University "St. Kliment Ohridski"
Bitola
Faculty of Information and
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Republic of North Macedonia

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AIIT 2025

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University “St. Kliment Ohridski” Bitola
Faculty of Information and Communication Technology - Bitola
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Introduction

As organizing partners of 15th International Conference on Applied Internet and Information Technologies AIIT 2025, we warmly welcome all participants, researchers, and colleagues joining us from various countries and universities, united by our shared commitment to advancing knowledge in the fields of computer science, applied Internet, and information technologies.

The AIIT conference has become a long-standing tradition of excellence and collaboration, co-organized by the Faculty of Information and Communication Technologies – Bitola, University "St. Kliment Ohridski," and the Technical Faculty "Mihajlo Pupin" – Zrenjanin, University of Novi Sad, Serbia. Over the past fifteen years, this partnership has fostered not only strong academic cooperation but also genuine friendship among our institutions and scholars.

This year's conference proudly continues that tradition, bringing together innovative research, diverse perspectives, and new insights into technologies that are shaping our digital future. The Scientific Program Committee once again faced the demanding task of selecting the highest-quality papers from more than sixty submissions spanning a wide range of topics—including Artificial Intelligence, Immersive Technologies, Mathematical Simulations, Data Science and Big Data Analytics, Knowledge and IT Management, Cybersecurity, Software Engineering, Data Mining, Digital Transformation, Behavioral Economics and Business, Social Engineering, Digital Humanities, Augmented Humanity, and Hybrid Intelligence. This ensures that the program reflects both scientific rigor and creative originality.

We would like to express our sincere gratitude to all reviewers for their dedicated work, as well as to the members of the Organizing Committee for their professionalism, commitment, and enthusiasm in preparing this event.

We are confident that these proceedings will provide an enriching and thought-provoking reading experience.

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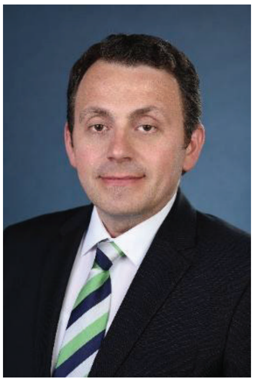

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Regular papers

ICT as a Catalyst for Effective Waste Management in the Circular Economy Context

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Abstract:
The circular economy (CE) proposes a systemic shift from the linear "take–make–dispose" model toward regenerative, closed-loop value creation. This paper examines how information and communication technologies (including Internet of Things (IoT) sensing, big data analytics, artificial intelligence (AI), blockchain, cloud and edge computing, and digital product passports DPPs) can accelerate the transition to circular practices across industries. We outline CE principles and policy drivers, analyze ICT enablers, and present regional insights from the Western Balkans, with a focus on North Macedonia. Case studies illustrate the challenges of e-waste management and the opportunities provided by digital tools. Findings indicate that ICT is not merely supportive but a transformative driver of circularity, providing transparency, predictive intelligence, and new business models.

Keywords:
Circular economy, e-waste management, ICT, IoT, digital product passport, circular economy action plan, ecodesign for sustainable products regulation, predictive intelligence

1. Introduction

The increasing scarcity of resources, coupled with climate change and waste growth, challenges the traditional "take–make–dispose" economic model [1][2]. The circular economy seeks to decouple growth from resource consumption by extending product lifetimes, enhancing recycling, and regenerating natural systems [3][7].

Globally, CE is supported by international agendas such as the UN Sustainable Development Goal 12 on sustainable consumption and production [5]. Within Europe, the European Green Deal and the Circular Economy Action Plan 2020 (CEAP 2020) provide regulatory and financial frameworks for embedding circularity in industries [1][2]. Complementary initiatives such as the Ecodesign for Sustainable Products Regulation (ESPR) and the planned roll-out of DPPs strengthen product transparency [3][13].

ICT is essential for implementing CE principles. IoT sensors and cloud platforms enable continuous monitoring of material and energy flows, supporting predictive maintenance and optimized resource use [8]. Empirical studies indicate that IoT-based monitoring systems can reduce waste generation by up to 30% and improve collection-route efficiency by 20–25%, depending on sensor density and data-integration maturity [8][9]. Artificial intelligence and big data analytics further enhance decision-making by identifying circular design opportunities and improving efficiency in recycling processes [9]. Meanwhile, blockchain technologies strengthen transparency and traceability within supply chains, promoting trust and accountability among stakeholders [10]. Yet adoption remains uneven, particularly in transition economies such as the Western Balkan countries, where infrastructural, interoperability, and financial barriers persist [15][16].

