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Life Cycle Costing in Industrial Production Cost Management: A Review Focused on Sustainability and Economic Efficiency

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Abstract: Cost management in industrial production is essential for competitiveness, especially in growing pressure for sustainable practices. This study addresses the Life Cycle Costing (LCC) technique, which allows companies to consider all costs throughout a product's life cycle, integrating economic and environmental aspects. The research seeks to answer the question of how LCC promotes sustainability and economic optimization in industrial sectors through a systematic literature review using the Methodi Ordinatio methodology. The analysis of 37 selected articles highlights that LCC facilitates the identification of cost-reduction opportunities and the promotion of sustainable practices, as well as improving energy efficiency and mitigating greenhouse gas emissions. The results confirm the effectiveness of LCC as a strategic tool that enables companies to develop more sustainable and economically viable strategies, positioning them competitively in a market increasingly focused on sustainability.

Keywords: Life Cycle Costing, Cost Management, Industrial Production, Sustainability, Economic Efficiency.

Life Cycle Costing na Gestão de Custos de Produção Industrial: Uma Revisão Focada na Sustentabilidade e Eficiência Econômica

Resumo: A gestão de custos na produção industrial é essencial para a competitividade, especialmente em um contexto de crescente pressão por práticas sustentáveis. Este estudo aborda a técnica de Life Cycle Costing (LCC), que permite às empresas considerar todos os custos ao longo do ciclo de vida de um produto, integrando aspectos econômicos e ambientais. A pesquisa busca responder como o LCC contribui para a promoção da sustentabilidade e otimização econômica em setores industriais, por meio de uma revisão sistemática da literatura utilizando a metodologia Methodi Ordinatio. A análise de 37 artigos selecionados destaca que o LCC facilita a identificação de oportunidades de redução de custos e promoção de práticas sustentáveis, além de melhorar a eficiência energética e mitigar emissões de gases de efeito estufa. Os resultados confirmam a eficácia do LCC como uma ferramenta estratégica que capacita as empresas a desenvolverem estratégias mais sustentáveis e economicamente viáveis, posicionando-as de maneira competitiva em um mercado cada vez mais voltado à sustentabilidade.

Palavras-chave: Life Cycle Costing, Gestão de Custos, Produção Industrial, Sustentabilidade, Eficiência Econômica.

1. Introduction

Cost management in industrial production determines business competitiveness in a globalized market, where operational efficiency and sustainability have become strategic requirements (GONG et al., 2019). As industries face increasing pressure to integrate sustainable practices into their operations, managing costs effectively and considering economic and environmental impacts becomes essential for long-term sustainability (ESMAEILIAN et al., 2020). According to the authors, methodologies beyond traditional costing methods, offering a comprehensive view of costs throughout the product life cycle, are increasingly relevant in this context.

Life Cycle Costing (LCC) is a strategic approach that allows companies to consider all the costs involved throughout a product's life cycle, from conception to disposal (DEGIETER et al., 2022). This technique provides an integrated view of costs and facilitates informed decision-making considering economic benefits and environmental impacts (ATIA et al., 2020). Recent research shows that LCC can identify significant long-term cost reduction opportunities and promote more sustainable production practices, contributing to the resilience of companies in an increasingly demanding economic environment (ARULNATHAN et al., 2022).

Despite progress in applying LCC, there are still considerable challenges in its implementation in highly complex sectors, such as high-tech manufacturing and the chemical industry (RODRIGUES; SILVA, 2024). According to the authors, while the current literature offers a robust understanding of the benefits of LCC in traditional sectors, such as construction and the automotive sector, there is a significant gap regarding its application in industries where operations are more dynamic and environmental impacts are more difficult to predict. This gap suggests an urgent need to explore how LCC can be adapted to deal with the particularities of these sectors, where innovation and sustainability must coexist with efficient cost management.

The application of LCC also faces methodological challenges, such as the difficulty of accurately predicting future costs and the complexity of quantifying environmental impacts throughout the entire life cycle of products (SUN; CARMICHAEL, 2017). In addition, the variation in industries' ability to integrate LCC into their operational processes highlights the need for a critical analysis of the barriers and facilitators of this technique (NAVES et al., 2019). Comparative studies across different sectors can offer valuable insights into the best practices for overcoming these challenges and the economic and environmental benefits LCC can provide in varying contexts (HINGST et al., 2023).

