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Prioritization of Barriers to Digitization for Circular Systems using Analytical Hierarchy Process

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Abstract: The increasing urgency for sustainable practices has motivated this research to explore the barriers hindering the adoption of digital technologies in circular systems. As industries seek to leverage IoT for enhanced efficiency and sustainability, understanding these barriers is crucial for effective implementation. This study employs a comprehensive, multi–dimensional approach, integrating insights from a literature review and expert interviews with industry professionals. Key findings reveal that technological complexity and high initial costs are the most significant barriers, highlighting the need for targeted strategies to address these challenges. Additional barriers include regulatory compliance issues and unclear return on investment, which further complicate the adoption process. The study's conclusion emphasizes that overcoming these barriers is essential for facilitating the successful integration of digital technologies in circular economies. Furthermore, the research identifies the necessity for future investigations into the interactions between these barriers and the effectiveness of various interventions. The novelty of this study lies in its holistic examination of the multifaceted barriers, combining qualitative insights with a structured analytical framework. This approach not only contributes to the existing literature on Digitization but also offers practical implications for stakeholders aiming to enhance sustainability and efficiency in their operations. By addressing the identified challenges, organizations can pave the way for a more circular and resilient future, ultimately driving innovation and growth in the rapidly evolving digital landscape.

Index Terms: AHP, Circular Systems, Digitization, Digitalization Barriers, Multi–criteria Decision–making, Sustainability.

1. Introduction

1.1. Background

Digitization and the Internet of Things (IoT) are pivotal in advancing circular economy systems by providing the necessary tools for comprehensive monitoring, analysis, and optimization of resource flows [1]. In a traditional linear economy, products are manufactured, used, and discarded, which results in significant waste and resource depletion. The circular economy aims to mitigate these issues by extending product lifecycles through reuse, recycling, and remanufacturing. Digitization plays a key role in facilitating this shift by enabling industries to track the entire lifecycle of products—from sourcing raw materials to end-of-life disposal [2]. Digital devices further enhance this tracking capability by collecting real-time data on parameters such as energy consumption, material usage, and operational efficiency. This data allows companies to identify opportunities to recycle, remanufacture, and reuse materials, keeping resources in circulation for longer periods, thereby reducing waste and the reliance on new raw materials [3].

In addition to tracking resource flows, digitization helps automate and optimize circular processes. For example, smart sensors powered by IoT can improve the accuracy of waste sorting by identifying and separating recyclable materials, thus reducing contamination and increasing recycling rates [4]. In the manufacturing sector, IoT devices enable predictive maintenance, allowing for timely repairs that minimize downtime and extend the life of machinery, ultimately improving resource efficiency [5]. Moreover, digitization supports innovative business models like "product-as-a-service," where consumers lease products instead of purchasing them. This approach ensures that manufacturers retain ownership and responsibility for the product throughout its lifecycle, encouraging designs that emphasize durability, repairability, and recyclability [6]. By promoting resource optimization and circular strategies, digitization and IoT not only drive economic growth but also align with broader environmental sustainability goals, fostering a more resilient and resource-efficient society [7,8].

However, despite the clear advantages of digitization in enhancing circular systems, industries face numerous challenges in adopting these technologies. These barriers include technological complexity, high implementation costs, and regulatory challenges. This raises critical questions: What are the most significant barriers to the adopting digitization in circular systems? And, how can these barriers be prioritized to help industries address the most critical issues? A structured approach to prioritizing these barriers is crucial for accelerating the adoption of these technologies, enabling companies to reap the full benefits of digitization for circularity. To address these questions, decision-making frameworks such as the Analytical Hierarchy Process (AHP) offer a systematic way to prioritize barriers based on their significance and impact. This study aims to explore these barriers in detail and provide insights into how AHP can be applied to rank and address the most pressing obstacles. By doing so, the research seeks to help industries focus on overcoming the most critical challenges, thereby facilitating the broader adoption of digitization in circular economy systems.

1.2. Research Objectives/Questions

The research problem focuses on identifying the common barriers that prevent the effective adoption of digital technologies in circular systems. Despite the recognized benefits of digitization for enhancing resource efficiency and sustainability, many organizations struggle to implement these technologies successfully. Understanding these barriers is critical for overcoming the challenges that hinder the transition to a circular economy.

The primary aim of this research is to prioritize the identified barriers to the adoption of digital technologies in circular systems. By providing insights into the most significant challenges, this study aims to assist strategic decision–makers in developing targeted strategies to facilitate the implementation of digitization in their organizations. This prioritization will enable stakeholders to focus their efforts on addressing the most critical issues, thereby accelerating the transition towards a more circular economy. This study seeks to answer the following research questions:

- What are the most critical barriers to the digitalization in circular systems?
- How can AHP be utilized to prioritize these barriers effectively?

1.3. Why Analytical Hierarchy Process for Prioritization?

The selection of the AHP as the primary decision-making framework for this research is driven by several key factors, which make it particularly well-suited to addressing the research objectives. AHP is a widely recognized multi-criteria decision-making (MCDM) method that allows for the systematic evaluation of complex problems involving multiple, often conflicting, criteria. Given the multifaceted nature of the barriers to digitization adoption in circular systems, AHP offers several distinct advantages that align with the requirements of this study.

The barriers to Digitization in circular systems span a wide range of factors, including technological, economic, social, regulatory, and environmental dimensions. AHP provides a structured approach for breaking down these complex factors into a hierarchical model, where each criterion and sub-criterion can be evaluated separately and then aggregated to form a holistic prioritization. This capability is crucial for this study, as it allows for a nuanced understanding of how different barriers interact and affect the overall decision-making process. Compared to other decision-making frameworks, such as the Simple Additive Weighting (SAW) or Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), AHP excels at capturing the hierarchical relationships between criteria and sub-criteria, making it an ideal choice for this research.