This paper contributes by providing a comprehensive review of the circular economy theory and policy foundations, followed by an analysis of the key information and communication technology enablers that facilitate the transition toward circularity. Furthermore, it discusses both global and regional case studies, with a particular emphasis on the implications for Macedonia, highlighting how digital transformation can accelerate the adoption of circular practices within emerging economies.

Methodologically, this study is grounded in a systematic literature review and comparative policy analysis, synthesizing academic research, institutional reports, and regional case studies to identify technological, regulatory, and socio-economic enablers of circularity

2. Theoretical framework

The CE paradigm consists of three principles: design out waste, keep materials in use, and regenerate natural systems [7]. Theoretical foundations include industrial ecology (which frames production systems as closed loops), the performance economy (which emphasizes service-based models, like leasing instead of ownership), and cradle-to-cradle design (which supports continuous cycles for biological and technical materials) [3][7].

In Europe, CEAP 2020 and ESPR operationalize these concepts by mandating repairability, recyclability, and transparency [2][3]. At a global scale, SDG (Sustainable Development Goal) 12 reinforces monitoring indicators such as material footprint and resource efficiency [5].

3. ICT enablers of circularity

Digital technologies supply the visibility, intelligence, and connectivity required to operationalize CE principles across industries. The following subsections highlight the key ICT domains and their roles as catalysts of circular economy practices.

- *IoT and sensors* - devices that enable real-time monitoring of materials and energy use. Predictive maintenance reduces downtime and waste [8],
- *Big data and AI* - machine learning models forecast demand, optimize design for recyclability, and support dynamic waste collection [9][10]. Digital twins simulate life cycles for better decision-making,
- *Blockchain and digital product passports* - blockchain ensures immutable records for material provenance and supports the EU's Digital Product Passport initiative, particularly in electronics and batteries [11][12][13],
- *Cloud and edge computing* - cloud systems provide scalability, while edge computing enables real-time processing at the source [12] and
- *Integrated digital architectures* - combining IoT, AI, cloud, and blockchain creates platforms for transparency and coordination across stakeholders [10].

To better illustrate the role of digital solutions in supporting circular practices, Table 1 summarizes the main categories of ICT technologies, their application areas within the circular economy, and the expected benefits reported in recent studies. This synthesis condenses insights from multiple domains (ranging from predictive maintenance with IoT sensors to transparency enabled by blockchain and digital product passports), showing how technology creates tangible pathways toward resource efficiency and waste reduction.

As shown in Table 1, each ICT technology addresses a distinct but complementary dimension of circularity. IoT and sensor networks provide real-time visibility into material and energy flows, enabling predictive maintenance and minimizing losses. Big data and AI contribute analytical power to forecast demand and optimize product design for recyclability. Blockchain and DPPs reinforce trust and transparency in secondary markets, while cloud and edge computing ensure scalable and efficient data processing. Finally, digital twins allow companies to test circular strategies virtually before implementation, reducing both risks and costs. Collectively, these technologies form an integrated digital architecture that underpins the successful transition from linear to circular business models.

Table 1:
ICT technologies enabling circular economy practices.

ICT Technology	Application in CE	Expected Benefit	Sources
IoT sensors	Real-time tracking of materials & energy use	Predictive maintenance, Reduced waste	[8][12]
Big data and AI	Demand forecasting, Design for recyclability	Optimized resources, Longer product life	[9][10]
Blockchain / DPP	Provenance & transparency in supply chains	Trust in refurbished goods, Recovery of materials	[11][13]
Cloud and edge computing	Scalable processing of IoT and operational data	Faster decisions, Efficient recycling ops	[12]
Digital twins	Life-cycle simulation & end-of-life planning	Better design, Extended lifespan	[10]

4. Industry and regional case studies

The global electronics sector illustrates both the urgency and opportunity of CE. The Global E- waste Monitor 2024 reports that documented collection and recycling remain near 22 % of total e- waste and may fall further without decisive action [17]. Leading manufacturers now deploy IoT sensors to track product lifecycles and automate returns for refurbishment. Global e-waste reached over 62 million tons in 2022, but only 14 million tons were documented as recycled [6]. Projections indicate >80 million tons by 2030, with a declining recycling rate [6].

