process can be quite expensive, often involving millions of dollars of software and associated human resources; Second, firms are unable to clearly measure the quality of data and, consequently, the quality of information derived from the data. Without this ability it becomes difficult, if not impossible, for firms to estimate the cost of poor data to the organization. Consider, for example, a marketing database that is used to mail promotional information to customers. What is the cost to the organization of sending the same mail to customers whose information appears multiple times in their databases? What are the opportunity costs of missing information on prospective customers? What extraneous costs are incurred for mail sent to incorrect addresses? To what degree do poor data affect the results of queries and reports that are used for decision making? To estimate such costs, it must be possible to measure the quality of the data and the derived information [188]. Haug et al. [189], proposes a graph that is showed in Figure 31. The vertical axis indicates the incurred, aggregated costs of dealing with poor quality data. The second and horizontal axis deals with the quality of data. The two curves in the figure represent costs inflicted by poor quality data and the costs of maintaining high data quality, respectively. The costs inflicted by poor quality data are, for example, faulty decisions based on poor data quality, whether this is of operational or strategic character. The costs of ensuring and maintaining high data quality simply refer to the work of assurance or improving data quality. The total costs associated with data quality are the aggregated cost of the two explained curves. There are two basic assumptions associated with Figure 31 [189]. Firstly, during data maintenance the focus is on the most critical data (i.e. the ones with the highest payoff per resources spent) before moving on to less critical ones. This implies that the first work of assuring data quality would have the greatest effect, i.e. the costs inflicted by poor quality data decreases exponentially. The second assumption is that the costs of the efforts to ensure high data quality are not causally related to their importance, i.e. focusing on a set of poor-quality data with great impact on costs is not necessarily cheaper than focusing on data with little impact on costs. Thus, the costs of assuring data quality are a linear relationship between data quality and assurance costs. Thus, it can be derived from Figure 31 that the connection between costs inflicted by poor quality data and costs of ensuring high data quality can be logically categorized as a trade-off, which is a situation involving the loss of one quality in return for gaining another quality.

The central thesis here is that extensively cleaning data, thereby ensuring high quality of the data, becomes less profitable at some point. This is illustrated by the dotted line termed “total costs”; although, Figure 31 seems to provide a very logical perspective on the estimation of the optimal data quality maintenance efforts, there is still some way to go, for this figure to be applied on an area of a company, the two types of costs need to be evaluated, i.e. the costs of maintaining data and the costs inflicted by poor quality data [189].

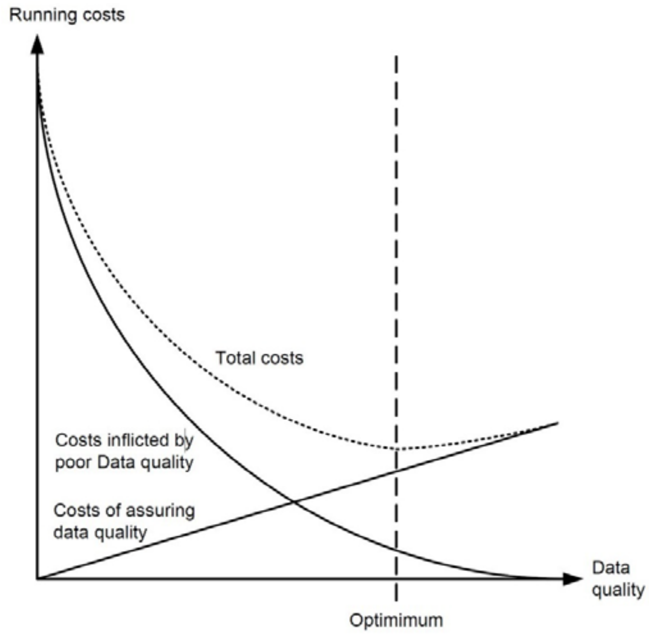

Figure 31 - Total costs incurred by data quality on the company.

2.2. Life Cycle

The set of ISO 5500X standards appears to respond to this need to better manage the life cycle of the organization's physical assets, ensuring the level of competitiveness without compromising the level of excellence of the products / services offered. The ISO 55001 standard proposes a methodology for managing assets in accordance with the Organization's strategic objectives, supporting decisions on acquisition, replacement and or disposal of them, in line with practices aimed at the environmental, social, and economic sustainability of the equipment and of the company itself. When replacing an asset, the organizations must ensure that the energy consumption of the equipment and its environmental impact shall justify their replacement. For all these aspects, among many others, ISO 5500X standards can make a decisive contribution to the implementation of a new, more sustainable economy based on innovative management of the physical assets that we depend on. The current competitive environment demands of the companies, are more and more a constant search in the improvement of processes in all aspects. Thus, in order to obtain a leading position, companies aim to maintain their standard above the competition [186].

According to ISO 55000:2014 [117], “Asset management enables an organization to examine the need for, and performance of, assets and asset systems at different levels. Additionally, it enables the application of analytical approaches towards managing an asset over the different stages of its life cycle (which can start with the conception of the need for the asset, through to its disposal, and includes the managing of any potential post disposal liabilities).”

Farinha [190] sets stages of a physical asset life cycle (Figure 32 [190]) that goes from the moment t1 (Decision about acquisition) until moment t8 (Renewal/withdrawal) and setting, for each stage, a set of aspects that must be taken into consideration.

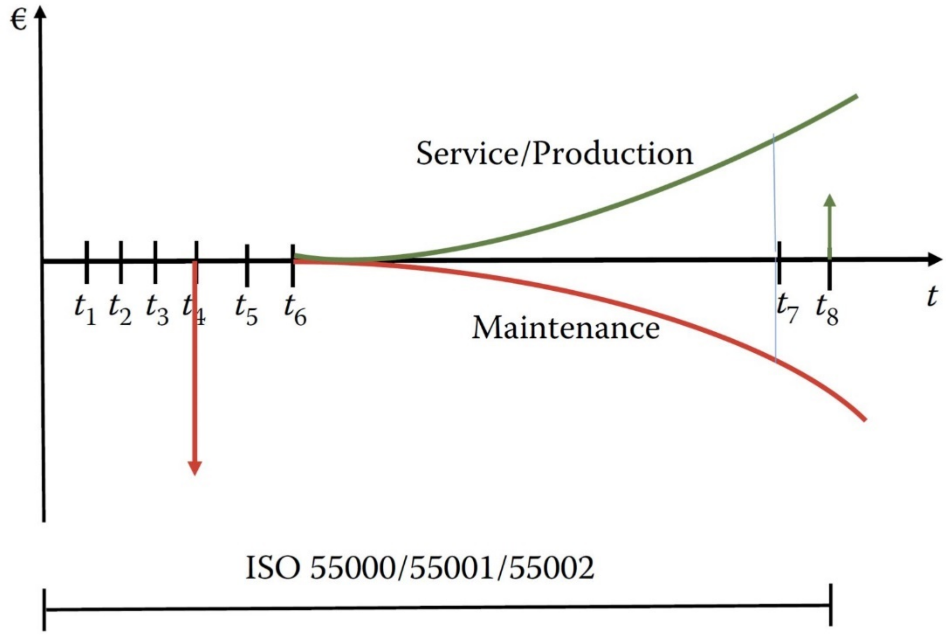

Figure 32 - Stages of a physical asset life cycle.

- t1 - Decision about acquisition
- t2 - Terms of reference
- t3 - Market consultation
- t4 - Acquisition
- t5 - Commissioning
- t6 - Starting production/maintenance
- t7 - Economic/lifespan issues
- t8 - Renewal/withdrawal

Other authors, such as Hastings [180], consider only four stages on life cycle (Figure 33, adapted of [180]). When defining economic life, the author states that the economic life of an asset is the life beyond which it becomes cheaper to replace an item than to keep operating it, basically the economic life is the life for which the equivalent annual cost of the life cycle costs is a minimum.

The author also describes a set of factors that should be considered when making asset replacement decision, such as:

- Level of service lagging behind the current requirements;
- Obsolescence, lack of spares or technical support;
- Reliability, maintainability, availability and safety issues of aging equipment, particularly with corrosion, fatigue and other degradation factors;
- Risk of significant in-service failure;
- Newer equipment provides benefits of performance, service or technical improvements;
- Changes in the role of equipment over time.

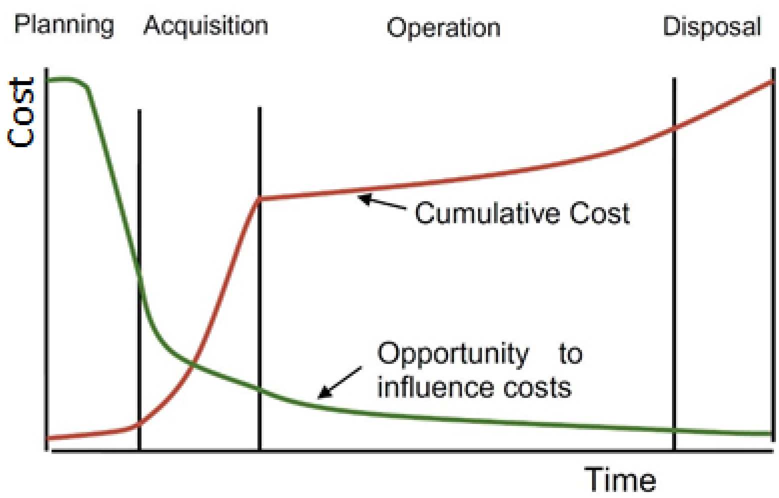

Figure 33 - Life cycle stages.

Other authors, such as Campbell *et al.* [140], bring the concept of Total Life-Cycle Asset Management (TLAM) stating that traditional views often ignored key phases on assets life-cycle, and claims that, even all the phases are considered in each of them; then, each phase ought to be treated individually without regarding to previous or consequent phases.

The author considers an eight life cycle phases (Figure 34 [140]) of use and planning, and all of them have a supporting financial management and technology attributes to consider; on other hand, he sets an asset strategy aligned with the company's business requirements, and describes activities, such as asset management practices, developing a comprehensive asset management strategy and a measurement program with key performance indicators (KPIs).

Figure 34 - Total life-cycle asset management.

When defining an approach to asset life cycle, Galar *et al.* [191] stat that the life cycle approach is a developmental or holistic approach, enabling the issues, that impact an asset, to be reviewed at different stages of its life.

The author reinforces that there is an opportunity to quantify the reliability and maintainability characteristics in the phase of design specification and, in particular, the maintainability requirements. Yet, according to the author, the life cycle is divided into five distinct phases (Figure 35 [191]).

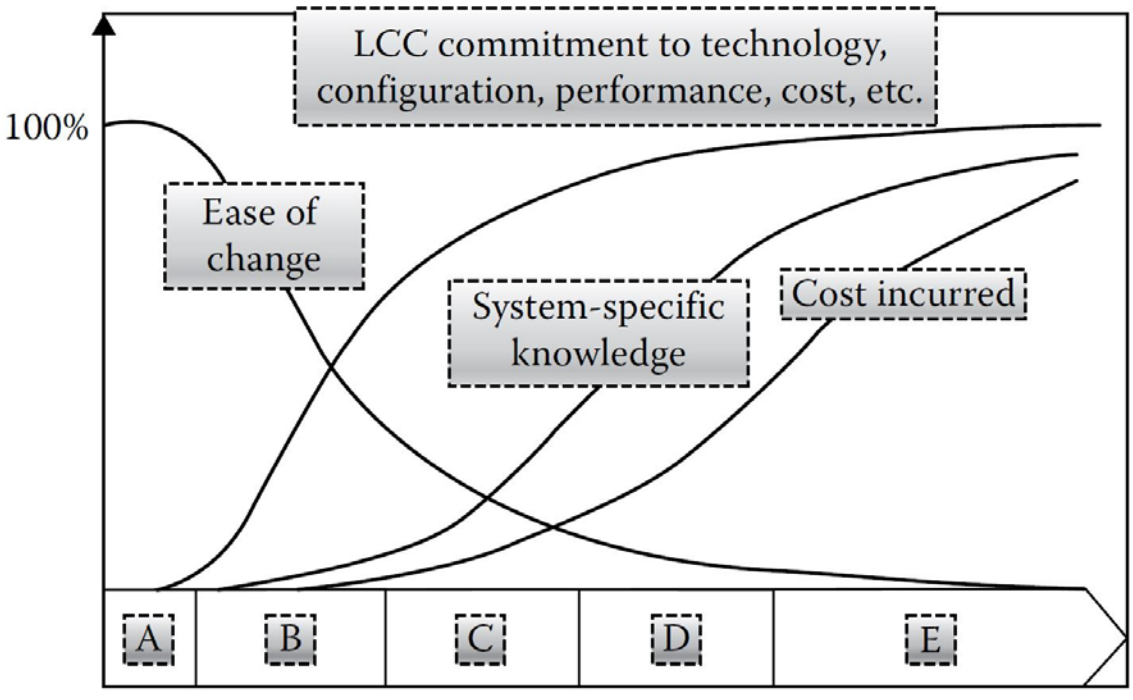

Figure 35 - Life cycle phases.

When presenting the life cycle, Galar *et al.* set the following five steps [191]:

i) Analysis and specification phase;
ii) Conceptual design phase;
iii) Design and development phase;
iv) Construction, production and commissioning phases;
v) Installation, system use, phase out, decommissioning and disposal phases.

Galar *et al.* [191] also present other more conservative life cycle (Figure 36 [191]).

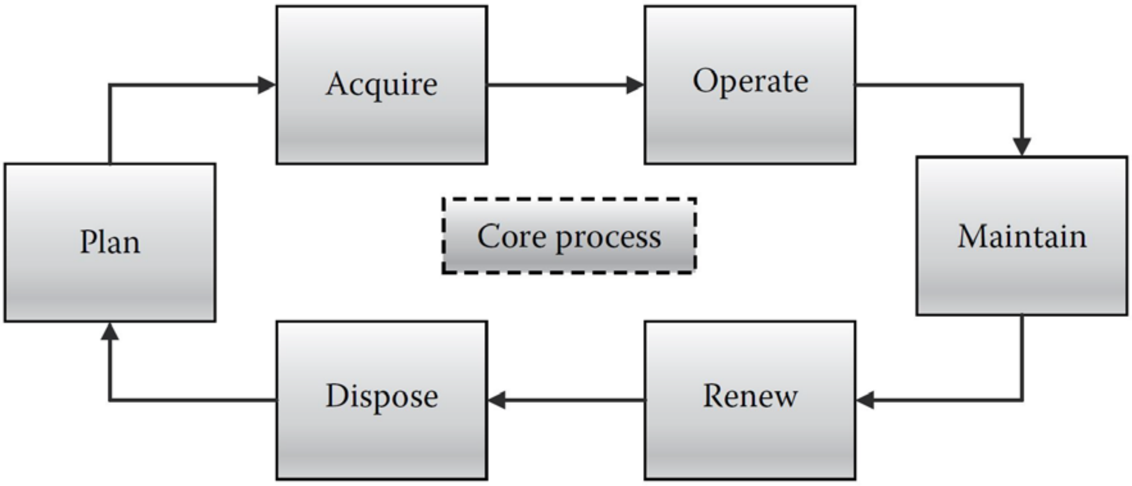

Figure 36 - Life cycle phases.

The authors reinforce the need of a strategic plan in order to start the life cycle, and move on to creation, operation, maintenance, and rehabilitation, to the final decommissioning and disposal at the end of the asset's life.
On the other side, Galar *et al.* declare that the life cycle can be shortened as assets reach the end of their effective life before they become non-functional (for example: regulations changes, the asset becomes noneconomic, the expected level of service increases, capacity requirements exceed design capability) and also technological developments and changes in user requirements are key factors impacting the effective life of an asset [191].

From the European Union Journal[2], "life-cycle" means all consecutive and/or interlinked stages, including research and development to be carried out, production, trading and its conditions, transport, use and maintenance, throughout the existence of the product or the works or the provision of the service, from raw material acquisition or generation of resources to disposal, clearance and end of service or utilisation.

[2] DIRECTIVE 2014/24/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 26 February 2014

According to the same journal there is a concern on the life cycles when contracting; its states are the following:

1. Life-cycle costing shall to the extent relevant cover parts or all the following costs over the life cycle of a product, service or works:
   a) costs, inherited by the contracting authority or other users, such as:
      i) costs related to acquisition;
      ii) costs of use, such as consumption of energy and other resources;
      iii) maintenance costs;
      iv) end of life costs, such as collection and recycling costs.
   b) costs imputed to environmental externalities linked to the product, service or works during their life cycle, providing that their monetary value can be determined and verified; such costs may include the cost of emissions of greenhouse gases and of other pollutant emissions and other climate change mitigation costs.
2. Where contracting authorities assess the costs using a life cycle costing approach, they shall indicate in the procurement documents the data to be provided by the tenderers and the method which the contracting authority will use to determine the life-cycle costs based on those data.
   The method used for the assessment of costs imputed to environmental externalities shall fulfil all the following conditions:
   a) it is based on objectively verifiable and non-discriminatory criteria. In particular, where it has not been established for repeated or continuous application, it shall not unduly favour or disadvantage certain economic operators;
   b) it is accessible to all interested parties;
   c) the data required can be provided with reasonable effort by normally diligent economic operators, including economic operators from third countries party to the GPA or other international agreements by which the Union is bound.
3. Whenever a common method for the calculation of life-cycle costs has been made mandatory by a legislative act of the Union, that common method shall be applied for the assessment of life-cycle costs.

2.3. Importance of Life Cycle Management

According to EN 60300–3–3:2004[3] products today are required to be reliable. They have to perform their functions safely with no undue impact on the environment and to be easily maintainable throughout their useful lives. The decision to purchase is not only

[3] Dependability management Part 3-3: Application guide – Life cycle costing (IEC 60300-3-3:2004)

influenced by the product's initial cost (acquisition cost) but also by the product's expected operating and maintenance cost over its life (ownership cost) and disposal cost. In order to achieve customer satisfaction, the challenge for suppliers is to design products that meet requirements and are reliable and cost competitive by optimizing acquisition, ownership and disposal costs. This optimization process should, ideally, start at the product's inception and should be expanded to consider all the costs that will be incurred throughout its lifetime. All decisions made concerning a product's design and manufacture may affect its performance, safety, reliability, maintainability, maintenance support requirements, etc., and, ultimately, determines its price and ownership and disposal costs.

Life cycle costing is the process of economic analysis to assess the total costs of acquisition, ownership, and disposal of a product. This analysis provides important inputs in the decision-making process in the product design, development, use and disposal. Product suppliers can optimize their designs by evaluation of alternatives and by performing trade-off studies. They can evaluate various operating, maintenance, and disposal strategies (to assist product users) to optimize LCC. Life cycle costing can also be effectively applied to evaluate the costs associated with a specific activity; for example, the effects of different maintenance concepts/approaches, to cover a specific part of a product, or to cover only selected phase or phases of a product's life cycle.

Life cycle costing is most effectively applied in the product's early design phase to optimize the basic design approach. However, it should also be updated and used during the subsequent phases of the life cycle to identify areas of significant cost uncertainty and risk.

The necessity for formal application of the life cycle costing process to a product will, normally, depend on contractual requirements. However, life cycle costing provides a useful input to any design decision-making process. Therefore, it should be integrated with the design process, to the extent feasible, to optimize product characteristics and costs.

According to Blanchard & Fabrycky [186], total system cost is often not visible, particularly those costs associated with the system operation and support. The cost visibility problem can be called the "iceberg effect", as illustrated in Figure 37 [186].

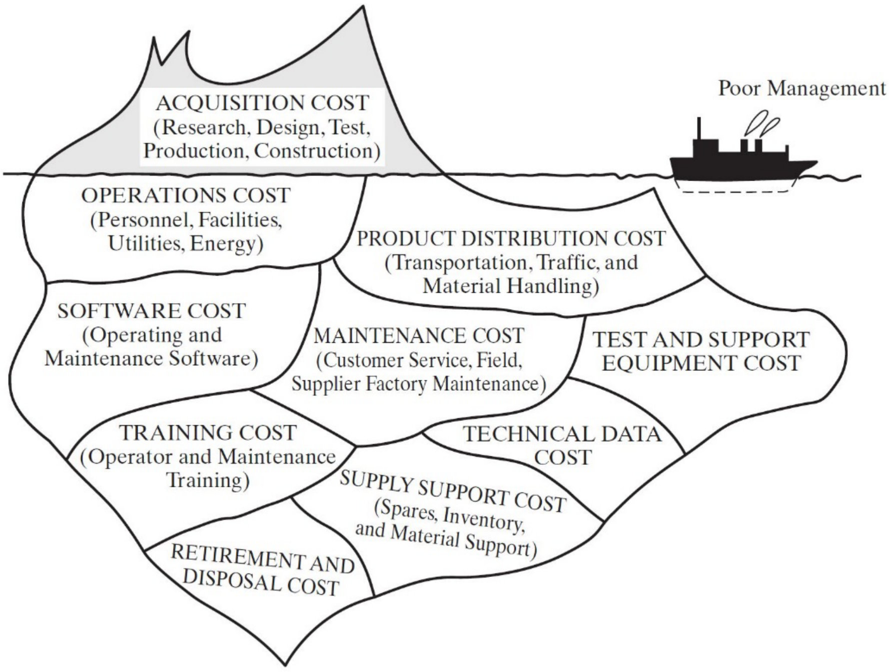

Figure 37 - Visibility of the elements of total LCC.

Many of the costs, as can be seen, are not visible, and, if we don't have tools to help, it will be a "sailing by sight".

2.4. Technology

Assets increasing technology is a fact on our days and cannot be ignored when preforming asset management and life cycle studies decisions on renewal or disposal, then it must consider the latest technology and its value for the organization.
Furthermore, when we consider more recent technologies, they are intrinsically linked to environmental issues, whether in the reduction of energy consumption or in the reduction of emissions in the case of equipment that burns liquid or gaseous fuels and also those of wood or mineral origin.
In this way, when the renewal of an asset or its disposal is considered, it must always be considered that this renewal brings the asset to a state as if it was new and with up-to-date technology.

2.5. Risk Management

When managing assets, risk management must be taken into consideration and carefully evaluated; the financial, environmental, and operational risks must also be taken into account.
ISO 31000 states that risk management are for those who create and protect value in organizations by managing risks, making decisions, setting and achieving objectives and

improving performance, and also declares that organizations of all types and sizes face external and internal factors and influences that make it uncertain, whether they will achieve their objectives [192].
When managing the external and internal risks in the context of the organization, these must include human behaviour and cultural factors.
Managing risk is based on the principles, framework and process, as illustrated in Figure 38 [192]: managing risk needs to be an efficient, effective and consistent activity.

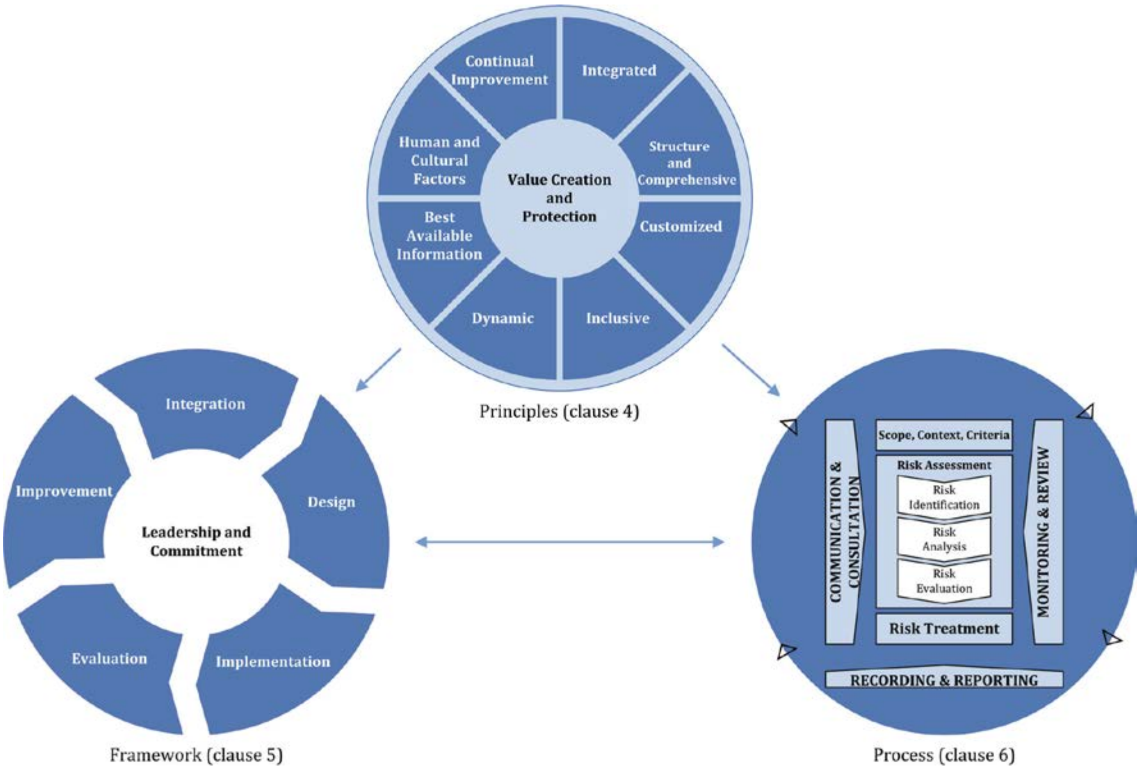

Figure 38 - Principles, framework and process.

While managing risk and because it is an iterative activity that assists organization in setting its strategy, aiming to achieve objectives, and making informed decisions, a PDCA cycle can be used; all activities related with risk management must also interact with interested parts.

2.6. ISO 55001 Implementation

Besides all the factors described in the previous sections, according to Pais *et al.*, [71], it is challenging to implement the ISO 55001 standard and a diagnostic model on the state of the organizations can greatly help on its implementation. Before beginning to implement the ISO 55001 standard, it is necessary to verify whether the organization is ready to begin this task. It is usually necessary to fine-tune many aspects before starting a great task like this. But where to start? What aspects do I need to correct before starting the default implementation? The diagnostic model presented is based on surveys, with several questions and with five possible answers, each possibility of response has a quantification and a critical classification. The result is a global positioning of the company with the identification of the various aspects to be corrected in order to be possible to implement the ISO 55001. A radar chart (Figure 39 [71]) provides a global “radiography” of the company diagnosis.

