Área temática: Gestão socioambiental

Título do trabalho: PERSPECTIVES AND CHALLENGES IN THE INTEGRATION OF ARTIFICIAL INTELLIGENCE IN LEAN PRACTICES IN THE CONTEXT OF CIRCULAR ECONOMY

Resumo

O artigo analisa a contribuição da Inteligência Artificial (IA) para as práticas Lean no ambiente empresarial e seu impacto na promoção da Economia Circular, explorando como a integração da IA pode otimizar processos produtivos, reduzir desperdícios e melhorar a sustentabilidade, ao mesmo tempo em que aborda desafios relacionados à adaptação organizacional e à privacidade dos dados. Nesse sentido, a pesquisa, de cunho exploratório e bibliográfico, utiliza uma abordagem qualitativa para examinar essas interseções. Por fim, se entende que, apesar do potencial transformador da IA, é necessário enfrentar barreiras éticas e tecnológicas, e desenvolver frameworks para orientar sua implementação eficaz.

Keywords: Inteligência Artificial, Lean, Economia Circular, Sustentabilidade, Eficiência Operacional.

Abstract

This article analyzes the contribution of Artificial Intelligence (AI) to Lean practices in the business environment and its impact on promoting the Circular Economy. It explores how the integration of AI can optimize production processes, reduce waste, and improve sustainability, while also addressing challenges related to organizational adaptation and data privacy. In this regard, the research, which is exploratory and bibliographic in nature, uses a qualitative approach to examine these intersections. Finally, it is understood that, despite AI's transformative potential, it is necessary to address ethical and technological barriers and develop frameworks to guide its effective implementation.

Keywords: Artificial Intelligence, Lean, Circular Economy, Sustainability, Operational Efficiency.

1. Introduction

From the advent of the Industrial Revolution in the mid-18th century, mass production became possible, emerging in a context where cities grew as people shifted from agriculture to industry and commerce, resulting in increased productivity in the West. However, there was both poverty and progress due to low wages and poor quality of life for workers at the time (Allen, R. C., 2017). From the early period of industries to the present day, this economic system has been sustained through the intensive extraction of scarce resources, leading to the depletion of the natural environment. This model is embedded within the scope of the linear economy, known as “take-make-waste,” where what is produced moves in one direction, towards disposal (Ellen MacArthur Foundation, 2016). In this sense, it is worth highlighting the inefficiency of this process, as it not only brings an unnecessary end to raw materials but also contributes to greater damage related to climate change.

Within this scenario, the concept of the circular economy emerges, which essentially focuses on eliminating waste and pollution, circulating raw materials, and regenerating nature (Ellen MacArthur Foundation, 2016). This model—despite ambiguity around the definition of the concept (Kirchherr et al., 2017)—has been increasingly disseminated over the years, given the current discussions on environmental issues and the waste of natural inputs. To mitigate the impasse regarding the concept of the circular economy, it is necessary to propose structures to operationalize the concept from an academic and practical perspective (Nagai & Torres Junior, 2024). These structures not only facilitate a clearer and more consistent understanding of the concept but also promote the effective implementation of practices and policies aimed at a more circular and sustainable economy.

In the context of waste reduction, it is worth mentioning the Lean concept, known for the Toyota Production System (Womack, J. P., Jones, D. T., Roos, D., 1990). The Lean philosophy promotes production on demand, avoiding unnecessary inventories and reducing resource waste, in addition to continuously optimizing processes. By attributing due importance to Lean in promoting the circular economy, the environmental impact from companies can be reduced, resulting in sustainable gains for the planet, as well as greater organizational efficiency.

A tool that can significantly contribute to Lean practices in organizations is artificial intelligence (AI), which has been gaining increasing prominence. In the context of Lean practices, AI has great potential to improve process efficiency, reduce waste, and promote sustainable practices, aligning with both lean manufacturing concepts and the circular economy. Through intelligent automation and autonomous decision-making provided by AI, organizational processes can become more agile and efficient. Due to these factors, there is a trend for artificial intelligence to become increasingly present in the daily lives of large companies.

The idea of an intelligent machine emerged in the context of World War II, when the Allies needed ways to combat the Axis. Alan Turing was able to create a machine whose algorithm could decipher German soldiers' codes, weakening adversary strategies and being a key piece for the war to come to an end. In this perspective, Turing associated humans' ability to rationalize ideas with what a machine could do, citing this thought in the 1950 article "Computing Machinery and Intelligence," which discusses how to build intelligent machines (Harvard University, 2017).