To contextualize the urgency of digital interventions in waste management, it is essential to examine the global dynamics of electronic waste. Over the past decade, the world has witnessed a steep increase in total e-waste generation, while the documented collection and recycling rates have remained disproportionately low. Figure 1 presents the trends in global e-waste generation and documented recycling between 2010 and projected values for 2030, highlighting the widening gap that underlines the critical role of ICT solutions in closing the loop.

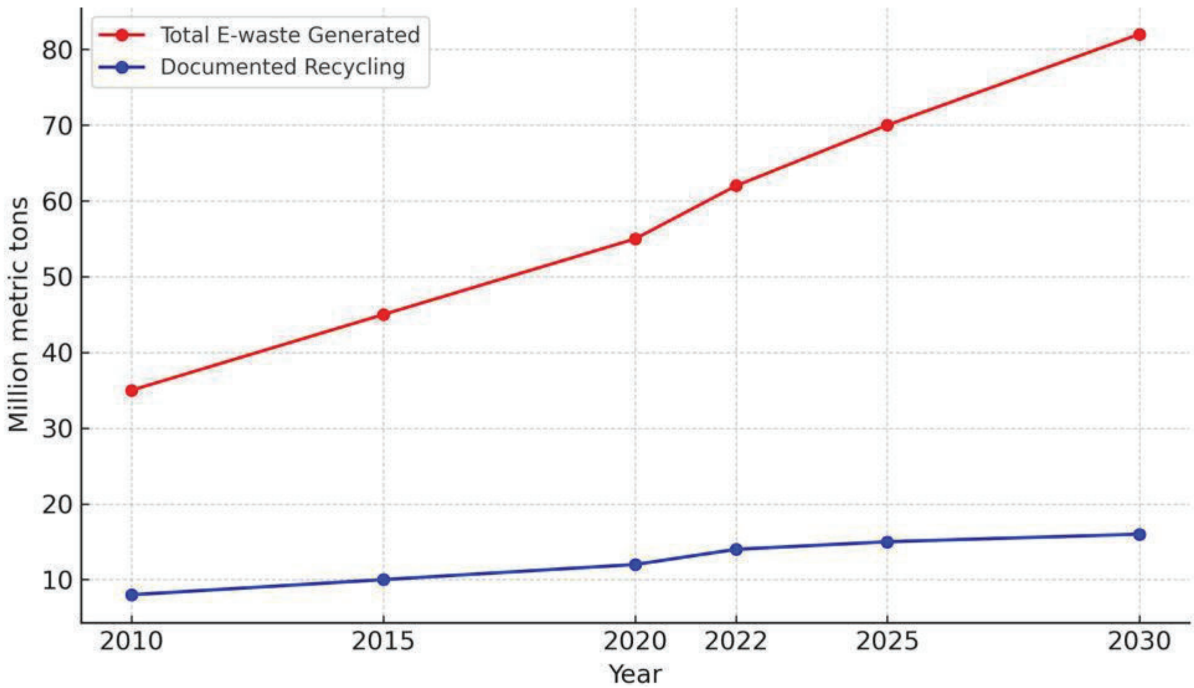

Figure 1: Global e-waste generation vs. documented recycling (2010–2030). Source: Global e-waste monitor 2024 [6]

While total e-waste volumes increased from approximately 35 million metric tons in 2010 to more than 62 million tons in 2022, documented collection and recycling grew only modestly, from 8 million to 14 million tons over the same period [6]. Projections from the Global E-waste Monitor 2024 suggest that by 2030, total e-waste could exceed 80 million tons, with the documented recycling rate declining to 20%. This widening discrepancy underscores systemic inefficiencies in global waste- management systems and highlights the urgent need for digital solutions (such as IoT-based monitoring, blockchain-enabled Digital Product Passports, and AI-driven analytics) to improve traceability, collection, and recovery processes. Without such interventions, the environmental and economic costs of unmanaged e-waste will continue to escalate, particularly in developing and transition economies.

4.1. CIRPASS digital product passport (DPP)

The electronics sector generates one of the fastest-growing waste streams worldwide. According to the Global E-waste Monitor 2024, documented collection and recycling accounted for just 22.3% of global e-waste, with projections that this rate could fall toward 20% by 2030 without stronger policy and technological interventions [17]. The European Union, through the CEAP and the ESPR, has introduced the concept of DPPs as a transformative mechanism to improve transparency and traceability in product life cycles [6][8].