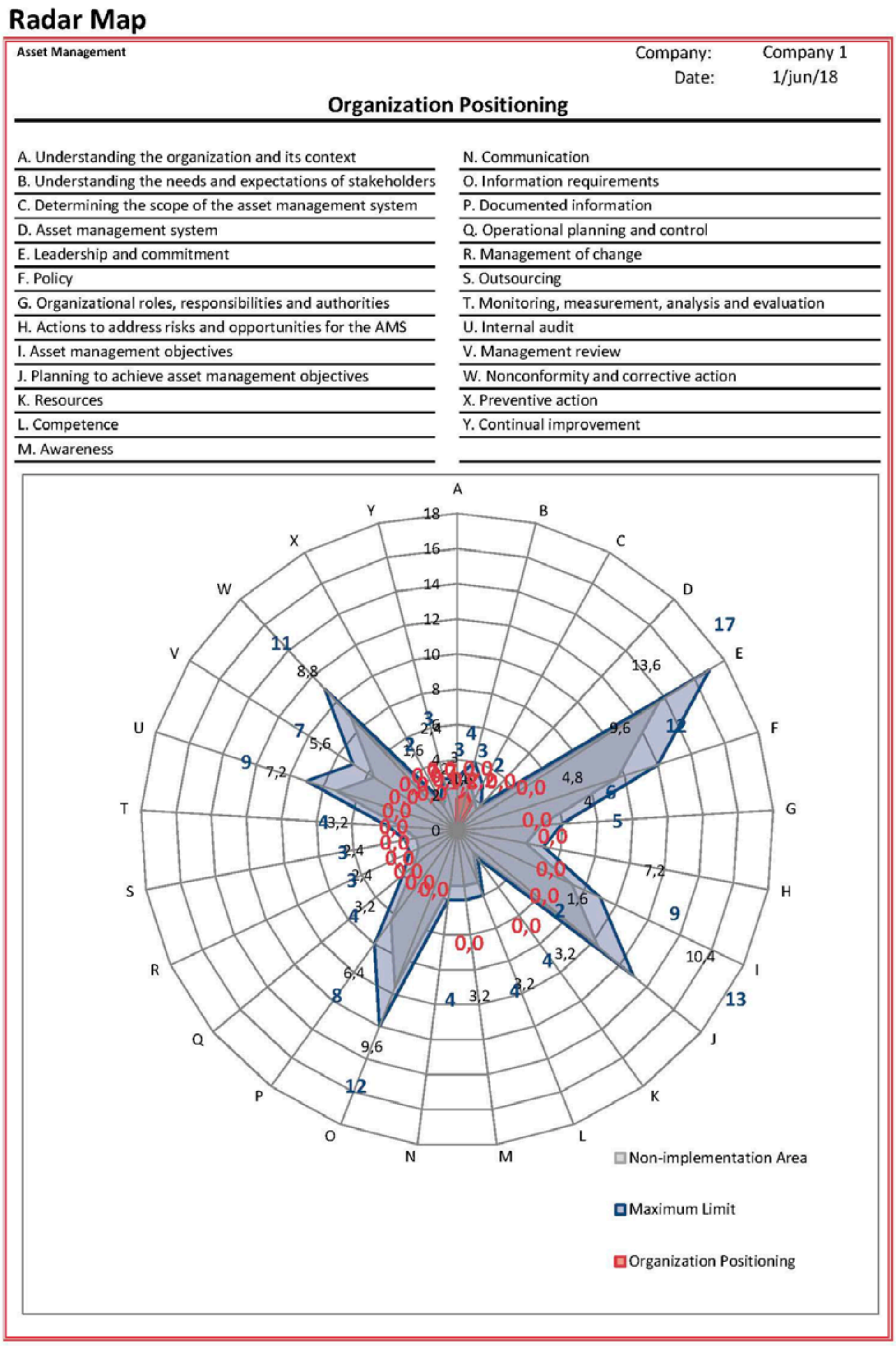

Figure 39 – Organization Radar Map

2.7. Measuring the Performance of Asset Management Systems

While some authors state that performance measurement of asset management systems remains a poorly understood area, both in terms of industrial practice as well as academic research, the same authors present Safety, Value Creation, Reliability and Cost as asset performance indicators [193].

EN 15341:2019 [194] brings a set of Sub Functions, Tools and Methodologies, having each group their own performance indicators based on their main areas, as shown on Table 8 [194].

Table 8 - Maintenance KPIs matrix.

SUB FUNCTIONS, TOOLS AND METHODOLOGIES	**KPIs**	**MAIN AREAS**			
Maintenance within physical asset management	PHAi	Sustainability i = 1 to 3	Capacity Effectiveness Integrity i = 4 to 11	Service Level i = 12 to 13	Economics i = 14 to 20
Sub-function 1 Health - Safety Environment	HSEi	Laws- Rules conformity i = 1 to 3	Statistical Records i = 4 to 12	Safe Practice i = 13 to 17	Prevention and Improvements i = 18 to 22
Sub-function 2 Maintenance Management	Mi	Strategy i = 1 to 3	Function i = 4 to 10	Technical Assessment i = 11 to 16	Continuous Improvement i = 17 to 22
Sub-function 3 People Competence	Pi	Maintenance Manager i = 1 to 3	Maintenance Supervisor/ Maintenance Engineer i = 4 to 9	Maintenance Technician Specialist i = 10 to 12	Education i = 13 to 21
Sub-function 4 Maintenance Engineering	Ei	Capability Criticality i = 1 to 3	Durability i = 4 to 9	Preventive Maintenance i = 10 to 16	Engineering Improvements i = 17 to 19
Sub-function 5 Organization and Support	O&Si	Structure and Support i = 1 to 8	Planning and Control i = 9 to 22	Productivity Effectiveness i = 23 to 28	Quality i = 29 to 30
Sub-function 6 Administration and Supply	A&Si	Economics i = 1 to 6	Budget &Control i = 7 to 19	Outsourcing services i = 20 to 25	Materials and spare parts i = 26 to 29
Information Communication Technology, Enabling technologies	ICTi	Management i = 1 to 6	Administration and Supply i = 7 to 10	Organization and Support i = 11 to 13	Engineering i = 14 to 20 TEC 18.20

When performing asset management and creating an asset management system, it is clear that the main document is the SAMP, and, in order to evaluate its effectiveness and measuring the performance, it is important to have key performance indicators (KPI's) that are clear and simple to use, and, at same time, they must indicate the fulfilling of the SAMP requirements according to ISO 550001; on the other side, aiming to help and bring the vision of the SAMP, a Balanced Scorecard (BSC) [195] can be a great tool in order to achieve the SAMP objectives.

The BSC was introduced in 1992 by professors Robert S. Kaplan and David P. Norton with the following quote "What you measure is what you get"; according to this, it is impossible to obtain the expected results if we can't measure the progress. In order to create a BSC, there is a need to identify the organization objectives in four perspectives (Figure 40) [196]:

- Financial - manage costs, increase profits, diversify revenue sources, increase market share;
- Customers - decrease waiting times, increase customer satisfaction, improve customer return rate;
- Internal Process - improve service efficiency, allocate resources efficiently, streamline review process;
- Learning and Growth - upgrade tech resources, sponsor employee continuing education, recruit highly skilled employees.

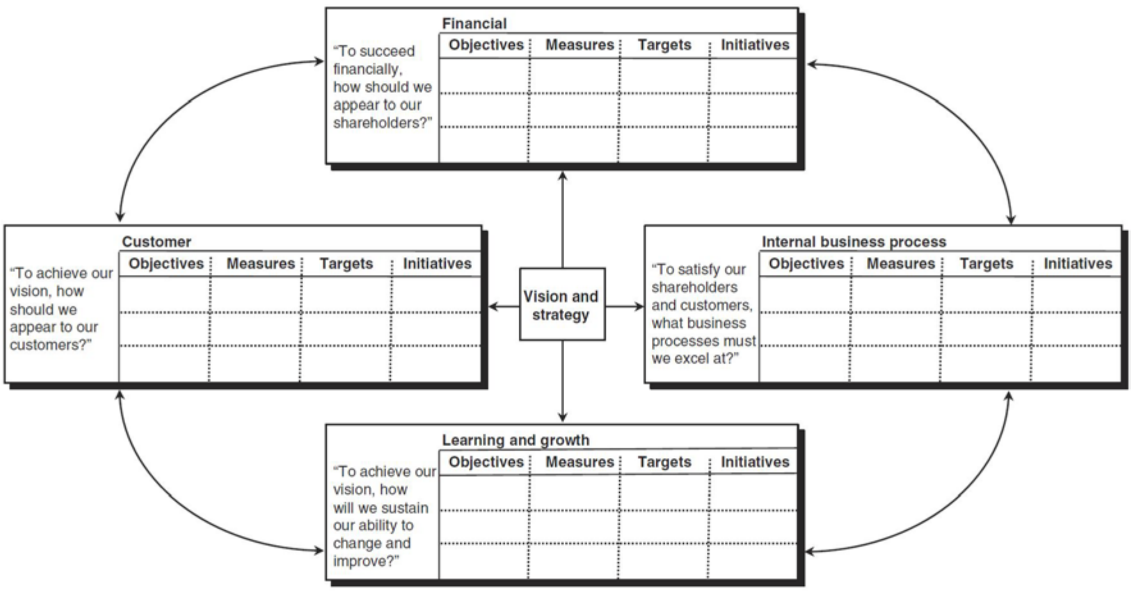

Figure 40 - Translating vision and strategy: four perspectives.

Other instruments for management include Peter's 1954 classic book "The Practice of Management", describing the concept of management by objectives, which states that each employee should have personal performance targets that are intimately related to the strategy for the company [197]. Robert Anthony expanded on earlier studies in the mid-1960s [198], [199], providing a comprehensive foundation for planning and control systems. Operational control, managerial control, and strategic planning were Anthony's three types of systems. The Japanese Management Movement, for example, brought improvements to Just-In-Time (JIT) production and quality during the 1970's and 1980's [200]. The Balanced Score, which is based on BSC and utilised as a benchmarking tool, was introduced by Punniyamoorthy & Murali in 2008 [201].

Till now 5,035 studies were published on the issue of the BSC, according to Scopus [202]. The BSC has been a widely utilised instrument in research, where improving has aroused considerable attention across the globe [203], in the USA, 60% of Fortune 1,000 organisations employ the BSC [204]. According to Anand et al. [205], using the BSC is a creative way to increase strategic awareness throughout the company. However, the BSC construct a thorough structure that links personal achievements and efforts to business-unit goals, supporting a comprehensive model [206].

While developing this chapter, a paper (I, referred in Tables 2 and 3) entitled "Optimizing the Life Cycle of Physical Assets – a Review" (DOI: 10.37394/23203.2020.15.42) was published in the Scopus-indexed journal, *WSEAS Transactions on Systems and Control* (Q4). The main focus was to bring a review of the literature on the life cycle models used in asset management and their primary issues; this is the first step in developing a model to optimise the life cycle of physical assets from an ISO 55001 perspective. The paper presented a table with models / approaches and its advantages and disadvantages.

Chapter 3

Integrated Life Cycle Investment Assessment Method

While searching for answers to the research questions, some studies have been carried out. The Integrated Life Cycle Investment Assessment Method (ILCIAM) is one of the outputs. The presented study gave rise to a paper published in an Q1 Scopus-indexed international journal. The following research questions were answered:

RQ 1: How can organizations increase value from their Physical Assets?

RQ 2: How can Physical Assets' Life cycle be optimized according to the organization's needs?

RQ 3: Which are the econometric models that can best be conjugated to Physical Assets' Life Cycle Assessment (LCA)?

3.1 Data

One of the major challenges is related with data, because only with reliable and complete data, outputs are reliable. Even when on these days. There is abundance of data due to its easy collection, this information is not always the best or easy to use. In some sectors there is few data collection, or the methods used to collect aren't reliable compromising the data collected, which brings a big challenge in order to validate research models. In order to use the model presented, it's important to the organizations to gather reliable data, so this is the first step for the organizations.

3.2 Econometric Models

In order to evaluate life cycle, it is important to measure it. The use of econometric models, introduced since the beginning of the 20^{th} century, has been a great help[207]. Nowadays econometric models regarding assets life cycle evaluation have been introduced [167], [190], [208], [209]. There are a number of related questions: Does the asset bring value to the organization? How can we calculate the value of the asset? These questions can be answered using the appropriate econometric models.

3.3 Life Cycle Assessment

While considering Life Cycle Assessment (LCA), Farinha *et al.* [210] discuss Terology, taking the assets global life cycle into account. The relevance of coordinating the environment with the organization's objectives is emphasised, along with the operation and maintenance when considering the environmental organizations goals. It may vary depending on the organisation. When considering LCA, the environmental impacts are essential and there are stages that are not taken into account but that influence the results of the LCA, such as those already mentioned.

3.4 Asset Management

The asset management tools and definitions in ISO 55000 [117] are presented. The standard covers the topic of value life cycle management and includes a number of essentials from a strategic standpoint, including Value, Alignment, Leadership, and Assurance. There are many different types of assets, and it's crucial to manage their life cycles in order to maximise their value. The implementation of decision-making processes is also essential, and stakeholders can support decisions about the assets of the organisation by using an econometric model.

The ISO 55001 [135] standard emphasises the use of processes and methods in the management of assets throughout their life cycles when defining asset management strategies. Econometric models are one method for performing life cycle analysis, and the Strategic Asset Management Plan (SAMP) ought to include them. ISO 55002 [106] specifies that 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 may have a time frame that is sufficient for covering the entire asset life; this time frame may correspond to the organization's own business planning period. In addition to the SAMP documents, the decision-making criteria allow for the determination of value realisation and consider the assets' long-term financial viability. The SAMP and its goals must be thinking about the complete asset portfolio while taking into account the asset management policy and the life cycle strategies of the various asset kinds, or general activity types, that should be used when designing the asset management plans.

According to ISO 55002 [106], the SAMP contains life cycle planning 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)".

In order to help the assessment of the asset's replacement period, econometric models are incorporated in the SAMP (Figure 41 [106]). The following is a presentation of additional ideas to support their analysis.

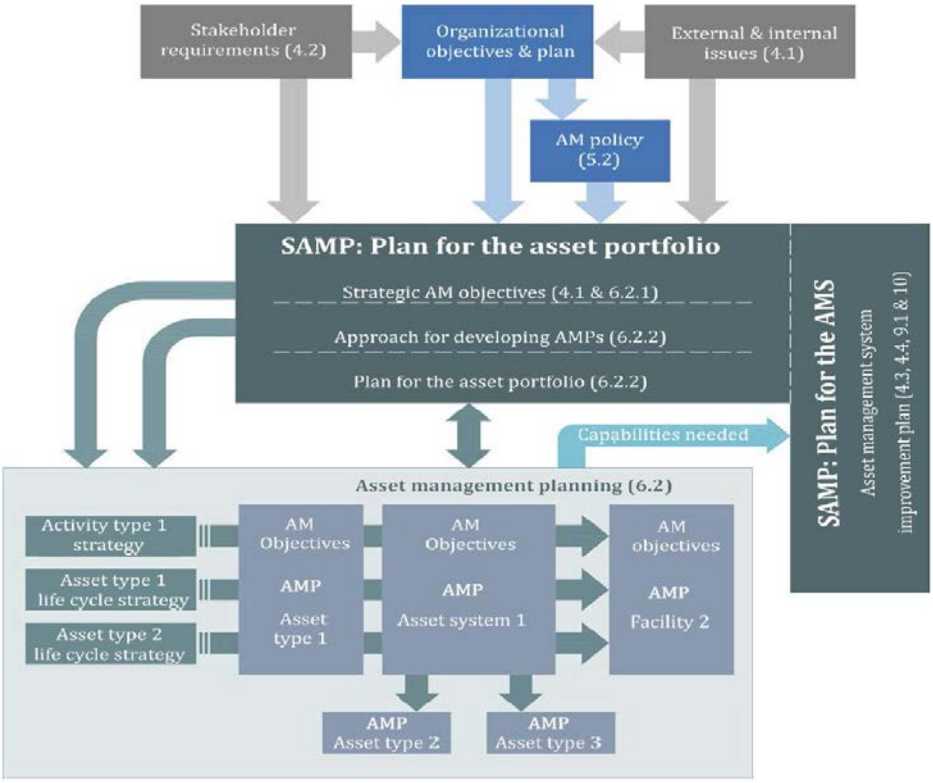

Figure 41 - SAMP concept diagram.

Labels: Refs—The clause numbers in Figure 9 relate to ISO 55001; AM—Asset Management; AMP—Asset Management Plan; SAMP—Strategic Asset Management Plan.

3.4.1 Models

A variety of scenarios and factors needs to be taken into account while conducting economic simulations and choosing whether to replace an asset. It is crucial to have accurate tools and information for interpreting the asset's condition [114]. The use of multivariate analyses [211], which can assist in addressing issues that are challenging to discover despite the requirement to apply a number of assumptions, is another method for avoiding errors.

The significance of Artificial Intelligence (AI), which can provide accurate information but requires solid databases, is also emphasised by Rodrigues et al. [15]. Deterioration is one of the primary causes for replacing an asset, according to Raposo et al. [212]. To support a sound decision on asset replacement, there is a necessity to select a suitable approach and highlight elements like acquisition cost, value of withdrawal, operating costs, maintenance costs, operating costs, inflation rate, and discount rate.

It is possible to extract information from each asset's historical data. Because it could be challenging to get information about renewal or withdrawal, the market can be consulted in the event of a renewal. Alternatively, Oliveira [213], Farinha [167], and Farinha [190] provide the following techniques for simulating the asset devaluation in the event of a withdrawal:

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

For replacing an asset, Farinha [167] uses a number of criteria. From a financial standpoint, the economic cycle is frequently utilised to identify the best time to operate, maintain, and idle capital in order to reduce average total costs. The lifetime is yet another method that is frequently utilised.

Another used method is the Uniform Annual Income (UAI), according to which an asset's life cycle ends when its operating expenses exceed its maintenance costs plus the amortisation of the capital cost of new or equivalent machinery.

The following information is required to compute the Uniform Annual Income and the ideal time to replace an asset:

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

Utilising the exponential technique, the depreciation value is determined. This method was chosen because better fitted the depreciation value on the studied assets. The formula, which is given as follows, calculates the annual cost of depreciation over the course of the equipment's life:

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

$$V_n = VC_{j-1} - d_j \quad (2)$$

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 ... n

V_n: Equipment value in period n = 1, 2, 3 ... n

The Present Net Value (PNV) represents the present value of an asset over a period of time, and the apparent rate represents the integration of inflation and capitalization rates.

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

$$PNV_n = II + \sum_{j=0}^{n} \frac{M_j + F_j}{(1 + i_A)^j} - \frac{V_n}{(1 + i_A)^j} \quad (3)$$

where:

II: Initial Investment

M_j: Maintenance in year j = 1, 2, 3, ... n

F_j: Functioning in year j = 1, 2, 3, ... n

i_A: Apparent rate

V_n: Value of the equipment over a period n = 1, 2, 3 ... n

The Apparent rate (i_A) is given by:

$$i_A = i_I + i_C + i_I \times i_C \quad (4)$$

where:

i_A: Apparent rate

i_I: Inflation rate

i_C: Capitalization rate

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

$$UAI_n = \frac{i_A(1 + i_A)^j}{(1 + i_A)^j - 1} * PNV_n \quad (5)$$

$$ROI = \sum_{j=1}^{n} \frac{CF_j}{(1 + i_A)^j} - II \quad (6)$$

where:

ROI: Return On Investment

II: Initial Investment

CF_j: Cash Flow in year j = 1, 2, 3, ... n

i_A: Apparent rate

The value of UAI_n, which stands for the multi-year period in which the asset should be replaced, is comparable to the minimum rent at which the machinery would need to be rented on an annual basis.

A novel strategy was developed using the exponential depreciation mechanism and uniform annual income. This strategy extends the asset's life cycle by factoring in additional investments such technological advancements, technology depreciation, and sustainability depreciation. The Present Net Value Integrated in Year n ($PNVI1_n$) method is represented by:

$$PNVI1_n = II + \sum_{j=0}^{n} \frac{IM_j + IF_j + TUI_j + TD_j + SD_j}{(1+i_A)^j} - \frac{V_n + \sum_{j=0}^{n} R_j}{(1+i_A)^j} \quad (7)$$

where:

II: Initial Investment

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

IF_j: Integrated Functioning in year j = 1, 2, 3, ... n

TUI_j: Technological Upgrade Investment in year j = 1, 2, 3, ... n

TD_j: Technology depreciation in year j = 1, 2, 3, ... n

SD_j: Sustainability depreciation in year j = 1, 2, 3, ... n

i_A: Apparent rate

V_n: Value of the equipment over a period n = 1, 2, 3 ... n

R_j: Residual value of the upgraded part n = 1, 2, 3 ... n

The Annual (n) Integrated Life Cycle Assessment ($ILCAM1_n$) and Integrated Return On Investment (IROI1) are given by:

$$ILCAM1_n = \frac{i_A(1+i_A)^j}{(1+i_A)^j - 1} * PNVI1_n \quad (8)$$

$$IROI = \sum_{j=1}^{n} \frac{CF_j}{(1+i_A)^j} - II \quad (9)$$

where:

$IROI$: Integrated Return On Investment

II: Initial Investment

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

i_A: Apparent rate

Figure 42 presents the outcomes.

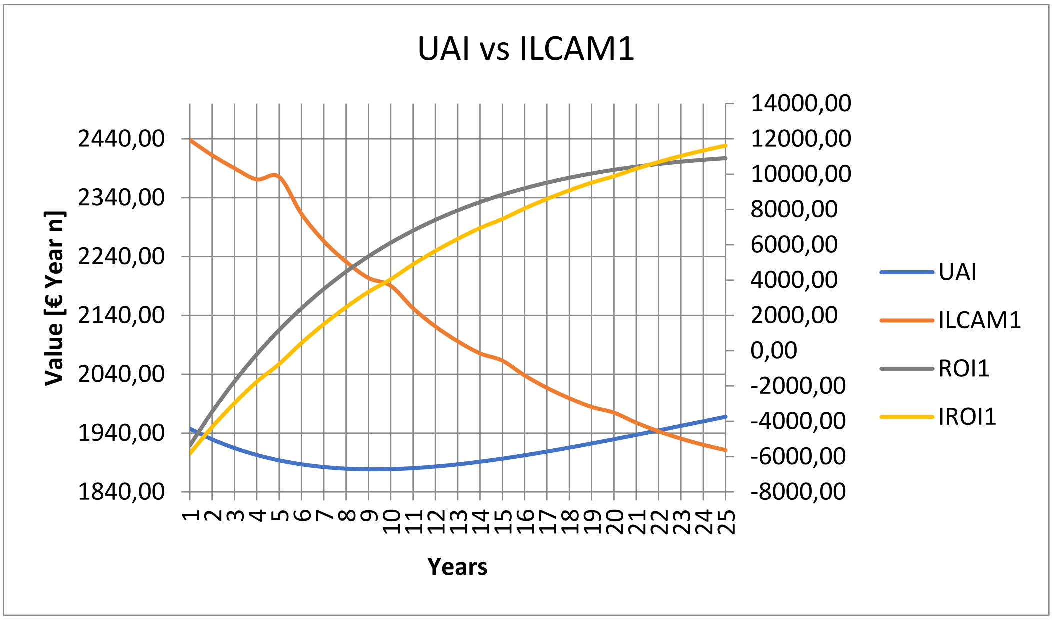

Figure 42 - UAI vs. Integrated Life Cycle Assessment First Method (ILCAM1).

A novel strategy (ILCAM2n) was evaluated based on the exponential depreciation method and the Minimization of Total Average Cost Method (MTAC):

$$\begin{cases} ILCAM2_n = \dfrac{\sum_{j=1}^{N} IM_j + IF_j + TUI_j + TD_j + SD_j}{n} + \dfrac{II - (V_n + \sum_{j=0}^{n} R_j)}{n} \\ IROI2 = \displaystyle\sum_{j=1}^{n} \frac{CF_j}{(1+i_A)^j} - II \end{cases} \quad (10)$$

where:

II: Initial Investment

IM_j: Integrated Maintenance in year j = 1, 2, 3, ... n

IF_j: Integrated Functioning in year j = 1, 2, 3, ... n

$TUI_{j:}$ Technological Upgrade Investment in year j = 1, 2, 3, ... n

$TD_{j:}$ Technology depreciation in year j = 1, 2, 3, ... n

SD_j: Sustainability depreciation in year j = 1, 2, 3, ... n

iA: Apparent rate

$V_{n:}$ Value of the equipment over a period n = 1, 2, 3 ... n

$R_{j:}$ Residual value of the upgraded part n = 1, 2, 3 ... n

$CF_{j:}$ Cash Flow in year j = 1, 2, 3 ... n

$IROI2$: Integrated Return On Investment

Figure 43 presents the outcomes.

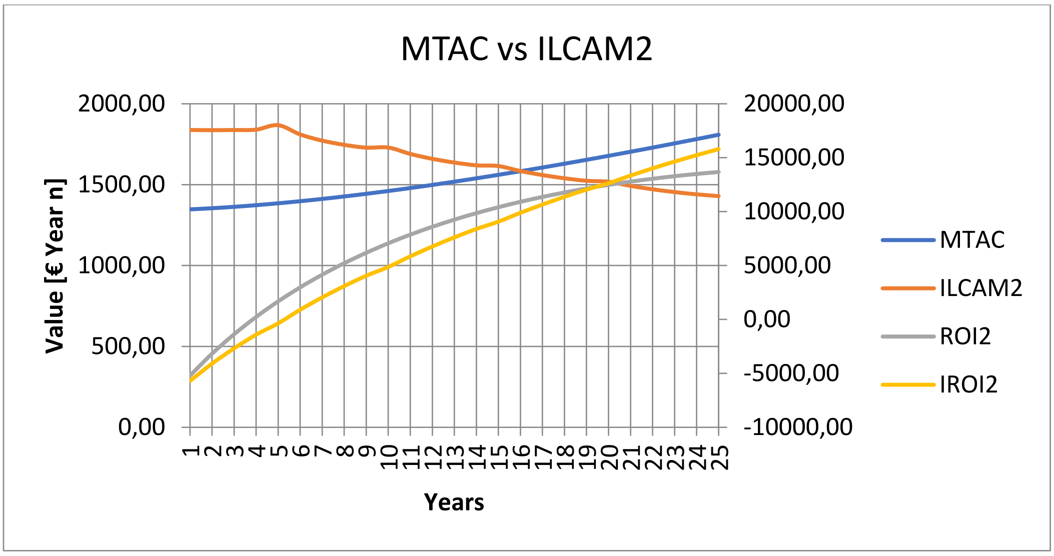

Figure 43 - MTAC vs. Integrated Life Cycle Assessment Second Method (ILCAM2).