One of the strengths of AHP is its ability to incorporate expert judgments in the evaluation process. The method allows decision-makers to use pairwise comparisons to express their subjective preferences between different criteria, and these comparisons are then translated into numerical values. In the context of this research, where expert opinions from various industry stakeholders (manufacturers, academics, and environmental advocates) were gathered, AHP provides a robust mechanism to aggregate these subjective inputs into a coherent prioritization of barriers. Other methods, such as Data Envelopment Analysis (DEA), are more suited for quantitative data analysis and may struggle to accommodate the qualitative, expert-driven insights central to this research.

AHP includes a consistency check, which is a significant advantage when dealing with human judgments, which can sometimes be inconsistent. By calculating a consistency ratio (CR), AHP helps ensure that the comparisons made by experts are reliable and that the final results are not biased by random or inconsistent inputs. This feature is particularly important in this study, where multiple experts were consulted, and ensuring the reliability of their judgments was crucial for the validity of the results. Alternative decision-making methods like TOPSIS or the Multi-Attribute Utility Theory (MAUT) do not offer an inherent mechanism to check for consistency in expert evaluations, making AHP a more reliable option in this context.

AHP is uniquely positioned to handle both qualitative and quantitative data, which is vital for a study that examines barriers that are both technical (quantitative) and perceptual or strategic (qualitative). The barriers identified in this study range from tangible economic costs to more abstract concerns like resistance to change or regulatory uncertainty. AHP's flexibility in assigning weights to criteria based on both qualitative judgments and quantitative measures makes it an appropriate tool for this research, where other methods like the ELECTRE (Elimination and

Choice Expressing Reality) method may fall short due to their limited ability to integrate both types of data.

Given that the aim of this research is to prioritize barriers to Digitization for strategic decision-making in circular systems, AHP is particularly suitable because it provides a clear and structured process for evaluating complex decisions. AHP's output—a ranked list of barriers—offers practical insights that can directly inform decision-makers about where to focus their efforts to overcome the most significant challenges. This makes it a more actionable tool compared to other MCDM methods that may require more complex interpretations of results, such as the Analytic Network Process (ANP), which, while powerful, may be too complex for this study's objective of straightforward prioritization.

1.4. Literature Review and Study Contribution

The integration of digitization within circular economy systems has gained significant attention in recent years, offering opportunities to enhance resource efficiency, monitor material flows, and extend product lifecycles. Several studies have explored the potential benefits of digitization for circular systems. For instance, Ghisellini et al. (2016) emphasized how real-time monitoring of production processes can lead to greater resource efficiency by reducing waste and optimizing recycling efforts [9]. Reuter (2016) similarly highlighted the role of digital technologies in enabling the metallurgical Internet of Things, particularly for monitoring recycling streams and improving material recovery rates [10]. These studies underscore the technological potential but often stop short of addressing the practical barriers that hinder the widespread adoption.

Despite these advancements, existing literature does not provide sufficient analysis of the barriers. Many studies focus primarily on the benefits and technical aspects, leaving critical gaps in understanding the specific obstacles organizations face. For example, while Vishwakarma et al. (2024) provide a comprehensive survey of challenges, the analysis lacks a focus on how these challenges are prioritized within the context of circular systems [11]. Similarly, Ali et al. (2022) discuss the complexities of implementation, such as data integration and interoperability, but fail to address how these issues intersect with the principles of circular economy [12].

Moreover, there is limited research applying decision-making frameworks to systematically prioritize these barriers. Existing studies, such as those by Lin and Wei (2023), offer insights into resource optimization through machine learning, but do not provide a structured approach to managing the challenges posed by Digitization in circular systems [13]. This is where the current study contributes significantly to the literature. By using the Analytical Hierarchy Process (AHP), this research not only identifies but also prioritizes the barriers to Digitization, offering a systematic approach to overcoming these challenges.

A. Identified Research Gaps

- Limited Application of Decision-Making Frameworks: There is a noticeable gap in the use of decision-making methodologies, such as AHP, to systematically address the complexity and interdependencies of these barriers. The application of such frameworks remains underexplored in the context of circular systems.
- Insufficient Focus on Organizational and Economic Barriers: Much of the existing literature focuses on the technical challenges of Digitization, such as data management and interoperability. However, there is limited analysis of organizational, economic, and regulatory barriers, which can be equally or more important for decision-makers in practice.

B. Novelty of the Research

This study addresses the aforementioned gaps by applying the Analytical Hierarchy Process (AHP) to prioritize the barriers. The novelty lies in the combination of qualitative insights from expert interviews with a structured, quantitative decision-making framework. By integrating these approaches, this research provides a comprehensive analysis that not only identifies barriers but ranks them in terms of their significance, offering a more actionable pathway for overcoming these challenges. This is a departure from existing studies that primarily focus on descriptive analyses of barriers without offering a clear prioritization strategy.

2. Research Methodology

The methodology utilized for prioritizing barriers was a comprehensive, multi–dimensional approach, as illustrated in Fig. 1. The process began with an extensive literature review aimed at identifying a diverse array of potential criteria and factors. This review provided a solid foundation for comprehending existing research, industry trends, and expert perspectives on relevant issues. Following this, to refine and substantiate the identified criteria, a survey and interview process was implemented with industry professionals, which included two manufacturers, two academics, and one environmental advocate, all of whom possessed over a decade of experience in the field. These stakeholders contributed their insights on the most relevant criteria based on their expertise and practical knowledge.