4.1.1. System concept and use cases

The Collaborative Initiative for a Standards-based Digital Product Passport for Stakeholder- Specific Sharing of Product Data for a Circular Economy or CIRPASS Project (2022–2025), funded by the EU Horizon programme, has developed and tested DPP use cases in three priority sectors: electronics, batteries, and textiles.

For electronics, two concrete use cases have been documented [13]:

- *Refurbished smartphones* - DPPs provide detailed information on device history, repair records, and component composition. This reduces information asymmetry between refurbishers and consumers, enabling trust in second-hand markets
- *Recovery of critical raw materials* - DPPs support recyclers by offering transparent data on the presence and location of valuable elements such as cobalt, lithium, and rare earths in small electronic devices. This facilitates efficient extraction and reduces dependency on virgin raw materials as described in the CIRPASS D2.2 use case on critical raw materials [13].

Both use cases highlight the potential of combining IoT-enabled identification, cloud or edge data platforms, and blockchain-based ledgers to ensure authenticity and prevent tampering [12][17].

Although CIRPASS is a pilot rather than a fully scaled deployment, its findings indicate that DPPs can significantly improve the efficiency and transparency of e-waste management. The project predicts measurable outcomes such as increased recovery rates of critical raw materials, higher consumer trust in refurbished electronics, and a reduced environmental footprint through extended product lifetimes [13]. As part of the Western Balkans, Macedonia’s circular economy roadmap [15] already identifies electronics and waste management as priority areas. Lessons from CIRPASS could be adapted to the local context as:

- *Regulatory alignment* - adoption of EU-aligned frameworks on product traceability and extended producer responsibility will be essential as part of accession processes,
- *Pilot initiatives* - municipalities such as Skopje could initiate small-scale pilots with electronics retailers, integrating DPP-based identification for returned devices,
- *Capacity building* - training refurbishers and recyclers to use DPP systems would create skilled jobs and improve competitiveness and
- *Regional collaboration* - a Western Balkan DPP hub, shared among multiple economies, could reduce costs and foster interoperability.

In the end, the CIRPASS case illustrates how ICT-driven solutions (particularly DPPs) can transform waste management from an afterthought into a strategic pillar of the circular economy. For Macedonia, the adoption of similar pilots would not only contribute to environmental goals but also align the country with EU market requirements, strengthening both sustainability and economic integration.

4.2. Regional perspective for Western Balkans and North Macedonia

The OECD's Roadmap for North Macedonia (2025) identifies e-waste as a priority sector [15]. Collection rates remain below EU averages (~15%), with significant infrastructural gaps [16][17]. Regional initiatives under the Green Agenda for the Western Balkans stress harmonization with EU policy [19][22]. Table 2 provides a comparative overview of e-waste generation, collection rates, and policy alignment across Western Balkan economies, illustrating both regional disparities and common challenges in the transition towards EU circular economy standards.

Table 2 Regional e-waste and Circular Economy Policy Alignment in the Western Balkans.

Country/Region	E-waste (kg/capita, 2022)	Documented Collection (%)	Policy Alignment with EU CEAP	Sources
NorthMacedonia	10.5	15	Partial (Roadmap 2025)	[15][16][18]
Albania	9.8	12	Early-stage	[18]
Serbia	14.2	20	Advanced	[18][19]
Bosnia&Herzegovina	12.7	18	Partial	[18]
Montenegro	11.3	17	Partial	[18]
Western Balkans Avg	11.7	16.4	Mixed	[18][19]

As shown in Table 2, the Western Balkans present significant disparities in e-waste generation and documented collection rates. Macedonia, with approximately 10.5 kg of e-waste generated per capita in 2022, demonstrates a collection rate of only 15%, which lags behind the EU average of over 40% [6][15]. Serbia shows relatively stronger performance (20%), while Albania remains at an early stage of circular economy adoption with the lowest collection rate of 12%. Across the region, the average collection rate of 16.4% highlights structural challenges in waste management systems, including limited infrastructure, financial constraints, and informal recycling practices. Policy alignment with the EU's CEAP remains partial in most countries, though Serbia is more advanced due to ongoing accession negotiations. These figures underline the urgent need for harmonized legislation, regional cooperation, and investment in digital infrastructures (particularly DPPs and IoT-enabled waste monitoring) to close the gap with EU standards and ensure progress towards sustainable circular practices.