A novel method (ILCAM3n) is presented, and it was based on the MTAC Reduced to Present Value (MTAC-RPV) and the exponential depreciation method:

$$\begin{cases} ILCAM3_n = \dfrac{1}{n}\sum_{j=1}^{N} \dfrac{(IM_j + IF_j + TUI_j + TD_j + SD_j)}{(1+i_A)^j} + \dfrac{II - \left(\dfrac{V_n + \sum_{j=0}^{n} R_j}{(1+i_A)^n}\right)}{n} \\ IROI3 = \sum_{j=1}^{n} \dfrac{CF_j}{(1+i_A)^j} - II \end{cases} \quad (11)$$

where:

II: Initial Investment

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

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

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

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

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

i_A: Apparent rate

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

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

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

$IROI3$: Integrated Return On Investment

Figure 44 presents the outcomes.

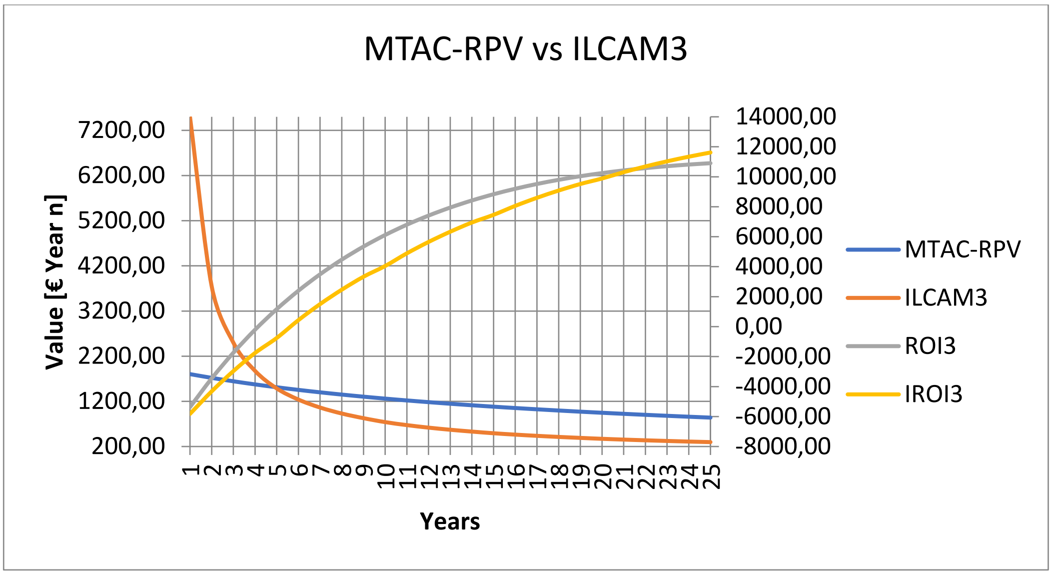

Figure 44 - MTAC-RPV vs. Integrated Life Cycle Assessment Third Method (ILCAM3).

The Integrated Life Cycle Assessment First Method, as depicted in Figure 42, is the one that more effectively adapts to this asset (bus) and yields conclusions that are suitable for replacement; these results are related with the initial investment and the expected useful life for this type of assets.

3.4.2 Integrated Models

The Present Net Value Integrated approach suggests variable maintenance investment, however investing more in technology and sustainable components will enhance MTBF, lower MTTR and MWT, for each individual equipment, and ultimately increase availability.

In addition to introducing the LCI, Farinha et al. [155] also propose the Global Result in Year n (GRn). The total return that a corporation can anticipate from an asset's life cycle from an investment perspective is produced by the GRn Formula (12), which includes the initial investment, the annual variable maintenance investments and benefits (production results) throughout the asset's life. The IRR represents a discount rate that makes the net present value (NPV) of all cash flows equal to zero in a discounted cash flow analysis. Figures 45 and 46 present the outcomes from the model introduced by Farinha et al. In figure 46 the final rent represents the difference between investments and benefits.

$$GR_n = \sum_{j=0}^{n} \frac{B_j * \frac{MTBF_j}{MWT_j + MTTR_J + MTBF_J}}{(1 + IRR_j)^j} + \sum_{j=o}^{n} \frac{F_j}{(1 + IRR_j)^j} + \sum_{j=o}^{n} \frac{M_j}{(1 + IRR_j)^j} + \sum_{j=0}^{n} \frac{B_j * \left(1 - \frac{MTBF_j}{MWT_j + MTTR_J + MTBF_J}\right)}{(1 + IRR_j)^j} + \sum_{j=o}^{n} \frac{I_j}{(1 + IRR_j)^j} \quad (12)$$

where:

$MTBF_j$: Mean Time Between Failures

MWT_j: Mean Waiting Time in year j = 1, 2, 3, ... n

$MTTR_j$: Mean Time to Repair

F_j: Functioning in year j = 1, 2, 3, ... n

M_j: Maintenance in year j = 1, 2, 3, ... n

IRR_j: Internal Rate of Return in year j = 1, 2, 3, ... n

I_j: Physical Asset Value in year j = 1, 2, 3, ... n

B_j: Benefit in year j = 1, 2, 3, ... n

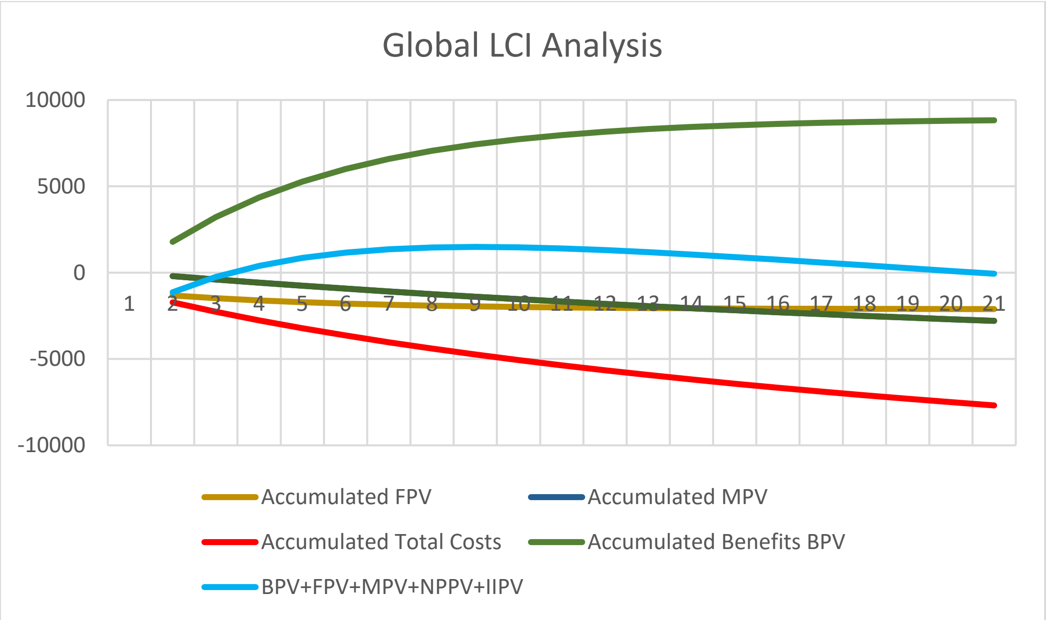

Figure 45 - Values of investment, functioning, and benefits annual financial results of the physical assets.

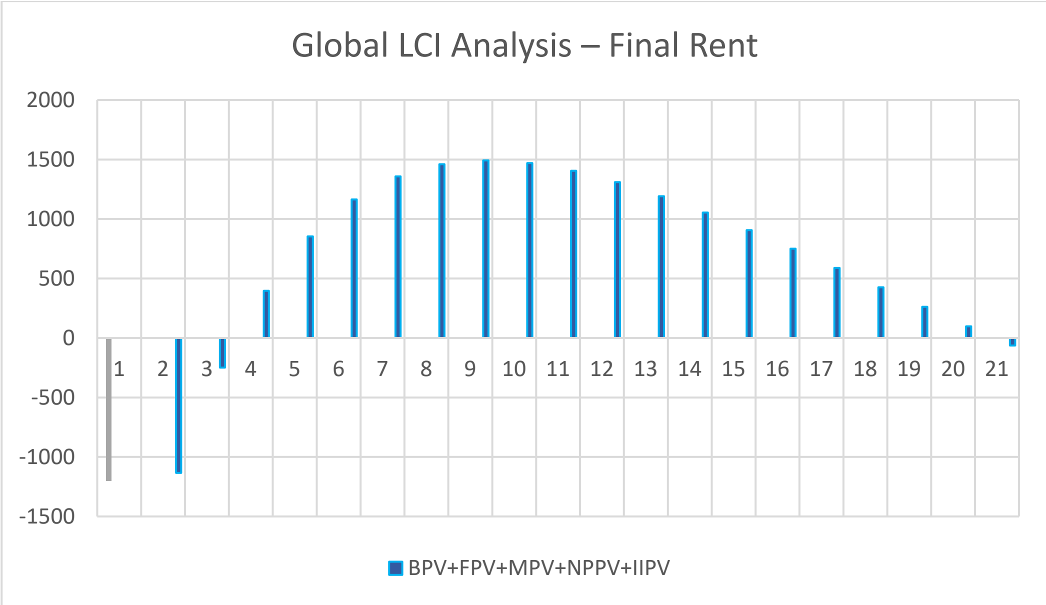

Figure 46 - Annual financial results of the physical asset.

where:

FPV: Functioning Present Value

BPV: Benefits Present Value

MPV: Maintenance Present Value

NPPV: Non Production Present Value

IIPV: Initial Investment Present Value

The comparison of ILCAM and GR_n demonstrates that the two approaches yield results that are comparable. Additionally, both are included in the SAMP.

The Integrated Life Cycle Investment Assessment Method (ILCIAM) Formula (13), was created based on the GRn by combining sustainability depreciation (SD), technology depreciation (TD), and technological upgrade investment (TUI):

$$ILCIAM = \sum_{j=0}^{n} \frac{B_j * \dfrac{MTBF_j}{MWT_j + MTTR_J + MTBF_J}}{(1 + IRR_j)^j} + \sum_{j=O}^{n} \frac{IF_j}{(1 + IRR_j)^j} + \sum_{j=O}^{n} \frac{IM_j}{(1 + IRR_j)^j} + \sum_{j=O}^{n} \frac{SD_j}{(1 + IRR_j)^j} + \sum_{j=O}^{n} \frac{TD_j}{(1 + IRR_j)^j} + \sum\nolimits_{j=0}^{n} TUI_j + \sum_{j=0}^{n} \frac{B_j * \left(1 - \dfrac{MTBF_j}{MWT_j + MTTR_J + MTBF_J}\right)}{(1 + IRR_j)^j} + \sum_{j=O}^{n} \frac{I_j}{(1 + IRR_j)^j} \quad (13)$$

where:

$MTBF_j$: Mean Time Between Failures

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

$MTTR_j$: Mean Time to Repair

IF_j: Integrated Functioning in year $j = 1, 2, 3, \ldots n$
IM_j: Integrated Maintenance in year $j = 1, 2, 3, \ldots n$
IRR_j: Internal Rate Return in year $j = 1, 2, 3, \ldots n$
SD_j: Sustainability depreciation in year $j = 1, 2, 3, \ldots n$
TD_j: Technology depreciation in year j = 1, 2, 3, … n
TUI_j: Technological upgrade investment in year $j = 1, 2, 3, \ldots n$
I_j: Physical Asset Value in year $j = 1, 2, 3, \ldots n$
B_j: Benefit in year $j = 1, 2, 3, \ldots n$

The final rent rises when sustainability depreciation and technology depreciation investment are combined. This happens as a result of decreased maintenance and operation investments brought about by technical advancement, as illustrated in Figures 47 and 48.

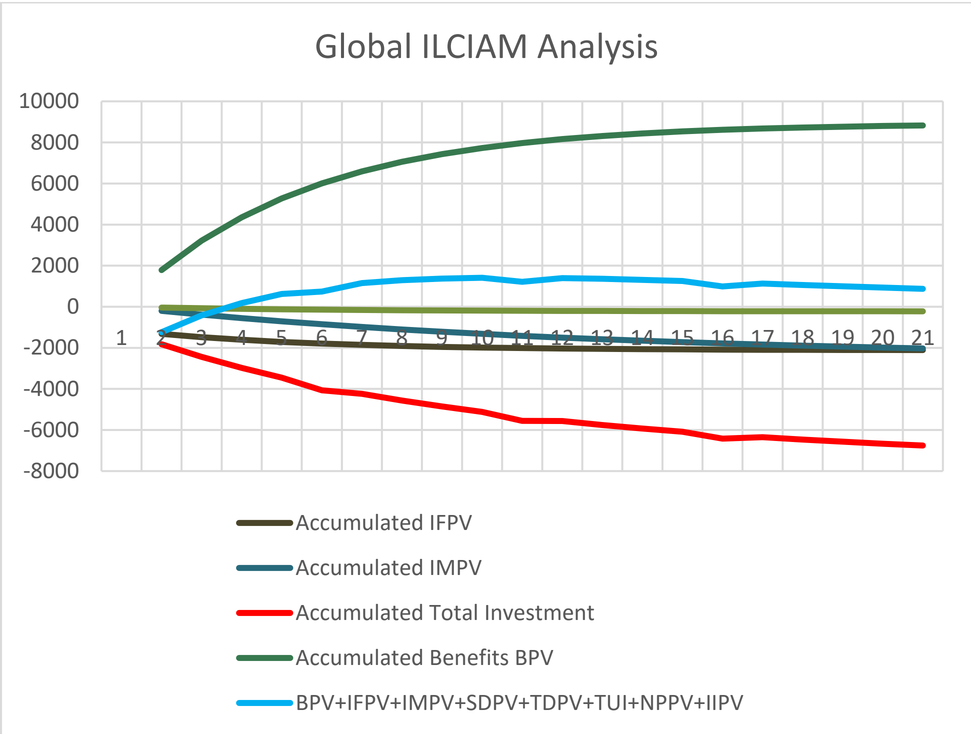

Figure 47 - Values of investment, functioning, and benefits.

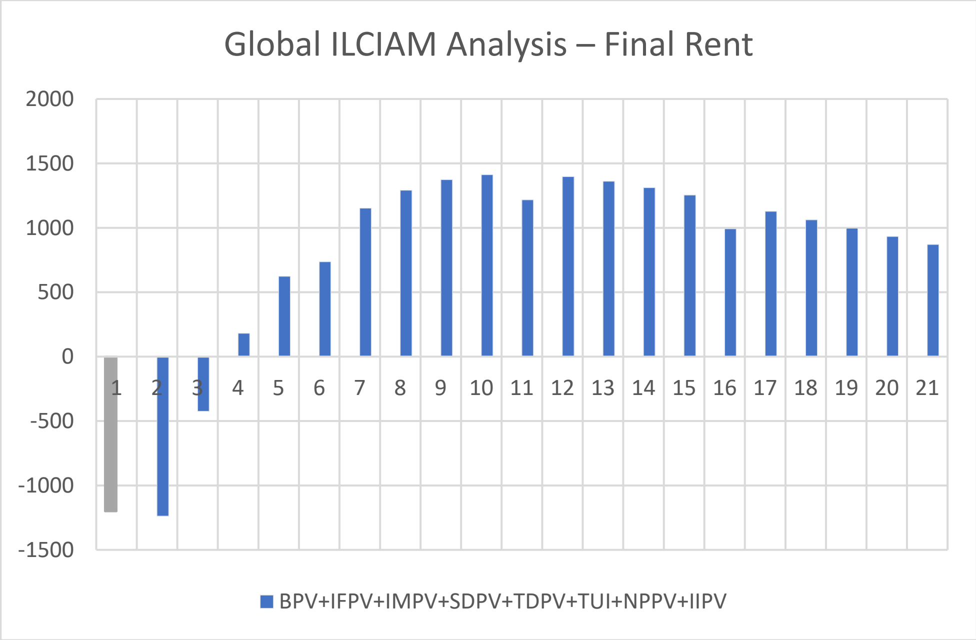

Figure 48 - Annual financial results of the physical asset.

where:

BPV: Benefits Present Value
*IFP*V: Integrated Functioning Present Value
IMPV: Integrated Maintenance Present Value
SDPV: Sustainability Depreciation Present Value
TDPV: Technological Depreciation Present Value
TUI: Technological Upgrade Integrated
NPPV: Non Production Present Value
IIPV: Initial Investment Present Value

Paper II (II, referred in Tables 2 and 3) entitled "Optimizing the Life Cycle of Physical Assets through an Integrated Life Cycle Assessment Method" (DOI: 10.3390/en14196128) was published in Scopus-indexed journal, *Energies* (Q1). Its main objective was to provide a mathematical model that would help managers maximise the life cycle of assets from an ISO 55001 perspective. In the paper, new models presented are Integrated Life Cycle Assessment First Method (ILCAM) and Integrated Life Cycle Investment Assessment Method (ILCIAM).

3.5 Discussion

The ILCAM demonstrates the rise in asset value and the creation of a more effective, environmentally friendly, and long-lasting asset through the replacement of essential components. The result, however, is not just an extension; it is a sustainable extension of a resource that can lower maintenance costs, be more dependable, and lower CO_2 emissions. It is possible to reduce the CO_2 emissions from some asset types to the same level as a new asset.

Buildings account for a sizable portion of energy usage [214], [215]. Replacement components on equipment with reduced CO_2 emissions led to an improvement in overall sustainability.
The Integrated Life Cycle Assessment First Method is more equipped to adapt to the studied assets (bus fleet), as shown in Figure 42. The asset's replacement year under UAI is identified as year 9; however, under ILCAM1, the asset's replacement year is extended to over year 25.
The cumulative total investment in ILCIAM diminishes, as seen by a comparison of Figures 45 and 47, and in Figures 46 and 48, the final rent is still positive in the 21st year of ILCIAM.
Whether the industry will be ready for this new paradigm is a crucial concern. With regard to sustainability, it is obvious that the design of assets can be adjusted to allow for the replacement of essential components with a brief life cycle. Therefore, the assets might make the replacement of some elements more easily if this is taken into account during the design process. The price of replacement can be decreased as a result.
The technical improvement lengthens the asset's useful life and encourages the reduction of waste, and raw material consumption; it also brings energy cost reductions, which in turn promotes the circular economy and sustainable development [54], [70], [71], [76], [216]–[219]. The asset's enhanced components can also be put back on the production line, updated with the newest technology, and put back on the market.
Can we put a price on our planet? Do we pay a price for our planet? The primary query is: how much are we willing to pay to live in a better environment, in which we can be certain that our offspring will have a bright future, even though these remain problems that we are unable to fully address?
We believe that for society and governments to successfully tackle this challenge, society must be willing to solely invest in sustainable assets, and governments must assist and encourage society through financial incentives.
Each company's Strategic Asset Management Plan (SAMP) needs to address these issues, and ISO55001 could be a useful tactical instrument to meet those objectives.
The models that are being shown can be applied to many assets. The Integrated Life Cycle Assessment First Method (ILCAM1) based on Uniform Annual Income (UAI) gave the best fit in the current case study, nonetheless. After being tested, additional models can be employed for assets with shorter or longer lifespan, as well as larger or lower initial investments.
Although the used model holds true for the data under analysis, other assets can behave differently. However, the technique that is being provided is a strong and reliable model that can be used to a variety of assets.

The two introduced methods (ILCAM and ILCIAM) establish replacement periods in different ways. The outcomes in the reviewed cases were consistent with the data that had been analysed, which supported the techniques. Both strategies result in longer replacement periods, smaller returns, and steeper beginning curves. The return, however, is considerable because the slope is steeper. The techniques are reliable and work well as a tool for making decisions in the SAMP.

3.6 Conclusion

In order to address the climate emergency, the strategies described in this article emphasise the requirement for increased asset sustainability. These techniques enable asset managers to determine not only the increase in the asset's worth but also the period at which a replacement or renewal should be undertaken. Additionally, the techniques emphasise the significance of adding value to assets in accordance with ISO 55001 and offer a fresh perspective on LCA. The methods encourage the circular economy by replacing individual parts as opposed to the entire asset.

Sustainability is a concept that is challenging to quantify. However, because so many elements must be taken into account, it is crucial to develop a way to determine the value of sustainability. Some of them are rather evident, such as fluorinated gases, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and nitrogen oxides (NO_x) emissions. Additionally, certain of these gases have been linked to respiratory illnesses, and it is possible to estimate how much discomfort a condition may cause.

While answering to the Research Question 1 (RQ 1), it’s possible to verify on the presented models that performing technological upgrades, the assets value increase and their life is extended and that represents more return on the assets. When we invest in maintenance, the availability of the asset increases, thus leading to fewer unforeseen stops. This way, greater production can be maintained and with the desired quality, also reducing the waste of defective parts or complaints regarding the service, in both of these situations, there is a risk of losing customers, which is also a factor in financial losses resulting in a reduction in the value produced by assets.

In order to respond to Research Question 2 (RQ 2), an increase in the availability and useful life of an asset, which is always related to its maintenance, is possible using the presented models to optimize the life cycle of the assets. It is known that if the investment in maintenance is reduced, the availability and useful life could be compromised. As a result, when those decisions are made, they need to be aligned with the organization's objectives and its needs. The presented models help managers understanding the asset's life cycle, allowing to identify when the asset needs to be replaced or how its life can be extended in alignment with the organization's objectives.

Using the provided models, it is feasible to respond to Research Question 3 (RQ 3), because the presented models fit when considering the Physical Assets' Life Cycle Assessment (LCA), they give a full understanding of the assets life cycle thus helping managers to use its results considering the decision-making criteria, considering the models presented that bring a quantitative support, which can easily be crossed with the values of the organization's decision-making criteria and the asset management system. The models are aligned with the factors that must be measured in the objectives of the asset management system, such as total cost of ownership, return on invested capital, environmental impacts, service levels, cost of the product or service, cycle cost life and expected useful life, those need to be translated to the strategic asset management objectives that are expressed in the SAMP. Those models need to be part of the SAMP in order to transpose the organizational objectives to strategic asset management objectives. At the same time, those models bring to the management activities the needed tool for decision-making. Besides, it is important to include in the SAMP a timescale that is adequate to cover the entire asset life, which may go beyond the organization's own business planning timeframe.

Chapter 4

Measuring the Performance of a Strategic Asset Management Plan through a Balanced Scorecard

In the quest for answers to the research questions, some studies have been carried out. A KPI board has been created to measure the SAMP's performance. The presented study gave rise to a paper published in a Q1 Scopus-indexed international journal, and the following research questions were answered:

> RQ 4: How can Strategic Asset Management Plan (SAMP) be designed to improve the Life Cycle of Physical Assets?
>
> RQ 5: How can Strategic Asset Management Plan (SAMP) performance be measured?

4.1 Methodology and Results to Measure the Strategic Asset Management Plan Performance

This methodology gave origin to a paper submitted to the Scopus-indexed journal *Sustainability*,: entitled "Measuring the Performance of a Strategic Asset Management Plan through a Balanced Scorecard".

4.1.1. Methodology

The aim of the research is to contribute to support the measurement the performance of a Strategic Asset Management Plan, by offering a new approach. For this purpose, a five steps methodology was used [220]:

a) Framing questions for a review
   - i) While building an Asset Management System (AMS) is it a core element to measure its performance?
   - ii) How can the SAMP performance be measured?
   - iii) Being the SAMP the central figure in the AMS, how can it be measured?

b) Identifying relevant work
   - i) Literature Review

c) Assessing the quality of studies
   i) Indexed papers from scientific libraries
d) Summarizing the evidence
   i) Using available data to demonstrate the robustness of the proposed model
e) Interpreting the findings
   i) The results obtained are discussed and identified the strong and the weakest aspects of the research

4.1.2. Results

4.1.2.1. Balance Scorecard

The Balance Scorecard (BSC) allows for the creation of Key Performance Indicators (KPIs) for monitoring maintenance management performance in accordance with the strategic goals of the company [221]. The BSC is customised for the organisation for which it is built. The BSC prioritises achieving performance goals while putting overarching strategy and vision at the forefront, in contrast to traditional measurements, which are control-oriented [222].

"What you measure is what you get", as stated by Kaplan & Norton [195], so it is obvious how crucial it is to measure the SAMP. Therefore, it is necessary to draw a comparison between the ISO 55001 requirements and the BSC perspectives (Table 9). In this table, the BSC perspectives are listed, and the authors have provided information about each of them, including relevant questions, fictitious measurements, physical asset intervention-related information, ISO 55001 requirements, and, finally, performance measurement KPIs.

Table 9 – Balanced Scorecard in SAMP

Perspectives	Questions	Measurements	Physical Assets Intervention	ISO 55001 Requirements	KPI
Financial Perspective	How to reduce costs? How to increase profitability? How to increase revenue?	Revenue, Expenses, ROI, Net Income	Maintenance policies; Availability vs Production	6.2.1; 6.2.2	ROI, EPS, RG
Customer Perspective	What are the customer's needs? What stakeholders expect? What interested parts expect?	Customer Satisfaction, Customer Retention	Quality level related to Physical Assets performance	4.1; 4.3; 5.3	NPS, RPR, RC, CSAT
Internal Business Process Perspective	What are my assets? What is the value of my assets? My assets are in line with the organization's objectives? What assets will focus on? How to extend the life-cycle of the assets? What are the non-core assets for the organization? What new assets are needed? How to dispose old assets? How to manage risk?	Inventory; Quality Control, Product Lead Time	Physical Assets Life-Cycle vs SAMP	4.4; 5.3; 6.2.1; 6.2.2	IQI, QCR, PLTF
Innovation Learning & Growth Perspective	Increase availability Improve reliability	Employee Skills, Employee Training, Employee Retention, Employee Satisfaction	Maintenance policies vs TPM	6.2.1; 6.2.2	ESR, ETR, ERR, ESI

4.1.2.2. Key Performance Indicators

The KPIs selected were based on measurements made in relation to certain ISO 55001 standards, KPIs, and groundings, as shown in Table 10.

