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Assessing Barriers to IoT Implementation in Circular Systems using Spherical Fuzzy AHP Approach

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The implementation of Internet of Things (IoT) technologies is vital for enabling circular systems that enhance resource efficiency and sustainability. However, several barriers hinder the successful implementation of IoT in such frameworks. This study employs the Spherical Fuzzy Analytic Hierarchy Process (SF-AHP) to identify, classify, and prioritize these barriers under uncertainty. Based on a combination of literature review and expert input, the barriers were grouped into four main categories: technical, financial, data and security, and infrastructure-related challenges. The findings reveal that data privacy and security concerns, technological complexity, and high initial costs are the most critical obstacles. Among all, data-related issues emerged as the top concern, reflecting the importance of trust, legal clarity, and cyber security in IoT implementation. Technical and financial barriers also significantly impact implementation, while infrastructure challenges are comparatively less severe. The study provides a structured decision-making framework to guide stakeholders in addressing high-priority barriers, facilitating the integration of IoT into circular economy models.

Keywords: Circular economy, Digitalization barriers, Internet of things, Multi–criteria decision–making, SF-AHP

Introduction

Background

The Circular Economy (CE) is a transformative approach that seeks to eliminate waste, preserve resources, and decouple economic growth from environmental degradation. Unlike the linear "take–make–dispose" model, circular systems emphasize strategies such as reuse, repair, remanufacturing, and recycling to extend product lifecycles and improve resource efficiency. The successful implementation of such systems requires a high degree of transparency, traceability, and operational control—attributes that are increasingly enabled by digital technologies, particularly the Internet of Things (IoT). IoT facilitates the collection and transmission of real-time data across connected devices, allowing organizations to monitor product usage, automate maintenance, and optimize supply chains, thereby enhancing the sustainability and efficiency of circular systems.[1,2]

Despite the growing recognition of IoT as an enabler of circular models, its practical integration remains limited. Challenges such as system complexity, fragmented data infrastructures, and lack of standardization hinder seamless implementation. In many industrial sectors, the technical and organizational readiness to embrace IoT for circularity is still evolving. Such disconnect between technological potential and actual implementation underscores the need to examine the barriers that restrict IoT deployment. Previous studies have discussed the theoretical benefits of IoT in circular systems but often fall short in evaluating real-world implementation challenges.[3,4] A deeper understanding of these barriers is necessary to bridge this gap and inform both policy and practice.

Research Motivation

The environmental and economic benefits of integrating IoT in circular systems are increasingly evident. IoT-enabled technologies allow for smarter production and consumption practices, such as predictive maintenance, real-time energy monitoring, intelligent waste sorting, and automated inventory tracking.[5] These capabilities support circular strategies by reducing energy consumption, minimizing waste, and optimizing the use of raw materials. Moreover, IoT opens avenues for innovative business models, such as product-as-a-service (PaaS), where companies retain ownership of products and are incentivized to enhance their durability and recyclability.[6] These benefits not only support environmental goals but also create competitive advantages for businesses.

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However, many organizations—especially small and medium-sized enterprises (SMEs)—are unable to fully leverage IoT due to multiple internal and external challenges. These include high implementation costs, lack of digital infrastructure, regulatory complexity, and cyber security risks.[7,8] Even firms willing to invest in digital technologies often lack the necessary skills or confidence in the return on investment. Despite these barriers, there are a limited number of empirical studies that systematically analyze or prioritize these challenges in the context of circular systems. Motivated by this gap, the present research aims to offer a structured and practical framework for identifying the most critical barriers to IoT implementation. By providing actionable insights, this study supports decision-makers in accelerating the digital transformation required for sustainable industrial systems.

Research Problem and Objectives

While the theoretical alignment between IoT and circular economy strategies is well-established, the real-world application of IoT in circular systems is fraught with implementation challenges. Studies have acknowledged the presence of barriers such as technological complexity, data governance issues, and financial constraints, but often treat them in isolation or without prioritization.[9,10] This fragmented understanding hampers the ability of organizations to allocate resources effectively or advocate for supportive policies. In addition, decision-makers often lack tools to compare the relative severity of barriers and make informed trade-offs, especially under uncertainty and incomplete information.

