Extended Abstract
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Building a Digital Circular Economy for Electrical and Electronic Equipment

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Introduction

The rapid development of digitalisation has brought disruptive changes to the economy and life, as well as a growth in the consumption of Electrical and Electronic Equipment (EEE). Waste Electrical and Electronic Equipment (WEEE) is now the fastest growing waste stream in the world (Balde et al., 2024). Despite this, less than a quarter of EEE is recovered globally. This means that the vast majority of WEEE is sent to landfill (Singh et al., 2020).

In the face of rising pollution, resource scarcity and supply chain volatility, there are growing calls for a Circular Economy in which product lifetimes are maximised and resources are kept in use for as long as possible (Kirchherr et al., 2017). This means that EEE is effectively reduced, reused, repaired, remanufactured, recycled and recovered (Potting et al., 2017) at the end of its lifecycle. Circular Economy has gained significant attention in the last decade from industry and policy makers (Geissdoerfer et al., 2017). Within this rapidly growing field, a body of research is growing on how digital technologies can enable a more circular economy (Pagoropoulos et al., 2017). For example, Despeisse et al. (2017) examine how 3D printing could unlock a Circular Economy by enabling localised remanufacturing; Voulgaridis et al. (2022) study applications of Internet of Things (IoT) in the Circular Economy to improve traceability; and Bressanelli et al. (2022) consider the role of digital twins in the Circular Economy as a way of improving inventory and demand information across the supply chain. At a policy level, there has also been increasing interest in how digitalisation can enable the Circular Economy. In 2022, the European Commission announced its Circular Economy Package, which identified for Digital Product Passports (DPP) as a key framework for improving material, component and product traceability as part of a Circular Economy (European Commission, 2022).

Despite their promise, there is limited knowledge as to how new digital technologies and capabilities such as IoT, Big Data and Digital Fabrication could be leveraged to support the transition to Circular Economy. Furthermore, it cannot be assumed that digitalisation will necessarily lead to sustainability gains and several circular economy rebound effects may take place (Zink and Geyer, 2017). Digitalisation may in fact lead to a proliferation of WEEE, if systems are not properly managed and implemented. This research aims to further explore the linkages between digitalisation and the circular economy, specifically in the EEE sector. It addresses the following research questions: (1) what are the current and future potential applications of digital (Industry 4.0) technologies in the EEE sector? (2) What are the main strengths, weaknesses, opportunities and threats related to the integration of digital technologies in the EEE sector?

Methods

To address these research questions, this study undertakes a state-of-the-art technology horizon scan of digital (Industry 4.0) technologies (including AI, Big Data, Digital Fabrication, Digital Twins, Internet of Things, Robotics and Automation, Virtual Reality/Augmented Reality) and their potential application in a CE for EEE. Empirical and academic case studies are systematically collected and analysed in order to identify the potential threats, opportunities, and likely future developments related to a digitally-enabled CE in the EEE sector. Ongoing evidence is collected from two ongoing CE and EEE research projects, led by the authors.

Results

The results of this study are presented as a typology of case studies (see example Table 1). Potential threats, opportunities, and likely future developments related to the development of a digital CE for EEE are presented, including discussion of a range of digital (Industry 4.0) technologies (see Table 2). These findings emphasize potential for these technologies to extend product lifetimes, optimize resource use, and support circular practices but also demonstrate critical challenges that must be addressed to realize these benefits fully.
Several strengths of Industry 4.0 technologies in enabling CE practices for EEE were identified. Among these, IoT technology stands out for its ability to enhance traceability and transparency through real-time product monitoring across the EEE lifecycle (Fernandes et al., 2023). This capability supports improved product repairability and facilitates quality control. Similarly, AI has a potential to improve the repair and maintenance processes. For example, AI-driven repair optimization (Liao et al., 2024), improves product designs by identifying recurring failure points.

Despite these strengths, several weaknesses were identified. For example, AI tools often rely on high-quality datasets, and any inaccuracies can undermine user trust. Additionally, the energy-intensive nature of AI development poses environmental concerns, potentially offsetting its benefits (Ligozat et al., 2021). Digital technologies such as blockchain and IoT are increasingly used to improve traceability and responsible sourcing of critical raw materials like cobalt and tungsten, addressing transparency gaps in resource extraction and mining (Sherpa and Sinha, 2021) The results highlight several opportunities for leveraging digital technologies to enable CE in the EEE sector. One such opportunity is AI-driven predictive maintenance, which can transform operational efficiency by proactively addressing issues (Shin et al., 2021).

	AI	Robotics and automation	IoT
10 Refuse			
9 Reduce	Motivo (n.d)		Hp printing as a service (n.d)
8 Rethink			
7 Reuse	Teleplan (Barteková & Börkey, 2022)		
6 Repair			
5 Refurbish	Lenovo (n.d) Circular Brain (n.d.)		
4 Remanufacture	eit manufacturing (n.d)	eit manufacturing (n.d)	
3 Repurpose			
2 Recycle	Sweeep (n.d)	Recycleye (n.d)	Velos (n.d)
1 Recover		AMP (n.d)	

Table 1. Examples applications of Industry 4.0 Digital Technologies in the Circular Economy for EEE

	SWOT
AM	S: Customisation, Small scale production, Production of spares, Weight saving W: Not suitable for mass production, Build quality O: Customisation and decentralised manufacturing
AI	S: Supply chain transparency, Predictive analytics and decision-making e.g. enhancing repairability W: Limited Accuracy O: Predictive Maintenance T: High energy consumption
Big Data	S: Predictive maintenance and reliability W: Data integration, complexity O: Improved design and innovation
IoT	S: Enhanced traceability and transparency O: Improved efficiency in recycling and maintenance
Robotics & automation	S: Efficiency in recycling W: Complex maintenance O: Scalable solutions T: Causing more E-waste
VR/AR	S: Enhanced training and maintenance efficiency W: High implementation costs O: Improved product design and customization T: Resistance to adoption

Table 2. Strengths, weaknesses, opportunities and threats related to Industry 4.0 Digital Technologies in the Circular Economy for EEE

Another is digital fabrication, which facilitates customization and decentralized manufacturing, reducing dependency on global supply chains and enhancing adaptability to local demands (Rao et al., 2022).

Finally, the study identifies threats that could hinder the effective integration of these technologies. AI's high energy consumption poses an environmental challenge, potentially offsetting its sustainability benefits. Similarly, robotics, if not planned for end-of-life, could inadvertently increase e-waste, undermining CE goals. Resistance to AR/VR adoption, driven by steep learning curves and job displacement fears, presents another critical challenge to widespread implementation (Jalo & Pirkkalainen, 2024). While Industry 4.0 technologies offer transformative potential for a digital CE in the EEE sector, their adoption must be carefully managed to mitigate associated risks and maximize benefits. Future research should explore strategies for mitigating these challenges while maximizing the benefits of digitalisation in enabling a circular economy for EEE.

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