Table 10 - The Key Performance Indicators and Grounding

KPI	Description	Grounding
ROI	Return On Investment	Measures the return on investment
EPS	Earnings per Share	Presents the profit increase
RG	Revenue Growth	Presents the revenue increase
NPS	Net Promoter Score	Measures customer experience
RPR	Repeat Purchase Rate	Measures the customers retention
RC	Revenue Concentration	Measures the revenue generated from the highest paying client
CSAT	Customer Satisfaction Score	Measures the happiness of the costumer with a product or service
QCR	Quality Control Rate	Measures the product / service quality
IQI	Inventory Quality Index	Measures the Inventory Quality
PLTF	Product Lead Time Forecast	Measures the time it takes to create a product and deliver it to a consumer
ESR	Employee Skills Rate	Measures the skills that employees have
ETR	Employee Training Rate	Measures the training that employees have
ERR	Employee Retention Rate	Measures the retention on employees
ESI	Employee Satisfaction Index	Measures the employees satisfaction

Table 11 lists the data required to compute the KPIs.

Table 11 – Data needed to calculate the KPI's

KPI	Data
ROI	Current Value of Investment
	Cost of Investment
EPS	Net Income - Preferred Dividends
	End-of-Period Common Shares Outstanding
RG	Initial Revenue
	Final Revenue
NPS	Percentage of Promoters - Percentage of Detractors
RPR	Number of customers who made a repeat purchase
	Number of customers
RC	Amount of revenue that your business earned from the best customer
	Amount by your business's total revenue
CSAT	Number of satisfied customers
	Total customers asked
QCR	Number of good products produced
	Total of product produced
IQI	Number of assets correctly inventoried
	Total of assets
PLTF	Estimated total time
	Real total time
ESR	Number of employees with skills to their work
	Total number of employees
ETR	Number of hours in training
	Number of hours planned for training
ERR	Total of new employees retained
	Total of new employees
ESI	(How satisfied are you with your job + How well does your job meet your expectations + How close is your workplace to your ideal job)/3

The information presented above illustrates how KPIs based on a BSC may be used to gauge SAMP performance.

"Being the SAMP the central figure in the AMS, how can it be measured?" is the last query to be addressed. Other techniques and equipment may be employed to measure the SAMP. The authors suggested a model that was based on the BSC and its views, primarily because it is a document that establishes the strategy to reach assets goals focused on the organisational objectives and also measuring the decision-making criteria.

4.1.2.3. Results

In Table 12, the calculated KPIs are displayed. Each KPI had a coefficient added to it so that it could have a value between 0 and 100, limiting it to the maximum value anticipated of 100. As shown in Table 12, KPIs like ROI, EPS, and RG are unlikely to reach the value of 100; these KPIs are the ones having values below 100 while also being the values anticipated for the relevant KPI.

Table 12 – Calculated KPI's

KPI	Data	Value	KPI Value	Unit
ROI	Current Value of Investment	22,36	11,78	%
	Cost of Investment	20,00		
EPS	Net Income - Preferred Dividends	106,05-0,43	7,04	€
	End-of-Period Common Shares Outstanding	15		
RG	Initial Revenue	5,36	17,91	%
	Final Revenue	6,32		
NPS	Percentage of Promoters - Percentage of Detractors	85% - 23%	62,00	%
RPR	Number of customers who made a repeat purchase	86	68,25	%
	Number of customers	126		
RC	Amount of revenue that your business earned from the best customer	2,35	72,31	%
	Amount by your business's total revenue	3,25		
CSAT	Number of satisfied customers	126	47,55	%
	Total customers asked	265		
QCR	Number of good product produced	12,69	88,37	%
	Total of product produced	14,36		
IQI	Number of assets correctly inventoried	64	77,11	%
	Total of assets	83		
PLTF	Estimated total time	54,00	90,00	%
	Real total time	60,00		
ESR	Number of employees with skills to their work	20	76,92	%
	Total number of employees	26		
ETR	Number of hours in training	58,00	100,00	%
	Number of hours planned for training	50,00		
ERR	Total of new employees retained	7	77,78	%
	Total of new employees	9		
ESI	(How satisfied are you with your job + How well does your job meet your expectations + How close is your workplace to your ideal job)/3	9 / 8 / 9	86,7	%

The information presented above shows how a BSC's KPIs produce values that make it possible to gauge SAMP performance. It goes without saying that data collected over a period of several years will be crucial for assessing the performance of SAMP throughout time. Improvement is one of the standards of ISO 55001, which encourages the application of the Deming Cycle (Plan-Do-Check-Act, or PDCA). This tool enables the identification of nonconformities, planning and implementation of adjustments, and ongoing process and system improvement.

As this chapter was being produced, the Scopus-indexed magazine *Sustainability* (Q1) released a paper (III, referred to in Tables 2 and 3) with the title "Measuring Performance of a Strategic Asset Management Plan through a Balanced Scorecard" (DOI: 10.3390/su152215697). The primary goal of this study was to offer managers tools to measure the performance of the SAMP, while helping them to apply corrective measures in order to solve non-conformities. When building this tool, the BSC was used and in its perspectives were integrated KPI's related with standard requirements.

4.1.2.4. Discussion

The SAMP is a crucial tool for organisations, especially those that own or manage significant physical assets like infrastructure, facilities, or equipment. It outlines the goals of asset management and the role of each asset in achieving the goals of the organisation. The SAMP provides the organisation with the essential alignment. It pulls together the demands of stakeholders, organisational goals and plans, as well as external and internal problems. Asset management's primary objective is to maximise the value of assets, hence the SAMP details each asset's life cycle activities (asset creation/acquisition, use/maintenance, renewal/disposal, etc.).

The usage of BSC raises the bar for evaluating SAMP performance and makes it simple to quantify each perspective and standard requirement, as well as identify which criteria still need to be addressed and what needs to be done to do so.

When evaluating the strengths and weaknesses of using BSC to measure SAMP, the primary weakness is the lack of information in the organisations and the need to change the organisational culture in order to promote the collection of good and reliable data; the strengths are related to BSC, because this is a tool that is well-known to the majority of managers, making adoption simple.

Goals can be added to the views listed in Table 10 of the BSC. Organisations have the option to specify their desired location while also determining where they are. Setting goals and objectives for each perspective and making them specific to each organisation can achieve this. The organisation maximises the value of its assets while achieving its goals in this area, resulting in economic growth.

Because organisations must adhere to ISO 31001 while using asset management (AM), which helps reduce environmental and social risks, AM can also be a great tool for achieving some of the United Nations (UN) Sustainable Development Goals, such as fair work and economic growth, industry, innovation, and infrastructure, as well as others related to risk.

The outcomes shown in (Table 12) for a particular organisation can differ depending on the country or activities utilised to evaluate the model. Results indicate that their SAMP is headed in the right direction.

The water firm whose data was used in this case study investigates and oversees the water supply and wastewater treatment systems for a region of around 100.000 people.

The numbers acquired after analysis are average for this particular activity, but when compared to acceptable values for this indication, KPIs like Net Promoter Score (NPS), Repeat Purchase Rate (RPR), Customer Satisfaction Score (CSAT), and Employee Skills Rate (ESR) can be improved. The organisation is not investing in the staff development that will commit the performance of this strategic resource, as shown by the last metric (ESR), which should be above 80%. As a result, this shows that the SAMP needs to be changed in order to improve certain KPI outcomes because it is either not yet built correctly or is not known for the firm. For instance, the CSAT received a value of 47,55%, which is low for an organisation. Results above 75% are often acceptable by organisations, and there is no set standard that governs CSAT values, which are determined by the sectors. A good result can be a value above 85%. The outcome of this case study shows that, most likely, the customer is not taken into account when decisions are made, and consumer satisfaction is not attained, which may be related to subpar product quality or subpar service delivery.

The KPIs utilised are broad indicators, and the industry, sectors, or locations that they apply to have well defined acceptable values for them. When the model is applied, the results should align with what is expected in that sector.

The following types of inquiries must be made: Are the complaints of the customers being addressed? Were steps to reduce or correct the nonconformities taken? Does the customer follow up with the nonconformities? Tools like the PDCA are well-known and straightforward to use to make continual improvements that can be utilised to remedy the nonconformities that led the customer to provide a negative review.

AM and the SAMP are associated with concepts like Economic Rationality (ER), Strategic Management (SM), and Sustainable Development Goals (SDGs).

These ideas are applicable and connected to the KPIs discussed and given. The suggested SAMP measurement instrument was evaluated using data from waters firms, and the stakeholders, who recognised the improvement in the indicated categories, validated the results.

4.1.2.5. Conclusions

These days, the asset management (AM) is a useful instrument for issues like sustainability, the circular economy, industrial symbiosis, business continuity, and others. The approach described in this research can facilitate and enhance the application of AM. It is crucial to have a strong Strategic Asset Management Plan (SAMP) because it is crucial when employing AM; however, this can only be done if we can gauge the performance that it offers. Utilising the Balanced Scorecard (BSC) makes it possible to quantify and assess SAMP performance.

The tool that is provided after the evaluation aids in addressing the nonconformities so that the SAMP is in line with the goals of the organisation. AM excellence can be attained by employing techniques like the PDCA cycle to systematically correct nonconformities. An AMS can be made better overall by using a BSC to track the performance of a SAMP. Sustainability and business continuity risk are thereby improved. On the other hand, ideas like economic rationality can be applied to alter employee conduct.

In responding to Research Question 4, the presented performance measurement tool will help to identify how the SAMP behaves in relation to the intended. SAMP is essential when considering the life cycle of physical assets, as SAMP contains information on the development of asset life cycle plans and must cover all life cycle activities including functional plans related to investments and energy management.

In this way, the model presented helps managers to align SAMP with activities related to the asset life cycle, understanding where improvements can be made, as poor management of the asset life cycle will be reflected in the ROI, in customer retention that is reflected in the quality of the product/service and in the customer experience, in the same way this management begins with an assets inventory with quality, this quality is reflected in the data contained therein which are necessary to use in the models introduced in the previous chapter.

To address Research Question 5, the introduced paper presents a model based on the BSC in order to evaluate the performance of SAMP, in this way the evaluation is measured in the four perspectives of the BSC, Learning and growth, Internal Processes, Customers and Financial, in each of the areas the requirements were framed of the standard relating to that scope, this way it is possible to understand whether the SAMP is complying with the requirements of the standard, at the same time evaluating its performance and development opportunities.

Therefore, when using the BSC, which is a well-known and widely used tool, it is possible while complying with the requirements of ISO 55001 to measure the performance of the SAMP. Therefore, the model presented responds to the needs of managers to measure the performance of their SAMP's.

Chapter 5

Discussion

5.1. Physical Asset Management

First of all, top management needs to set the organizational objectives and plans; without them, asset management makes no sense. Second, top management needs to be actively engaging, promoting, directing, and supporting, as well as communicating and monitoring the performance, effectiveness, and ongoing improvement of the assets, asset management, and the asset management system. Top management should make sure that it demonstrates leadership and commitment. The manner in which these can be exhibited depends upon a number of variables, including an organization's size and complexity, culture, and management style. Third, top management has the ability to assign responsibility and supply resources in order to fulfil all the objectives [106].

For both businesses and people, managing physical assets is essential for a number of reasons. First of all, managing physical assets allows to realize value from assets. In order to achieve it, other aspects must be considered, such as cost management, risk management, life cycle, energy management, maintenance management, productivity improvement, regulatory requirements, decision-making criteria, sustainability, financial planning, long-term planning, asset tracking and others that can fit in specific organizations.

While the main focus of physical asset management is to realize value from assets, the main function in order to realize value from assets is life cycle management. While focusing on life cycle management, it is important to bring tools to managers, to properly manage the physical assets life cycle. This way, they can realize value from assets.

When managing the physical assets, managers must take into account the balance of cost, risk, performance, and value creation.

5.2. Physical Assets Life Cycle

Models to manage physical assets life cycle have been presented on this thesis and published on scientific journal papers. Besides the normal investments associated, such as maintenance and operation, other factors like technological upgrade, technological depreciation and sustainability depreciation, are also accounted for, while introducing

the technological upgrade, the investment on maintenance and operation decrease. Ultimately, the asset lifespan was extended.
As the main objective of physical asset management is to obtain value from the assets as their useful life is extended, but not at any cost, with the integration of technological upgrades we can ensure that the asset complies with the latest environmental obligations and avoid fines. In this way, we can ensure that we increase the asset's lifespan while guaranteeing sustainable production, thus achieving greater value from the asset.

5.3. Strategic Asset Management Plan

While SAMP is the main document when performing asset management, all the asset management is translated in processes and actions. There are strategies for maintenance management, risk management, energy efficiency, life cycle management, cost optimization, decision-making criteria, AMS performance, continuous improvement and others. Those strategies and objectives are related with the organization objectives. A good SAMP is the key to the success of all the AMS. If not built properly, it will fail. It is clear the need to measure the SAMP. Only by measuring it evaluation can be performed, and the continuous improvement can be achieved.

5.4. Strategic Asset Management Plan Performance Measurement

When building a SAMP, it is important to measure and evaluate if the results are the expected. The author presented a model in order to measure the SAMP performance.
Its purpose is to help managers, in the process of continuous improvement, to identify the non-conformities and help them to introduce corrective measures in order to achieve the organization objectives and goals; this is possible through the proper key performance indicators (KPI).
The constraints of the models presented in this research are tied to the acquired data since reliable data is necessary to get reliable findings. Most often, this is a serious issue that hasn't been resolved within the culture of the company. It is a proven truth that having quality data is crucial for having good indications.
It will be crucial to create tools, in the future, to assist organisations in gathering accurate data, which is a key issue for today's organisations.
What planet do we want to leave for future generations? may be the key question for everyone.

Chapter 6

Conclusions and Future Work

6.1 Problem Summary

Asset management (AM) is based on bringing value from the assets, but also to enable to meet the stakeholders' needs and expectations; asset management can bring organizations to an upper level. But in order to fulfil it there are main questions to be raised, how can the assets life cycle be improved? How can asset management performance be measured? What KPI's should or can be used? When working on the state of the art these gaps were identified and given their importance, they were the subject of investigation and study.

The big affirmation on management always is: how can I manage what I don't measure? That is the main problem when performing asset management, and it is important to fulfil this gap in order to succeed.

So, this thesis aims to help managers, by bringing tools to help them managing assets life cycle and measuring the asset management system (AMS) based on the strategic asset management plan (SAMP) that while being the central part of the AMS. Measuring the SAMP performance, that transposes the objectives of the asset management system into processes and tasks in order to achieve those objectives, is a perfect indicator on how the whole system is being conducted and, at same time, giving tools to managers to identify non-conformities in order to correct them.

6.2 Contributions of the Work to the State-of-the-Art

The findings of the conducted research show that the created models can help to improve assets life cycle and measure the SAMP performance, while identifying the requirements that need to be improved.

Particularly, this work brings new mathematical models with quantifiable results, framed within asset management, something that was not found in previous works. At the same time, tools are introduced to obtain the measurement of performance on the asset management system based on its SAMP. This measurement also translates into quantifiable values and are not subjected to different interpretations.

These models were tested in different business activities and proved to be widely used, but small adaptations may be necessary in more specific situations.

6.3 Future Works

Future study may also need to take into account the addition of a risk co-efficient, as defined by ISO 55001. According to the Standard, organisations must make sure that asset management-related risks are taken into account while developing their contingency plan. When reducing or prolonging an asset's life cycle, risk factors must be taken into account.

Governments need to focus more on the introduction of sustainability and technology depreciation benefits and to show how they can benefit from the shift from a linear to a circular economy, as well as from the sustainable extension of asset life cycles by using ISO 55001 standard.

Future studies will assess novel strategies and their impact on the circular economy's sustainability by taking new technology and sustainable aspects into account, thus bringing new models to quantify sustainability and risk.

Risk and sustainability can become something that is challenging to quantify mathematically, but only mathematical models allow for the creation of "universal" quantifications that can be applied to any organisation regardless of its line of business, necessitating the development of tools in that way.

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Appendices

Appendix A

Optimizing the Life Cycle of Physical Assets – a Review

E. Pais[1,2], J. T. Farinha[3,4], A. J. M. Cardoso[2], H. Raposo[1,3,4]

[1]Industrial Engineering and Management, Universidade Lusófona de Humanidades e Tecnologia, Lisbon, PORTUGAL

[2]CISE - Electromechatronic Systems Research Centre, University Beira Interior, Covilhã, PORTUGAL

[3]ISEC – Instituto Superior de Engenharia de Coimbra, Coimbra, PORTUGAL

[4]CEMMPRE - Centre for Mechanical Engineering, Materials and Processes, Coimbra, PORTUGAL

Abstract: Life cycle optimization has been a concern over decades; it has been clear that an asset well-kept will have a longer life with a higher return for the organization; this life cycle depends of several factors.

The standard ISO 55001 defines a set of requirements that, when implemented and maintained, guarantee the good performance of an organization's asset management, responding to stakeholders need and expectations and ensuring the value creation and maintenance as well as a global vision of assets on the Optimizing the Life Cycle of Physical Assets. The organizations where physical asset management is of major importance include all those that involves facilities, machinery, buildings, roads and bridges, utilities, transportation industries, oil and gas extraction and processing, mining and mining processing, chemicals, manufacturing, distribution, aviation and defence.

However, since ISO 55001 is a new standard in the global market, due to its necessity to involve all the organization its implementation becomes difficult; but, it is clear that an organization that certifies by the ISO 55001 is ahead on life cycle optimization because it is part of its requirements; so, what model of life cycle optimization to use? Is there anyone that fits on the ISO 55001? Can an existing one be adapted to be used according to ISO 55001 requirements?

The approaches of this paper bring a literary review of life cycle models used in asset management and their major concerns, this is the beginning to build a model to optimize the life cycle of physical assets including the ISO 55001 perspective.

Key-Words: ISO 5500X; Physical Assets; Life Cycle; Optimization; Sustainability

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1 Introduction

Asset management has been a concern since early years; nowadays, it is one of the most debated topics due to some events on the past decades; on this events we can recall some with major loss, like the Piper Alpha – North Sea (1988), Texas City Refinery – Texas (2005), Deep Water Horizon / Macondo – Gulf of Mexico (2010), Amuay Refinery – Venezuela (2012); the common points among all is the lack of risk evaluation and lack of communication. Thus, asset management becomes an important science field because integrates an aim of activities like maintenance, risk, processes, systems, resources management, etc., and also health safety and environment.

ISO 55000 defines asset management as a "coordinated activity of an organization to realize value of assets". According to Hastings [1], the need for asset management as a recognized discipline arises from the complex technical nature of modern systems. Let us take an example from aeronautics field. A contrast can be drawn between, on the one hand, the Wright Brothers Flyer of 1903 (Figure 1), which was the first aircraft to achieve controlled flight and, on the other hand, the modern aeronautics industry.

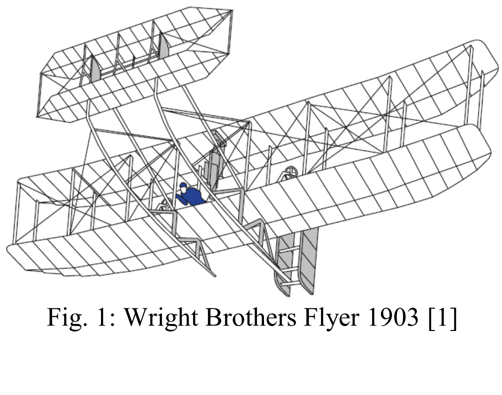

Fig. 1: Wright Brothers Flyer 1903 [1]

Initially, the Wright brothers designed, built, flew, repaired, and financed their own aircraft. They did not need asset management as a separate activity. However, aviation today involves flight operations, engineering, maintenance, finance, human resources, and a wide range of asset types on a huge scale. Figure 2 gives some indication of this. It is this vast increase in complexity, across a wide range of industries, which has led to the need for asset management as a recognized discipline.

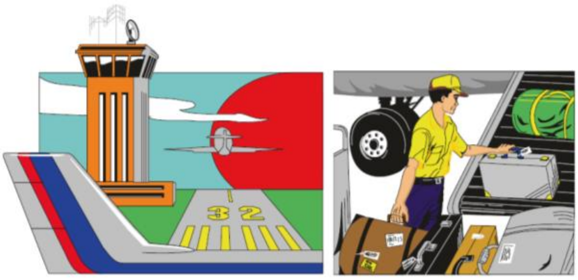

Fig. 1: Modern aviation industry assets [1]

According to Meireles *et al*. [2], ISO 5500X standards brings a new economic and sustainability cycle. Therefore, the extension of the life cycle of physical assets, its adequate maintenance, reuse, renovation and recycling are strategic variables in its management.

An adequate management of physical assets as well as the optimization of their life cycle are aspects that are determinant from a global sustainability perspective.

In addition, ISO 55001 standard defines the certification requirements, considering that any Organization should emphasize on its Strategic Plan what are the sustainable principles regarding its assets as well as highlighting them in its Strategic Asset Management Plan (SAMP).

When replacing an asset, the Organizations must ensure that the energy consumption of the equipment and its environmental shall justify their replacement. For all these aspects, among many others, ISO 5500X standards can make a decisive contribution to the implementation of a new, more sustainable economy based on innovative management of the physical assets of all we depend [3].

According to Raposo *et al*. [4], the current competitive environment demands, more and more, of the companies, is a constant search in the improvement of processes in all aspects. Thus, in order to obtain a leading position, companies aim to maintain their standard above the competition.

It is from this perspective that the identification of the optimum moment of substitution of an asset can be the competitiveness of organizations, through the reduction of costs that may be indexed to the maintenance policy used that can extend the asset life.

Companies are increasingly compelled to rationalize their costs, including maintenance costs, which, in the area of energy efficiency, are decisive for the organization’s competitiveness. Those responsible for maintenance are therefore also forced to become effective and previously only efficient; the volume and quality of the resources available to them to meet their objectives have become crucial.

The ISO 5500X standards set out to meet this need to manage the life of the organization's physical assets, ensuring the level of competitiveness without compromising the level of excellence of the products / services offered. The ISO 55001 standard proposes a methodology for managing the assets in accordance with the strategic objectives of the organization, supporting decisions to acquire, replace and disposal, aligned with practices that aim at the environmental, social and economic sustainability of equipment and the organization itself.

Van der Lei, *et al*., [5] say that to overcome the challenges in different asset management, methods have been developed aimed to improve the asset life cycle. Smarter design can lead to improved operation. Likewise, improved operation and maintenance lead to lower replacement costs and may provide the basis for better design. Following this development, the design and operation and maintenance phases have seen a rise in methods and tools for engineering asset management.

Asset management stresses that it is key to consider the whole life cycle of the assets. This development is new as traditionally the improvement of the design, operation and maintenance phases have been separate management tracks. Engineering asset management is an interdisciplinary field that involves research fields like, life cycle costing; maintenance and reliability; risk assessment; change management.

Asset management is seen as a life cycle approach that covers the activities of the organization that undertakes to achieve its goals. This, in contrast to the assets, being something, an organization owns and must maintain. In the life cycle perspective, the management of the asset life cycle is central to the operational success of the organization.

Many times, asset management is described as maintenance, but asset management is an interdisciplinary field and involves research fields as: life cycle costing, maintenance & reliability, risk assessment, change management.

Hastings [1] describes asset management as a set of activities associated with:

- Identifying what assets are needed;
- Identifying funding requirements;
- Acquiring assets;
- Providing logistic and maintenance support systems for assets;
- Disposing or renewing assets.

So, as to effectively and efficiently meet the desired objective.

From this definition we see that asset management encompasses a broader and quite different set of activities from “maintenance”, which is primarily concerned with keeping existing equipment in operating condition.

Asset Management according ISO 55001 deals not with isolated activities but with all, where every part is important and must be taken in consideration to have decisions made by a group and not individuals. Because not all changes can be made at the same time, this will lead to prioritizing and may look like a bad decision for a group but it is the better to the all; till this happens optimal asset management decisions cannot be possible; so, what is an optimal asset management decision? This can be a decision that maximizes the value of assets in a long term by aligning them to the organization purposes and objectives and this can change from company to company [3].

So, Asset Management is an umbrella for bringing a lot of existing good practices together, and for filling some of the remaining gaps. It aligns what we do to clear business goals and ensures that the component activities operate in harmony. It requires some sophisticated technical solutions but the most important element of all is the human one – shared understanding, motivation, trust and collaboration to find the best combined outcome, rather than local and short-term self-interest. There is no real doubt that integrated “Asset Management”, or whatever it may be called in the future, is becoming a vital business discipline. Yet there is a significant gap between those who “think they already do it”, and those who realise the challenges and rewards of the integration/alignment step (and are investing heavily in the merger of new technical solutions, management processes and the human factors).

Those companies that have had the vision and faith to adopt such an approach have universally recognised the tangible benefits – in some cases this has ensured continued company survival, in others it represents their key competitive edge in the next phase of global performance pressure, [6].

This paper is divided in five sections which are the following:

1. The first section is an introduction to the theme;
2. The second section is the state of the art;
3. The third section are proposals;
4. The fourth section is a discussion;
5. The fifth the conclusions.

2 State of the Art

2.1 The Models

Acording to Amadi-Echendu [7], physical asset management involves a wide range of disciplines and processes covering the life-cycle stages of creating, establishing, exploiting and divesting a physical asset in a balanced manner to satisfy the continuum of constraints imposed by business strategy, economy, ergonomics, technical and operational integrity, and regulatory compliance.