In light of these considerations, the focus of the present study falls on the integration of artificial intelligence (AI) into Lean practices and its impact on companies. Although there are various approaches to implementing sustainable and efficient practices, this work specifically focuses on the intersection between AI and Lean practices in business operations, exploring how this integration can enhance the transition to a circular economy.

Thus, considering the synergy between Lean concepts, AI, and the circular economy, the guiding question is: How does the integration of artificial intelligence (AI) into Lean practices affect the operational efficiency of companies and their ability to promote an effective transition to the circular economy, considering additional challenges, ethical aspects, and security involved? From this perspective, it is essential to investigate the impact of AI integration into Lean practices on the operational efficiency of companies and their transition to the circular economy in light of contemporary challenges faced by the business environment. Understanding the effects of this integration allows for the exploration of opportunities for improvements in operations and sustainability, addressing ethical, security, and operational issues to maximize benefits for organizations and society.

The general objective (GO) of this article is to analyze the contribution of artificial intelligence to the objectives of Lean practices in the business environment, evaluating whether its integration truly results in benefits aligned with the principles of the circular economy. The specific objectives involve: i) exploring the challenges and additional complexities that AI integration can bring to the organizational environment (SO1); understanding the ethical and security aspects of AI application in companies (SO2); and iii) identifying best practices for implementing AI in Lean practices, aiming to facilitate adoption and maximize operational and sustainable benefits (SO3).

2. Literature Review

2.1. Circular Economy

The concept of the circular economy has garnered significant traction in recent years, although critics contend that its meaning varies among different individuals (Kirchherr et al., 2017). Despite the plethora of definitions concerning this topic, one of the most esteemed was proposed by the Ellen MacArthur Foundation (2016), which delineates CE as a system wherein material waste is minimized and nature is regenerated. This notion emerges in response to the imperative need to mitigate climate change, a phenomenon that has become increasingly prominent. The potential for resource circulation presents a compelling avenue, as finite resources can have their utility extended, thereby contributing positively to the natural environment.

The three tenets of the circular economy are predicated upon the following principles: addressing and eradicating waste and pollution (1), circulating products and resources themselves (2), and regenerating nature (3) (The Ellen MacArthur Foundation, 2016). Furthermore, the objectives of CE are manifold, given the diverse perspectives surrounding the concept. For an elucidate example, it is pertinent to mention that, according to Kirchherr et al. (2017), the primary objective of CE is the attainment of sustainable development. Franco et al. (2021, cited by de Oliveira, C. T., & Oliveira, G. G. A., 2023) highlight that the concept aims to guide organizations towards strategic decisions pertaining to sustainability. Hence, it is evident that the concept of economic circularity, in addition to prioritizing the preservation of nature and its biodiversity, also addresses corporate and societal needs.

Moreover, according to the World Economic Forum (2014, cited in Weetman, C. & Serra, ACC, 2019), projections estimate that the global population will reach 9 billion by the year 2030, necessitating even greater consumption of natural inputs in a scenario where their supply could be adversely affected by rising average global temperatures. In this context, the principles of the circular economy seek to utilize and circulate materials efficiently, contributing to a milieu where population demand is expected to increase.

From this vantage point, it is essential to underscore the study by Aguilar-Hernandez, G. A. et al. (2021), which employed a systematic approach and meta-analysis to investigate the impacts of transitioning to a circular economy, analyzing the macroeconomic, social, and environmental effects. The article scrutinized moderate and ambitious circular economy scenarios from 2020 to 2050, with particular emphasis on 2030. The ambitious scenarios projected an increase in GDP ranging from 0.1% to 14.0%, while the moderate scenarios indicated smaller increases. Concerning employment, the ambitious scenarios demonstrated a significant rise, whereas the moderate scenarios exhibited minimal impacts. Both scenarios evidenced a reduction in CO_2 emissions. The analysis concludes that the transition to a circular economy can yield macroeconomic, social, and environmental benefits by 2030. Moreover, considering the premise of efficient and productive utilization of the planet's resources, the proposed changes could impact the global supply chain and potentially reduce raw material costs (The Ellen MacArthur Foundation, 2023). This underscores that the concept of more efficient resource utilization and nature regeneration can have salutary impacts on the economy.