Against this backdrop, this study seeks to fill a significant gap in the literature by conducting a comprehensive review of Life Cycle Costing's main contributions to cost management in industrial production. By addressing both the sectors in which LCC has already been widely applied and those in which the technique still faces implementation challenges, this study aims to offer a holistic view of best practices, limitations, and opportunities for the future of cost management with a focus on sustainability. Furthermore, by identifying emerging trends and obstacles yet to be overcome, this research seeks to provide a solid basis for future academic research and practical applications of LCC in various industrial contexts.

Therefore, considering the growing importance of LCC in industrial production cost management, this study proposes the following research question: **How does the Life Cycle Costing (LCC) technique contribute to promoting sustainability and economic optimization in different industrial sectors?** To achieve this objective, this study uses a systematic literature review, employing the multi-criteria Methodi Ordinatio methodology, which allows the selection and classification of articles based on criteria such as impact factor (IF), number of citations (Ci), and year of publication (PAGANI et al., 2015, 2017; CAMPOS et al., 2018).

The structure of this article is organized as follows: after the introduction, section 2 explores the theoretical framework, while section 3 details the research methods used. Section 4 presents and discusses the results of the analysis. Finally, section 5 offers the conclusions, highlighting the main contributions of the study and proposing directions for future research.

2. Literature Review

2.1 Life Cycle Costing: concepts and evolution

Life Cycle Costing (LCC) is a cost management methodology that emerged in the 1960s and 1970s, initially applied in sectors such as defense and construction, where the longevity of products and systems required a comprehensive analysis of costs throughout the entire life cycle (DEGIETER et al., 2022). The technique was developed to include all the costs involved, from acquisition to disposal, offering a complete view of the expenses associated with a product or system (RODRIGUES; SILVA, 2024). Over time, according to the authors, LCC has expanded to other industrial sectors, driven by the growing need for more sustainable practices and the search for resource optimization throughout the life cycle of products.

As it has evolved, LCC has come to be recognized not only as a cost management tool but also as a strategy for business decision-making, especially in contexts where sustainability is a priority (BACHMANN et al., 2024). With increasing environmental concerns and the need for economic efficiency, LCC has become an essential practice in production engineering to reduce waste and maximize return on investment. According to Ippolito et al. (2024), its application has expanded to sectors such as automotive, energy, and manufacturing, where companies have begun to realize the importance of evaluating costs throughout the useful life of products.

Building the LCC involves identifying and quantifying all the costs associated with a product's life cycle, from design to disposal (KAMBANOU, 2020). According to the author, these costs include direct expenses, such as materials and labor, and indirect expenses, such as maintenance, energy, and environmental impacts. The application of LCC requires a detailed analysis of each phase of the life cycle, considering the durability of materials, the energy efficiency of processes, and waste disposal costs (IPPOLITO et al., 2024).

Conceptually, LCC differs from other cost management techniques in that it adopts a long-term perspective, focusing not only on immediate costs but also on future costs and the impacts of business decisions over time (KAMBANOU, 2020). This contrasts with traditional methodologies, such as absorption costing or variable costing, which focus on the costs incurred during production, neglecting the later stages of the product's life cycle.

Compared to Activity-Based Costing (ABC) and Target Costing techniques, LCC offers a more comprehensive and integrated view of costs, considering economic and environmental aspects (RIVERO; EMBLEMSVÅG, 2007). According to the authors, while ABC focuses on allocating indirect costs based on resource-consuming activities, LCC incorporates costs associated with the operation and disposal of products. Target Costing seeks to adjust production costs to achieve a profit margin, while LCC aims to optimize costs throughout the life cycle without compromising sustainability and quality.