In 1996, Vanier *et al*. [8] used the Building Envelope Life Cycle Asset Management project (BELCAM) (Figure 3), to provide models, methods and tools to meet these needs, and to assist building researchers and scientists in delivering their evaluation of the service life of building envelope components. This approach incorporates access to information technology such as: The Internet and the World Wide Web; Information technology tools, such as classification systems and product modelling; Life cycle economic principles; Service life and durability research; Risk analysis and reliability assessment; User functional requirement models; and maintenance management strategies. This type of framework for managing data, information and knowledge could be used to predict the service life of other building or construction systems.

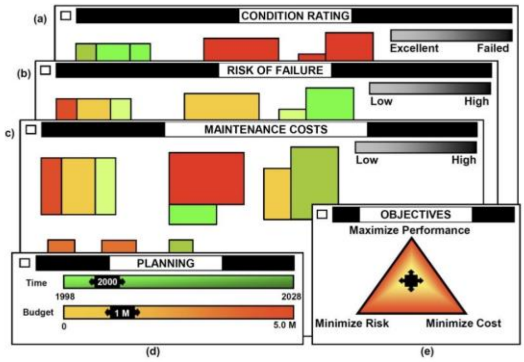

Fig. 3: BELCAM Decision-support Tool [8]

Malano *et al*. [9] on their work in irrigation and drainage show concern on the hydraulic infrastructure that fulfil most of the service; this infrastructure consists of many individual assets including dams, canals, control structures, pumps, etc., that are usually dispersed over very large areas. Their concern rose as governments embrace economic reform policies that promote the transfer of operation and management functions to irrigators, proper accounting of the cost incurred in providing irrigation and drainage services becomes more necessary. They state that asset management is a process that integrates all these life cycle events with the need to provide an agreed level of service. An asset management program considers all the events occurring over the life cycle of the infrastructure and comprises a strategic and integrated analysis of the life cycle of the infrastructure as part of the continuous organisation management review. The ultimate outcome of an asset management program is to bring into focus the actual cost of owning and operating the infrastructure assets to provide a defined level of service. As such, it provides a clear picture for the organisation and customers of the financial implications when providing this level of service (Figure 4).

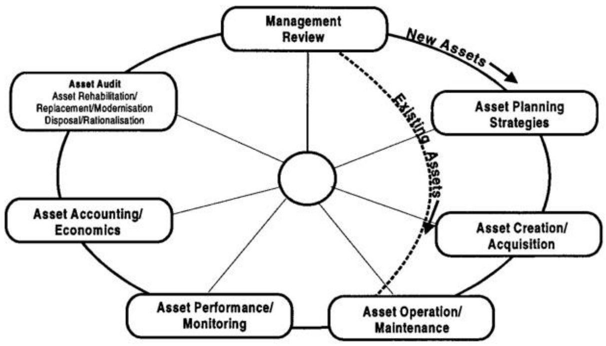

Fig. 4: Elements of an asset management program [9]

In 2005, Malano *et al*. [10] present an Asset Management Modelling Framework (AMMF) that enables the quantification of on-going ownership costs and operation costs: A Life Cycle Cost (LCC) model for the evaluation of alternative irrigation and drainage asset management strategies.

An asset management modelling framework consists of two main components:

1) A database of assets consisting of geographical location of assets, design features, maintenance records and asset condition and performance;
2) An analysis module which enables the modelling of future asset strategies including the calculation of future liabilities and life cycle asset costing associated with alternative courses of action.

Asset condition refers to the fitness of the asset to perform the function for which it was intended. The condition of assets is the result of several factors including wear and tear, quality of maintenance, age and quality of construction. It is a key measure necessary to determine the residual life of assets and, therefore, the future actions that may be required. It is also important to provide some idea of the overall reliability of the system to deliver the designed irrigation and drainage services. Aspects of reliability are related to the actual condition of the assets and their risk of failure.

Vanier [11] emphasis an assessing decision-support tools for municipal infrastructure planning. He identifies the extent of the asset management market in North America, addressing the need for decision-support tools for municipal-type organizations, identifying the challenges for maintenance, repair and renewal planning faced by asset owners and managers. Integration with existing systems such as Computerized Maintenance Management Systems (CMMS), Geographic Information Systems (GIS) and corporate legacy systems are seen as the largest challenge for developing and using decision-support tools in the area of asset management. The author classifies various stages of implementation for asset management using the six "Whats" questions that asset managers should ask about the status of their portfolio:

1) What do you own?
2) What is it worth?
3) What is the deferred maintenance?
4) What is its condition?
5) What is the remaining service life?
6) What do you fix first?

The activities of a consortium in the area of strategic asset management are introduced with a limited number of decision-support applications, but none provides a comprehensive solution to address the current needs for planning the municipal infrastructure.

On the other hand, Campbell [12] did not profess an asset management speech itself; he describes asset management through a nine steps process as described in Figure 5 and goes a step further in explaining the fundamentals of the asset management process.

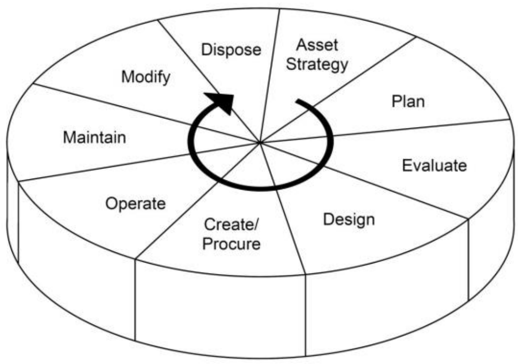

Fig. 5: Asset Management Process [12]

From the South African perspective (Figure 6), the basic asset lifecycle management model is described in the National Treasury guidelines. An asset's life cycle can be defined as the period that an entity can predict by using an asset in an economically effective and efficient manner to promote the entity's provision of services or trade. The National Treasury guidelines further states that the period covers all stages of an asset's life: acquisition; use and maintenance; and eventual alienation. This period is described as the useful life of the asset for the entity and may differ from the physical life of the asset [13].

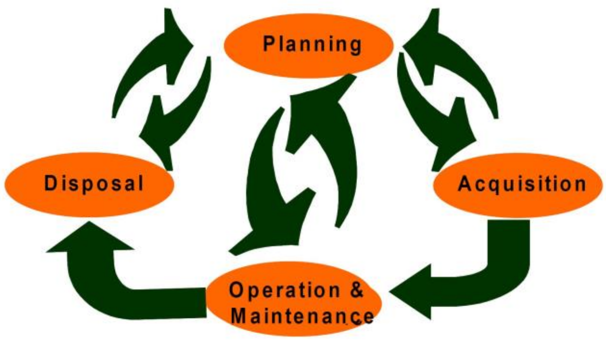

Fig. 6: Asset Life Cycle Management [13]

In 2008, Haffejee & Brent [14] proposed an integrated Asset Life Cost Management (ALCM) model (Figure 7), derived from an amalgamation of Life Cost Management (LCM) and asset management theories. This integrated ALCM refers to the management of assets over their complete life cycle, from before acquisition to disposal, considering economic, environmental, social and technical factors and performances.

They noted that strategic assets may include non-physical assets such as intellectual capital, but in terms of the model they proposed, only refers to physical assets.

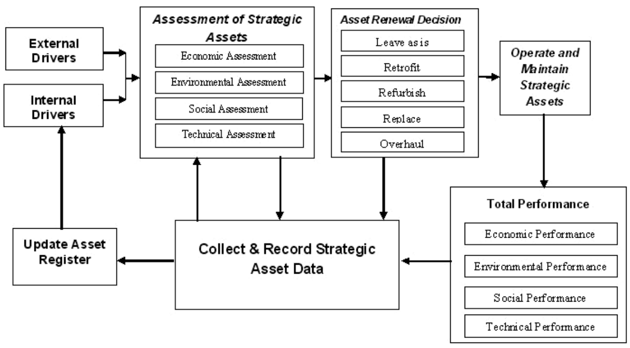

Fig. 7: Integrated ALCM Model [14]

Schuman & Brent [15] stated that a comprehensive life cycle management approach assures that the processes used across projects are consistent and that there is effective sharing and coordination of resources, information and technologies. All life cycles within a system must be considered, which spans the conception of ideas until the retirement of the entire system. Within the process industry environment, LCM defines the processes for acquiring and supplying system products and services that are configured from the system components of hardware and humans. In addition, LCM provides for the assessment and improvement of the life cycles:

- The development cycle of a system, production plant or facility is initiated with the identification of a need (Figure 8);
- The system, production plant or facility require maintenance and support during their operational lifetime in order to continue to fulfil the identified need;
- A life cycle approach is, therefore, required to reduce operating and maintenance costs, to optimise the productivity of the plant and maintenance and to support the design, which should be engineered concurrently to the performance of the system;
- The requirements regarding the system effectiveness in terms of reliability, availability and maintainability are of equal importance to the functional requirements of throughput, quality, capital cost, schedule, etc. It is critical that the first-mentioned requirements should also be defined during the conceptual phase.

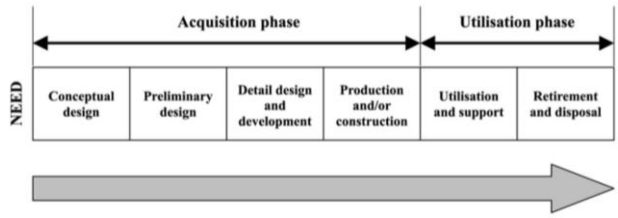

Fig. 8: Life cycle phases of process asset systems [15]

These fundamental concepts must be viewed as part of an effective asset management strategy, which has become a focus area of many companies to acquire and sustain a competitive advantage within a global economy.

Schuman & Brent [15] proposed an ALCM model for the process industry that integrates the different frameworks that have been discussed above, which is illustrated in Figure 9. Thereby, the model consists of three levels: the project management framework; the asset life cycle; and operational reliability. The model is further described based on the different components of the asset life cycle level.

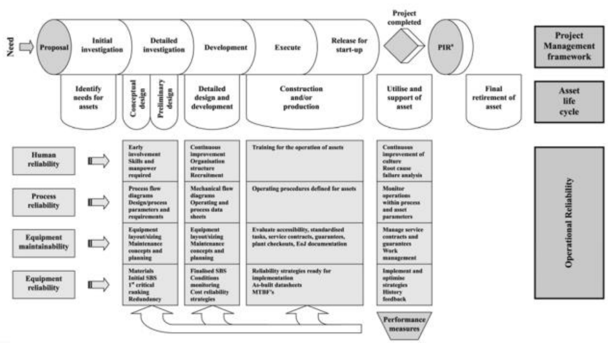

Fig. 9: The proposed asset life cycle management [15]

Farinha [16] sets stages of a physical asset life cycle (Figure 10) that goes from the moment t_1 (Decision about acquisition) until time t_8

(Renewal/withdrawal), setting for each stage a set of aspects that must be taken into consideration.

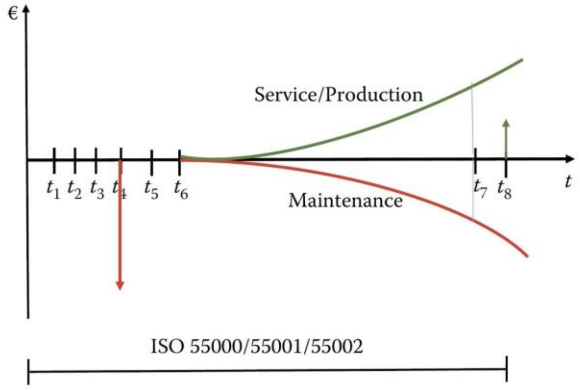

Fig. 10: Stages of a physical asset life cycle [16]

- t_1—Decision about acquisition
- t_2—Terms of reference
- t_3—Market consultation
- t_4—Acquisition
- t_5—Commissioning
- t_6—Starting production/maintenance
- t_7—Economic/lifespan issues
- t_8—Renewal/withdrawal

Table 1 shows the models and approaches, and their advantages and disadvantages, about Physical Asset Management.

Table 1: Models / Approaches with advantages and disadvantages

Model / Approach	**Author**	**Year**	**Pros**	**Cons**
Asset Management Process	Campbell	1995	• Nine steps process	• Not a model
BELCAM Decision-support Tool	Vanier *et al*	1996	• Gathers information only in order to use in the analysis of life cycle	• Based on buildings • Don't introduce mathematical models
Asset Management Program	Malano *et al*	1999	• Introduce elements of an asset management program	• Based on water utility • Don't introduce mathematical models • Not a model
Asset Life Cycle Management	National Treasury guidelines	2004	• Sets a framework for asset management	• Not a model
Asset Management Modelling Framework	Malano *et al.*	2005	• LCC model is proposed • Introduce mathematical models	• Requires lots of data that may not be available
Asset Life Cycle Management	Schuman & Brent	2005	• Introduce elements of an asset management program	• Don't introduce mathematical models
Asset Life Cost Management	Haffejee & Brent	2008	• Considers economic, environmental, social and technical factors and performances • Assets management from before acquisition to disposal	• Based on water utility • Don't introduce mathematical models

2.2 Life Cycle

From the European Union Journal[1] 'life-cycle' means all consecutive and/or interlinked stages, including research and development to be carried out, production, trading and its conditions, transport, use and maintenance, throughout the existence of the product or the works or the provision of the service, from raw material acquisition or generation of resources to disposal, clearance and end of service or utilisation;

According the same journal there is a concern on the life cycles when contracting; it states the following:

1. *Life-cycle costing shall to the extent relevant cover parts or all of the following costs over the life cycle of a product, service or works:*
   a) *costs, borne by the contracting authority or other users, such as:*
      i) *costs relating to acquisition;*
      ii) *costs of use, such as consumption of energy and other resources;*
      iii) *maintenance costs;*
      iv) *end of life costs, such as collection and recycling costs.*
   b) *costs imputed to environmental externalities linked to the product, service or works during its life cycle, provided their monetary value can be determined and verified; such costs may include the cost of emissions of greenhouse gases and of other pollutant emissions and other climate change mitigation costs.*
2. *Where contracting authorities assess the costs using a life-cycle costing approach, they shall indicate in the procurement documents the data to be provided by the tenderers and the method which the contracting authority will use to determine the life-cycle costs on the basis of those data. The method used for the assessment of costs imputed to environmental externalities shall fulfil all of the following conditions:*
   a) *it is based on objectively verifiable and non-discriminatory criteria. In particular, where it has not been established for repeated or continuous application, it shall not unduly favour or disadvantage certain economic operators;*
   b) *it is accessible to all interested parties;*
   c) *the data required can be provided with reasonable effort by normally diligent economic operators, including economic operators from third countries party to the GPA or other international agreements by which the Union is bound.*
3. *Whenever a common method for the calculation of life-cycle costs has been made mandatory by a legislative act of the Union, that common method shall be applied for the assessment of life-cycle costs.*

2.3 Importance of Life Cycle Management

According to [2]EN 60300−3−3:2004 products today are required to be reliable. They have to perform their functions safely with no undue impact on the environment and be easily maintainable throughout their useful lives. The decision to purchase is not only influenced by the product's initial cost (acquisition cost) but also by the product's expected operating and maintenance cost over its life (ownership cost) and disposal cost. In order to achieve customer satisfaction, the challenge for suppliers is to design products that meet requirements and are reliable and cost competitive by optimizing acquisition, ownership and disposal costs. This optimization process should, ideally, start at the product's inception and should be expanded to consider all the costs that will be incurred throughout its lifetime. All decisions made concerning a product's design and manufacture may affect its performance, safety, reliability, maintainability, maintenance support requirements, etc., and, ultimately, determines its price and ownership and disposal costs.

Life cycle costing is the process of economic analysis to assess the total costs of acquisition, ownership and disposal of a product. This analysis provides important inputs in the decision-making process in the product design, development, use and disposal. Product suppliers can optimize their designs by evaluation of alternatives and by performing trade-off studies. They can evaluate various operating, maintenance and disposal strategies (to assist product users) to optimize LCC. Life cycle costing can also be effectively applied to evaluate the costs associated with a specific activity; for example, the effects of different maintenance concepts/approaches, to cover a specific part of a product, or to cover only selected phase or phases of a product's life cycle.

Life cycle costing is most effectively applied in the product's early design phase to optimize the basic design approach. However, it should also be updated and used during the subsequent phases of the life cycle to identify areas of significant cost uncertainty and risk.

The necessity for formal application of the life cycle costing process to a product will, normally, depends

[1]DIRECTIVE 2014/24/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 26 February 2014

[2] Dependability management Part 3-3: Application guide – Life cycle costing (IEC 60300-3-3:2004)

on contractual requirements. However, life cycle costing provides a useful input to any design decision-making process. Therefore, it should be integrated with the design process, to the extent feasible, to optimize product characteristics and costs.

According to Juárez [17], making fixed assets investment decision is not easy in the hospitality industry. The investment in assets cannot easily be reversed, and the companies must extract the most profit from them. So, these would expect that the investment made is followed by an increase in their profits. Increasing investment in fixed assets or having a proper development on infrastructures, combined with an increase in the value of fixed assets, do not clearly lead to improvements in financial health, in this industry. The relationship is complex and involves recurrence patterns and independency of the fixed assets or infrastructure value.

For Campbell *et al.* [18], asset management is many things, done well. It is when a plant performs up to its design standards and equipment operates smoothly when needed. Its maintenance costs tracking on budget, with reasonable capital investment; it is high service levels and fast inventory turnover; it is motivated, competent trades - Most of all, asset management excellence is the balance of performance, risk, and cost to achieve an optimal solution.

Companies, increasingly, face a competitive environment, requiring the development of more efficient and cost-effective operations than ever before. Many asset heavy organizations are under intense pressures such as globalization, shifting markets, outsourcing, and external regulation. All of these factors drive organizations to increase productivity, to reduce costs, and to improve product quality. A 1% improvement in performance can be worth millions of dollars annually for a manufacturer. In addition, service rates are often regulated, making business survival dependent on efficient management of capital assets using best practices and standards. Organizations are now looking for ways to extend the capabilities of their existing systems.

In the past, asset management was most often described in terms of maintenance management with an exclusive focus on the programs, procedures, and tasks necessary to optimize uptime of an organization's equipment. Today, it requires active life cycle management of the major assets and components from design and inception to disposal, to achieve an edge against competition. A strategic view of asset management first requires new consideration of which assets are to be managed.

According to ISO 55000:2014, "Asset management enables an organization to examine the need for, and performance of, assets and asset systems at different levels. Additionally, it enables the application of analytical approaches towards managing an asset over the different stages of its life cycle (which can start with the conception of the need for the asset, through to its disposal, and includes the managing of any potential post disposal liabilities)."

According Blanchard and Fabrycky [19], total system cost is often not visible, particularly those costs associated with system operation and support. The cost visibility problem can be called the "iceberg effect", as illustrated in Figure 11.

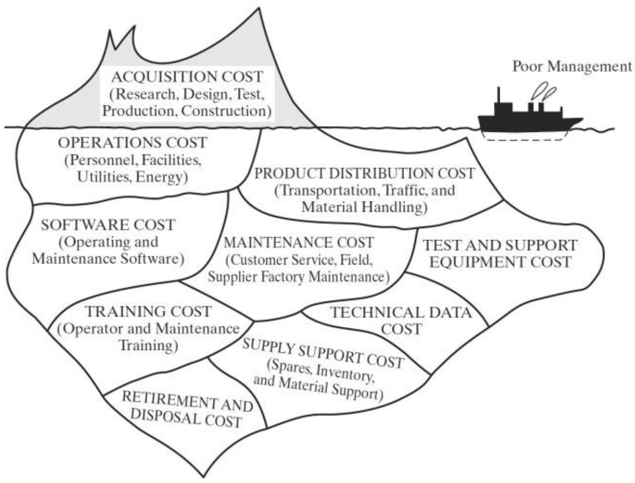

Fig. 11: Visibility of the elements of total LCC [19]

Many of the costs, as we can see, are not visible, and, if we don't have tools to help, it will be a "sailing by sight".

Silva *et al.* [20] stat that the management of assets in electric power systems has played an important role in the strategic scenario of electric power companies, mainly in the aging of the equipment present in the transmitters and distributors' parks.

As those devices life cycle is extended, it is justifiable to develop methodologies that prematurely identify their health condition, taking into account, not only historical series, but also all available tools of analysis that currently companies own for equipment.

2.4 Data Quality

One of the most accepted definition of information quality is given is by Juran *et al.*, [21]: "fitness for use". This definition expresses the fact that information quality is something dependent on the context and high-quality information for a purpose that can be considered low quality for a different purpose.

In order to achieve a good performance in asset management it is strategic to rely on good and reliable information; according to Redman [22], the estimated total cost for poor data quality has been estimated as 8-12% of revenue range, and 40-60% of a service organization's expense that may be consumed as result of poor data; those ranges are considered a good working estimate for the cost of poor data quality, and, at the operational level, poor data qualify lowers employees job satisfaction. One simply cannot expect the sales manager dealing with customers whose productions have been delayed or whose comfort of an administrative staff dealing with buildings and equipment's problems to exhibit a high level of positive morale.

First, poor quality data compromises decision-making; it is a widely accepted maximum that decisions are no better than the data on which they are based, and since any decision of consequence depends on thousands of pieces of data, the chance that decision is based only on good data is extremely small; the slightest suspicion of poor data quality often hinders managers from reaching any decision, and, many times, the most relevant data may be simply unavailable. While all decisions involve some amount of uncertainty, decisions based on the most relevant, complete, accurate, and timely data have a better chance of advancing the organizations goals. Second, at the tactical level, poor data quality makes more difficult to reengineer; many reengineering projects aim to put the right data in the right place at the right time to better serve a customer, making difficult to serve a customer when data is not correct. Finally, just poor data decreases employee job satisfaction, and also increases the mistrust that internal organizations may have one to another; it is made clear that departments in the organizations have needs overlapped, but if each department keeps its own data, sometimes they will find out that they have different data concerning the same issue.

Increasingly, however, those who design databases must support managerial decision-making activities rather than traditional transaction-oriented systems; for a variety of reasons data in such systems may not be of ideal quality - decision makers often must utilize data that are inherently unverifiable, often referred to as soft data. Those charged with designing databases that support decision making, frequently are dealing with imperfect data; so, managers must make decisions in spite of the imperfections of data found in databases; an affective decision-maker can compensate for various deficiencies the data may possess, especially if the decision-maker is acquainted with the data's idiosyncrasies. But this intuitive knowledge is lost, however, whenever data are used by various parties for purposes other than the original, which increasingly is the case, especially as data warehouses become more prevalent. Those potential users who do not possess an intuitive feel for the data may well be forced either to accept the data, which implicitly assumes that all data values are equally valid, or, at the other extreme, to avoid using data whose quality they cannot personally guarantee; these leads that many decision-support systems are not fully utilized for exactly this reason. The most effective format for presenting data-quality information could be a function of the decision-making process or strategy; conjunctive decision making assumes that the decision depends upon a known and specified set of criteria, and, for each of these criteria, a minimum acceptable level is established. The decision-maker must choose from among several possible options; in order to make the decision, each option must be evaluated on each of the criteria. An option is acceptable so long as the evaluation on each of the criteria is at least as large as the specific minimum for that criterion; if the evaluation is below the minimum for even one criterion, then that option is not acceptable [23].

According to Woodall *et al.*, [24], maintaining a good quality of information is vital, yet keeping information is a difficult task, and many leading asset management organisations have difficulty in planning and executing successful information quality management practices. According to this approach, it makes sound the asset management decisions, such as whether to replace or maintain an ageing underground water pipe, are critical to ensure that organisations maximise the performance of their assets. These decisions are only as good as the information which supports them; basing decisions on poor quality in formation can potentially result in great losses that can be economic, environmental, human and others.

3 Proposals

3.1 Asset management implementation

It's clear that "sailing by sight" isn't the way to take an organization to a good ashore; there must be tools to help on the navigation process. There are many tools, but most of them lack a numerical validation. Econometric, Quantitative models with a mathematical support must be part of any reasonable approach.

To optimize the life cycle of physical assets, the first tool must be the ISO 55001 Standard based on models previously described; it also must be based on EN 60300-3-3:2017 concerning the life cycle costing, EN 15341:2007 regarding the key performance indicators and ISO 31000:2018 to risk management.

There must be built a Strategic Asset Management Plan (SAMP) based on the models presented. The SAMP must have financial and environmental indicators; for example, the balanced scoreboard is excellent to use with SAMP; there are different techniques.

Khodakarami *et al.* [25] stats that, in different project management processes, there are different aspects of uncertainty. The most obvious area of uncertainty is in estimating duration for a particular activity. Difficulty in this estimation can arise from a lack of knowledge of what is involved as well as from the uncertain consequences of potential threats or opportunities. This uncertainty arises from one or more of the following:

- Level of available and required resources;
- Trade-off between resources and time:
- Possible occurrence of uncertain events (i.e., risks):
- Causal factors and interdependencies including common casual factors that affect more than one activity (such as organizational issues);
- Lack of previous experience and use of subjective rather than objective data;
- Incomplete or imprecise data or lack of data at all;
- Uncertainty about the basis of subjective estimation (i.e., bias in estimation).

The best-known technique to support project scheduling is CPM. This technique, which is adapted by the most widely used project management software tools, is purely deterministic. It makes no attempt to handle or quantify uncertainty. However, several techniques, such as program evaluation and review technique (PERT) and Graphical Evaluation and Review Technique (GERT) incorporates uncertainty.

PERT incorporates uncertainty in a restricted sense by using a probability distribution for each task; those uncertainty factors are related with the lack of knowledge about the duration for each task and, as consequence, the total project; because a SAMP differs from different organizations, only in this way we can plan activities that we don't fully know. Instead of having a single deterministic value, three different estimates (pessimistic, optimistic, and most likely) are approximated. Then the "critical path" and the start and finish date are calculated using distributions' means and applying probability rules. Results in PERT are more realistic than CPM, but PERT does not address explicitly any of the sources of uncertainty previously listed. But most of the SAMP's implementation can be supported by the Program Evaluation Review Technique (PERT); using this method, we can have answers for the following questions:

- What is the expected total time to finish the project?
- What is the duration (start and the completion times) for each activity?
- Which critical activities must be completed to reach the estimated project time?
- How much delay can be tolerated for non-critical activities in order to reach the estimated project time?
- What is the cost to speed up a project to meet a targeted completion time?
- What is the probability of completing a project within a given time slot?
- What is the time interval to the project completion?