5. Challenges and limitations

Despite promising technological capabilities, the integration of information and communication technologies into circular economy strategies faces a range of systemic obstacles, like:

- **Regulatory and policy gaps** - while the European Green Deal and the Circular Economy Action Plan set ambitious targets, national transposition and enforcement remain uneven across EU members and accession countries [6][7][8][9][19]. Western Balkan economies, including Macedonia, are aligning with EU standards, yet discrepancies in waste-management infrastructure, procurement rules, and environmental enforcement slow progress [21].
- **Financing and market barriers** - circular business models often require substantial up-front investment in sensing infrastructure, analytics platforms, and staff training [12][16]. Many small and medium-sized enterprises - SMEs (the backbone of regional economies)

lack access to affordable credit and risk-sharing mechanisms [20][21]. Without supportive fiscal instruments such as green bonds, tax incentives, or extended producer responsibility schemes, private actors hesitate to adopt capital-intensive ICT solutions.

- **Data privacy and cybersecurity** - IoT sensors, blockchain-based product passports, and cross-industry data-sharing raise significant privacy concerns under GDPR and related frameworks [6][19]. Breaches could expose proprietary formulas, customer usage patterns, or material sourcing information. Although blockchain provides immutability, it cannot prevent the input of false data (GIGO or "garbage in, garbage out"), necessitating multi-layered verification and access controls [18][19].
- **Technical and interoperability issues** - heterogeneous data formats and legacy industrial systems hinder seamless integration. Digital twins and real-time analytics depend on interoperable standards and high-quality datasets; however, many municipal and industrial actors maintain siloed or incomplete records [12][13][14][16]. Without common ontologies and open APIs, the benefits of predictive analytics and cross-supply-chain optimization remain limited.
- **Social and cultural factors** - effective circular transitions also depend on behavioral change. Public awareness of reuse, repair, and recycling remains low in parts of the Western Balkans [21][22][23][24]. Workforce upskilling is essential to operate advanced analytics, cybersecurity frameworks, and IoT infrastructure. Absent targeted education and incentives, even well-designed technological solutions may fail to achieve scale.

6. Conclusion and directions for further work

This paper has demonstrated that digital technologies are not merely auxiliary tools but transformative drivers of circularity. ICT is not simply supportive but transformative for the CE transition. IoT, AI, cloud or edge, and blockchain enable predictive intelligence, transparency, and resource efficiency. Case studies from global e-waste trends, CIRPASS pilots, and North Macedonia show both opportunities and persistent gaps. Looking ahead, three strategic directions may emerge:

1. **Standardization and interoperability** - developing open data standards, shared ontologies, and secure APIs will allow SMEs and municipalities to join multi-actor platforms without prohibitive costs,
2. **Innovative financing** - green bonds, public–private partnerships, and extended producer responsibility mechanisms can lower the cost of digital infrastructure, particularly for SMEs and
3. **Human capital and governance** - upskilling programs, privacy-by-design frameworks, and transparent data-governance policies will build public trust and ensure that circular ICT systems remain secure and equitable.

By bridging technological innovation with policy, financing, and human-centered design, information technologies can anchor a resilient, low-carbon, and inclusive circular economy regionally (in the Western Balkan) and globally.

6.1. Methodological limitations

While this study provides a conceptual and analytical overview of ICT's role in advancing circular economy practices, several methodological limitations should be acknowledged. The analysis primarily relies on secondary data sources and policy documents, without empirical validation through field measurements, stakeholder surveys, or quantitative modeling. Consequently, the presented insights reflect synthesized evidence rather than statistically tested results. Moreover, regional comparisons are constrained by data availability and inconsistency across national reporting frameworks. Future research should adopt mixed-method approaches, including case-based modeling, pilot monitoring, and econometric analysis, to validate and quantify the real impact of ICT-enabled circular interventions under diverse socio-economic conditions.

Future work should investigate large-scale pilot implementations to validate the scalability, interoperability, and performance of ICT-enabled circular systems under real-world conditions. Furthermore, advanced research into governance architectures, user adoption dynamics, and ethical constraints will be critical for designing secure, resilient, and sustainable digital infrastructures supporting the circular economy.

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