The objective of this research is to identify, categorize, and prioritize the key barriers hindering IoT implementation in circular systems using SF-AHP. It is well-suited for such analysis, as it allows decision-makers to express judgments with linguistic terms, incorporates uncertainty, and provides consistent, quantitative results.[11] This study addresses two main research questions:

(1) What are the most significant barriers impeding IoT implementation in circular systems?

(2) How can SF-AHP be used to prioritize these barriers effectively to support strategic decision-making? What are the most critical barriers to the implementation of IoT and digitalization in circular systems?

Contribution

From a practical perspective, this research delivers a ranked list of barriers grouped into four main categories: technical, financial, data and security, and infrastructure-related challenges. The prioritization helps stakeholders understand where to focus their resources and interventions. For instance, the study finds that data privacy and security concerns, technological complexity, and high initial costs are the top barriers. These insights can inform the design of targeted policy instruments, training programs, and technology standards. Overall, this work bridges a knowledge gap and provides both methodological and empirical contributions.

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

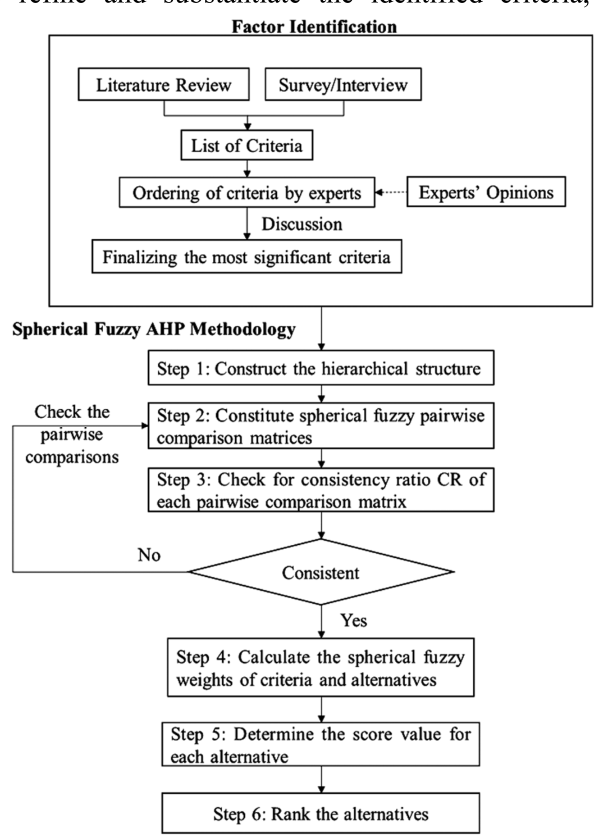

Fig. 1 — Research methodology

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.

The Spherical AHP methodology[11] used in this study followed a systematic process to prioritize criteria (as per Fig. 1):

Step 1: A hierarchical structure is created. The top–tier represents the model's objective, which is determined by a scoring index. The second level consists of n criteria that are utilized to evaluate the alternatives defined in the third level of the structure.

Step 2: Formulate pairwise comparison matrix using linguistic terms (as demonstrated in Table 1):

The calculation of the score indices (SI) for each alternative is performed using Eqs (1) and (2).

$$\mathrm{SI} = \sqrt{\left|100 * \left[\left(\mu_{\tilde{A}_s} - \pi_{\tilde{A}_s}\right)^2 - \left(v_{\tilde{A}_s} - \pi_{\tilde{A}_s}\right)^2\right]\right|} \quad \ldots (1)$$

for AM, VH, HI, SM, and EI.

$$\frac{1}{\mathrm{SI}} = \frac{1}{\sqrt{\left|100*\left[\left(\mu_{\tilde{A}_s}-\pi_{\tilde{A}_s}\right)^2-\left(v_{\tilde{A}_s}-\pi_{\tilde{A}_s}\right)^2\right]\right|}} \quad \ldots (2)$$

for SL, LI, VL, and AL.

Table 1 — Linguistic measures of importance

Definition	(μ, v, π)	Score Index (SI)
Absolutely more importance (AM)	(0.9,0.1,0.0)	9
Very high importance (VH)	(0.8,0.2,0.1)	7
High importance (HI)	(0.7,0.3,0.2)	5
Slightly more importance (SM)	(0.6,0.4,0.3)	3
Equally importance (EI)	(0.5,0.4,0.4)	1
Slightly lower importance (SL)	(0.4,0.6,0.3)	1/3
Low importance (LI)	(0.3,0.7,0.2)	1/5
Very low importance (VL)	(0.2,0.8,0.1)	1/7
Absolutely low importance (AL)	(0.1,0.9,0.0)	1/9

Step 3: The Consistency Ratio (CR) threshold of 10% is utilized for this purpose (calculated using equation (3)).

$$CR = \frac{CI}{RI} \quad \ldots (3)$$

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

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad \ldots (4)$$

where, $\lambda_{\max}$is Eigenvalue and n is number of criteria. The Random Index (RI) used in equation (3) is a standard value against each n.