For more complex SAMP implementations it may be used the Graphical Evaluation and Review Technique (GERT), that was developed to handle stochastic network structure (network with activities that have probability of occurrence associated with them and time to perform activity is a random variable). In GERT branches of the network are described with two (or more) parameters i.e. one, probability that the branch is traversed and time duration. Therefore, it allows for conditional and probabilistic treatment of logical relationships.

Another benefits of GERT scheduling is it is capable of handling iterative activities which CPM and PERT both do not allow, so after collecting data and describing branches of network; one-branch equivalent function between nodes is obtained and this equivalent function is converted into two performance measures of the network, i.e.: (1) the probability that a specific node is realized and (2) The Moment Generating Function (MGF) of the time associated with an equivalent network. Afterwards, inferences concerning the system under study are made from the information obtained.

The GERT approach addresses most of the limitations associated with PERT/ CPM technique. GERT also allows loops between tasks which makes it able to include iterative activities in network. The main drawback associated with the GERT technique is that it requires complex simulation tools to model GERT system, this is one of the reasons to be used only for more complex SAMP implementations [26].

3.1 Asset management diagnosis

To help on the implementation of ISO 55001, Pais *et al.* [27] present a method of diagnosing the state of the organization, that corresponds to a set of surveys in which the evaluation of the responses indicates the position of the company in relation to the application of the standard, the result is a radar map (Figure 12) where can be seen the position of the organization regarding ISO 55001 implementation.

Each question is related with the points presented on the radar chart as follows:

A. Understanding the organization and its context
B. Understanding the needs and expectations of stakeholders
C. Determining the scope of the asset management system

D. Asset management system
E. Leadership and commitment
F. Policy
G. Organizational roles, responsibilities and authorities
H. Actions to address risks and opportunities for the AMS
I. Asset management objectives
J. Planning to achieve asset management objectives
K. Resources
L. Competences
M. Awareness
N. Communication
O. Information requirements
P. Documented information
Q. Operational planning and control
R. Management of change
S. Outsourcing
T. Monitoring, measurement, analysis and evaluation
U. Internal audit
V. Management review
W. Nonconformity and corrective actions
X. Preventive actions
Y. Continual improvement

The use of this tool will help to check where the organization is and in what direction must go in order to implement an ISO 55001 certification.
Raposo *et al.* [4] presents a importance of the investment analysis in life cycle cost using econometric models, to support this choice he stats that equipment replacement is a broad concept that ranges from the selection of similar assets, to replace existing ones, to the evaluation of assets that act in completely different ways in the performance of the same function, such as more energy efficient equipment.

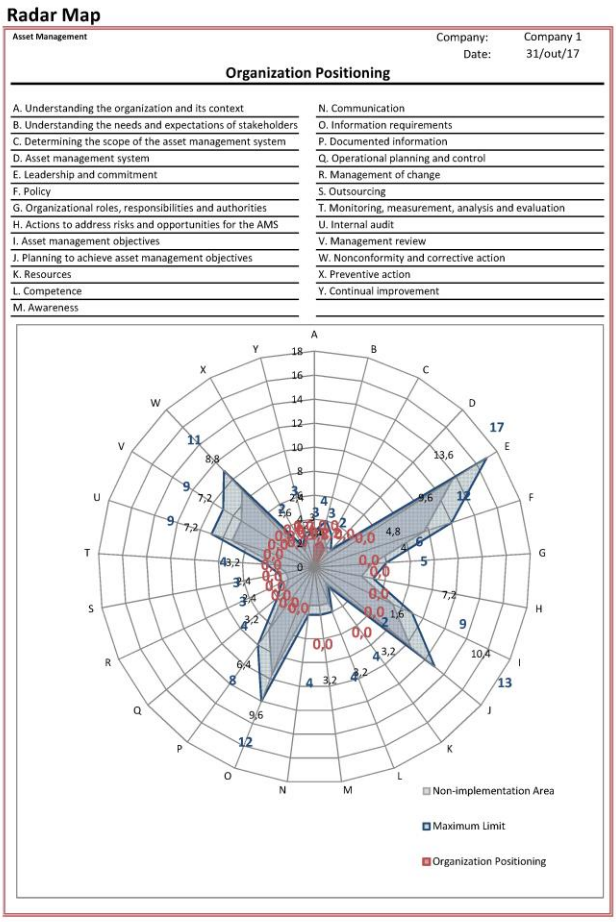

Fig. 12: Radar Map [27]

There are several non-exclusive causes that make replacement equipment economical, being deterioration one of them that is manifested by excessive operating and rising maintenance costs. This subject has been researched by several authors, with interesting results, as is shown, in the field of urban passenger transport, by the references [28], [29] and [30].
There are situations in which, with the change of a current operation, an equipment loses the ability to operate efficiently, that is, the equipment becomes inadequate.

4 Discussion

This paper presents a review about the optimization of the Life Cycle of Physical Assets. However, it is based on this short State of The Art review the authors are defining some research questions to guide the next research.
As was described in the previous sections, the optimization of life cycle will rely upon a SAMP, because the actual life cycle assessments are closed upon them and, normally, related with economics; so, to optimize the life cycle, we need to use a broader

scope where environment and others must be included. On other side, econometric models must be used to proper calculate the equipment and facilities value in each time of their life cycle; only knowing their current value, the decisions can be done regarding their maintenance, recondition or disposal. Life cycle costing is one of the areas in asset management activities where ISO 55001 is the first standard that gathers a broader number of areas to bring the asset management to a higher level.

Some models have been presented on this paper, but none of them show how to implement or use ISO 55001 and, most of them, are based on theoretical concepts without mathematical support, what is fundamental to aid decisions. Most of the models presented have not been validated and, without a validation, it is impossible to know if they are pragmatic enough and, even if they can be applied, they are not easy to use. These difficulties make this tools only available for large organizations with financial and specialized human resources.

This change will be a step forward to increase the sustainability of the organizations as their physical assets life's increase; on other hand, the whole life of the organization will increase due to the good "health" of the same, based on a good maintenance. So, the further works related with this theme must consider different areas, like the ones described on ISO 55001, with a SAMP based on econometric models and mathematical management support with a good balanced scoreboard to pilot the organization.

5 Conclusions

This paper took some highlights and some relevant questions about the management of physical assets life cycle, aiming to reduce their cost and to know the state of each asset at any moment. This approach is focused on implementing an Asset Management System (AMS) based on a clear Strategic Asset Management Plan (SAMP). At this moment it is very difficult to implement it due to the lack of information, which is just in a close circle of consultants, that provides services in the area, even many of them understand clearly how an AMS and a SAMP can improve the performance of the assets regarding to their life cycle costing.

The use of ISO 55001 will bring an umbrella over a series of areas that, in many cases, were managed independently, without any integration among them; without this integration the conflicts among the areas were not considered, causing occurrences that had not been taken into account and, sometimes, the risks associated.

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Appendix B

energies

Article

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

José Edmundo de Almeida Pais [1,2,*], Hugo D. N. Raposo [3,4], José Torres Farinha [3,4], Antonio J. Marques Cardoso [2] and Pedro Alexandre Marques [1]

1 EIGeS—Research Centre in Industrial Engineering, Management and Sustainability, Lusófona University, 376, 1749-024 Lisboa, Portugal; pedro.alexandre.marques@ulusofona.pt
2 CISE—Electromechatronic Systems Research Centre, University of Beira Interior, 6201-001 Covilhã, Portugal; ajmc@ubi.pt
3 Centre for Mechanical Engineering, Materials and Processes (CEMMPRE), University of Coimbra, 3030-788 Coimbra, Portugal; hugo.raposo@isec.pt (H.D.N.R.); tfarinha@isec.pt (J.T.F.)
4 Instituto Superior de Engenharia de Coimbra, Polytechnic of Coimbra, 3030-199 Coimbra, Portugal
* Correspondence: edmundo.pais@ubi.pt; Tel.: +351-918991614

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.

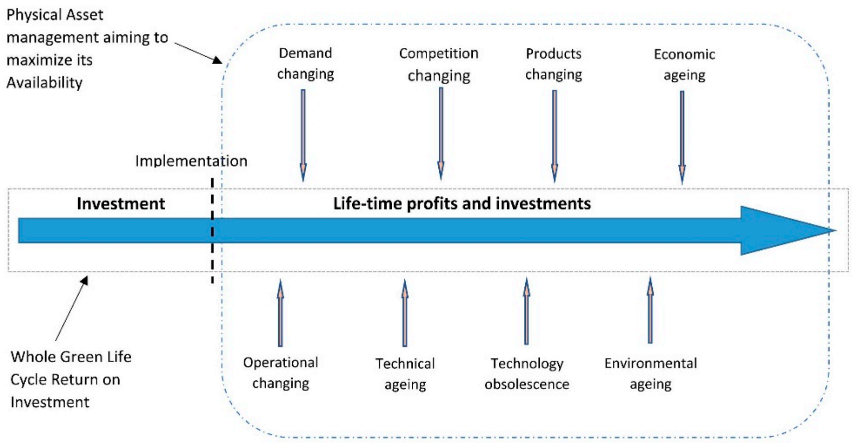

Figure 1. The focus of asset management (adapted from: [31]).

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.

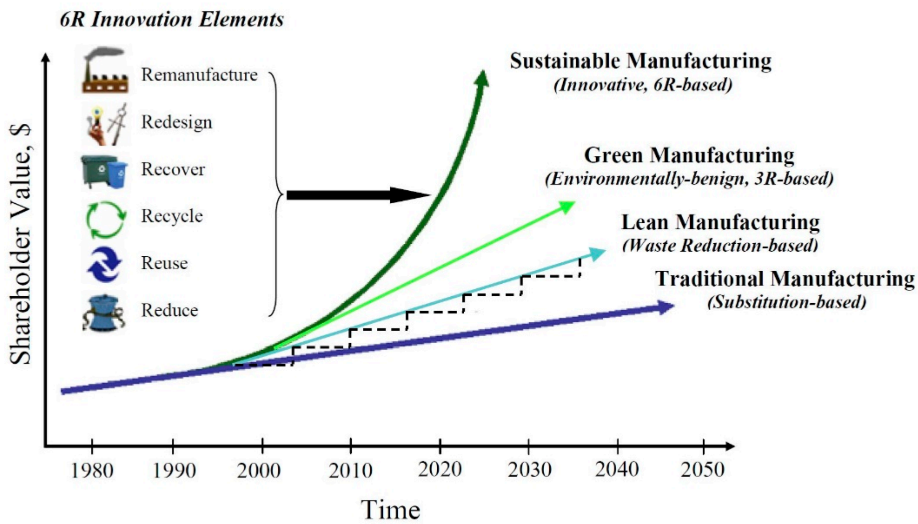

Figure 2. Sustainable manufacturing for the twenty-first century (Source: [33]).

CO_2 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_2 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_2. In 2019, China, the United States, India, EU27 + UK, Russia, and Japan—the world's biggest CO_2 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_2. 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_2 emissions: EU27 + UK (−3.8%), the United States (−2.6%), Japan (−2.1%), and Russia (−0.8%) [34].

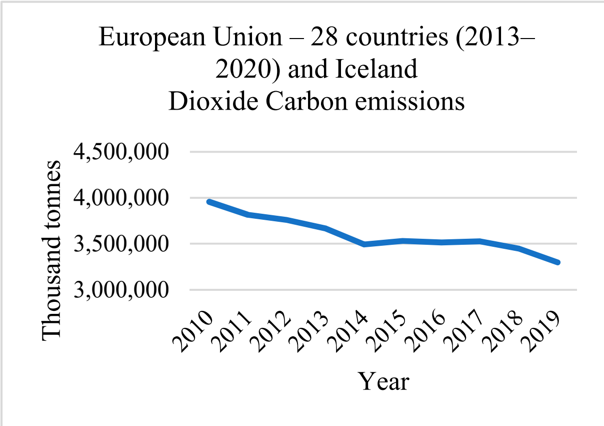

Figure 3. European Union-28 countries (2013–2020) and Iceland Dioxide Carbon emissions, adapted from Greenhouse gas emissions by source sector [35].

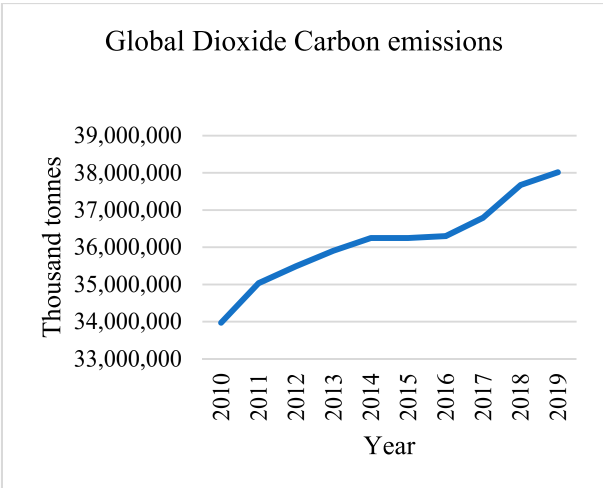

Figure 4. Global Dioxide Carbon emissions, adapted from Fossil CO_2 emissions of all world countries—2020 Report [34].

> "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).

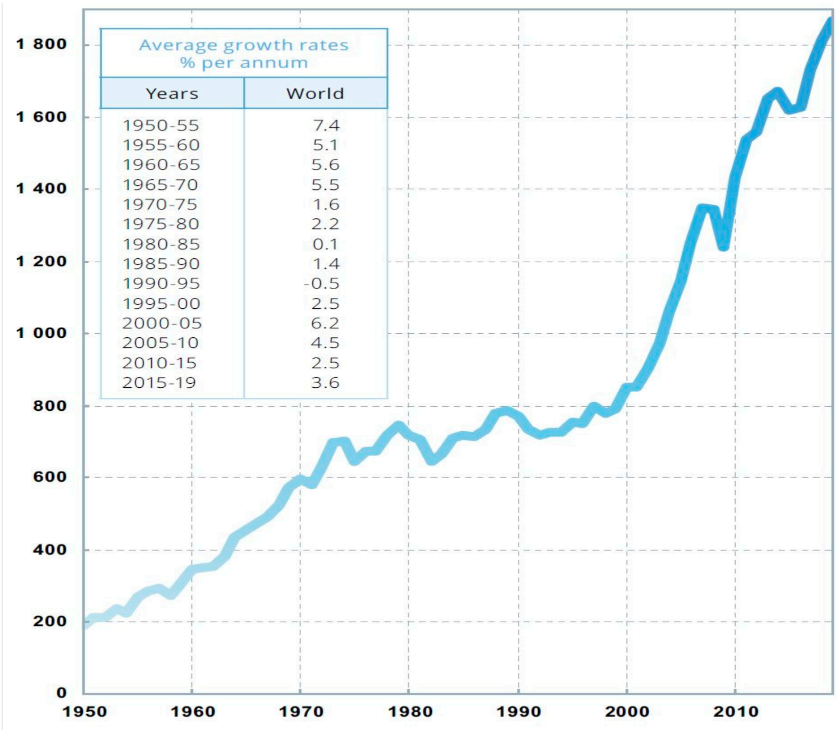

Figure 5. Crude steel production, million tonnes (Source: [37]).

The use of steel scrap reduces the emission of CO_2 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_2, and the use of a ton of stainless steel reduces emissions by 4.3 t CO_2 [38].

In addition to significantly reducing CO_2 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^2 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 [1]	22 August
1986	30 October	2004	30 August	2021	29 July
1987	23 October				

[1] 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_2 emissions is a current concern. Previous research has examined the incorporation of technological upgrades, and technological and sustainability depreciation, to reduce the CO_2 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	Campbell	1995	• Nine step process	• Not a model
BELCAM Decision-support Tool	Vanier et al.	1996	• Gathers information only in order to use in the analysis of life cycle	• Based on buildings • Don't introduce mathematical models
Asset Management Program	Malano et al.	1999	• Introduce elements of an asset management program	• Based on water utility • Don't introduce mathematical models • Not a model
Asset Life Cycle Management	National Treasury guidelines	2004	• Sets a framework for asset management	• Not a model
Asset Management Modelling Framework	Malano et al.	2005	• LCC model is proposed • Introduce mathematical models	• Requires lots of data that may not be available
Asset Life Cycle Management	Schuman and Brent	2005	• Introduce elements of an asset management program	• Don't introduce mathematical models
Asset Life Cost Management	Haffejee and Brent	2008	• Considers economic, environmental, social, and technical factors and performances; • Assets management from before acquisition to disposal;	• Based on water utility • Don't introduce mathematical models

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 comparation 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].

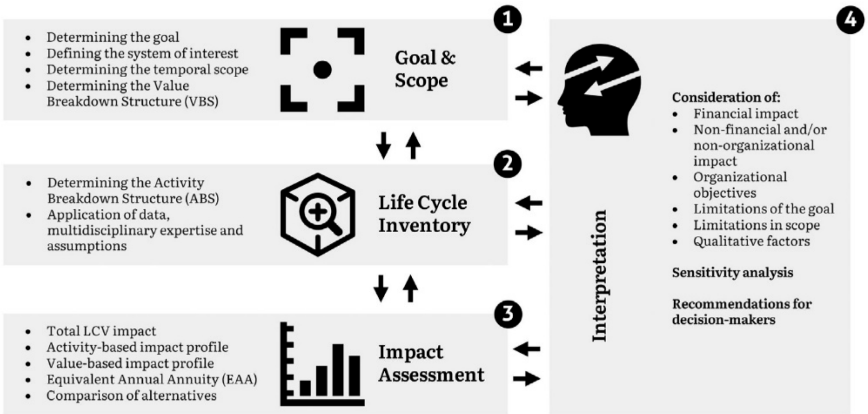

Figure 6. Life Cycle Valuation (LCV) assessment framework (Source: [64]).

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_2 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).

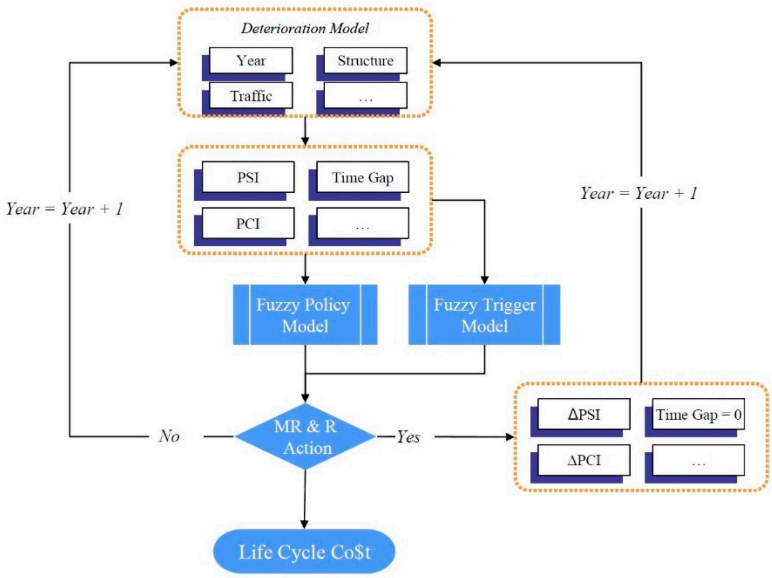

Figure 7. Fuzzy logic-based project selection algorithm (Source: [62]).

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 (MTACM-RPV) [77].

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

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

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

$$\begin{gathered} C'_n = \frac{\sum_{i=0}^{n} C_{Mi}}{n} \\ C''_n = \frac{V_A - V_{Cn}}{n} \\ C_n = C'_n + C''_n \end{gathered} \tag{2}$$

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_j: Cost of Maintenance in year $j = 1, 2, 3, \ldots\ n$
CO_j: Cost of Operation in year $j = 1, 2, 3, \ldots\ n$
i_A: Apparent rate
V_n: Value of the equipment over a period $n = 1, 2, 3 \ldots\ n$
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.

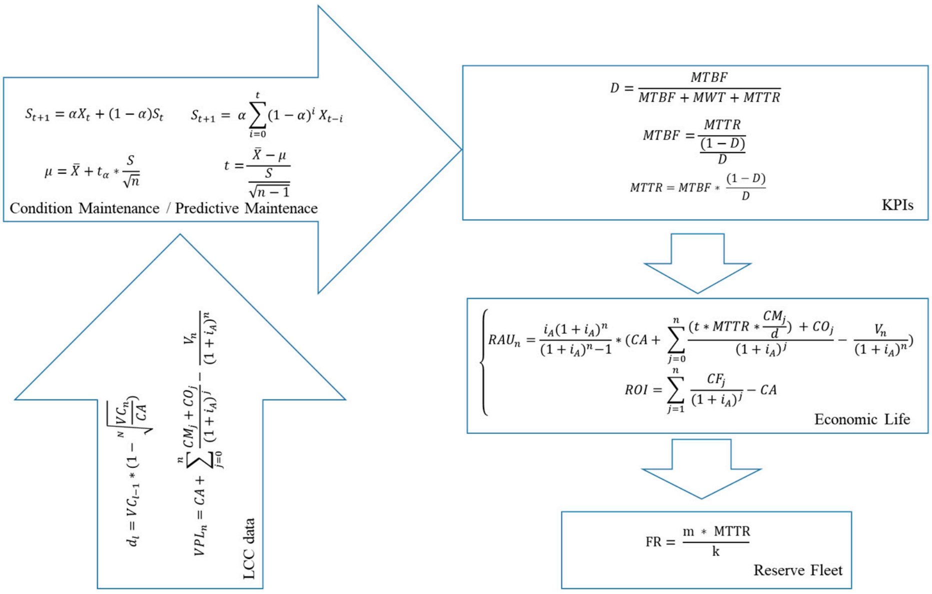

Figure 8. Model Integrated Reserve Fleet Assessment (MIAFRA) (Source: [53]).

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.

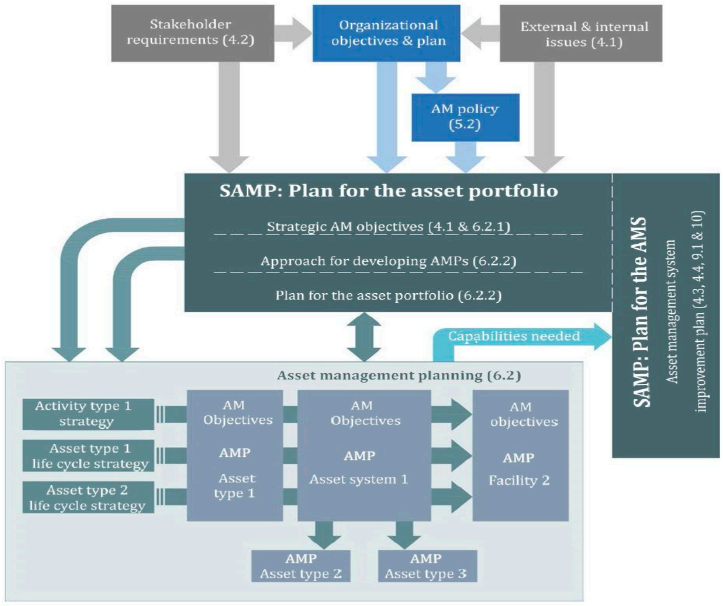

Figure 9. SAMP concept diagram (Source: [54]). Labels: Refs—The clause numbers in Figure 9 relate to ISO 55001; AM—Asset Management; AMP—Asset Management Plan; SAMP—Strategic Asset Management Plan.

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:

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

$$V_n = VC_{j-1} - d_j \tag{6}$$

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 . . . n
V_n: Equipment value in period n = 1, 2, 3 . . . 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, . . . n
F_j: Functioning in year j = 1, 2, 3, . . . n
i_A: Apparent rate
V_n: Value of the equipment over a period n = 1, 2, 3 . . . 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, . . . 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 ($PNVI1_n$), given by:

$$PNVI1_n = II + \sum_{j=0}^{n} \frac{IM_j + IF_j + TUI_j + TD_j + SD_j}{(1 + i_A)^j} - \frac{V_n + \sum_{j=0}^{n} R_j}{(1 + i_A)^j} \quad (11)$$

where:

II: Initial Investment

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

The Annual (n) Integrated Life Cycle Assessment (*ILCAM1n*) and Integrated Return Over Investment (*IROI1*) are given by:

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

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

where:

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

The results are presented in Figure 10.

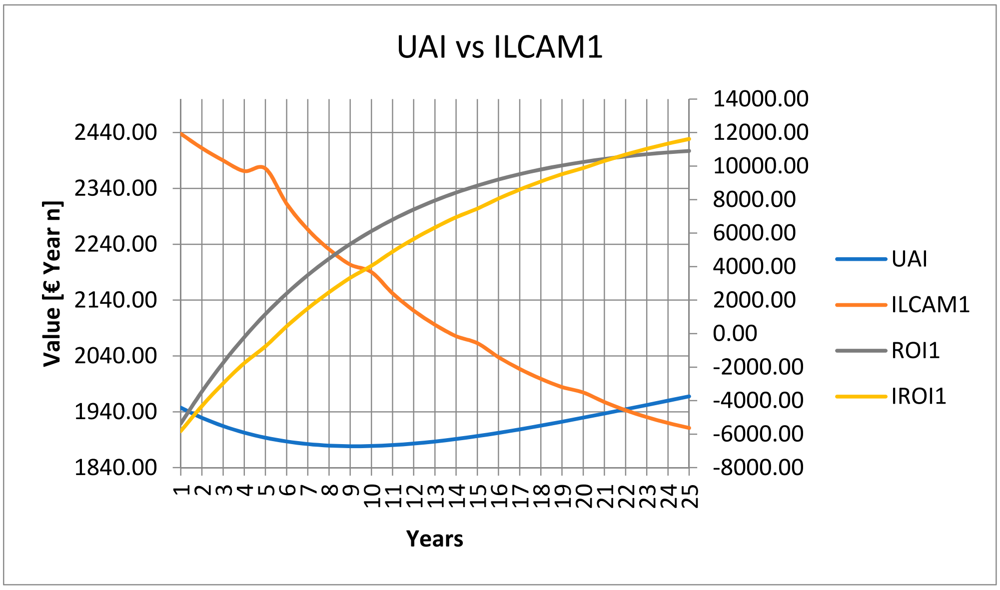

Figure 10. UAI vs. Integrated Life Cycle Assessment First Method (ILCAM1).