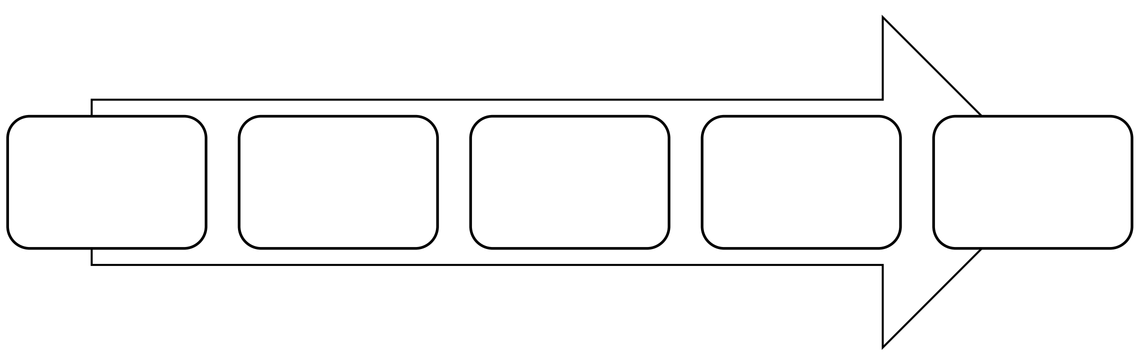
Therefore, the concept of the circular economy aspires to ensure a future characterized by reduced resource wastage, with a focus on positively influencing both the natural environment and the global economic system. To actualize the full potential of this concept, it is imperative to disseminate novel ideas that can foster more efficient and less wasteful production.

2.2. Lean Practices and Circular Economy Relationship

In accordance with the topic of waste reduction envisioned within the scope of the circular economy, it is worth mentioning the concept of Lean production (or popularly known as lean manufacturing), disseminated by authors James P. Womack, Daniel T. Jones, and Daniel Roos in the book "The Machine that Changed the World" in 1990 (Briales, JA, 2022). The focus of Lean is on using inputs as efficiently as possible, aiming to avoid as much waste as possible on the production line. In this aspect, lean manufacturing emerges as an alternative to the mass production practices of the linear economy, which not only do not seek to reduce waste but also do not contribute to regenerating nature.

Womack and Jones (1997, cited in Briales, JA, 2022) defined the five steps of the lean manufacturing process. This flowchart underpins the importance of each step of the method, emphasizing how Lean can be crucial in ensuring operational efficiency. In this context, defining customer value (1) highlights the importance of understanding stakeholder needs and aligning processes accordingly; establishing flows (2) concerns creating a sequence of operations to ensure minimal interruptions; letting the flow flow (3) is related to the need to mitigate obstacles that may hinder production pace; adopting a pull production system (4) focuses on producing only what is necessary in terms of actual demand, to avoid unnecessary stocks and ensure efficiency, as seen in the Toyota Production System; and finally, the pursuit of operational excellence (5), which focuses on waste elimination and continuous process improvement. It is clear, therefore, that the Lean production approach not only emphasizes the importance of each stage of the process but also highlights how the application of these principles is essential for waste reduction and ensuring efficiency.

Figure 1 - Lean’s five steps.



Source: The Authors (2024)

In recent years, increasing pressures from governments, regulatory bodies, and society have led companies to align business practices with principles of environmental sustainability (Caldera, H. T. S., Desha, C., & Dawes, L., 2017). Thus, for example, the Lean philosophy - which encompasses concepts of production efficiency and sustainable practices - was present in the case of Toyota, as the company focused on waste reduction and proved to be efficient (Herron and Hicks, 2008, Ōno, 1988, cited in Caldera, H. T. S., Desha, C., & Dawes, L., 2017).

Considering how the Lean mindset focuses on the efficiency of its resources, it is necessary to emphasize its opposition to traditional forms of production (Nagai & Torres Junior, 2024), which is of paramount importance for the transition to a circular economy. From this perspective, it is possible to observe synergy between the two, where lean manufacturing can contribute to regenerating nature because its focus on reducing waste means less pollution during production. Moreover, the efficient use of resources also poses a significant benefit to nature, as the extraction of natural inputs can be reduced while maintaining production at the same scale.

Thus, the practices of the Lean philosophy in organizations can be of paramount importance for the transition to the circular economy, creating a scenario where resources are used more efficiently and environmental impacts are significantly reduced. This harmonious integration of both concepts not only boosts the competitiveness of companies but also contributes to building a more balanced and resilient future in terms of sustainability.

2.3. Artificial Intelligence

Artificial intelligence (AI) has been increasingly in the spotlight in recent years, especially with the emergence of new tools from companies like Microsoft, Nvidia, OpenAI, Adobe, among other major technology firms. AI follows the idea of building machines that possess similar capacities to humans in perception, reasoning, and processing vast amounts of data (Berente et al., 2021; Wang et al., 2019 cited in Schoormann et al., 2023). From this perspective, there are many possibilities that this technology can offer to the population.

