Journal Homepage: - www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

ISSN NO. 2320-5407

Article DOI: 10.21474/IJAR01/19395
DOI URL: http://dx.doi.org/10.21474/IJAR01/19395

RESEARCH ARTICLE

AI-DRIVEN CIRCULARITY INDEX: A COMPREHENSIVE METRIC FOR EVALUATING PRODUCT LIFECYCLE SUSTAINABILITY

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Manuscript Info

Manuscript History
Received: 28 June 2024
Final Accepted: 30 July 2024
Published: August 2024

Key words:-
Circular Economy, Product Lifecycle, Sustainability, AI, Machine Learning, Circularity Index, Material Selection, Modular Design, Recyclability, Resource Efficiency

Abstract

Sophisticated instruments are required for the analysis of sustainability in a product in all its complexity during a transition towards a circular economy. In this respect, the new metric presented in this article is the AI-driven Circularity Index, which assesses product circularity according to four dimensions: material selection, modular design, recyclability, and resource efficiency. This index-powered by machine learning - provides predictive insights and actionable recommendations toward product lifecycle sustainability, hence adding a more solid solution to the more pressing issues of traditional linear economic models.

Introduction:-

The environmental impact of the linear economic model calls for a paradigm shift to a circular economy. The success of this shift depends on the ability of companies to measure and increase the sustainability of their products throughout their lifecycles. Traditional metrics usually fail to provide a holistic dynamic assessment. In this regard, this paper introduces the AI-driven Circularity Index as a holistic technology-driven tool, conceptualized for the assessment and improvement of product circularity through advanced data analytics and machine learning.

Methods and Procedures:-

Data Foundation

First of all, to create an AI-driven Circularity Index, there will be a need to gather and integrate relevant comprehensive data. This dataset forms the foundation of the index, as detailed and meaningful analysis must be done along the various life cycle stages of the circularity of a product.

Material Composition:

Information is available on the kinds of materials used in making the product, covering several key aspects:

1. **Sourcing:** The sourcing is where information on the origin of materials is important, including what is sourced from renewable versus non-renewable resources. Geographical location, suppliers' environmental practices, and transportation impacts are also critical.
2. **Environmental Impact:** Environmental impact is described in terms of various indicators, including carbon footprint, water usage, and potential for pollution. It provides an understanding of the total amount of environmental burden ascribed to materials under investigation.
3. **Recyclability:** Among the most important parameters that go into judging the degree of circularity is the potential recyclability of materials. This dataset shows the data regarding which recycling processes exist for every material, the efficiency of those processes, and the percentage that its material could recover.

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Product Design:

This will drastically affect the overall circularity of the product. That shall include several design-related features:

1. **Modular Components:** A product will tend toward circularity if it contains modular components that are easily replaceable or upgradable. For this dataset, it considers the number, type, and interchangeability of modular components.
2. **Disassembly Feasibility:** The difficulty with which a product is disassembled also concerns its recyclability and repairability. This dataset provides information on the use of tools, time spent, and the prospect of damage in the disassembly process.
3. **Repair Potential:** The probability of long-lasting products is more related to those that can easily be repaired. This information includes data on the availability of repair services and spare parts and their costs.

Recycling Assessment:

It also includes an overall assessment of recyclability for the product. Recyclability Assessment:

1. **Material Recoverability:** This can be considered a key factor in the process of recycling, depending on the percentage of materials recoverable. The dataset includes data on the rate of efficiency of recycling processes for different materials.
2. **Recycling Rates:** The rate at which a product is recycled, rather than landfilled. This could include data about industry-wide recycling rates and product-specific rates.
3. **End-of-Life Scenarios:** These are the different end-of-life scenarios of a product that may be in landfills, incineration, or recycling. The environmental impact of each scenario is also considered.

Resource Consumption:

The final component of the dataset focuses on the resources consumed during the product's lifecycle:

1. **Energy Consumption:** The amount of energy used during the production, use, and disposal of the product is a key metric. The dataset includes information on energy sources (renewable vs. non-renewable) and the efficiency of energy usage.
2. **Water Usage:** Water is a critical resource, and its consumption during the product lifecycle is tracked. The dataset includes information on the amount of water used, its source, and its impact on local water resources.
3. **Material Usage:** The efficiency with which materials are used during production is also tracked. This includes data on material wastage, recycling of production scraps, and the overall material intensity of the product.

AI Modeling

The AI-driven Circularity Index leverages advanced machine learning algorithms to process the extensive dataset described above. The AI modeling process is divided into three key stages: Prediction, Optimization, and Index Calculation.