Step 4: The weights of each alternative with respect to each criterion is obtained.

Step 5: At this point, there are two effective methods for performing the calculation. The first method uses the score function described in equation (5) to break down the criteria weights and derive a crisp value.

$$S\left(\tilde{w}_j^S\right) = \sqrt{\left|100 * \left[\left(3\mu_{\tilde{A}_s} - \frac{\pi_{\tilde{A}_s}}{2}\right)^2 - \left(\frac{v_{\tilde{A}_s}}{2} - \pi_{\tilde{A}_s}\right)^2\right]\right|} \quad \ldots (5)$$

Next, the normalization of criteria weights is carried out using equation (6), followed by the application of spherical fuzzy multiplication described in equation (7).

$$\bar{w}_j^s = \frac{S\left(\tilde{w}_j^s\right)}{\sum_{j=1}^{n} S\left(\tilde{w}_j^s\right)} \quad \ldots (6)$$

$$\tilde{A}_{S_{ij}} = \bar{w}_j^s * \tilde{A}_{S_i} = \left(1 - \left(1 - \mu_{\tilde{A}_{S_i}}^2\right)^{\bar{w}_j^s}\right)^{1/2}, v_{\tilde{A}'_{S_i}}^{\bar{w}'_j}\left(\left(1 - \mu_{\tilde{A}_{S_i}^2}^2\right)^{\bar{w}_j^s} - \left(1 - \mu_{\tilde{A}_{S_i}^2}^2 - \pi_{\tilde{A}_{S_i}^2}^2\right)^{\bar{w}_j^s}\right)^{1/2} \quad \ldots (7)$$

The final score ($\tilde{F}$) is calculated using equation (8).

$$\tilde{F} = \sum_{j=1}^{n} \tilde{A}_{S_{ij}} = \tilde{A}_{S_{i1}} + \tilde{A}_{S_{i2}} + \cdots + \tilde{A}_{S_{in}} \quad \ldots (8)$$

In another approach spherical fuzzy global weights are determined using equation (9).

$$\prod_{j=1}^{n} \tilde{A}_{S_{ij}} = \tilde{A}_{S_{i1}} * \tilde{A}_{S_{i2}} * \ldots * \tilde{A}_{S_{in}} \quad \ldots (9)$$

Result and Discussion

Despite the promising benefits, several common barriers hinder the effective implementation. Previous

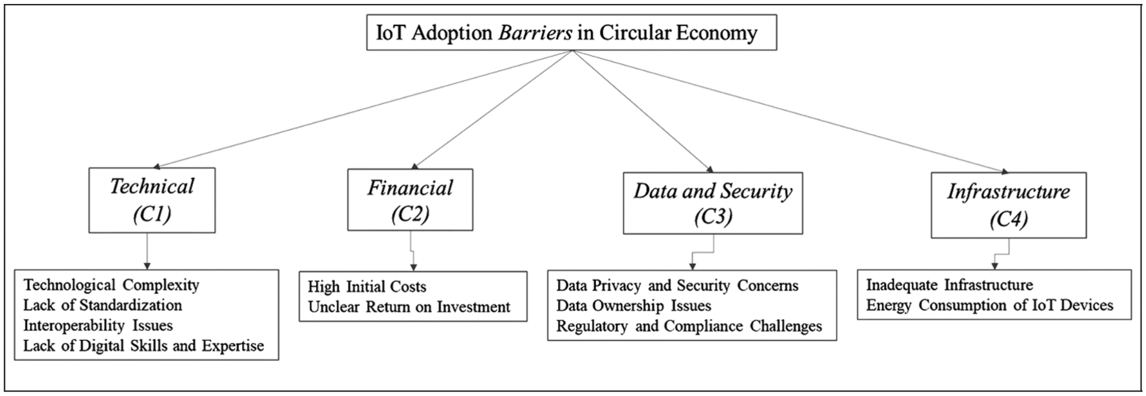

Fig. 2 — Hierarchical structure of factors affecting IoT implementation

studies underscore the need to address these barriers to facilitate a smoother transition. The hierarchical structure is shown in Fig. 2. The identified barriers are listed below:

Technical Barriers (C_1)

- **Technological Complexity (C_{11})**[13]**:** Integrating IoT into existing systems can be technically complex, particularly in industries reliant on legacy technologies. Organizations may struggle with compatibility issues between new IoT devices and their existing systems, requiring significant time and resources for effective integration. Additionally, the need for continuous updates and maintenance of IoT systems adds to this complexity.
- **Lack of Standardization (C_{12})**[14]**:** The absence of standardized protocols for IoT 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 IoT solutions in supporting circular economy practices.
- **Interoperability Issues (C_{13})**[7]**:** Many IoT 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.
- **Lack of Digital Skills and Expertise (C_{14})**[15]**:** The successful implementation of IoT 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.

Economic/Financial Barriers (C_2)

- **High Initial Costs (C_{21})**[9]**:** Implementing IoT 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 IoT initiatives, despite the long–term benefits of increased efficiency and resource optimization.
- **Unclear Return on Investment (ROI) (C_{22})**[16]**:** Many companies struggle to articulate the potential ROI from investing in IoT 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.

Data and Security Barriers (C_3)

- **Data Privacy and Security Concerns (C_{31})**[17]**:** The interconnectivity of IoT 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 increases. Companies are often hesitant to adopt IoT technologies due to fears of compromised sensitive data, which can lead to financial losses and reputational damage.
- **Data Ownership Issues (C_{32})**[7]**:** Questions regarding data ownership arise in collaborative

environments where multiple stakeholders are involved in IoT implementations. Confusion over who owns the data generated can create legal uncertainties that deter organizations from fully committing to IoT implementation.

- **Regulatory and Compliance Challenges (C_{33})[18]:** Varying regulations regarding data protection, environmental standards, and intellectual property rights can create complex compliance issues for organizations adopting IoT 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 IoT, fearing potential penalties or operational disruptions if they fail to adhere to these regulations.

Infrastructure Barriers (C_4)

- **Inadequate Infrastructure (C_{41})[19]:** The successful deployment of IoT 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 IoT technologies, limiting their ability to leverage the benefits of a circular economy.
- **Energy Consumption of IoT Devices (C_{42})[12]:** The operation of IoT 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.

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 categories and subcategories are given in Table 2 and Table 3. On the other hand, global weights and rank of each factor which are derived from Table 4, is given in Table 5.

Table 2 — Pairwise Comparison Matrix for main categories

Factors	**C1**	**C2**	**C3**	**C4**
Technical (C1)	EI	VH	HI	SM
Financial (C2)	VL	EI	SL	EI
Data and security (C3)	LI	SM	EI	HI
Infrastructure (C4)	SL	EI	LI	EI

Table 3 — Pairwise Comparison Matrix for subcategories

	Technical factors (C_1)			
	C_{11}	**C_{12}**	**C_{13}**	**C_{14}**
C_{11}	EI	HI	VH	VH
C_{12}	LI	EI	HI	HI
C_{13}	VL	LI	EI	SM
C_{14}	VL	LI	SL	EI
	Financial factors (C2)			
	C_{21}	**C_{22}**		
C_{21}	EI	HI		
C_{22}	LI	EI		
	Data and Security factors (C3)			
	C_{31}	C_{32}	C_{33}	
C_{31}	EI	VH	HI	
C_{32}	VL	EI	SL	
C_{33}	LI	SM	EI	
	C_{41}	C_{42}		
C_{41}	EI	HI		
C_{42}	LI	EI		

Table 4 — Results from the SF–AHP model

Criteria	Spherical fuzzy weights			Defuzzified values
	Membership	Non–membership	Degree of hesitancy	
C_{11}	0.637	0.351	0.275	17.738
C_{12}	0.594	0.419	0.238	16.623
C_{13}	0.395	0.614	0.242	10.629
C_{14}	0.470	0.527	0.272	12.734
C_{21}	0.617	0.370	0.292	17.051
C_{22}	0.512	0.501	0.246	14.135
C_{31}	0.665	0.338	0.222	18.831
C_{32}	0.539	0.459	0.301	14.663
C_{33}	0.588	0.418	0.255	16.362
C_{41}	0.354	0.638	0.261	9.306
C_{42}	0.497	0.499	0.312	13.344