The responses collected from the surveys and interviews were systematically analyzed to uncover recurring themes and to rank the criteria based on their perceived importance. To conclude the process, a consensus–building exercise was conducted, involving further discussions and deliberations among the experts to finalize the most critical criteria for inclusion in the study. This methodology facilitated a thorough and inclusive approach to identifying factors, integrating both established literature and expert opinions to develop a comprehensive list of criteria.

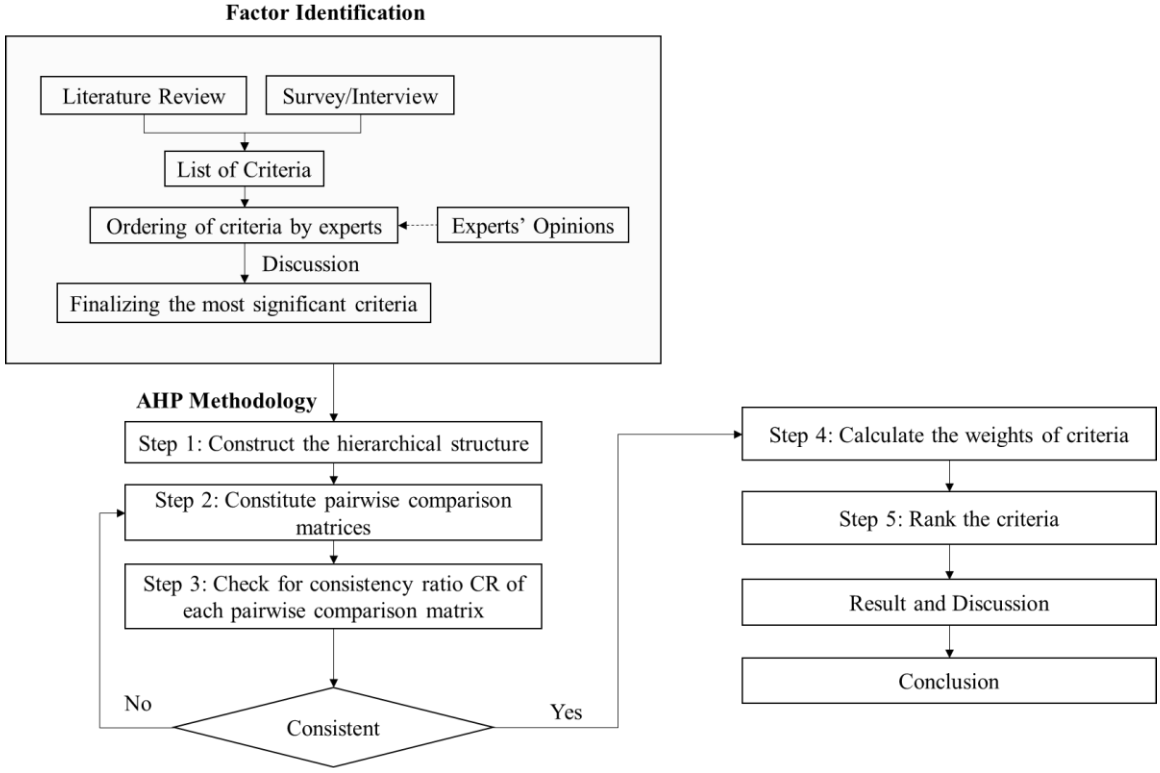

Fig.1. Research methodology

The AHP methodology [14] used in this study followed a systematic process to prioritize criteria (as per Fig. 1):

Step 1: Construct the Hierarchical Structure

The hierarchical structure was constructed to organize the criteria into a logical framework. This structure consisted of a top–level criterion representing the overall objective, with subsequent levels containing sub–criteria related to different aspects of CE implementation.

Step 2: Constitute Pairwise Comparison Matrices

Pairwise comparison matrices were developed to capture the relative importance of criteria at each level of the hierarchy. Experts were asked to compare each criterion against every other criterion within the same level, assigning numerical values based on their perceived importance as shown in Table 1. The majority is taken as a basis to deal with multiple responses.

Table 1. Linguistic measures of importance

Degree of Preference	**Score Index (SI)**
Absolutely more importance (AM)	9
Very high importance (VH)	7
High importance (HI)	5
Slightly more importance (SM)	3
Equally importance (EI)	1
Slightly lower importance (SL)	1/3
Low importance (LI)	1/5
Very low importance (VL)	1/7
Absolutely low importance (AL)	1/9

Step 3: Calculate the Weights of Criteria

Using the validated pairwise comparison matrices, the weights of criteria were calculated through the AHP algorithm using eq(1) and eq(2). These weights represented the relative importance of each criterion in achieving the overall objective of CE implementation.

$$GMi = \left(\prod_{i=1}^{A} x_i\right)^{\frac{1}{A}} \tag{1}$$

Where, GM_i represents the geometric mean of each, x_i are the individual values of alternatives, A is the total number of factors/alternatives.

$$\text{Weight}_i = \frac{GM_i}{\sum_{i=1}^{A} GM} \tag{2}$$

Step 4: Rank the Criteria

Based on their calculated weights, the criteria were ranked in order of importance. This ranking provided valuable insights into which criteria were considered most critical for addressing barriers and facilitating the transition to a CE.

Step 5: Check for Consistency Ratio (CR) of Pairwise Comparison Matrix

To ensure the reliability of the pairwise comparisons, consistency ratios (CRs) were calculated for each matrix using eq(3). If the CR fell within an acceptable range (10%), indicating reasonable consistency in the judgments, the comparisons were deemed valid and proceeded to the next step.

$$CR = \frac{CI}{RI} \tag{3}$$

The Consistency Index (CI) is calculated as follows using eq(4):

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{4}$$

Where the maximum eigenvalue of the matrix, denoted as λ_{max}, is used in conjunction with the number of criteria (n) in the calculation. The Random Index (RI) used in eq(3) is determined by considering the number of criteria utilized in the research study.