Furthermore, AI incorporates different algorithmic approaches (Schoormann et al., 2023), where it is necessary to highlight the composition of artificial intelligence, which includes subsets of Machine Learning (ML) and Deep Learning (DL). Although AI is proficient in solving logically defined problems, it often fails in tasks that require pattern recognition at higher levels (e.g., speech recognition or image classification). It is in these more complex tasks that ML and DL methods excel (Choi, R. Y., et al., 2020).

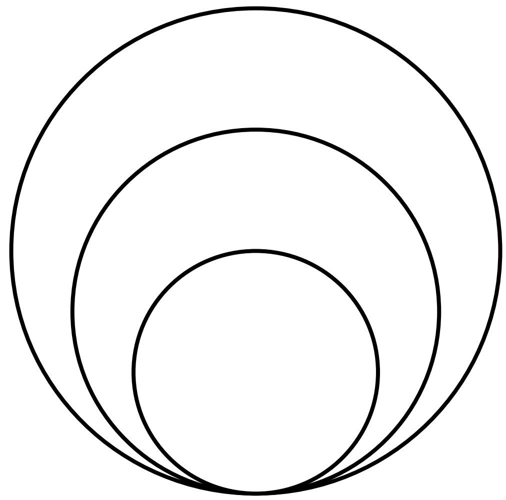
Machine Learning is defined as algorithms that have the ability to learn through patterns and experiences, in addition to the provided data, with the aim of making predictions (Bishop, 2006). For example, in machine learning, a computer is provided with a dataset and associated outputs, where the computer learns and generates an algorithm that describes the relationship between the two (Choi, R. Y., et al., 2020). In this sense, ML can be used as a highly useful tool from data analysis to automation of complex tasks.

Within ML, there are four commonly used learning methods, each useful for solving different tasks: supervised (1), where supervised learning employs patterns in the training dataset to associate features with the target, allowing an algorithm to make predictions on future datasets. This method is called supervised because the model deduces an algorithm from the feature-target pairs, being informed by the target about the accuracy of its predictions; unsupervised (2), unlike supervised learning, unsupervised learning aims to identify patterns in a dataset and categorize individual instances in the dataset into such categories. These algorithms are unsupervised because the patterns that may or may not exist in a dataset are not informed by a target and are left to be determined by the algorithm; regarding semi-supervised (3), it can be considered as an intermediate point between supervised and unsupervised learning and is particularly useful for datasets containing both labeled and unlabeled data; and finally, reinforcement learning (4), which involves training an algorithm for a specific task where there is no single correct answer, but a general outcome is desired, being the closest attempt to model human learning experience, as it also learns through trial and error, in addition to data alone (Choi, R. Y., et al., 2020). Thus, these methods offer distinct approaches to solving a variety of problems, given the diversity and flexibility of the Machine Learning field.

Deep Learning is a subfield of Machine Learning that attempts to learn high-level abstractions in the data using hierarchical architectures (Yanming Guo, et al., 2016). DL is widely used to solve problems in speech recognition, image recognition, object detection, and natural language processing. In this sense, the concept is named "deep" because it involves more than one stage of nonlinear feature transformation (Anurag Bhardwaj, Wei Di, Jianing Wei, 2019).

Deep Learning uses artificial neural networks (ANNs) with multiple layers to learn complex patterns in data. Therefore, DL can extract high-quality representations from unstructured data (e.g., images, audio, and text). These deep neural networks are composed of many interconnected neurons, which can learn automatically from data, rather than relying on predefined rules. The concept of deep learning has revolutionized many areas of AI, including computer vision and natural language processing, as well as statistical techniques, such as Support Vector Machines (SVM), which are often integrated into deep learning for classification and regression problems (Dong, S., et al., 2021).

Figure 2 - Deep Learning vs. Machine Learning.



Source: adapted from FourWeekMBA (2024)

The idea of an intelligent machine emerged in the context of World War II, where the Allies needed to find ways to combat the Axis powers. Alan Turing was able to create a machine whose algorithm could decipher the codes of German soldiers, weakening enemy strategies and being a key factor in bringing the war to an end. From this perspective, Turing associated the human capacity to rationalize ideas with what a machine could potentially achieve, articulating this notion in his 1950 article "Computing Machinery and Intelligence," which delves into the theme of constructing intelligent machines (Harvard University, 2017).