2.2 LCC and Corporate Sustainability

Life Cycle Costing (LCC) is widely recognized as an effective tool for promoting sustainability in companies, especially in industrial sectors with significant environmental impacts. Authors such as Atia et al. (2020) point out that LCC allows companies to make more sustainable choices, opting for materials and processes that, despite higher initial costs, result in lower costs and impacts throughout the product's life cycle. This approach contributes to reducing operating costs and mitigating companies' environmental impacts.

Recent studies highlight LCC's role in corporate sustainability, showing its ability to align economic and environmental objectives. Knauer and Möslang (2018) show that companies that adopt LCC tend to invest in more sustainable technologies and production processes, which not only improves efficiency in the use of resources but also strengthens the company's reputation with stakeholders. In addition, LCC encourages innovation, as companies constantly seek solutions that reduce costs throughout the life cycle while maintaining a commitment to sustainability.

LCC stands out for its ability to quantify and compare the environmental costs of different design alternatives and production processes. It provides a solid basis for decisions to minimize environmental impact and promote long-term sustainability (KAMBANOU; SAKAO, 2020). By considering factors such as energy consumption, carbon emissions, and waste disposal, LCC allows for a comprehensive and accurate analysis of environmental implications, as demonstrated by studies that prove significant reductions in the environmental impacts of products and industrial processes (HALL, 2018).

In addition to the environmental benefits, LCC is recognized for its ability to generate lasting economic value for companies. Studies have shown that applying LCC can identify significant savings throughout the life cycle of products by reducing maintenance costs, improving energy efficiency, and extending the useful life of products (ROBERTS et al., 2020). According to the authors, these savings increase profitability and reinforce companies' commitment to sustainability, promoting continuous improvements.

However, implementing LCC presents challenges, such as the complexity of collecting and analyzing the necessary data and uncertainty in estimating future costs. The need for a cultural change within organizations for LCC to fully integrate into decision-making is also often pointed out as a significant barrier (HIGHAM et al., 2015). Despite this, there is a consensus in the literature that, when applied well, LCC can offer substantial competitive advantages, aligning with sustainability goals and boosting organizational performance.

In summary, LCC is an essential technique for companies seeking to integrate sustainability and economic efficiency into their operations. Its ability to offer a comprehensive view of costs throughout the product life cycle positions it as a critical component in sustainability strategies, generating significant benefits for both the environment and organizations' financial results (KNAUER; MÖSLANG, 2018). This understanding positions the LCC as a practice that prepares companies to face the challenges of a market increasingly focused on sustainability.

3. Methodology

To investigate how the Life Cycle Costing (LCC) technique contributes to the promotion of sustainability and economic optimization in different industrial sectors, a systematic literature review was carried out using the multi-criteria Methodi Ordinatio methodology, which ranks articles based on impact factor (IF), citation count (Ci), and publication year, as described in Equation 1 (PAGANI et al., 2015, 2017; CAMPOS et al., 2018).

$$InOrdinatio = \left(\frac{IF}{1000} \right) + \alpha * [10 - (ResearchYear - PublishYear)] + \left(\sum C_i \right) \quad (1)$$

The methodological process involved the following steps:

Stage 1. Establishment of the research intention: The definition of the central objective consists of analyzing how LCC promotes sustainability and optimizes costs in industrial sectors.

Stage 2. Preliminary search in databases: A preliminary search was carried out in the Scopus and Web of Science databases using keywords related to LCC and industrial production.

Step 3. Definition and combination of keywords: The keywords used in this study include variations of the terms "Life Cycle Costing" and "Industrial Production," applying Boolean operators as follows: ("life cycle costing" OR "LCC" OR "life-cycle costing" OR "whole life costing" OR "whole-life costing") AND ("industrial production" OR "manufacturing" OR "industrial operations" OR "industrial processes" OR "industrial output").

Stage 4. Final search in the databases: The final search resulted in 7,123 articles, of which 6,677 were in Scopus and 446 in Web of Science. After filters for "Title, Abstract, Keywords" and restriction to research articles, 485 articles were selected, as shown in Table 1.