By following this structured AHP methodology, the study was able to systematically prioritize criteria and provide actionable recommendations for stakeholders.

3. Results and Discussions

Despite the promising benefits, several common barriers hinder the effective adoption of digital technologies in circular systems. Previous studies underscore the need to address these barriers to facilitate a smoother transition towards a more circular economy. The barriers are classified into PESTLE framework [15]. The hierarchical structure is shown in Fig. 2.

3.1. Political Barriers

- Regulatory and Compliance Challenges: Varying regulations regarding data protection, environmental standards, and intellectual property rights can create complex compliance issues for organizations adopting Digital technologies. Companies must navigate a patchwork of local, national, and international laws, which can be daunting, particularly for small and medium–sized enterprises (SMEs) that may lack legal resources. The uncertainty surrounding compliance can deter companies from investing in digitization, fearing potential penalties or operational disruptions if they fail to adhere to these regulations [16].
- Lack of Government Incentives: Government support in the form of policies or financial incentives for adopting digital technologies in circular economy initiatives is often lacking. Without such support, organizations may struggle to justify the initial costs associated with IoT implementation. A lack of public funding or investment in infrastructure necessary for Digitization can further exacerbate this issue, leading to slower adoption rates [17].

3.2. Economic Barriers

- High Initial Costs: Implementing digital technologies typically requires substantial upfront investments in hardware (e.g., sensors, devices), software, and system integration. For many organizations, especially SMEs, these costs can be prohibitively high, especially when faced with the uncertainty of ROI. The financial burden can discourage companies from pursuing digital initiatives, despite the long–term benefits of increased efficiency and resource optimization [18].
- Unclear Return on Investment (ROI): Many companies struggle to articulate the potential ROI from investing in technologies for circular systems. This uncertainty can stem from a lack of case studies demonstrating clear financial benefits or metrics for measuring success. The ambiguity surrounding cost savings, efficiency gains, and other advantages can lead to hesitation in making significant investments.

- Fragmented Supply Chains: The complexity of supply chains often poses a challenge to the successful implementation. In many industries, supply chains are fragmented and lack the necessary integration for effective tracking of materials and resources. This fragmentation makes it difficult to implement circular practices, as companies may have limited visibility into their supply chain processes and may not be able to effectively manage resource flows [19].
- Cost of Data Storage and Management: Digital systems generate vast amounts of data, which require robust storage and management solutions. The costs associated with data storage, processing, and analytics can quickly accumulate, posing a barrier for organizations, particularly those with limited budgets. As the volume of data grows, the associated costs for storage and management can become a significant financial burden [20].

3.3. Social Barriers

- Resistance to Change: Cultural resistance within organizations can impede the adoption of new technologies. Employees accustomed to traditional processes may be reluctant to embrace new digital solutions, leading to pushback against implementation efforts. Additionally, concerns about how digitization may change job roles and responsibilities can contribute to this resistance [21].
- Lack of Digital Skills and Expertise: The successful adoption requires a workforce equipped with specific skills in areas such as data analytics, programming, and cyber security. Many organizations face a shortage of qualified personnel who can drive IoT initiatives forward. This skills gap is particularly pronounced in SMEs, where resources for training or hiring specialized staff are limited [22].
- Concerns about Job Displacement: The fear of job loss due to automation can lead to reluctance among employees to support digital transformation efforts. This concern can create a significant barrier, as companies may encounter resistance from their workforce, hindering the successful integration of new technologies [23].

3.4. Technological Barriers

- Technological Complexity: Integrating digitization into existing systems can be technically complex, particularly in industries reliant on legacy technologies. Organizations may struggle with compatibility issues between new devices and their existing systems, requiring significant time and resources for effective integration. Additionally, the need for continuous updates and maintenance of systems adds to this complexity [24].
- Data Privacy and Security Concerns: The interconnectivity of devices raises significant data privacy and security concerns. As organizations collect and share large amounts of data, the risk of cyber–attacks and data breaches increase. Companies are often hesitant to adopt technologies due to fears of compromised sensitive data, which can lead to financial losses and reputational damage [25].
- Lack of Standardization: The absence of standardized protocols across industries leads to fragmented systems that are difficult to integrate and scale. Different companies may adopt varying technologies and communication standards, complicating interoperability. This lack of standardization can limit the effectiveness of solutions in supporting circular economy practices [26].
- Interoperability Issues: Many devices struggle to communicate effectively with one another due to differences in technologies, protocols, and standards. This lack of interoperability can hinder the implementation of integrated circular processes, resulting in inefficiencies and reduced effectiveness in managing resources [27].
- Inadequate Infrastructure: The successful deployment of solutions often relies on advanced infrastructure, including high–speed internet and cloud computing capabilities. In regions where such infrastructure is lacking, organizations may face significant challenges in implementing technologies, limiting their ability to leverage the benefits of a circular economy [28].
- Poor Data Quality: The effectiveness of digital solutions is heavily dependent on the quality of the data generated. Inaccurate or inconsistent data from IoT sensors can lead to poor decision–making and limit the effectiveness of circular systems. Organizations must ensure robust data management practices to maintain high–quality data [29].

3.5. Legal Barriers

- Data Ownership Issues: Questions regarding data ownership arise in collaborative environments where multiple stakeholders are involved. Confusion over who owns the data generated can create legal uncertainties that deter organizations from fully committing to Digitization.
- Intellectual Property Concerns: Companies may hesitate to adopt technologies due to fears that sensitive proprietary information could be exposed or misappropriated. This concern over intellectual property rights can create a significant barrier to the adoption of digital technologies in circular systems [30].