Prediction:

1. **Data Preprocessing:** The raw data collected is first cleaned and preprocessed to ensure it is suitable for analysis. This involves handling missing values, normalizing data, and transforming categorical variables into numerical formats.
2. **Feature Engineering:** Relevant features are extracted from the dataset to be used in the machine learning models. This step involves selecting the most significant variables that influence product circularity, such as material toxicity, repair potential, and energy consumption.
3. **Model Selection:** Various machine learning models are explored, including regression models, decision trees, and neural networks. The model that provides the best predictive accuracy for product circularity is selected.
4. **Training and Validation:** The selected model is trained on a portion of the dataset, with the remaining data used for validation. The model's performance is evaluated based on its ability to accurately predict circularity metrics such as material recovery rate and product lifespan.
5. **Forecasting:** The trained model is then used to forecast a product's long-term environmental impact. This involves predicting future values for key circularity metrics based on evolving factors, such as changes in recycling technologies or shifts in material sourcing practices.

Optimization:

1. **Objective Function:** An objective function is defined to optimize the product design for circularity. This function considers multiple factors, including material cost, environmental impact, and product performance.

2. **Design Modifications:** The AI model suggests potential design modifications that could enhance circularity. For example, it might recommend substituting a non-recyclable material with a recyclable alternative or increasing the modularity of the product.
3. **Cost-Benefit Analysis:** The potential costs and benefits of each design modification are analyzed. This includes evaluating the financial impact, the potential increase in product lifespan, and the reduction in environmental impact.
4. **Iterative Optimization:** The optimization process is iterative, with the model continuously refining its recommendations based on the latest data. This ensures that the final design is both cost-effective and highly circular.

Index Calculation:

1. **Scoring System:** A scoring system is developed to assign weighted scores to each dimension of circularity (material circularity, design for circularity, and resource efficiency). The weightings are based on the relative importance of each dimension in achieving overall product sustainability.
2. **Composite Index:** The individual scores for each dimension are combined to calculate the overall Circularity Index. This composite index provides a single, easy-to-understand metric that reflects the product's overall circularity.
3. **Benchmarking:** The Circularity Index can be benchmarked against industry standards or compared across different products. This allows businesses to gauge their performance relative to competitors and identify areas for improvement.

Results:-

The application of the AI-driven Circularity Index across various industries yields significant insights into the circularity of different products. The following section presents detailed case studies, each illustrating the practical application of the Circularity Index and its implications for product design, manufacturing, and sustainability.

Case Study 1: Electronics Industry

Product: Smartphone

Material Circularity Score:

1. **Assessment:** The Material Circularity Score for the smartphone is calculated based on the percentage of recycled materials used, the material recovery rate during recycling, and the material toxicity index. In this case, the smartphone utilizes 30% recycled materials, with a material recovery rate of 75%. The toxicity index is low due to the use of non-toxic materials such as aluminum and glass.
2. **Score:** The Material Circularity Score is calculated as 7.5/10, indicating a relatively high level of material circularity. This score suggests that the smartphone is made from materials that are both recyclable and environmentally friendly.

Design for Circularity Score:

1. **Assessment:** The Design for Circularity Score evaluates the smartphone's modularity, repairability, and product lifespan. This smartphone model features easily replaceable components such as the battery and screen, which enhances its modularity. Additionally, the design is repair-friendly, with a high availability of spare parts and repair services.
2. **Score:** The Design for Circularity Score is 8/10, reflecting the smartphone's strong design features that support circularity. The high score is attributed to the product's modular components, repairability, and expected long lifespan.

Resource Efficiency Score:

1. **Assessment:** The Resource Efficiency Score is based on the energy and water consumption during production, as well as the material intensity of the smartphone. This model uses 10% less energy and 20% less water during production compared to industry averages. The material intensity is also optimized, with minimal wastage during manufacturing.
2. **Score:** The Resource Efficiency Score is 7/10, indicating a moderate level of resource efficiency. While the smartphone performs well in terms of energy and water consumption, there is still room for improvement in reducing material intensity.

Overall Circularity Index:

1. **Calculation:** The Overall Circularity Index is calculated as a weighted average of the Material Circularity, Design for Circularity, and Resource Efficiency scores. The weights are assigned based on the relative importance of each dimension to overall product sustainability.
2. **Score:** The smartphone's Overall Circularity Index is 7.7/10, placing it in the upper echelon of circular products within the electronics industry. This score indicates that the smartphone is designed with circular economy principles in mind, with strong performance in material circularity and design for circularity.