Table 1 – Search in databases			
	Scopus	Web of Science	Total
All fields	6.677	446	7.123
Title, Abstract, Keywords	484	305	789
Title, abstract, keywords, and research articles	280	205	485

Source: Authors (2024)

Stage 5. Filtering procedures: After the final search, a rigorous filtering process was carried out, which eliminated 182 duplicate articles, 12 articles without essential information (such as year, author, or title), 84 articles published more than a decade ago (to ensure the relevance and timeliness of the studies), and 67 articles that were not aligned with the proposed theme. At the end of this process, 345 articles were excluded, resulting in a final portfolio of 140 articles.

Step 6. Identification of variables: The variables used for classification included impact factor (IF), number of citations (Ci), and year of publication, taken from databases and Google Scholar.

Step 7. Classification of articles using InOrdinatio: Using the InOrdinatio equation (Equation 1) and assigning $\alpha = 10$, articles with an InOrdinatio equal to or more excellent than 200.00 were selected, totaling 37 articles (Table 2).

Table 2 – Final Portfolio
Articles included in literature review
Dong et al. (2018); Li et al. (2016); Fagnoli et al. (2018); Garcia-Muiña et al. (2018); Kokare et al. (2023); Zhang et al. (2019); Bradley et al. (2018); Hoosain et al. (2020); Albizzati et al. (2021); Mendoza et al. (2019); Sanchez et al. (2020); Wohner et al. (2020); Gosavitr et al. (2023); Tushar et al. (2022); Vasishta et al. (2023); Schmidt et al. (2019); Lu et al. (2017); He et al. (2020); Cordella et al. (2021); Delogu et al. (2016); Huang et al. (2017); Lv et al. (2019); Yang et al. (2017); Visentin et al. (2019); Kokare et al. (2023); Mami et al. (2017); Kluczek (2019); Ding et al. (2021); Auer et al. (2017); Heidari et al. (2022); Ye et al. (2021); Bornschlegl et al. (2016); Hadi and Heidari (2021); Gasia et al. (2021); Zhang et al. (2020); Weerasinghe et al. (2021); Manco et al. (2023).

Source: Authors (2024)

Step 8. Search for full articles: The 37 articles were completed, allowing for a detailed analysis.

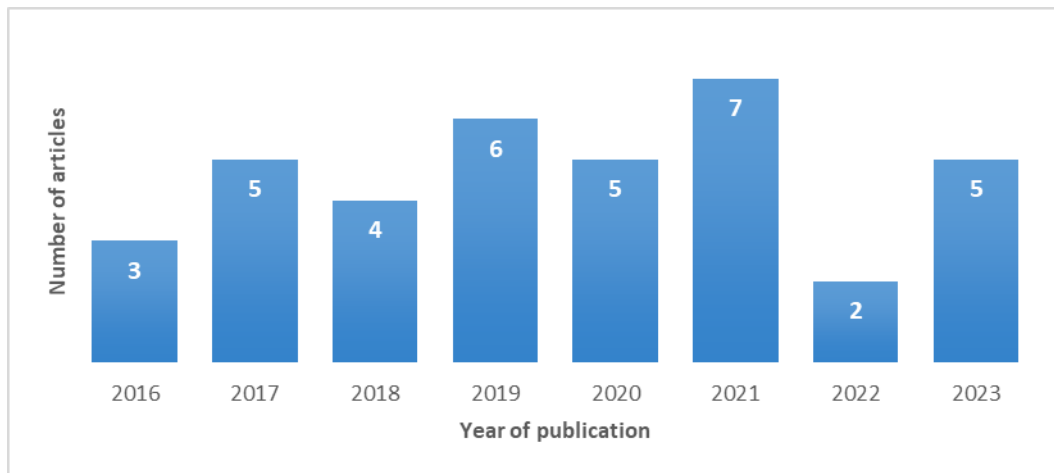
Stage 9. Final reading and systematic analysis of the articles: A systematic reading and analysis of the 37 articles was conducted using tools such as Excel, Mendeley, JabRef, and VOSviewer, focusing on the contributions of LCC to sustainability and economic optimization.