3.6. Environmental Barriers

- Energy Consumption of Digital Devices: The operation of devices requires energy, which raises concerns about the environmental impact of deploying large numbers of connected devices. In industries focused on sustainability, this energy consumption can counteract the benefits of implementing circular practices [31].

- Electronic Waste from Digital Devices: As Digital devices become obsolete, managing electronic waste poses a significant challenge. The potential increase in electronic waste associated with widespread Digitization can offset some of the environmental benefits that circular systems aim to achieve[32].
- Uncertain Environmental Impact: Organizations may find it challenging to quantify the overall environmental benefits. This uncertainty can lead to skepticism about the sustainability of adopting these technologies, hindering their implementation [33].

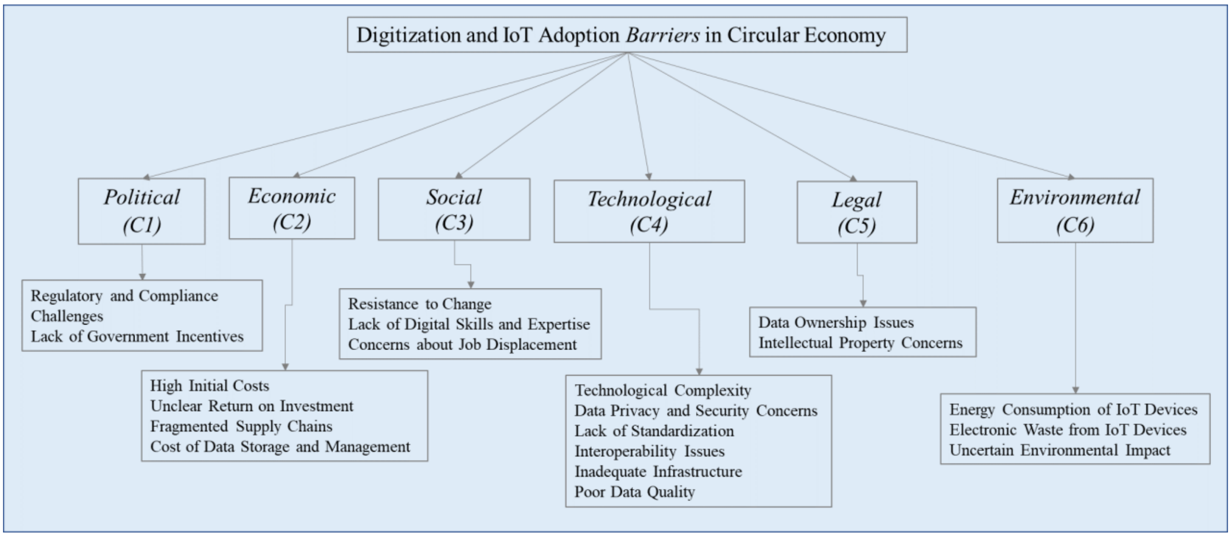

Fig.2. Hierarchical structure of factors affecting digitization

The AHP analysis delves deeply into the multifaceted landscape of sustainability unveiling critical insights into the varying degrees of importance among different factors. Through a systematic classification of factors into distinct categories, the analysis offers a comprehensive overview of the key determinants shaping sustainability outcomes. The pairwise comparison matrix for main and subcategories categories is given in Table 2 and Table 3. On the other hand, global weights and rank of each factor in consideration is given in Table 4. The results of this study provide a comprehensive overview of the barriers to Digitization in circular systems, categorized into political, economic, social, technological, legal, and environmental factors. Notably, the technological barriers stand out as the most significant, with a global weight of 0.447, indicating their critical role in hindering progress in this area.

The results indicate that technological complexity emerged as the most significant barrier to the adoption of digital technologies in circular systems, receiving the highest ranking in the Analytical Hierarchy Process (AHP) analysis. This finding aligns with previous studies that have highlighted the inherent difficulties organizations face when integrating advanced technologies into existing systems, particularly those relying on legacy infrastructure. The complexity stems from multiple factors, including interoperability challenges between new devices and older systems, the need for continuous updates, and the technical expertise required to manage and maintain these technologies [9]. Many organizations, especially small and medium-sized enterprises (SMEs), lack the resources or expertise to address these challenges effectively. As the adoption of digital solutions requires a sophisticated technological infrastructure, companies are often faced with a steep learning curve, which deters them from fully committing to digital transformation [34].

Another crucial aspect of technological complexity is the issue of interoperability—the ability of different systems and devices to communicate effectively. In industries with fragmented supply chains or reliance on multiple technology platforms, achieving seamless interoperability is a significant challenge. The lack of standardized protocols and the diversity of technologies in use across different sectors exacerbate this problem. This explains why technological complexity was ranked so highly: it not only affects the initial implementation of digital systems but also hinders scaling and ongoing optimization of these systems [10]. The need to bridge various technologies and ensure they operate in harmony is a formidable barrier that many organizations struggle to overcome.