Case Study 2: Automotive Industry

Product: Electric Vehicle (EV)

Material Circularity Score:

1. **Assessment:** The Material Circularity Score for the electric vehicle is determined by the percentage of recycled materials used in the vehicle's construction, the material recovery rate during recycling, and the toxicity of the materials used. The EV features a high percentage of recycled aluminum and steel, with a material recovery rate of 85%. The toxicity index is moderate due to the presence of lithium-ion batteries, which require careful disposal.
2. **Score:** The Material Circularity Score is 7/10, indicating that the EV has a relatively high level of material circularity. However, the score is slightly lower than the smartphone due to the challenges associated with battery disposal.

Design for Circularity Score:

1. **Assessment:** The Design for Circularity Score evaluates the EV's modularity, repairability, and product lifespan. The EV is designed with modular components, such as replaceable battery packs and interchangeable interior parts. However, the repairability of the EV is limited by the complexity of its electronic systems.
2. **Score:** The Design for Circularity Score is 6.5/10, reflecting the EV's modularity but also highlighting the challenges in repairability. The score suggests that while the EV is designed for circularity, there are opportunities for improvement in making the vehicle easier to repair.

Resource Efficiency Score:

1. **Assessment:** The Resource Efficiency Score is based on the energy and water consumption during the production of the EV, as well as the material intensity of the vehicle. The production of the EV is energy-intensive, but the vehicle's efficiency during use offsets this impact. Water consumption during production is low, and material wastage is minimal due to advanced manufacturing techniques.
2. **Score:** The Resource Efficiency Score is 8/10, indicating a high level of resource efficiency. The EV's energy efficiency during use is a significant factor in achieving this score.

Overall Circularity Index:

1. **Calculation:** The Overall Circularity Index for the EV is calculated as a weighted average of the Material Circularity, Design for Circularity, and Resource Efficiency scores. The weights are assigned based on the relative importance of each dimension to overall product sustainability.
2. **Score:** The EV's Overall Circularity Index is 7.2/10, placing it among the more circular products in the automotive industry. This score reflects the EV's strong resource efficiency and material circularity, with room for improvement in design for circularity, particularly in repairability.

Case Study 3: Consumer Goods Industry

Product: Refillable Shampoo Bottle

Material Circularity Score:

1. **Assessment:** The Material Circularity Score for the refillable shampoo bottle is based on the percentage of recycled materials used, the material recovery rate during recycling, and the material toxicity index. The bottle is made from 100% recycled plastic, with a material recovery rate of 90%. The toxicity index is very low due to the use of non-toxic, food-grade plastic.
2. **Score:** The Material Circularity Score is 9/10, indicating a very high level of material circularity. The use of 100% recycled materials and the high recovery rate contribute to this strong performance.

Design for Circularity Score:

1. **Assessment:** The Design for Circularity Score evaluates the refillable shampoo bottle's modularity, repairability, and product lifespan. The bottle is designed to be easily refilled and reused multiple times, with a lifespan of several years. The design is simple and robust, with no moving parts that could fail.
2. **Score:** The Design for Circularity Score is 9/10, reflecting the bottle's excellent design for circularity. The high score is due to the product's reusability, longevity, and ease of use.

Resource Efficiency Score:

1. **Assessment:** The Resource Efficiency Score is based on the energy and water consumption during the production of the bottle, as well as the material intensity of the product. The production process is highly efficient, with minimal energy and water usage. The material intensity is also low, as the bottle is designed to use a minimal amount of plastic while maintaining durability.
2. **Score:** The Resource Efficiency Score is 8.5/10, indicating a high level of resource efficiency. The efficient production process and low material intensity are key factors in achieving this score.

Overall Circularity Index:

1. **Calculation:** The Overall Circularity Index for the refillable shampoo bottle is calculated as a weighted average of the Material Circularity, Design for Circularity, and Resource Efficiency scores. The weights are assigned based on the relative importance of each dimension to overall product sustainability.
2. **Score:** The refillable shampoo bottle's Overall Circularity Index is 8.8/10, making it one of the most circular products in the consumer goods industry. This score reflects the product's outstanding performance in all three dimensions of circularity, making it a model for sustainable design.

Future Research Directions:-

The development of the AI-driven Circularity Index marks a significant step forward in the assessment and enhancement of product circularity. However, several avenues for future research could further refine and expand the capabilities of this metric.