Table 5 — Global weights and rank

Classification	Class weight	Factor	Global weight	Rank
Technical (C1)	0.358	Technological complexity	0.110	2
		Lack of standardization	0.103	4
		Interoperability issues	0.066	10
		Lack of digital skills and expertise	0.079	9
Financial (C2)	0.193	High initial costs	0.106	3
		Unclear return on investment	0.088	7
Data and security (C3)	0.309	Data privacy and security concerns	0.117	1
		Data ownership issues	0.091	6
		Regulatory and compliance challenges	0.101	5
Infrastructure (C4)	0.140	Inadequate infrastructure	0.058	11
		Energy consumption of IoT devices	0.083	8

The analysis reveals that data and security concerns are the most dominant barriers affecting IoT implementation in circular systems. Among these, data privacy and security concerns stand out as the highest-ranked barrier, indicating the critical importance of trust, cybersecurity, and risk mitigation in digital ecosystems. Organizations are particularly wary of data breaches and unauthorized access, especially in multi-stakeholder environments, where data is frequently shared across devices and platforms. This concern is further compounded by uncertainties in data ownership and compliance, both of which were ranked significantly high. These findings point to the necessity of robust legal frameworks, secure data architectures, and clear governance models to address these apprehensions.

Technical barriers also emerged as highly significant, with technological complexity ranking second overall. This reflects the challenges organizations face in integrating IoT into legacy systems and managing continuous updates, system compatibility, and device interoperability. A lack of standardization and interoperability issues further aggravates this complexity, as fragmented communication protocols and proprietary technologies hinder seamless operation. While lack of digital skills was relatively lower in ranking, it still presents a tangible barrier, particularly for small and medium-sized enterprises with limited access to specialized talent. These results suggest that investment in technical training, standardized platforms, and modular architectures could significantly ease implementation challenges.

Financial concerns, particularly high initial costs, are another major inhibitor. Ranked third overall, the upfront investment required for IoT deployment—including hardware, software, and integration—is often a significant burden for many organizations. This is especially true when compounded by the uncertainty surrounding return on investment, which itself was ranked seventh. The difficulty in quantifying the tangible benefits of IoT in circular systems, coupled with a lack of long-term case studies, results in hesitation among decision-makers. Addressing these concerns requires a combination of financial incentives, shared investment models, and clearer performance indicators to illustrate the value proposition of IoT.

Infrastructure-related barriers were found to be the least critical among all groups. Inadequate infrastructure was the lowest-ranked factor, suggesting that in many industrial contexts, the basic connectivity and computational infrastructure needed for IoT deployment is either present or considered manageable. However, energy consumption of IoT devices remains a moderate concern, especially given the sustainability goals of circular systems. The potential contradiction between deploying energy-intensive devices for sustainability purposes necessitates further innovation in low-power technologies and renewable energy integration.

The results underscore that while all identified barriers pose challenges, they vary significantly in terms of impact and priority. The high-ranking of data, technical, and financial issues points to the need for integrated strategies that address these concerns holistically. Solutions should involve multi-stakeholder collaboration, supportive policy frameworks, capacity building, and transparent metrics for performance evaluation. By systematically addressing the most critical barriers, stakeholders can accelerate the integration of IoT into circular systems and advance toward more resilient and sustainable production models.

Conclusions

This study employed the Spherical Fuzzy AHP method to identify and prioritize barriers to IoT implementation in circular systems. The analysis revealed that data privacy and security concerns, technological complexity, and high initial costs are the most significant barriers, indicating the need for enhanced trust, better system integration, and improved financial feasibility. Barriers were categorized into technical, financial, data and security, and infrastructure groups. Data-related challenges emerged as most critical, suggesting that regulatory clarity and secure data management are essential for implementation. Technical issues like lack of standardization and interoperability also require coordinated solutions. Financial concerns, particularly unclear return on investment, limit implementation, especially in resource-constrained organizations. Infrastructure barriers were ranked lowest, indicating growing digital readiness in many regions. The study provides a structured framework for strategic decision-making. Limitation of this research is its numbers and subjectivity from experts to expert. Future research should expand stakeholder diversity, examine sector-specific differences, and explore the dynamic interplay between barriers to support effective policy and planning.

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