The initial milestone of AI occurred in 1956 with the Logic Theorist program, where researchers aimed to create algorithms in machines that mimicked the human intellectual capacity to solve problems, drawing inspiration from Alan Turing's ideas. The project was part of the historic Dartmouth Summer Research Project on Artificial Intelligence (DSRPAI) conference, where the term "artificial intelligence" was coined by John McCarthy. However, the conference did not meet the organizers' expectations, although there was consensus that AI was achievable (Harvard University, 2017).

Over the subsequent decades, this idea was portrayed in pop culture. For example, the book "Do Androids Dream of Electric Sheep?" (1968), later adapted into the film "Blade Runner" (1982), depicts a reality where replicants - androids that are an allusion to the concept of artificial intelligence - possess advanced cognitive abilities, even developing feelings and self-awareness. Although there was no significant advancement in AI at the time of the release of this work portraying a dystopian future, it already raised questions about how far the creation of an intelligent machine could go.

Despite all the ethical implications surrounding artificial intelligence, it has become increasingly present in our daily lives. In contemporary times, we live in the era of Big Data - a context where there are significant challenges for researchers and professionals due to the exponential growth rate of data, surpassing humans' current capacity to design storage and analytical systems capable of managing large amounts of data effectively (Begoli & Horey, 2012, cited in Ibrar Yaqoob, et al., 2016). For example, artificial intelligence - through its immense amount of stored data - can perform many applications that can benefit the population (e.g., credit analysis for financial institutions, accurate disease diagnoses based on medical images, autonomous vehicle operation enhancing traffic safety, among others).

Despite the many benefits of AI, it is also necessary to highlight concerns regarding the technology. Due to its high capacity for process automation and information processing, artificial intelligence can perform certain activities with greater performance than humans (Kai-Fu Lee, 2021). Furthermore, as AI learning technology expands, it will come to know us better than we know ourselves, as digital applications (websites, apps, among others) may understand not only our motivations for each click - already captured today - but also our actions, movements, and speech - in a secure manner, within privacy limits. Thus, with the elucidation of AI's high capacity, it is possible that the way we work will change, as a large portion of data becomes digitized, AI algorithms can also contribute to decision-making. Regarding manufacturing jobs, according to Kai-Fu Lee (2021), the risk of job reduction becomes greater because robots with AI technology can perform multiple tasks throughout the day without interruptions. Therefore, the increasing integration of artificial intelligence into our lives is fundamentally reshaping the nature of work and raising important questions about its social and economic impact.

Thus, the possibilities for innovation behind artificial intelligence are undeniable. The tool is increasingly becoming part of our lives, assisting us in repetitive and manual tasks, as well as contributing to reasoning. However, implications regarding unemployment, ethics, and privacy surrounding AI also arise. Therefore, it is necessary for these issues to be addressed to mitigate such risks, ensuring that artificial intelligence is deployed responsibly and ensures inclusion to harness its benefits.

2.4. AI as a Key for a Transition to Circular Economy

Currently, artificial intelligence and the circular economy are two megatrends that, when in synergy, can contribute to a regenerative and sustainable future. Based on AI's potential across various sectors, the transition to a circular economy can occur quickly and effectively, even faster than it would without AI (The Ellen Mac Arthur Foundation, 2019). In addition to exploring the benefits, it is also important to analyze the challenges and what can be done to ensure the equitable and comprehensive integration of both into society.

In this regard, there are three potential opportunities for how AI-enabled technologies can contribute to the circular economy: product design - the projection - of circular products, components, and materials (1), operating circular business models (2), and optimizing infrastructure to ensure circular flows of products and materials (3) (The Ellen Mac Arthur Foundation and Google, 2019).

Artificial intelligence can contribute to product design by being a key factor in substituting harmful chemicals and materials. AI can assist in distributed manufacturing with technologies like 3D printing, using locally available materials, ensuring they have value as they are recycled (The Ellen Mac Arthur Foundation and Google, 2019). The power of AI lies in its ability to continuously improve with more data, according to Kai-Fu Lee (2021). However, the obstacle to harnessing the potential of artificial intelligence in this regard lies in the fact that much of the data is proprietary and inaccessible, limiting the possibilities for using AI in material design.