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

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

where:

II: Initial Investment

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

The results are presented in Figure 11.

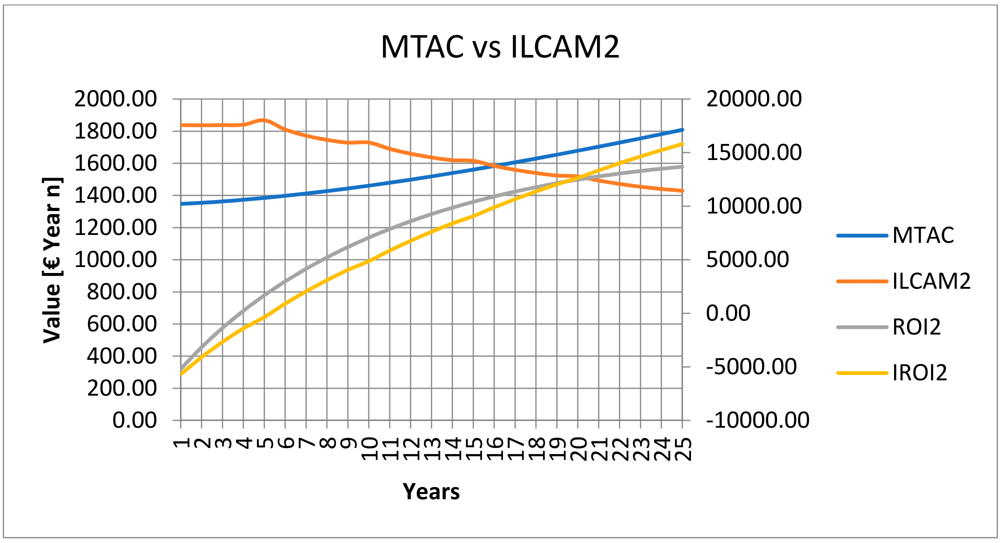

Figure 11. MTAC vs. Integrated Life Cycle Assessment Second Method (ILCAM2).

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

$$\begin{cases} ILCAM3_n = \frac{1}{n}\sum\limits_{j=1}^{N}\frac{(IM_j+IF_j+TUI_j+TD_j+SD_j)}{(1+i_A)^j} + \frac{II-\left(\frac{V_n+\sum_{j=0}^{n}R_j}{(1+i_A)^n}\right)}{n} \\ IROI3 = \sum\limits_{j=1}^{n}\frac{CF_j}{(1+i_A)^j} - II \end{cases} \quad (15)$$

where:

II: Initial Investment
IM_j: Integrated Maintenance in year $j = 1, 2, 3, \ldots n$
IF_j: Integrated Functioning in year $j = 1, 2, 3, \ldots n$
TUI_j: Technological Upgrade Investment in year $j = 1, 2, 3, \ldots n$
TD_j: Technology depreciation in year $j = 1, 2, 3, \ldots n$
SD_j: Sustainability depreciation in year $j = 1, 2, 3, \ldots n$
i_A: Apparent rate
V_n: Value of the equipment over a period $n = 1, 2, 3 \ldots n$
R_j: Residual value of the upgraded part $n = 1, 2, 3 \ldots n$
CF_j: Cash Flow in year $j = 1, 2, 3 \ldots n$
$IROI3$: Integrated Return Over Investment

The results are presented in Figure 12.

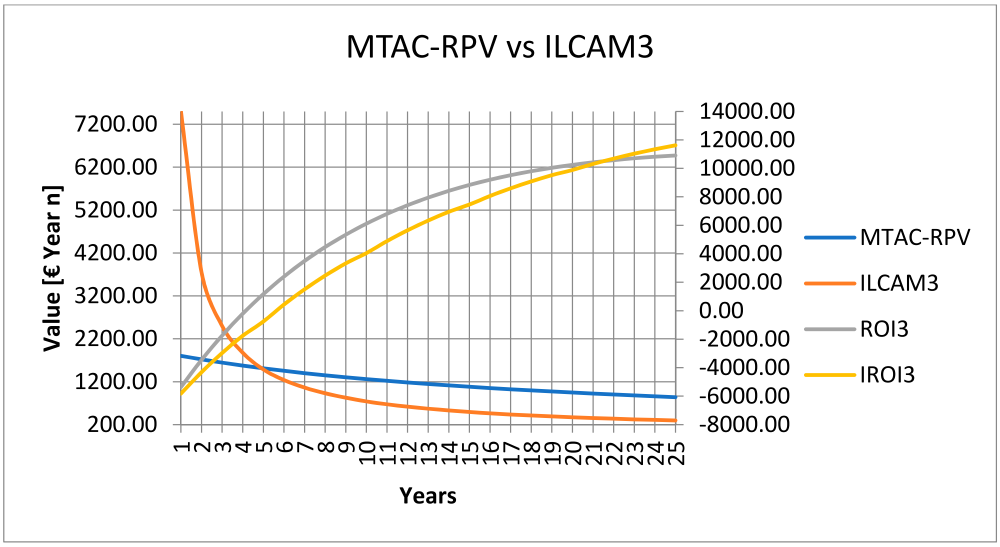

Figure 12. MTAC-RPV vs. Integrated Life Cycle Assessment Third Method (ILCAM3).

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 (GRn). The GRn 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.

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

where:

$MTBF_j$: Mean Time Between Failures
MWT_j: Mean Waiting Time in year $j = 1, 2, 3, \ldots n$
$MTTR_j$: Mean Time to Repair
F_j: Functioning in year $j = 1, 2, 3, \ldots n$
M_j: Maintenance in year $j = 1, 2, 3, \ldots n$
IRR_j: Internal Rate of Return in year $j = 1, 2, 3, \ldots n$
I_j: Physical Asset Value in year $j = 1, 2, 3, \ldots n$
B_j: Benefit in year $j = 1, 2, 3, \ldots n$

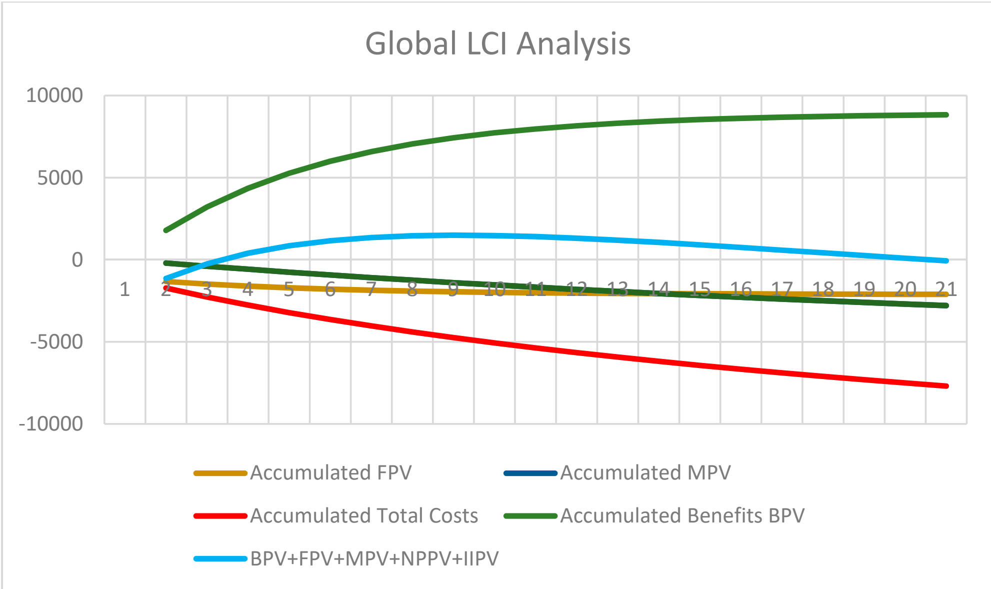

Figure 13. Values of investment, functioning, and benefits [41].

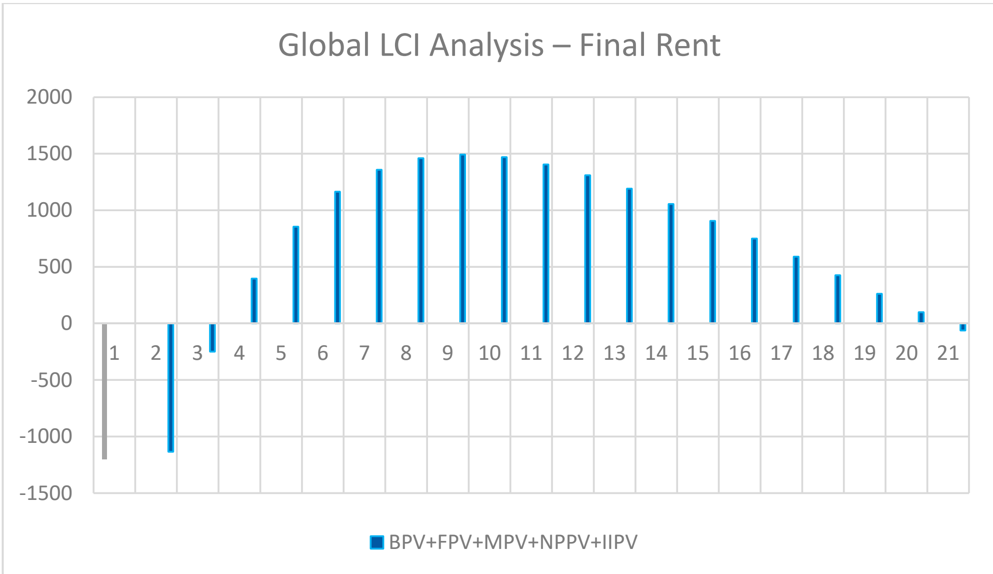

Figure 14. Annual financial results of the physical asset [41].

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*):

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

where:

$MTBF_j$: Mean Time Between Failures
MWT_j: Mean Waiting Time in year $j = 1, 2, 3, \ldots n$
$MTTR_j$: Mean Time to Repair
IF_j: Integrated Functioning in year $j = 1, 2, 3, \ldots n$
IM_j: Integrated Maintenance in year $j = 1, 2, 3, \ldots n$
IRR_j: Internal Rate Return in year $j = 1, 2, 3, \ldots n$
SD_j: Sustainability depreciation in year $j = 1, 2, 3, \ldots n$
TD_j: Technology depreciation in year j = 1, 2, 3, . . . n
TUI_j: Technological upgrade investment in year $j = 1, 2, 3, \ldots n$
I_j: Physical Asset Value in year $j = 1, 2, 3, \ldots n$
B_j: Benefit in year $j = 1, 2, 3, \ldots n$

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.

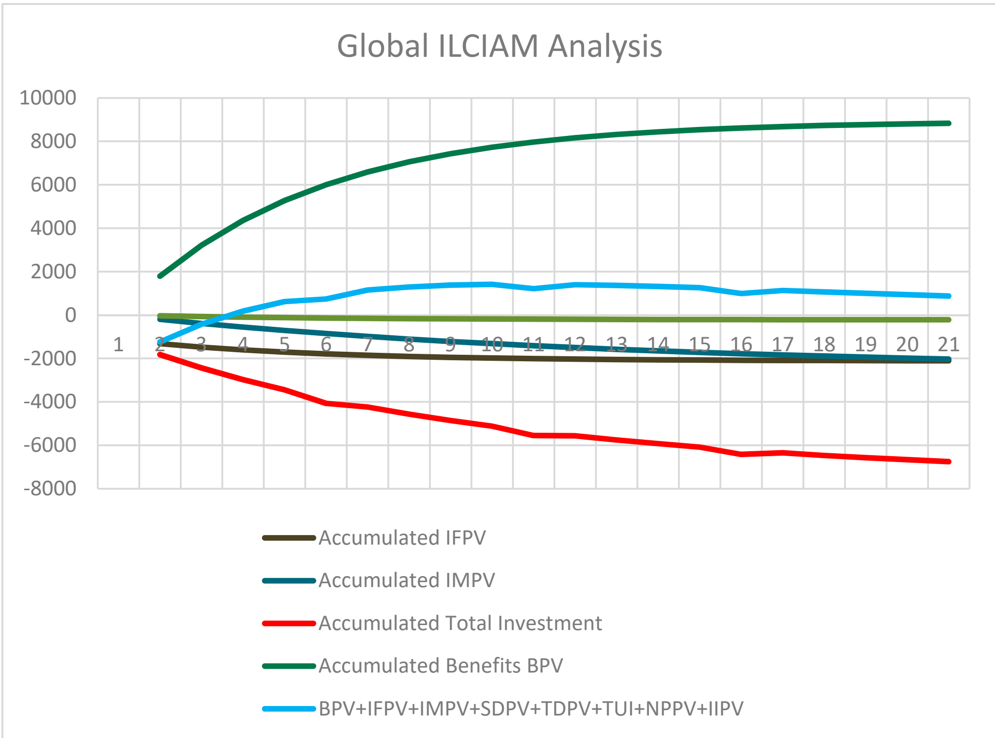

Figure 15. Values of investment, functioning, and benefits.

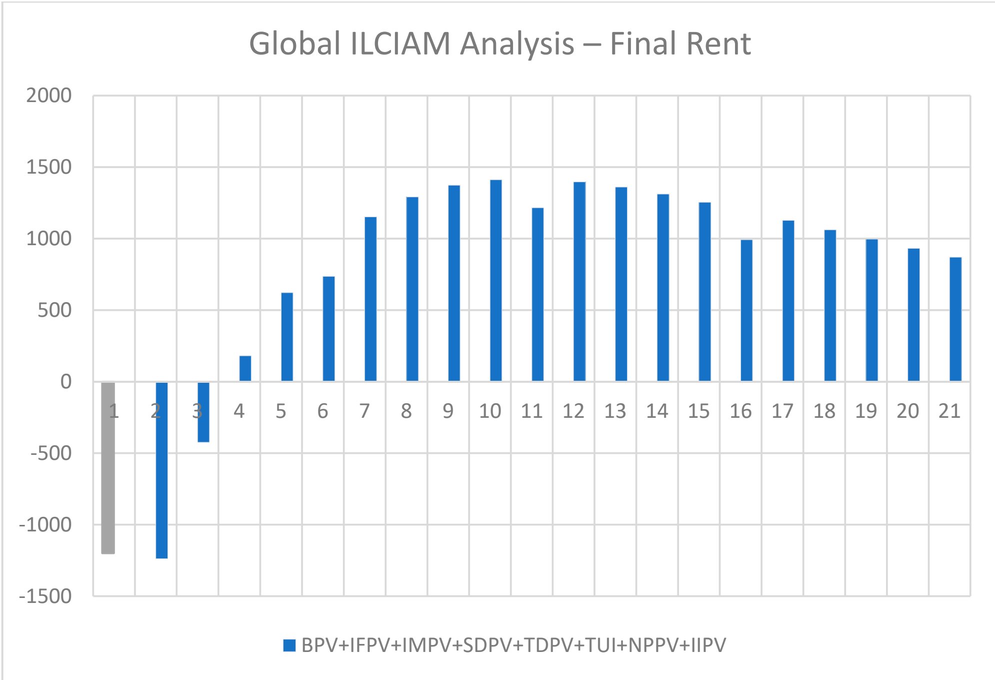

Figure 16. Annual financial results of the physical asset.

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_2 emissions. In certain types of asset, the CO_2 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_2 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_2), methane (CH_4), nitrous oxide (N_2O), nitrogen oxides (NO_x), 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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Appendix C

sustainability

MDPI

Article

Measuring the Performance of a Strategic Asset Management Plan through a Balanced Scorecard

José Edmundo de-Almeida-e-Pais [1,2,*], Hugo D. N. Raposo [3], José Torres Farinha [3], Antonio J. Marques Cardoso [2], Svitlana Lyubchyk [1] and Sergiy Lyubchyk [1]

1 Lusófona University, RCM2+ Research Centre for Asset Management and Systems Engineering, Campo Grande, 376, 1749-024 Lisboa, Portugal; p5322@ulusofona.pt (S.L.); p6349@ulusofona.pt (S.L.)
2 CISE—Electromechatronic Systems Research Centre, University of Beira Interior, 6201-001 Covilhã, Portugal; ajmc@ubi.pt
3 Instituto Superior de Engenharia de Coimbra, Polytechnic Institute of Coimbra, RCM2+ Research Centre in Asset Management and System Engineering, 3030-199 Coimbra, Portugal; hugo.raposo@isec.pt (H.D.N.R.); tfarinha@isec.pt (J.T.F.)
* Correspondence: edmundo.pais@ubi.pt

Abstract: The purpose of this paper is to propose a tool to measure the performance of a Strategic Asset Management Plan (SAMP) based on a Balanced Scorecard (BSC). The SAMP converts organizational objectives into asset management objectives, as well as specifies the role of the asset management system, providing support to achieve asset management objectives. The SAMP becomes the heart of the organization and integrates the long-term, medium-term, and short-term plans. In the SAMP, the balance among performance, costs, and risks are taken into consideration in order to achieve the organization's objectives. On the other hand, the SAMP is a guide to set the asset management objectives while describing the role of the Asset Management System (AMS) in meeting these objectives. Since the SAMP is the central figure of AMS, it is important to measure its performance and should be built and improved through an iterative process. This indicates that it is not just a document, it is "the document" that should be treated as a "living being", which needs to adapt to internal and external changes quickly. The BSC is an excellent tool where, through the appropriate Key Performance Indicators (KPIs), the progress can be measured, and is supported by four perspectives: Financial, Customer, Internal Business Process, and Learning and Growth.

Keywords: ISO 5500X family; sustainability; asset management; physical assets; SAMP; balanced scorecard

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1. Introduction

1.1. Framework

Nowadays, sustainability is becoming a major issue mainly due to the growing demand. For example, in Portugal, from 1995 to 2015, the urban area increased by 40.2% [1]. This growth is the fruit of population demand for new infrastructures (housing, factories, roads, etc.) and this issue is replicated worldwide [2–5]. Essentially, this reflects the increase in needed resources.

On the other hand, some authors link economic sustainability with the management of physical assets [6], while other authors state that, in many industries, maintenance procedures can significantly contribute to the pursuit of sustainable development [7]. Therefore, the use of assets is linked with sustainability in order to develop sustainable economies. The benefits of these assets are reflected in terms of innovation and knowledge-based technologies, thus linking innovation, knowledge, and the environment [8].

Therefore, it is important to implement strategies that successfully increase the sustainability of the environment based on complementary assets [9]. It might be difficult for decision makers to maintain an asset's performance in accordance with rational repair strategies because they may neglect to create suitable maintenance plans or fail to maintain the assets. Organizations face pressure from all over the world to guarantee the sustainability of their assets [10]. Concerns about sustainability and safety are raised over whether essential installation maintenance is being sufficiently funded to guarantee long-term viability [11].

Industry 4.0 technologies are being rapidly incorporated into Asset Life Cycle Management (ALCM). In the manufacturing sector, industries look for opportunities to meet sustainability objectives [12] using Industry 4.0 technologies [13]. Moreover, companies expect to achieve sustainable outcomes using these technologies [14]. By utilizing technologies like Neural Networks for modeling pavement performance in order to improve sustainability [15], companies basically expect to have the highest production while utilizing the fewest resources. For this to happen, it is important that assets have predictive maintenance policies to increase their availability [16–19].

On the other hand, one of the concerns about sustainability is related to global warming and rising sea levels [20], and these changes bring more vulnerability to climate disasters. In addition, the global water cycle is becoming more intense as a result of climate change, with dry areas becoming drier and wet areas becoming wetter. Nearly half of the world's population, around 3.6 billion people, currently reside in places that may be water deficient for at least one month out of the year [21–24]. Other scenarios that widely acknowledge climate change as a reality are the occurrences that have taken place in 2021, including severe drought in Madagascar, a snowfall in Brazil, and summertime flooding in central Europe [25]. Previous studies have established a connection between climate change and the increase in temperature due to CO_2 emissions [25].

For example, Portugal had an extreme drought event from January 2022 to September 2022 [26], reaching over 60% of extreme drought in the territory; on the other hand, in December 2022, the region of Lisbon was hit by an intense precipitation event, reaching values of 17.1 mm/m^2 in 10 min and causing floods all over Lisbon [27].

Drought brings the need to find other resources of water for all purposes and that requires investment. However, when dealing with floods, the authors refer to a massive economic breakdown, enormous loss of life, destruction in housing and infrastructures, agriculture, and other similar events [28–33].

Since the earth's natural resources are scarce and finite [34–45], there is a need to better manage these resources. Some authors claim that an efficient utilization of natural resources improves the economic advancement results [46–48], while other authors reinforce the need to reduce waste and reuse equipment at the end of their lives as well as whether to rebuild them [49,50]. At this point, it is important to emphasize the importance of reduce, reuse, recycle, recover, redesign, and remanufacture [51]. The basic goal is to maximize the life cycle, realize and produce value from the assets, and maintain the value and sustainability of the assets through appropriate management [25].

According to the World Commission on Environment and Development (WCED), "Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [52].

Nowadays, the circular economy is becoming very important regarding the need to achieve sustainable development [53]. As the need for reduction, reuse, recovery, and recycling of materials and energy has become a priority, the circular economy plays a major role in achieving these priorities [54,55], reinforcing the need for a transition from the linear economy that started in the industrial revolution to the priority needs of the circular economy. The biological processes in which nothing is wasted serve as an inspiration for the circular economy. Despite certain misconceptions about the circular economy concept, previous authors [56–64] have advocated the necessity of the circular economy to achieve sustainable development because it can be used as a tool to attain sustainability.

Nowadays, sustainable development can be achieved by relying on every development. In addition, we need to use energy in a sustainable way through reducing consumption and finding renewable energy sources [65–70] and low carbon energy sources, while developing low consumption equipment and energy efficient projects. As a result, we will feel more inclined to make investments [71] and bring about economic growth [72].

Energy sources have always been crucial to the advancement of human society. Energy has been the primary engine behind the advancement of modern civilization since the industrial revolution [39]. While the energy consumption growth rate is aligned with the economic growth rate, the population growth rate tends to decrease each year [73,74].

Some authors state that economic growth is improved by investing in physical assets and energy use, but at the expense of environmental sustainability [75]. Luciani [76] shows how the speed of the switch to renewable energy affects economic growth whether or not it will be maintained. On the other hand, investing in physical assets makes it easier to integrate cutting-edge technologies into the production process, which will facilitate the needed transition [77].

The transition to Asset Management (AM) leads to a great advantage because it makes it easier to train qualified workers, to improve knowledge transfers, to acquire leading alternative management platforms, etc. [75]. This improves not only the transition to renewable energy, but also the sustainable use of energy, which leads to economic growth [78,79]. When considering AM, there are some steps to build it and the SAMP is the main document that details the asset management objectives. Moreover, it explains their relationship to the organizational objectives and the framework required to achieve the asset management objectives [80]. In order to build a reliable SAMP, it is necessary to have accurate data [81]. As the SAMP is the main document, it is important to be able to measure its performance and quality—no studies to date have examined this issue. Furthermore, if we want to evaluate the SAMP's performance, then we need to measure and improve it. With this objective, the authors present a new tool to fill this gap.

1.2. Methodology and Research Questions

The aim of this research is to contribute and provide support to measure the performance of a strategic asset management plan by offering a new approach. For this purpose, a five-step methodology was used [82]:

(a) Framing questions for a review
  - (i) While building an Asset Management System (AMS), is it a core element to measure its performance?
  - (ii) How can we measure the SAMP performance?
  - (iii) Since the SAMP is the central figure in the AMS, how can it be measured?

(b) Identifying relevant work
  - (i) Section 2 provides the literature review.

(c) Assessing the quality of studies
  - (i) Indexed papers from scientific libraries.

(d) Summarizing the evidence
  - (i) Using available data to demonstrate the robustness of the proposed model.

(e) Interpreting the findings
  - (i) The results obtained are discussed and the strongest and weakest aspects of the research are identified.

1.3. Paper Structure

This paper is structured as follows:

1. Section 2 synthesizes the relevant literature on the performance measuring tool of a strategic asset management plan;
2. Section 3 presents the scorecard;
3. Section 4 presents the performance measuring tool of a strategic asset management plan through a balanced scorecard;

4. Section 5 presents a discussion;
5. Section 6 offers the conclusions.

2. Literature Review

When considering asset management, the value must be closely related to the organization's objectives and the asset management objectives compatible with those objectives [83]. Pais et al. [84] considered asset management as an umbrella where good practices are brought together. On the other hand, Raposo et al. [85] stated that asset management suggests a way for managing assets in line with the strategic goals of the organization, enabling choices on their purchase, replacement, and/or disposal, which improves sustainability and the organization itself. All of these objectives and the results of the actions taken to achieve them should be measurable [86].

Roda and Garetti [87] presented a Total Cost of Ownership (TCO) evaluation methodology based on a cost and performance model in nine steps, with the first six steps being related to performance evaluation and the remaining three steps related to cost evaluation:

1. Process understanding and the system's components identification;
2. Identification of failure modes or stop causes of each component;
3. Reliability, maintainability, and operation data acquisition (Time between Failures (TBF) and Time to Repair (TTR));
4. Modeling of the as-is system through Reliability Block Diagram (RBD) logic;
5. Simulation (Monte Carlo);
6. Technical performance calculation of the system;
7. Cost model setting;
8. Cost data acquisition;
9. Calculation of TCO.

For the modeling and calculation steps from 4 to 6, the model uses software R-MES Project©.

Simões et al. [88] conducted an analysis of 345 various performance metrics for maintenance management. This study offered suggestions for creating performance metrics; however, it only examined a portion of the Asset Management (AM).

Wang et al. [89] developed performance measures for AM. They adapted the Balanced Scorecard (BSC) and stated that it is important to combine asset management with a BSC. The authors presented a framework for designing performance measures (Figure 1). Utilizing a BSC combined with AM, as well as establishing objectives and performance measures and descriptions, the authors presented a lack of numerical elements that can be quantified.