4. Results and discussion

4.1 Analysis of results

The analysis of the 37 articles selected provides a detailed overview of the evolution of research into Life Cycle Costing (LCC) in industrial production, emphasizing sustainability and economic efficiency. As illustrated in Figure 1, the distribution of publications over the years shows a growing academic interest in the subject, with significant variations between 2016 and 2023. The years 2019 and 2021 stood out, with peaks of 6 and 7 articles published, respectively, signaling the consolidation of LCC as an area of growing importance in scientific literature.

Figure 1 – Number of publications per year



Source: Authors (2024)

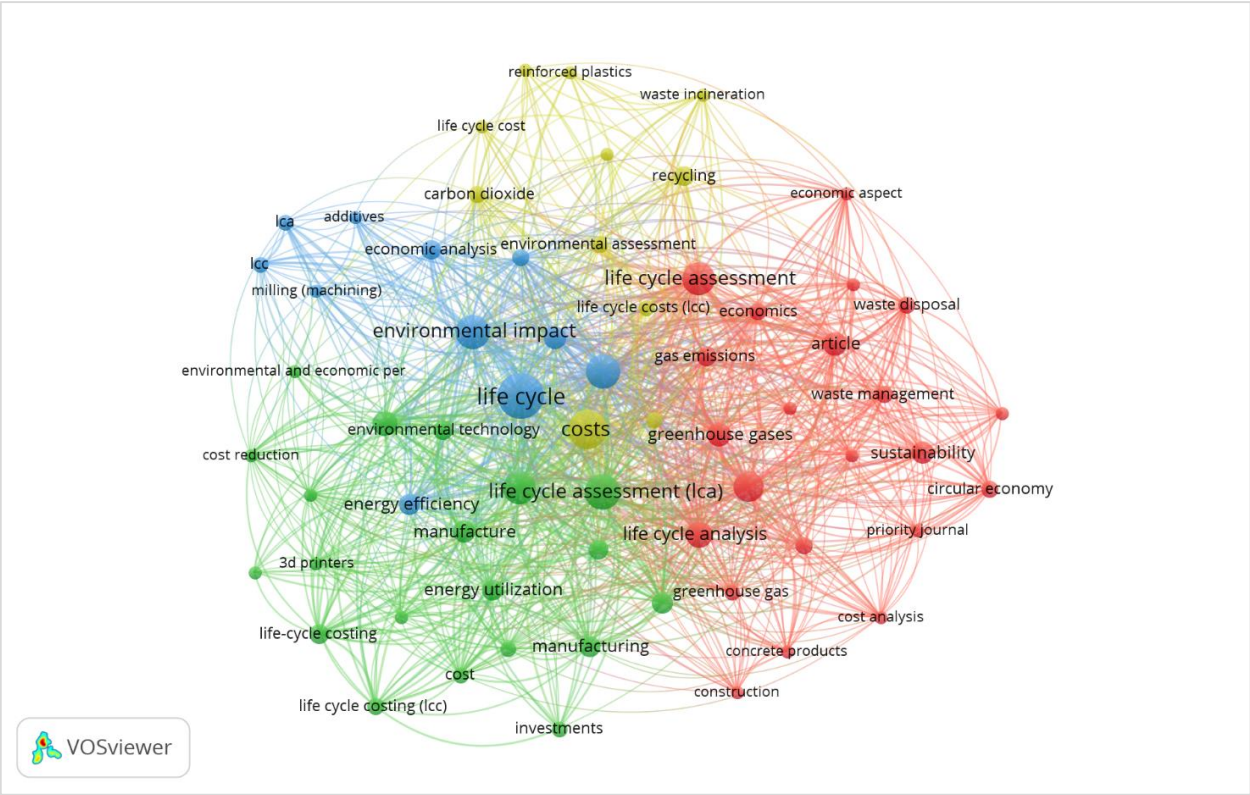
Among the most cited articles in the portfolio, five are particularly influential in the field. The article by Garcia-Muiña et al. (2018), entitled "The Paradigms of Industry 4.0 and Circular Economy as Enabling Drivers for the Competitiveness of Businesses and Territories," leads with 242 citations, a milestone in integrating Industry 4.0 and Circular Economy for business competitiveness. Li et al. (2016) also stand out with 205 citations in their study on the environmental and financial performance of mechanical recycling of carbon fiber-reinforced polymers. The article by Dong et al. (2018) contributes significantly with 184 citations, addressing the economic and environmental evaluation of CFRP waste management routes. Fargnoli et al. (2018) bring essential insights into implementing service-product systems for sustainability and customer satisfaction, accumulating 156 citations. Finally, the study by Hoosain et al. (2020), which explores the impact of the 4th Industrial Revolution's digital technologies and circular thinking on the Sustainable Development Goals, is cited 135 times.