Operating circular business models involves disrupting commercial functions (sales, marketing, customer support, among others) based on the principles of the circular economy. According to a study by the Ellen Mac Arthur Foundation and Google (2019), an example of how artificial intelligence can be used in this context relates to dynamic pricing, as there is complexity in determining prices for product-as-a-service or recycled items, given the multitude of variables that affect the price of a tradable item (Roberts, H., Zhang, J., Bariach, B. et al., 2022). From this perspective, Machine Learning - which is part of artificial intelligence - can be a key tool for this impasse, due to its use of statistical techniques and knowledge patterns. In this view, the application of dynamic pricing through artificial intelligence offers a sophisticated and adaptable approach to determining the value of recycled and reused products, dynamically considering the influence of various variables that impact their price over the lifecycle.

Furthermore, it is necessary to highlight one of the main characteristics of the circular economy, which involves the regeneration of raw materials, in the sense that products are consumed and reused as much as possible. However, there are some challenges for sustainable practices related to the circular economy idea due to the difficulty of waste sorting. The effective recovery of valuable materials requires homogeneous and pure material and product flows. At this point, the better the material flows are pre-sorted and separated, the higher the level of recovery, the more components can be identified for reuse and remanufacturing, and the higher the quality of the materials extracted during recycling (The Ellen Mac Arthur Foundation and Google, 2019). To mitigate the challenges involved, AI can be used in a context where the machine is trained to detect glass, metal, and plastic objects using different shapes, levels of degradation, sizes, colors, and different levels of contamination (Ahmed and Asadullah, 2020). Thus, artificial intelligence enables enhanced valorization of materials and products within the circular economy.

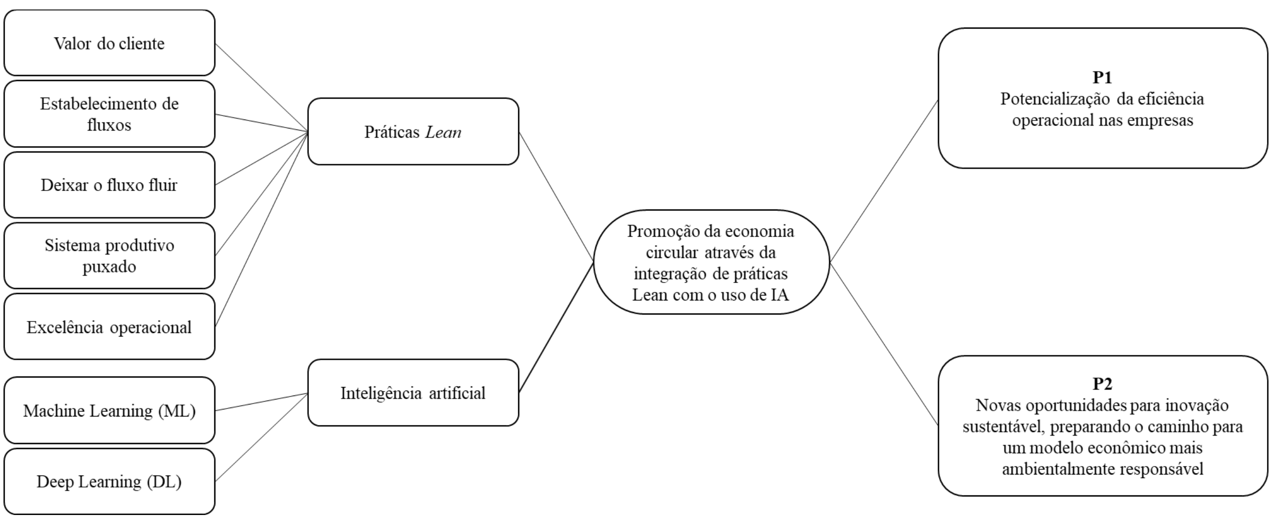
Thus, artificial intelligence can be a key factor in transitioning to the circular economy by combining AI's adaptive and learning capabilities with the principles of the circular economy, paving the way for a smarter and more responsible approach to resource use.

2.5. Conceptual Framework

The conceptual framework of this article is represented by the integration of key variables that incorporate the concepts of Lean practices and Artificial Intelligence (AI) for the promotion of a circular economy. The variables associated with Lean practices include Customer Value, Flow Establishment, Operational Excellence, Pull Production System, and Continuous Flow. The AI variables are centered on Machine Learning (ML) and Deep Learning (DL), which are technologies that provide advanced data processing and prediction capabilities.

These variables form the basis for explaining the propositions that represent anticipated responses to the research questions. This approach helps guide the information-gathering process, ensuring that the research is systematically directed towards achieving the study's objectives.

Figure 3 - Conceptual framework.