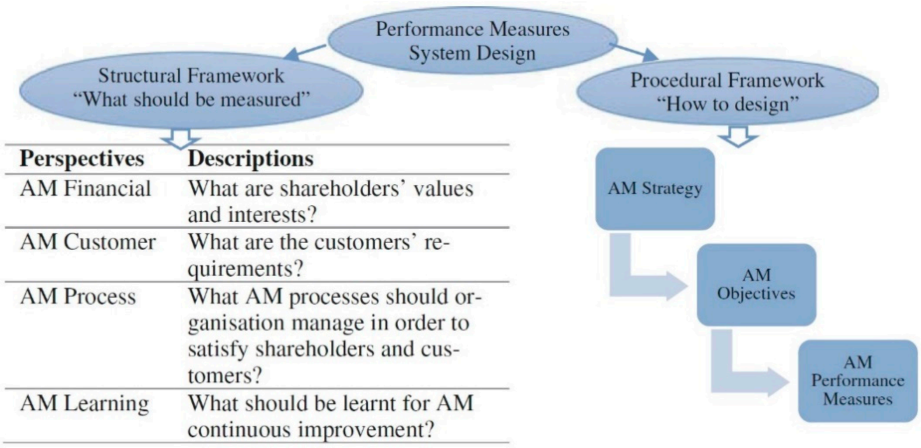

Figure 1. Framework for designing performance measures (Adapted from [89]).

Arthur et al. [86] sought the need to create a "line of sight" using a Balanced Scorecard (BSC). To achieve this, the following phases were selected:

1. Develop the AM strategy and identify AM objectives;
2. Select performance indicators;
3. Test for alignment or line of sight;
4. Reflect on the process and outcomes.

The authors also selected performance indicators and the need to have a "line of sight" to the asset management objectives.

Utilizing the BSC approach, Arthur et al. [86] developed their own top-down strategy map for creating performance measures. However, this novel strategy failed to solve the engineering asset management system's integrative complexity because performance measures should be designed from multiple perspectives.

Regarding performance measurement (PM), Abdul-Nour et al. [90] stated that PM in asset management systems is typically studied from a maintenance viewpoint rather than a global perspective, supporting their affirmation of Kumar et al. [91], Simões et al. [88], and Maletič et al. [92].

Regarding measuring asset performance, Wijnia [93] stated that "what gets measures gets done"; however, the author was concerned about the value to deliver and the validity of the indicators. In order to evaluate asset performance, the author considers a pragmatic solution but provides two questions:

1. Is it really only about delivering an absolute amount, like the produced volume, the availability of an asset, or staying within budget limits?
2. Or is it more about ensuring that the available resources are used in the most effective and efficient way, like driving towards the best value per unit of cost or the lowest cost per unit of production?

Wijnia [93] considered the second question to be more aligned with continual improvement, but his conclusion considered that while setting targets is a common practice, this is a difficult task, and the use of ratio indicators is an easier way. On the other hand, he considered that it could be applied across international boundaries, while under one's control, these conditions contravene the standards for conducting reliable indications.

Pais [54] presented a model to diagnose the organization's state using ISO 55001. This model is a tool to help implement and continuously improve the ISO 55001. It has 25 surveys and a total of 154 questions, with the results presented on a radar map (Figure 2).

In 2007, Crespo presented a maintenance management model (Figure 3) [94]. Based on this model, Parra et al. [95] presented an audit tool for Asset Management, Operational Reliability, and Maintenance Survey (AMORMS).

The AMORMS is an audit that aims at helping the management process of ISO 55001. It is based on eight phases:

1. Definition of the maintenance objectives and KPIs;
2. Asset priority and maintenance strategy definition;
3. Immediate intervention on high impact weak point;
4. Design of the preventive maintenance plans and resources;
5. Preventive plan, schedule, and resources optimization;
6. Maintenance execution assessment and control;
7. Asset life cycle analysis and replacement optimization;
8. Continuous improvement and new technologies.

From these eight phases, 150 survey questions are generated, with the result being a radar map. Moreover, this model provides supportive tools to help in process management.

Another model for audits presented by the same author is the Asset Management Survey ISO 55001 (AMS-ISO 55001), which is based on the asset management norm ISO 55001 [96]. It is focused on auditing the processes of the asset life cycle in managing according to ISO 55001 and is based on the ISO 55001 requirements:

1. Context of the organization;

2. Leadership;
3. Planning;
4. Support;
5. Operation;
6. Performance evaluation;
7. Improvement.

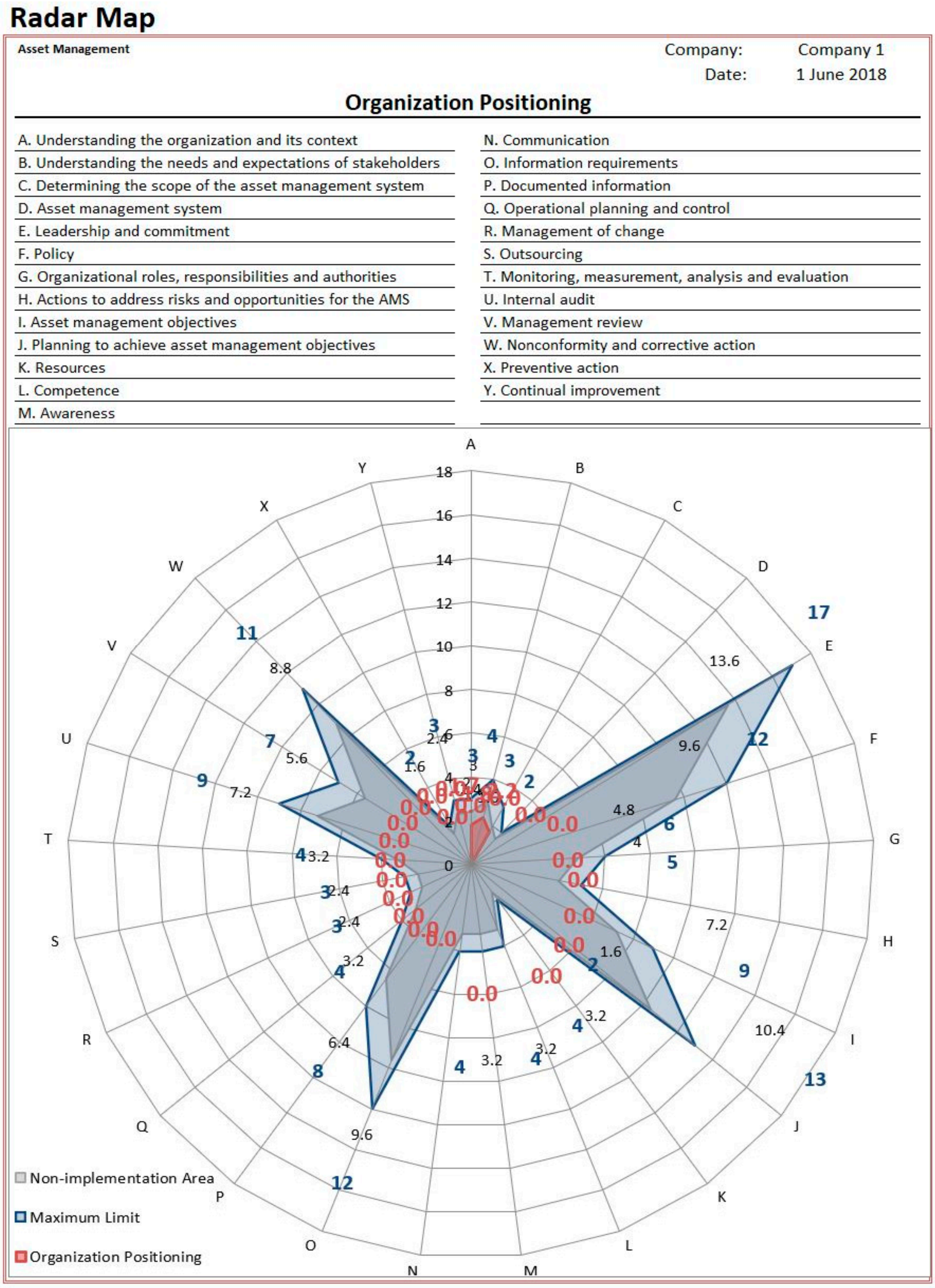

Figure 2. Radar map (Adapted from [54]).

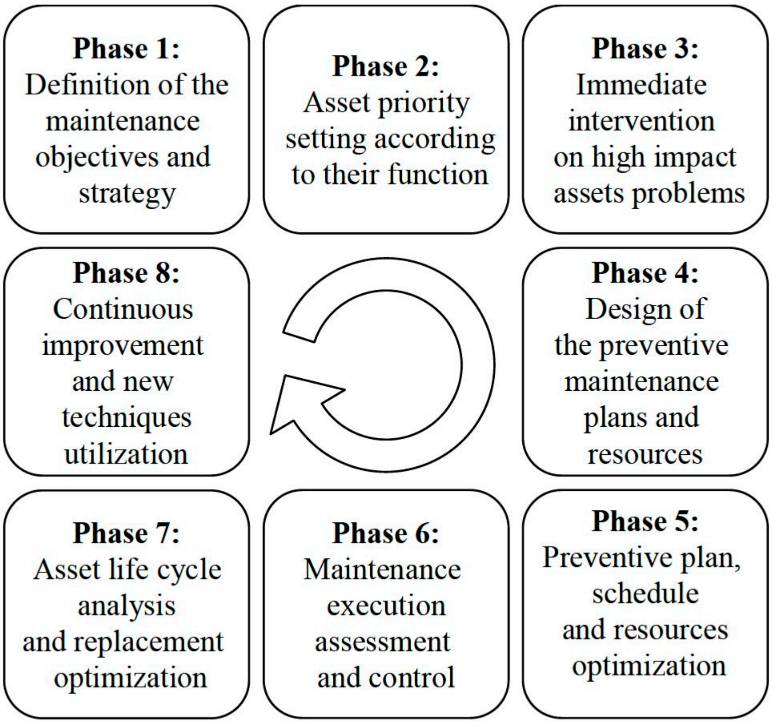

Figure 3. Maintenance management model (Adapted from [94]).

In order to measure performance (PM), Folan and Browne [97] divided it into two core areas:

1. Recommendations for performance measures;
2. Recommendations and issues for PM framework and system design.

The first emphasizes good performance measures, whereas the second focuses on recommendations regarding the design and development of PM and suggests the use of BSC.

Regarding measuring the performance of a document, such as the Strategic Asset Management Plan (SAMP), there is no study to date that presented any report or research about it. Filling this gap is very important to help the organizations evaluate their SAMP as the central document in the AMS.

3. Balanced Scorecard

The first research question (While building an Asset Management System (AMS), is it a core element to measure its performance?) is answered by the SAMP itself, since it is the main document that details the asset management objectives. Its importance and central figure in the Asset Management System (AMS) are clear. Moreover, its purpose is to provide a precise framework for strategic asset decision making, which is aligned with the organizational performance targets. This is demonstrated in this section.

The Balanced Scorecard (BSC) has been introduced in 1992 by Robert S. Kaplan and David P. Norton [98]. As they presented the BSC, the authors started with a strong statement that is widely used today: “What you measure is what you get”. Recently, Robert S. Kaplan in his book with a chapter entitled “Conceptual Foundations of the Balanced Scorecard” [99], cited Lord Kelvin (1883): “I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind. If you cannot measure it, you cannot improve it”.

In the same book and chapter, the author explains why he and David P. Norton introduced the BSC, stating that they held the opinion that managers need measurement just as much as scientists did. Companies have to incorporate the measurement of intangible assets into their management systems if they want to improve the management of their intangible assets [99].

The BSC translates vision and strategy into four perspectives: Financial, Customer, Internal Business Process, and Learning and Growth. Each one of these perspectives has its own objectives, measures, targets, and initiatives [99]. This tool was inspired in a project developed in the 1950s by the corporate staff of General Electric (GE) to create performance metrics for the company's decentralized business units [100].

The GE team developed one financial and seven nonfinancial metrics to measure performance:

1. Profitability (measured by residual income);
2. Market share;
3. Productivity;
4. Product leadership;
5. Public responsibility (legal and ethical behavior and responsibility to stakeholders including shareholders, vendors, dealers, distributors, and communities);
6. Personnel development;
7. Employee attitudes;
8. Balance between short-range and long-range objectives.

The roots of the BSC are found in these eight objectives. In the eighth objective, the balance between short-range and long-range objectives can be complex. An example of GE is their management asserting that business pressure for quick profits caused them to forsake long-term goals and their civic duties.

Other management tools, such as Peter with his classical book in 1954, "The Practice of Management", introduce the management by objectives, where the employees should have personal performance goals that are closely aligned with the business plan [101]. In the mid-1960s, Robert Anthony built upon earlier researches [102,103] and offered a thorough framework for systems of planning and control. Anthony distinguished three types of systems: operational control, managerial control, and strategic planning.

In the 1970s and 1980s, other movements have arisen such as the Japanese Management Movement bringing advancements in Just-In-Time (JIT) production and quality [104]. In 2008, Punniyamoorthy and Murali [105] introduced the balanced scorecard, which is based on BSC and is used as a benchmarking tool.

According to Scopus [106], 5035 studies were published on the subject of the balanced scorecard. The BSC tool has been widely used in research and sparked intense interest worldwide [107]. The balanced scorecard has been used by 60% of Fortune 1000 organizations in the USA [108]. Anand et al. [109] claimed an inventive method of using the balanced scorecard to raise strategic awareness within the firm.

Yet, the BSC establishes a comprehensive framework that connects individual accomplishments and efforts to business unit goals, reinforcing a holistic model [110].

According to the BSC collaborative, there are four barriers to strategic implementation [105]:

1. Vision barrier—No one in the organization understands the strategies of the organization;
2. People barrier—Most people have objectives that are not linked to the strategy of the organization;
3. Resource barrier—Time, energy, and money are not allocated to those things that are critical to the organization. For example, budgets are not linked to strategy, resulting in wasted resources;
4. Management barrier—Management spends a small amount of time on strategy and a large amount of time on short-term tactical decision making.

Even if the BSC concept has been widely embraced and applied in the corporate sector [111–113] such as education, it did not occur with significance [114]. Despite their short use in education, there are some studies and implementations [114–121].

No researches exist to support the use of BSC in evaluating the performance of the SAMP. There are some studies and implementations of performance measures of the Asset Management System (AMS) that emphasize the results [122–124] to measure the system and, in particular, the SAMP and its performance to understand whether it complies with ISO 55001 requirements.

Based on the above-mentioned, the importance of measuring the SAMP performance is clear and it is a core element of the AMS. As a result, the AMS is being measured, and it can be improved and considered in the organizational objectives direction.

4. Balanced Scorecard in a Strategic Asset Management Plan

This section attempts to answer the second and third research questions. First, it starts with the second question: How can we measure the SAMP performance?

The Balanced Scorecard (BSC) is tailored to the organization for which it is established and enables the development of Key Performance Indicators (KPIs) for tracking maintenance management performance in line with the strategic goals of the business [125]. Contrary to traditional metrics, which are control oriented, the balanced scorecard prioritizes attaining performance goals while putting the overarching strategy and vision at the forefront [126].

The KPIs used were chosen by taking into consideration the pretended measurements concerning specific ISO 55001 requirements. The KPIs and groundings are presented in Table 1.

Table 1. The key performance indicators and groundings.

KPI	Description	Groundings
ROI	Return On Investment	Measures the return on investment
EPS	Earnings per Share	Presents the profit increase
RG	Revenue Growth	Presents the revenue increase
NPS	Net Promoter Score	Measures customer experience
RPR	Repeat Purchase Rate	Measures the customers retention
RC	Revenue Concentration	Measures the revenue generated from the highest paying client
CSAT	Customer Satisfaction Score	Measures the happiness of the costumer with a product or service
QCR	Quality Control Rate	Measures the product/service quality
IQI	Inventory Quality Index	Measures the inventory quality
PLTF	Product Lead Time Forecast	Measures the time it takes to create a product and deliver it to a consumer
ESR	Employee Skills Rate	Measures the skills that employees have
ETR	Employee Training Rate	Measures the training that employees have
ERR	Employee Retention Rate	Measures the retention on employees
ESI	Employee Satisfaction Index	Measures the employees satisfaction

As stated by Kaplan and Norton [98], “What you measure is what you get”; therefore, the importance of measuring the SAMP is clear. As a result, a parallel between the ISO 55001 requirements and the BSC perspectives is required to be established. In Table 2, the BSC perspectives are indicated, and for each one, the authors introduced the related questions, pretended measurements, the related physical assets intervention, ISO 55001 requirements and, finally, the KPIs to measure performance.

Table 2. Balanced scorecard in SAMP.

Perspectives	Questions	Measurements	Physical Assets Intervention	ISO 55001 Requirements	KPI
Financial Perspective	How to reduce costs? How to increase profitability? How to increase revenue?	Revenue, Expenses, ROI, Net Income	Maintenance policies; Availability vs. Production	6.2.1; 6.2.2	ROI, EPS, RG
Customer Perspective	What are the customer's needs? What stakeholders expect? What the interested parties expect?	Customer Satisfaction, Customer Retention	Quality level related to Physical Assets performance	4.1; 4.3; 5.3	NPS, RPR, RC, CSAT
Internal Business Process Perspective	What are my assets? What is the value of my assets? My assets are in line with the organization's objectives? What assets will I focus on? How to extend the life cycle of the assets? What are the non-core assets for the organization? What new assets are needed? How to dispose of old assets? How to manage risk?	Inventory, Quality Control, Product Lead Time	Physical Assets Life Cycle vs. SAMP	4.4; 5.3; 6.2.1; 6.2.2	IQI, QCR, PLTF
Innovation Learning and Growth Perspective	Increase availability Improve reliability	Employee Skills, Employee Training, Employee Retention, Employee Satisfaction	Maintenance policies vs. TPM	6.2.1; 6.2.2	ESR, ETR, ERR, ESI

The data needed to calculate the KPIs are presented in Table 3.

Table 3. Data needed to calculate the KPIs.

KPI	Data
ROI	Current Value of Investment
	Cost of Investment
EPS	Net Income—Preferred Dividends
	End-of-Period Common Shares Outstanding
RG	Initial Revenue
	Final Revenue
NPS	Percentage of Promoters—Percentage of Detractors
RPR	Number of customers who made a repeat purchase
	Number of customers
RC	Amount of revenue that your business earned from the best customer
	Amount by your business's total revenue
CSAT	Number of satisfied customers
	Total customers asked
QCR	Number of good products produced
	Total of product produced
IQI	Number of assets correctly inventoried
	Total of assets
PLTF	Estimated total time
	Real total time
ESR	Number of employees with skills to their work
	Total number of employees

Table 3. *Cont.*

KPI	Data
ETR	Number of hours in training / Number of hours planned for training
ERR	Total of new employees retained / Total of new employees
ESI	(How satisfied are you with your job + How well does your job meet your expectations + How close is your workplace to your ideal job)/3

Based on the above-mentioned, it is demonstrated how the KPIs based on a BSC may help to measure the SAMP performance.

The last question to answer is: "Being the SAMP the central figure in the AMS, how can it be measured?". Other ways and tools are available for use in order to measure the SAMP. The authors proposed a model based on the BSC and its perspectives, mainly because it is a document that sets the strategy to achieve asset goals focused on the organization's objectives and measures the decision-making criteria.

The calculated KPIs are presented in Table 4. To obtain a value between 0 and 100, a coefficient was introduced in each KPI. In this way, the KPI was limited to 100, which is the maximum value expected. The KPIs, such as ROI, EPS, and RG, are unlikely to achieve the value of 100, as can be seen in Table 4. These KPIs are the ones with values under 100 but, at same time, they are the values expected for the respective KPI.

Table 4. Calculated KPIs.

KPI	Data	Value	KPI Value	Unit
ROI	Current Value of Investment	22.36	11.78	%
	Cost of Investment	20.00		
EPS	Net Income—Preferred Dividends	106.05–0.43	7.04	€
	End-of-Period Common Shares Outstanding	15		
RG	Initial Revenue	5.36	17.91	%
	Final Revenue	6.32		
NPS	Percentage of Promoters—Percentage of Detractors	85–23	62.00	%
RPR	Number of customers who made a repeat purchase	86	68.25	%
	Number of customers	126		
RC	Amount of revenue that your business earned from the best customer	2.35	72.31	%
	Amount by your business's total revenue	3.25		
CSAT	Number of satisfied customers	126	47.55	%
	Total customers asked	265		
QCR	Number of good product produced	12.69	88.37	%
	Total of product produced	14.36		
IQI	Number of assets correctly inventoried	64	77.11	%
	Total of assets	83		

Table 4. *Cont.*

KPI	Data	Value	KPI Value	Unit
PLTF	Estimated total time	54.00	90.00	%
	Real total time	60.00		
ESR	Number of employees with skills to their work	20	76.92	%
	Total number of employees	26		
ETR	Number of hours in training	58.00	100.00	%
	Number of hours planned for training	50.00		
ERR	Total of new employees retained	7	77.78	%
	Total of new employees	9		
ESI	(How satisfied are you with your job + How well does your job meet your expectations + How close is your workplace to your ideal job)/3	9/8/9	86.7	%

As previously mentioned, it is demonstrated how the KPI values of the BSC results permit the measurement of the SAMP performance. Clearly, it will be very important to have data during a time window of several years to evaluate the performance of SAMP over time. One of the ISO 55001 requirements is improvement, which induces the use of the Deming Cycle (Plan-Do-Check-Act, PDCA). This tool permits the identification of nonconformities to plan and make the corrections, as well as to continuously improve the processes and systems.

5. Discussion

For organizations, especially those that own or manage large physical assets, such as infrastructure, facilities, or equipment, the SAMP is an essential tool, as a document where the role of the assets is clarified as well as the objectives of asset management needed to achieve the organization's objectives. The SAMP brings the necessary alignment in the organization. It brings together stakeholder requirements, organizational objectives and plans, as well as external and internal issues [80]. As the main goal for asset management is to bring value from the assets, the SAMP describes all the activities of each asset during its life cycle (asset creation/acquisition, utilization/maintenance, renewal/disposal, etc.) (ISO 55002) [80].

The use of a Balanced Scorecard (BSC) is brought to an upper level regarding the measurement of the SAMP performance and can easily quantify each perspective and each standard requirement, while helping to see which requirements need to be improved and what is necessary to be carried out to improve them.

When considering strengths and weaknesses while using BSC to measure the SAMP, the main weakness is the lack of information in the organizations and the need to change the organization's culture in order to promote the gathering of good and reliable data. The strengths are related to the BSC because this is a well-known tool for most managers, which makes it easy for adoption.

The perspectives described on the BSC (Table 2) can be complemented with goals. The organizations, while checking where they are, can also set where they want to be. This can be made by setting goals and objectives for each perspective, with these goals being individually focused in each organization. While improving and reaching goals concerning their assets, the organization is maximizing the assets' value, thus bringing about economic growth.

Asset Management (AM) can also be an excellent tool to help achieve some of the United Nations (UN) Sustainable Development Goals, such as the decent work and economic growth, industry, innovation and infrastructure and others related with risk, because while using AM, the organizations need to comply with ISO 31000 guidelines, which helps to mitigate environmental and social risks.

The results obtained in (Table 4) for a specific organization can vary across activities or countries, focusing on the organization used to test the model. The results show that their SAMP is on the right path.

The organization who's data are used in this case study is from a water company that explores and manages water supply and wastewater sanitation systems for an area of about 100,000 inhabitants.

By analyzing the results, the obtained values are in the average of this specific activity; however, the KPIs, such as Net Promoter Score (NPS), Repeat Purchase Rate (RPR), Customer Satisfaction Score (CSAT), and Employee Skills Rate (ESR) can be improved when compared to the acceptable values for this indicator. This last indicator (RPR) demonstrates that the organization is not investing in the employee's formation, which will commit the performance of this strategic resource; this indicator should be above 80%. As a consequence, this demonstrates that the SAMP has not yet been built correctly or is not known for the company; therefore, changes must be made to improve these KPI results. For example, the CSAT obtained the value of 47.55%, which is low for an organization. Results above 75% are accepted across most organizations, while values concerning the CSAT are defined by sectors and there is no standard that regulates them; a good result can be a value of above 85%. The result in this case study indicates that the customer, probably, is not taken into consideration when decisions are made, and customer satisfaction is not achieved, which can be related to poor product quality or bad service delivery.

The KPIs used are general indicators and their acceptable values are well defined in the industry, sectors, or areas. Moreover, when the model is used, the results should be aligned with what is expected in that sector.

Questions like the following ones must be placed: the customers' complains are being addressed? Measures were taken to correct or lessen the nonconformities? There is a follow up with costumers concerning the nonconformities? Tools like the PDCA are well known and simple to use in order to make a continuous improvement that can be used to correct the nonconformities that led the costumer to give a bad review.

Principles such as Economic Rationality (ER), Strategic Management (SM), or Sustainable Development Goals (SDGs) are aligned with AM and within the SAMP.

These principles can be applied and are related with the KPI presented and discussed. The proposed SAMP measuring tool was validated using data from water companies and the results were validated by the stakeholders, recognizing the improvement in the described areas.

6. Conclusions

Nowadays, the Asset Management (AM) is a great tool to help address issues such as sustainability, circular economy, industrial symbiosis, business continuity, etc. The method presented in this paper can help and improve the use of AM. The Strategic Asset Management Plan (SAMP) plays a very important role using AM; therefore, it is important to have a robust SAMP that can only be achieved if we are able to measure the performance that it provides. The use of a Balanced Scorecard (BSC) allows for measuring the SAMP performance and can be easily evaluated.

After the evaluation, the tool presented helps to correct the nonconformities in order to have a SAMP aligned with the organization's objectives. The use of tools such as PDCA cycle will help to systematically correct the nonconformities and achieve excellence in AM. The use of a Balanced Scorecard (BSC) to measure the performance of a Strategic Asset Management Plan (SAMP) improves the SAMP and allows for an overall improvement of the AMS. This results in improving sustainability and business continuity risk. On the other hand, principles such as economic rationality can be used with the aim to improve the employee's behavior.

The limitations of the model are related to the data collected, which should be reliable in order to obtain credible results. This is a major problem most of the time, and has not yet been solved in the organization's culture. In fact, to have good indicators, it is essential to have good data.

In future works, it is important to develop tools to help the organizations collect good and reliable data, which is a major problem in today's organizations.

Finally, the main question for everyone's consideration is this: What planet do we want to leave for posterity?

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