Advanced Material Analysis

Nanomaterials and Bio-based Materials:

1. **Challenges:** As the use of advanced materials such as nanomaterials and bio-based materials becomes more prevalent, there is a need for more sophisticated analysis tools. These materials often exhibit unique properties that are not adequately captured by traditional circularity metrics.
2. **Research Focus:** Future research should focus on developing methods to assess the circularity of these advanced materials, considering factors such as biodegradability, potential for nano-pollution, and the lifecycle impacts of bio-based materials. This research could lead to the development of new sub-metrics within the Circularity Index, specifically tailored to these emerging material categories.

Integration with Supply Chain Data

Real-time Circularity Monitoring:

1. **Challenges:** The Circularity Index currently relies on historical data to assess product sustainability. However, integrating real-time supply chain data could provide more dynamic and accurate assessments.
2. **Research Focus:** Future research should explore the integration of real-time data from suppliers, manufacturers, and distributors into the Circularity Index. This could involve the use of blockchain technology to ensure data integrity and transparency. By incorporating real-time data, the Circularity Index could offer more immediate insights and recommendations, allowing companies to respond quickly to changes in their supply chains.

AI-Driven Design Optimization

Generative Design Algorithms:

1. **Challenges:** While the current AI model suggests design modifications to enhance circularity, there is potential for even more advanced design optimization techniques.
2. **Research Focus:** Future research could focus on developing generative design algorithms that automatically create product designs optimized for circularity. These algorithms could consider a wide range of factors, including material selection, modularity, and resource efficiency, to generate designs that maximize circularity while meeting other product requirements.

Circular Economy Policy Integration
Regulatory Compliance and Incentives:

1. **Challenges:** The success of the Circularity Index depends not only on its technical accuracy but also on its alignment with regulatory frameworks and incentives.
2. **Research Focus:** Future research should explore how the Circularity Index can be integrated with national and international circular economy policies. This could involve developing policy-specific versions of the index that help companies comply with regulations and take advantage of incentives for sustainable practices. Research could also examine the potential for the Circularity Index to influence policy development, by providing a robust and standardized metric for circularity.

Consumer Behavior Analysis
Impact of Circular Products on Consumer Choices:

1. **Challenges:** The Circularity Index primarily focuses on the product lifecycle from a manufacturing and environmental perspective. However, consumer behavior plays a critical role in the success of circular products.
2. **Research Focus:** Future research should investigate how the Circularity Index and its associated product labels influence consumer choices. This could involve studying consumer perceptions of circularity, willingness to pay for more sustainable products, and the impact of circularity labels on purchasing decisions. Insights from this research could lead to more effective communication strategies that promote circular products to consumers.

Cross-Industry Applications
Sector-Specific Circularity Metrics:

1. **Challenges:** While the Circularity Index has been applied across various industries, each sector has unique challenges and opportunities related to circularity.
2. **Research Focus:** Future research should focus on developing sector-specific versions of the Circularity Index, tailored to the unique characteristics of different industries. For example, the construction industry may require metrics that account for the long lifespan of buildings and the potential for material reuse in new projects. By developing customized circularity metrics, the Circularity Index could provide more relevant and actionable insights for different sectors.

Machine Learning Model Refinement
Explainable AI and Transparency:

1. **Challenges:** The complexity of machine learning models can sometimes make it difficult for users to understand how circularity scores are calculated.
2. **Research Focus:** Future research should focus on developing more transparent and explainable AI models for the Circularity Index. This could involve using techniques such as decision trees or rule-based models that clearly explain the scores assigned to different products. By enhancing transparency, the Circularity Index could build greater trust among users and encourage wider adoption.

Discussion:-

The introduction of the AI-driven Circularity Index represents a significant advancement in the assessment of product sustainability. This novel metric integrates data across material circularity, design for circularity, and resource efficiency to offer a comprehensive and actionable evaluation of product lifecycle sustainability. The results and case studies highlight the effectiveness and utility of the Circularity Index, providing valuable insights for industries striving to embrace circular economy principles.

Strengths and Innovations
Comprehensive Evaluation:

The AI-driven Circularity Index distinguishes itself from traditional metrics through its holistic approach to evaluating circularity. By incorporating detailed data on material composition, design features, recycling processes, and resource consumption, the index provides a thorough assessment of a product’s sustainability. This comprehensive evaluation goes beyond mere compliance with recycling standards, offering a nuanced understanding of how different design and material choices impact overall circularity.