Source: The Authors (2024)

In this article, (P1) indicates that the integration of Lean practices and AI can increase operational efficiency in companies, optimizing processes and reducing waste, which is a critical aspect of achieving a circular economy. Meanwhile, (P2) postulates that by facilitating sustainable innovation, this integration paves the way for a more environmentally responsible economic model, ultimately contributing to the broader goals of sustainability and resource efficiency.

These propositions were designed to provide a deeper understanding of the relationships between key variables and to identify the factors that influence the success of the transition to a circular and sustainable economy. The propositions will be tested and explored through the methodological approaches outlined in this study.

3. Research Methodology

To achieve the objectives proposed by the study, an exploratory research method with a bibliographic approach was employed, analyzing various materials already developed by experts who are references in each theme mentioned in the article. The qualitative approach was used to analyze the integration of artificial intelligence into Lean practices and to promote the transition to a circular economy. In this regard, according to Waters, C. K. (2007), philosophical research on exploratory experimentation began with the observation that experimentation in science is not always guided by theory; sometimes, experimentation is exploratory in nature. Following this line of thought, the use of exploratory methods allows new perspectives to emerge, enabling discoveries that go beyond the limits of established theories.

According to GIL (2008), bibliographic research uses previously developed material, such as books and scientific articles, and is essential for covering a wide range of phenomena, especially when the necessary data is geographically dispersed. It is particularly useful in historical studies, where past events can only be known through secondary sources. However, this approach presents risks, as the data may have been collected or processed incorrectly. To minimize these risks, researchers should verify the conditions under which the data were obtained, thoroughly analyze the information, and compare various sources to avoid errors.

Furthermore, according to Stebbins R.A. (2001), to understand any phenomenon well, it is better to start by observing it in broad and non-specialized terms. In other words, first the forest, then study its trees individually. The tendency to rely on formulas reverses this precept, causing many people to get lost in the forest, while also contributing to problems of incomplete explanation and failed prediction about social life.

The choice to adopt exploratory research as a study method was based on the need to obtain a broad and initial understanding of the integration of artificial intelligence into Lean practices within the context of the circular economy. Considering that this is an emerging theme and is in the stage of conceptual development, the choice of the exploratory approach is justified by its ability to reveal the underlying complexities and intersections between the objects to be analyzed.

Therefore, the use of exploratory and bibliographic research was a strategic choice to address a theme as dynamic and evolving as the one this work proposes to tackle. By adopting a qualitative and non-restrictive approach, it was possible to explore the inherent intersections and complexities of these concepts, providing a robust and well-founded initial view that can serve as a basis for future studies.

4. Analysis and Discussion of Results

Aiming to understand the effectiveness of integrating artificial intelligence into business practices - aligned with Lean concepts and the circular economy - data were collected through exploratory research of a bibliographic nature, seeking to identify the complexities of intersection among the concepts explored by the study. Thus, through this analysis, the goal is to provide a broader view of how the combination of these elements can effectively contribute to optimizing processes, reducing waste, and promoting sustainability within organizations.

From this perspective, the reviewed literature emphasizes the trend of implementing AI in Lean practices. According to Chomklin, A. et al. (2023), the theme related to the use of AI in modern production has seen a significant increase in publications in recent years. The research highlights that despite the existing promises of efficiency associated with AI, there are certain challenges, such as decision-making and data privacy. This underscores the need to mitigate these challenges in order to optimize outcomes in environments utilizing lean manufacturing.

Artificial intelligence techniques are increasingly being applied in predictive maintenance within the production environment, using Machine Learning algorithms—such as decision trees, regressions, SVM, among others - to analyze large volumes of data and provide the necessary understanding regarding the state of machines. Additionally, Deep Learning techniques - which involve deep neural networks—are the most commonly used due to their ability to handle complex data patterns that are not easily captured by traditional ML algorithms, such as in images, videos, or other unstructured data sources.

Moreover, Antosz, K. et al. (2020) also highlight that the integration of AI and the exploration of new tools can further enhance Lean practices, emphasizing the practical application of decision rules and expert systems. For instance, decision rules - obtained through Lean methods - offer a comprehensive view of the relationships between productive activities and the outcomes achieved, allowing companies to adjust their strategies to better align with the principles of this approach. By implementing an expert system based on these rules, companies can select more effective actions and integrate them into existing processes. This system improves the effectiveness of maintenance practices and contributes to continuous improvement, helping to reduce waste and increase operational efficiency.

In this line of reasoning, the studies discussed by Antosz, K. et al. (2020) provide a solid foundation for the construction and organization of processes. Although there are limitations in the research, particularly concerning the principles and methods presented, they are widely applicable in production contexts. Therefore, the research suggests that, to maximize the benefits of integrating AI with lean manufacturing, it is essential to explore new tools and recommended methods.