Keyword analysis, conducted using VOSviewer software, identified the main thematic areas covered in the literature on LCC in industrial production. The keywords were grouped into four main clusters, as illustrated in Figure 2.

The Red Cluster concentrates on sustainability, circular economy, and waste management themes. Keywords such as "life cycle assessment" (17 occurrences), "life cycle costing" (14 occurrences), and "sustainability" (8 occurrences) emerge as central, reflecting the importance of these approaches in minimizing environmental impacts and promoting more sustainable industrial practices. In the Green Cluster, energy efficiency and economic and environmental performance stand out, with terms such as "cost-benefit analysis" (17 occurrences), "environmental economics" (7 occurrences), and "energy utilization" (7 occurrences). This cluster emphasizes cost-benefit analysis and energy efficiency as economic viability and industrial competitiveness pillars.

The Blue Cluster focuses on environmental impacts and strategic decision-making in the industrial context. Terms such as "environmental impact" (18 occurrences), "life cycle" (34 occurrences), and "decision making" (8 occurrences) reflect the growing relevance of considering environmental impacts in business decisions, particularly in strategic planning and sustainable innovation. Finally, the Yellow Cluster groups together keywords related to cost analysis and carbon management, with "costs" (25 occurrences), "carbon dioxide" (5 occurrences), and "recycling" (6 occurrences) standing out. This cluster highlights the importance of efficient management of costs and carbon emissions for the economic sustainability of industrial operations.

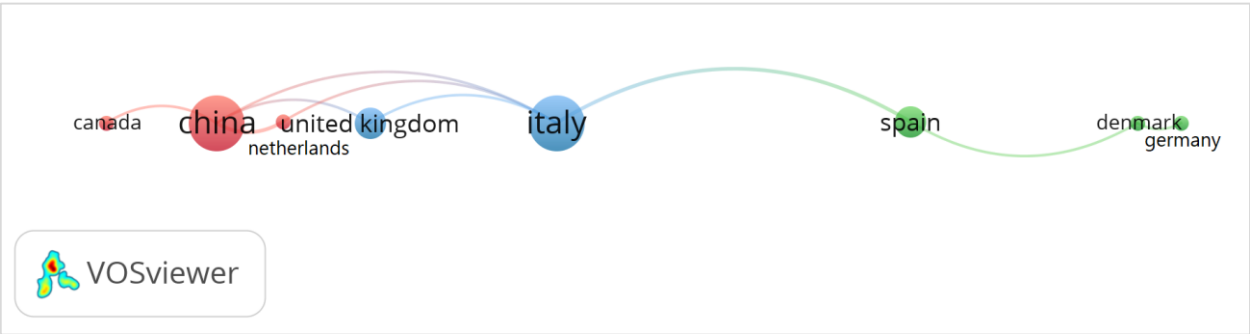
Figure 2 – Final Portfolio Keywords



Source: Authors (2024)

The analysis of international collaborations, visualized with VOSviewer, revealed a significant cooperation network between countries in research on LCC and its applications in industry. Figure 3 shows the network of co-authorships, highlighting eight countries with robust connections. China appears as one of the leading centers of collaboration, strongly connected to countries such as the United Kingdom and Italy, which also play important roles in scientific production on the subject.

Figure 3 – Collaboration network of countries



Source: Authors (2024)

4.2. Discussion

4.2.1. Progress in promoting sustainability

Life Cycle Costing (LCC) has established itself as a strategic tool for integrating sustainability into industrial management, as demonstrated by the 37 articles analyzed. Its ability to incorporate environmental considerations into cost analysis throughout the life cycle of products is highlighted by Albizzati et al. (2021) and Lu et al. (2017), allowing companies to efficiently manage the costs associated with carbon emissions and energy consumption. In addition, Mendoza et al. (2019) and Auer et al. (2017) highlight how the LCC encourages the adoption of more sustainable materials and processes, such as the use of recyclable materials and the implementation of the circular economy, which is essential for reducing waste and extending the useful life of products, as corroborated by Manco et al. (2023).