Table 2. Pairwise comparison matrix for main categories

Factors	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**Weight**
Political (C1)	1.000	0.333	3.000	0.200	0.500	2.000	0.093
Economic (C2)	3.000	1.000	5.000	0.333	2.000	3.000	0.213
Social (C3)	0.333	0.200	1.000	0.143	0.250	0.500	0.039
Technological (C4)	5.000	3.000	7.000	1.000	4.000	6.000	0.447
Legal (C5)	2.000	0.500	4.000	0.250	1.000	3.000	0.145
Environmental (C6)	0.500	0.333	2.000	0.167	0.333	1.000	0.062

Table 3. Pairwise comparison matrix for subcategories

Political Factors (C_1)							
	C_{11}	**C_{12}**					**Weight**
C_{11}	1.000	5.000					0.833
C_{12}	0.200	1.000					0.167
Economic factors (C2)							
	C_{21}	**C_{22}**	**C_{23}**	**C_{24}**			**Weight**
C_{21}	1.000	3.000	5.000	7.000			0.564
C_{22}	0.333	1.000	3.000	5.000			0.263
C_{23}	0.200	0.333	1.000	3.000			0.118
C_{24}	0.143	0.200	0.333	1.000			0.055
Social factors (C3)							
	C_{31}	C_{32}	C_{33}				**Weight**
C_{31}	1.000	3.000	5.000				0.637
C_{32}	0.333	1.000	3.000				0.258
C_{33}	0.200	0.333	1.000				0.105
Technological factors(C4)							
	C_{41}	C_{42}	C_{43}	C_{44}	C_{45}	C_{46}	**Weight**
C_{41}	1.000	3.000	5.000	7.000	3.000	5.000	0.417
C_{42}	0.333	1.000	3.000	5.000	3.000	5.000	0.251
C_{43}	0.200	0.333	1.000	3.000	3.000	4.000	0.141
C_{44}	0.143	0.200	0.333	1.000	2.000	3.000	0.076
C_{45}	0.333	0.333	0.333	0.500	1.000	3.000	0.075
C_{46}	0.200	0.200	0.250	0.333	0.333	1.000	0.039
Legal factors (C5)							
	C_{51}	C_{52}					**Weight**
C_{51}	1	3					0.750
C_{52}	0.333	1.000					0.250
Environmental Factors (C6)							
	C_{61}	C_{62}	C_{63}				**Weight**
C_{61}	1.000	3.000	5.000				0.637
C_{62}	0.333	1.000	3.000				0.258
C_{63}	0.200	0.333	1.000				0.105

In contrast, barriers such as unclear return on investment (ROI) and fragmented supply chains, while significant, were ranked lower. This can be attributed to the fact that these barriers, though important, are more likely to be resolved once the technological foundations for digital adoption are in place. For example, organizations may find it difficult to quantify the benefits of digital transformation initially, but as these systems become more integrated and efficient, clear financial benefits often emerge through improved resource optimization and reduced operational costs [11]. Additionally, while supply chain fragmentation presents obstacles to digital implementation, it is often seen as an issue that can be mitigated over time with better integration and collaboration across stakeholders.

Economic barriers, such as high initial costs, were also ranked as critical but fell behind technological complexity. This ranking suggests that while the upfront financial investment in digital technologies is significant, organizations are more likely to view these costs as a long-term investment, especially when there is a clear strategic imperative for transformation. In some cases, organizations may seek government incentives or public-private partnerships to alleviate the financial burden, which further explains why this barrier was ranked lower than technological complexity [35].

Another interesting finding from the analysis is the relatively lower ranking of social barriers, such as resistance to change and the lack of digital skills. This can be interpreted in two ways: firstly, organizations may view technological and economic barriers as more immediate and pressing challenges, which need to be addressed before social issues can be tackled. Secondly, it reflects the growing recognition that workforce training and change management programs can be implemented relatively quickly once the technological and economic foundations are in place. Resistance to change, while important, may not be perceived as a critical issue until the more fundamental barriers to digital adoption are resolved.

The high ranking of technological complexity in this study highlights its critical role in shaping the adoption of digital solutions in circular systems. The complexity of integrating new technologies, coupled with interoperability challenges and the need for continuous technological upgrades, creates a significant barrier that organizations must overcome. Meanwhile, economic and social barriers, while important, are often seen as secondary challenges that can be addressed as part of a broader strategic approach to digital transformation. Future research should focus on exploring specific strategies for overcoming technological complexity, particularly through the development of standardized protocols and enhanced technical support for organizations.

Table 4. Global weights and rank

Classification	Class weight	Factor	Global Weight	Rank
Political (C1)	0.093	Regulatory and Compliance Challenges	0.077	5
		Lack of Government Incentives	0.015	16
Economic (C2)	0.213	High Initial Costs	0.120	2
		Unclear Return on Investment	0.056	7
		Fragmented Supply Chains	0.025	12
		Cost of Data Storage and Management	0.012	17
Social (C3)	0.039	Resistance to Change	0.025	13
		Lack of Digital Skills and Expertise	0.010	18
		Concerns about Job Displacement	0.004	20
Technological (C4)	0.447	Technological Complexity	0.186	1
		Data Privacy and Security Concerns	0.112	3
		Lack of Standardization	0.063	6
		Interoperability Issues	0.034	10
		Inadequate Infrastructure	0.034	11
		Poor Data Quality	0.018	14
Legal (C5)	0.145	Data Ownership Issues	0.109	4
		Intellectual Property Concerns	0.036	9
Environmental (C6)	0.062	Energy Consumption	0.040	8
		Electronic Waste	0.016	15
		Uncertain Environmental Impact	0.007	19

4. Sensitivity Analysis

In this study, a sensitivity analysis was conducted to evaluate how changes in the weights assigned to various criteria influence the final ranking of barriers. The purpose of this analysis is to test the robustness of the AHP model and to ensure that the prioritization of barriers is stable, even when there are variations in stakeholder inputs. Sensitivity analysis was performed by systematically varying the weights of the main criteria—technological, economic, social, political, legal, and environmental barriers—and observing how these changes affected the ranking of the barriers. Each criterion's weight was increased and decreased by 10%, while keeping the weights of the other criteria proportionally adjusted to maintain a total weight of 100%. This approach allowed us to assess the impact of individual criteria on the overall barrier ranking.