Predictive Capabilities:
One of the most notable innovations of the Circularity Index is its use of advanced machine learning algorithms to predict future circularity outcomes. The ability to forecast long-term environmental impacts based on evolving factors such as changes in recycling technologies and material sourcing practices allows companies to make proactive adjustments. This predictive capability helps businesses anticipate potential challenges and opportunities, enabling more informed decision-making and strategic planning.

Actionable Recommendations:
The index not only evaluates product circularity but also provides actionable recommendations for improvement. By suggesting design modifications and assessing their cost-benefit implications, the Circularity Index empowers businesses to enhance their products' sustainability. This practical approach bridges the gap between theoretical sustainability goals and real-world implementation, offering a clear pathway for companies to achieve higher circularity scores.

Case Study Insights:
Electronics Industry:
The case study of the smartphone illustrates how the Circularity Index can be used to evaluate and enhance product circularity in the electronics sector. The smartphone's high Material Circularity and Design for Circularity scores reflect its use of recycled materials and modular design. However, the moderate Resource Efficiency score highlights areas for improvement in energy and water consumption during production. This case study demonstrates the index's ability to provide a balanced view of product sustainability, identifying both strengths and areas for enhancement.

Automotive Industry:
The evaluation of the electric vehicle (EV) shows the Circularity Index's effectiveness in addressing the complexities of the automotive sector. The EV's high Material Circularity and Resource Efficiency scores are tempered by challenges in repairability. This case study underscores the index's capacity to highlight industry-specific challenges and provide targeted recommendations for improvement, such as enhancing repairability to boost the Design for Circularity score.

Consumer Goods Industry:
The refillable shampoo bottle represents an exemplary case of high circularity, with excellent scores across all dimensions. The index's ability to identify and celebrate best practices in product design and resource efficiency is evident in this case study. The strong performance of the refillable bottle serves as a model for other products and industries, showcasing the potential for circular design principles to achieve superior sustainability outcomes.

Areas for Future Research:
Advanced Material Analysis:
The Circularity Index could be further refined by incorporating advanced materials such as nanomaterials and bio-based materials. Research into the unique properties and lifecycle impacts of these materials is essential for developing sub-metrics that accurately reflect their circularity. This enhancement would ensure the index remains relevant as new materials and technologies emerge.

Integration with Supply Chain Data:
Integrating real-time supply chain data into the Circularity Index represents a significant opportunity for improvement. By incorporating real-time information from suppliers and manufacturers, the index could offer more dynamic and accurate assessments. Research into blockchain technology for data integrity and transparency could further enhance the index's effectiveness in real-time monitoring.

AI-Driven Design Optimization:
Future research could focus on developing generative design algorithms that automatically create product designs optimized for circularity. These algorithms could consider a wide range of factors, including material selection and modularity, to generate designs that maximize circularity while meeting other product requirements. This advancement would enhance the index's ability to drive innovative and sustainable design solutions.

Circular Economy Policy Integration:
Aligning the Circularity Index with regulatory frameworks and incentives is crucial for its broader adoption. Research should explore how the index can be integrated with national and international circular economy policies, potentially influencing policy development and helping companies comply with regulations. This alignment would ensure that the index supports both industry practices and policy objectives.

Consumer Behavior Analysis:
Understanding how the Circularity Index and its associated product labels influence consumer choices is essential for maximizing its impact. Research into consumer perceptions and the effectiveness of circularity labels could lead to more effective communication strategies and increased consumer adoption of circular products. Insights from this research could also inform the development of more engaging and informative product labels.

Cross-Industry Applications:
Developing sector-specific versions of the Circularity Index tailored to the unique characteristics of different industries would provide more relevant and actionable insights. For example, the construction industry may require metrics that account for material reuse in new projects. Customizing the index for various sectors would enhance its applicability and effectiveness across diverse industries.

Machine Learning Model Refinement:
Enhancing the transparency and explainability of the machine learning models used in the Circularity Index is crucial for building user trust. Future research should focus on developing more transparent models that provide clear explanations for the scores assigned to different products. This improvement would encourage wider adoption and acceptance of the Circularity Index.

Conclusion:-

The AI-driven Circularity Index represents a significant advancement in evaluating product lifecycle sustainability. Its comprehensive approach, predictive capabilities, and actionable recommendations offer a valuable tool for businesses striving to embrace circular economy principles. By addressing the strengths and limitations identified in the case studies and exploring avenues for future research, the Circularity Index can continue to evolve and provide even greater value in the pursuit of sustainable product design and manufacturing. As industries and technologies advance, the Circularity Index stands poised to play a crucial role in guiding the transition towards a more sustainable and circular economy.

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