Within the conceptual framework of the article, it is necessary to understand how the integration of AI with lean manufacturing can promote the circular economy. In this regard, it is first important to differentiate the circular economy (CE) from sustainability, as although both share environmental concerns, the difference lies in certain objectives: CE is a concept currently on the rise and focuses on ensuring minimal waste and the regeneration of nature, while also emphasizing responsibility on the part of producers—i.e., the companies themselves. The concept of sustainability has a broader scope, as it involves not only the environment but also society and the economy. Furthermore, sustainability distributes responsibilities among all economic agents (Geissdoerfer, M., 2017).

Thus, Ciliberto et al. (2021) highlight the importance of integrating lean manufacturing with the principles of the circular economy and Industry 4.0 technologies—including AI—as an effective approach to optimizing processes, reducing waste, and promoting sustainability in organizations. This combination allows companies to develop business strategies oriented towards sustainability while also anticipating consumer choices and regulatory decisions. The digitalization of production processes, made possible by AI, helps create more efficient and customized supply chains, minimizing the use of natural resources and promoting the recovery of raw materials through reverse logistics. However, the implementation of this integrated approach still faces significant challenges, particularly concerning stakeholder engagement to support the transition to more sustainable and digitalized production processes. Despite these barriers, the combination of these concepts presents considerable potential to transform industrial production, aligning with the goals of an economy that prioritizes efficient resource use and waste reduction.

Therefore, this evidence underscores the relevance of the intersection between artificial intelligence and the Lean concept for promoting the circular economy. However, the cited challenges elucidate the need for a cautious approach to the application of these technologies and concepts, especially regarding practical adoption by companies. Additionally, it is worth noting that, as a bibliographic review, the present research is limited by the nature and quality of the available sources, which may affect the generalization of the results. Moreover, the absence of empirical data prevents a direct assessment of the impact of these integrations in real production environments.

5. Conclusions

In this way, the study thoroughly explored how the application of AI, when aligned with the principles of lean manufacturing, can offer substantial gains in terms of operational efficiency, waste reduction, and alignment with sustainable activities— all of which are crucial components for ensuring the transition to a regenerative economic model.

The integration of AI with Lean has the potential to transform business operations, given AI's ability to process large volumes of data in real-time, continuously optimize production processes, eliminate waste, and enable more agile and accurate decision-making. From this perspective, ethical considerations are also important, as AI-driven automation raises concerns about job security, data privacy, and more. Under these conditions, as companies adopt AI to enhance their operations, it is necessary for these technologies to be implemented transparently and responsibly.

Moreover, the study identified that the effective integration of AI into Lean practices can accelerate the transition to a circular economy, analyzing that this transition depends on various factors, including companies' ability to adapt their operations—a scenario where AI can be considered a catalyst in this process.

However, the article diligently demonstrates that this integration is not without challenges. Implementing AI in Lean environments requires not only technological adaptation but also substantial changes in organizational structures and corporate culture. Additionally, data security and privacy remain critical issues, especially in a scenario where AI plays an increasingly central role in business decision-making.

Furthermore, one of the main challenges identified is stakeholder engagement, based on the principle that the transition to more sustainable and technologically integrated practices requires the involvement of everyone from managers and workers to consumers. Thus, adopting Lean practices along with the potential of artificial intelligence requires a shift in organizational mindset that values continuous innovation, experimentation, and flexibility. In this sense, companies need to be willing to invest in training and upskilling their workforce to ensure that everyone involved is aligned with the new processes and technologies.

Within the context of the study, although the article may offer a qualitative and significant contribution to the theoretical understanding of these integrations, it is important to highlight the need for future research that can provide a more fruitful empirical basis for the conclusions of this study. While the literature review has provided a comprehensive view of the possibilities and challenges, the absence of empirical data limits the ability to analyze and draw conclusions for specific contexts.

Additionally, the creation of theoretical and methodological frameworks that facilitate the materialization of these concepts within companies will be of great value for advancing research and practice in this field. These frameworks can serve as guides for companies that wish to implement AI in their Lean operations in a way that aligns with the principles of the Circular Economy, helping to identify best practices, avoid common pitfalls, and maximize benefits for both organizations and society as a whole.

Thus, companies that aim to promote the transition to a more circular economy should adopt an expansive approach to innovation and sustainability, which includes not only the adoption of new technologies but also the reevaluation of business models, production strategies, and supply chains to ensure they align with the principles of the Circular Economy.

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