Table 5. Sensitivity analysis

Criteria	Original Weight	Modified Weight (+10%)	Modified Weight (-10%)	Effect on Barrier Ranking
Technological Barriers	0.447	0.492	0.402	No change in top ranking barriers; Technological complexity remains the top barrier in all cases.
Economic Barriers	0.213	0.234	0.192	Small shift: High initial costs move up slightly when increased by 10%, but technological complexity remains top.
Social Barriers	0.039	0.043	0.035	Minimal impact: Resistance to change slightly rises with increased weight but remains low overall.
Political Barriers	0.093	0.102	0.084	Small impact: Regulatory challenges show a slight increase in importance when the weight increases by 10%.
Legal Barriers	0.145	0.16	0.131	Moderate effect: Data ownership issues rise slightly when the weight increases, but no significant overall change.
Environmental Barriers	0.062	0.068	0.056	Minimal effect: Energy consumption gains importance with higher weight but does not change the overall barrier rankings significantly.

The sensitivity analysis confirms that the prioritization of barriers in the AHP model is robust to moderate changes in stakeholder inputs. The most significant barriers—technological complexity and high initial costs—remain consistently at the top of the ranking across different scenarios. This stability suggests that strategic efforts to address these barriers should be prioritized, as their critical importance holds true even under varying weight distributions. The findings from this sensitivity analysis enhance the credibility of the results, providing confidence that the prioritization derived from the AHP framework accurately reflects the most pressing barriers to digitization adoption in circular systems.

5. Conclusions

This research highlights the complex barriers to Digitization in circular systems, with technological complexity and high initial costs identified as the most pressing challenges. By prioritizing these barriers, stakeholders can craft targeted strategies that address these critical issues, fostering a more sustainable and innovative future for Digital applications. However, the study is limited by its reliance on qualitative data from a small number of industry professionals, which may not reflect the diverse perspectives across different sectors. Future research should aim for a larger sample size and incorporate quantitative methods to further validate these findings and explore the interactions between barriers. Additionally, investigating strategies such as innovative financing models and collaborative frameworks will be essential for facilitating successful digital integration in circular economies. Ultimately, addressing these barriers is crucial for enhancing the sustainability and efficiency of digital technologies, paving the way for a more circular and resilient future.

Recommendations for Practitioners and Policymakers

To overcome the barriers to the adoption of digital technologies in circular systems, several strategies can be implemented. First, investing in comprehensive training and skill development programs will help organizations address the lack of digital expertise. Public-private partnerships can alleviate high initial costs, especially for small and medium-sized enterprises, by sharing technological infrastructure and providing financial incentives such as subsidies and low-interest loans. Policymakers should also create flexible regulatory frameworks that support innovation, including regulatory sandboxes that allow companies to experiment with new technologies. Standardizing protocols across industries is essential to address interoperability issues, and increased funding for research and development will drive innovations in resource tracking and waste reduction. Additionally, developing secure data-sharing platforms will enhance collaboration across the supply chain, enabling better resource management. Finally, offering incentives for businesses adopting circular models, such as product-as-a-service, will promote sustainability and material recovery, accelerating the transition to a circular economy.

References

[1] Vishwakarma AK, Chaurasia S, Kumar K, et al, Internet of things technology, research, and challenges: a survey, *Multimed Tools Appl*, (2024), https://doi.org/10.1007/s11042-024-19278-6.

[2] Ali O, Ishak MK, Bhatti MKL, Khan I, Kim K-I, A Comprehensive Review of Internet of Things: Technology Stack, Middlewares, and Fog/Edge Computing Interface, *Sensors*, 22(3) (2022) 995, https://doi.org/10.3390/s22030995.

[3] Khanna A & Kaur S, Internet of Things (IoT), Applications and Challenges: A Comprehensive Review, *Wireless Pers Commun*, 114 (2020) 1687–1762, https://doi.org/10.1007/s11277-020-07446-4.

[4] Reuter MA, Digitalizing the circular economy: Circular economy engineering defined by the metallurgical internet of things, *Metall Mater Trans*, B, 47 (2016) 3194–3220, https://doi.org/10.1007/s11663-016-0735-5.

[5] Soori M, Arezoo B & Dastres R, Internet of things for smart factories in industry 4.0, a review, *Internet of Things and Cyber-Physical Systems*, 3 (2023) 192–204, https://doi.org/10.1016/j.iotcps.2023.04.006.

[6] El Agamy AbdelKader A, Innovation to sustainability in design, *Int J Design Fashion Stud*, 6(2) (2023) 55–68, https://dx.doi.org/10.21608/ijdfs.2024.276050.1021.

[7] Lin KY & Wei SH, Advancing the industrial circular economy: the integrative role of machine learning in resource optimization, *J Green Econ Low Carbon Dev*, 2(3) (2023) 122–136, https://doi.org/10.56578/jgelcd020302.

[8] Turskis Z & Šniokienė V, IoT-Driven Transformation of Circular Economy Efficiency: An Overview, *Math Comput Appl*, 29(4) (2024) 49, https://doi.org/10.3390/mca29040049.

[9] P. Ghisellini, C. Cialani, and S. Ulgiati, "A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems," Journal of Cleaner Production, vol. 114, pp. 11–32, 2016. Available: https://doi.org/10.1016/j.jclepro.2015.09.007

[10] Reuter, M. (2016). Digitalizing the Circular Economy: Circular Economy Engineering Defined by the Metallurgical Internet of Things. Metallurgical and Materials Transactions B. 47. 10.1007/s11663-016-0735-5.

[11] Vishwakarma, A. K., Chaurasia, S., Kumar, K., et al., "Internet of Things Technology, Research, and Challenges: A Survey," Multimedia Tools and Applications, 2024.