LCC also stimulates sustainable innovation, which is essential for companies seeking to stand out in an increasingly sustainability-oriented market, as Hadi and Heidari (2021) and Zhang et al. (2020) noted. In addition, LCC aligns economic and environmental goals with business strategies, resulting in superior operational performance and a more significant commitment to sustainability (DELOGU et al., 2016). Energy efficiency, another critical aspect addressed by LCC, is highlighted by Kluczek (2019) and Heidari et al. (2022), who show how reducing energy consumption contributes to lower operating costs and greenhouse gas emissions, as also noted by Vo Dong et al., (2018).

Finally, Weerasinghe et al. (2021) and Garcia-Muiña et al. (2018) emphasize that LCC offers an integrated view of economic and environmental impacts, allowing for more balanced decisions in line with contemporary sustainability demands.

4.2.2. Efficiency and economic optimization

LCC is widely recognized for its effectiveness in economic optimization, allowing a detailed analysis of costs throughout the life cycle of products. He et al. (2020) and Visentin et al. (2019) show that LCC facilitates the identification of opportunities to save money and avoid unexpected expenses, as well as providing an accurate assessment of return on investment (ROI). Li et al. (2016) reinforce that this integral approach helps in making more sustainable economic decisions in the long term.

Operational efficiency, highlighted by Sanchez et al. (2020) and Kokare et al. (2023), is maximized using LCC, which reduces waste and improves competitiveness by lowering operating costs. Yang et al. (2017) complement this by showing that LCC allows for the effective management of all costs associated with a product, resulting in higher profit margins.

In addition, LCC plays a crucial role in long-term cost management, as noted by Vasishta et al. (2023) and Gosalvitr et al. (2023), by enabling more accurate planning and budgeting, which is essential for companies' financial stability. Mami et al. (2017) point out that this predictability and cost control improves competitiveness in the market. LCC also promotes strategic cost management, aligning economic decisions with long-term objectives, as Huang et al. (2017) and Cordella et al. (2021) highlighted. This approach ensures that companies are well-prepared to face future challenges while maintaining economic efficiency and environmental responsibility.

In short, the review of the 37 articles confirms that LCC is essential for promoting sustainability and optimizing the economy in industries. Its application allows for more informed decisions, improving operational efficiency and ensuring long-term economic viability, which is crucial for companies in an increasingly competitive and sustainability-oriented business environment.

5. Conclusions

The main results of this study highlight that the Life Cycle Costing (LCC) technique is critical to promoting both sustainability and economic efficiency in industries. The analysis of the 37 articles revealed that LCC not only facilitates the identification and management of costs throughout the life cycle of products but also integrates environmental considerations into business decisions. By incorporating environmental impact and associated costs, LCC proved to be a robust tool that allows companies to reduce waste, improve energy efficiency, and, at the same time, mitigate greenhouse gas emissions. These aspects are crucial in a global scenario where pressure for more sustainable business practices is growing.

The interpretation of the results reveals that LCC is more than a cost management tool; it is a strategic approach that aligns companies' economic objectives with environmental goals, preparing them to face increasing regulatory demands and stakeholder expectations. By providing an integrated view of costs and benefits throughout the life cycle of products, LCC enables companies to make more informed decisions and develop strategies that ensure their competitiveness and long-term sustainability.

The importance of this research for the industrial field lies in validating LCC as a robust method applicable in different industrial contexts with a direct impact on sustainability and economic optimization. By providing empirical evidence on the benefits of LCC, this study contributes to disseminating cost management practices that are economically viable and environmentally responsible. In the face of growing demand for sustainable practices and economic efficiency, applying LCC offers companies a significant competitive advantage, enabling them to position themselves strategically in a market that values innovation and sustainability.

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