[12] Ali, Omer, Mohamad Khairi Ishak, Muhammad Kamran Liaquat Bhatti, Imran Khan, and Ki-Il Kim. 2022. "A Comprehensive Review of Internet of Things: Technology Stack, Middlewares, and Fog/Edge Computing Interface" Sensors 22, no. 3: 995. https://doi.org/10.3390/s22030995

[13] K. Y. Lin and S. H. Wei, “Advancing the industrial circular economy: The integrative role of machine learning in resource optimization,” J. Green Econ. Low-Carbon Dev., vol. 2, no. 3, pp. 122–136, 2023. https://doi.org/10.56578/jgelcd020302.

[14] Joshi M, Motor Insurance Policy Selection: A Joint Spherical Fuzzy Analytic Hierarchy Process (SF-AHP) and Combined Compromise Solution (CoCoSo) Approach, *J Sci Ind Res*, 83(2) (2024) 183–190, https://doi.org/10.56042/jsir.v83i2.4302.

[15] Dalirazar S & Sabzi Z, Strategic analysis of barriers and solutions to development of sustainable buildings using PESTLE technique, *Int J Constr Manag*, 23(1) (2023) 167–181, https://doi.org/10.1080/15623599.2020.1854931.
[16] de Römph TJ & Van Calster G, REACH in a circular economy: The obstacles for plastics recyclers and regulators, *Rev Eur Comp Int Environ Law*, 27(3) (2018) 267–277, https://doi.org/10.1111/reel.12265.
[17] Kazancoglu I, Sagnak M, Kumar Mangla S & Kazancoglu Y, Circular economy and the policy: A framework for improving the corporate environmental management in supply chains, *Bus Strategy Environ*, 30(1) (2021) 590–608, https://doi.org/10.1002/bse.2641.
[18] Badhotiya GK, Avikal S, Soni G & Sengar N, Analyzing barriers for the adoption of circular economy in the manufacturing sector, *Int J Product Perform Manag*, 71(3) (2022) 912–931, https://doi.org/10.1108/IJPPM-01-2021-0021.
[19] Chen Q, Feng H & de Soto BG, Revamping construction supply chain processes with circular economy strategies: A systematic literature review, *J Clean Prod*, 335 (2022) 130240, https://doi.org/10.1016/j.jclepro.2021.130240.
[20] Uçar E, Le Dain MA & Joly I, Digital technologies in circular economy transition: evidence from case studies, *Procedia CIRP*, 90 (2020) 133–136, https://doi.org/10.1016/j.procir.2020.01.058.
[21] Droege H, Raggi A, Ramos TB, Overcoming current challenges for circular economy assessment implementation in public sector organisations, *Sustain*, 13(3) (2021) 1182, https://doi.org/10.3390/su13031182.
[22] Sumter D, de Koning J, Bakker C & Balkenende R, Key competencies for design in a circular economy: Exploring gaps in design knowledge and skills for a circular economy, *Sustain*, 13(2) (2021) 776, https://doi.org/10.3390/su13020776.
[23] Fairbrother P & Banks M, A Just Transition for Labour: The Challenges of Moves to a Circular Economy, *Relations industrielles/Industrial Relations*, 78(2) (2023), https://doi.org/10.7202/1109482ar.
[24] Pagoropoulos A, Pigosso DC & McAloone TC, The emergent role of digital technologies in the Circular Economy: A review, *Procedia CIRP*, 64 (2017) 19–24, https://doi.org/10.1016/j.procir.2017.02.047.
[25] Upadhyay A, Mukhuty S, Kumar V & Kazancoglu Y, Blockchain technology and the circular economy: Implications for sustainability and social responsibility, *J Clean Prod*, 293 (2021) 126130, https://doi.org/10.1016/j.jclepro.2021.126130.
[26] Ávila-Gutiérrez MJ, Martín-Gómez A, Aguayo-González F & Córdoba-Roldán A, Standardization framework for sustainability from circular economy 4.0, *Sustain*, 11(22) (2019) 6490, https://doi.org/10.3390/su11226490.
[27] Bressanelli G, Adrodegari F, Pigosso DC & Parida V, Circular economy in the digital age, *Sustain*, 14(9) (2022) 5565, https://doi.org/10.3390/su14095565.
[28] Mignacca B & Locatelli G, Modular circular economy in energy infrastructure projects: Enabling factors and barriers, *J Manag Eng*, 37(5) (2021) 04021053, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000949.
[29] Lin KP, Yu CM & Chen KS, Production data analysis system using novel process capability indices-based circular economy, *Ind Manag Data Syst*, 119(8) (2019) 1655–1668, https://doi.org/10.1108/IMDS-03-2019-0166.
[30] Ballardini RM, Kaisto J, Similä J, Developing novel property concepts in private law to foster the circular economy, *J Clean Prod*, 279 (2021) 123747, https://doi.org/10.1016/j.jclepro.2020.123747.
[31] Ramadoss TS, Alam H & Seeram R, Artificial intelligence and Internet of Things enabled circular economy, *Int J Eng Sci*, 7(9) (2018) 55–63, DOI:10.9790/1813-0709035563.
[32] Awasthi AK, Li J, Koh L, Ogunseitan OA, Circular economy and electronic waste, *Nat Electron*, 2 (2019) 86–89, https://doi.org/10.1038/s41928-019-0225-2
[33] Zhang Y, Wang Y, Yadav BK, Application of Circular Economy and Uncertainty Planning in Analyzing the Sustainable Closed-Loop Supply Chain Network Design, *Math Probl Eng*, 2022(1) (2022) 5320974, https://doi.org/10.1155/2022/5320974
[34] Lee, I. and Lee, K. (2015) The Internet of Things (IoT): Applications, Investments, and Challenges for Enterprises. Business Horizons, 58, 431-440. https://doi.org/10.1016/j.bushor.2015.03.008
[35] Stahel, W. R., "The Circular Economy: A User's Guide," 2019.

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