Digital solutions for a circular electronics value chain

A thought paper for International E-Waste Day 2021

Copyright and publication information

ISBN Paper version: 978-92-61-35241-7

ISBN Electronic version: 978-92-61-35251-6

Acknowledgements

This thought paper was written by Yondeen Sherpa (ITU) and Deepali Sinha (Sofies Group), with contributions by Rosie McDonald (ITU), Shramana Dey (Sofies Group), Arunita Bose (Sofies Group), Garam Bel (ITU), Vanessa Gray (ITU), Pascal Leroy (WEEE Forum), Magdalena Charytanowicz (WEEE Forum), James Horne (WEEE Forum), and Dulip Tillekeratne (GSMA).

The authors thank the experts who generously contributed their time and insights under conditions of anonymity. They extend special thanks to the WEEE Forum and GSMA for their support and allowing them to benefit from their network of members.

Design: Luke Stephenson | www.stephensondesign.eu

Table of Contents

Figures

International E-Waste Day
Powered by the WEEE Forum

About International E-Waste Day:

International E-Waste Day (IEWD) takes place on 14 October each year and was introduced in 2018 by the WEEE Forum with the support of its members. It serves to raise the public profile of WEEE recycling and encourage consumers to return their end-of-life gear for responsible recycling or to consider reuse or repair. In 2020, ITU collaborated with the WEEE Forum on IEWD to produce a thought paper on Internet Waste and help promote the importance of responsible recycling of WEEE. Strong partnerships are key to achieving this. The WEEE Forum and ITU have continued to partner for IEWD 2021, by preparing this thought paper on Digital Solutions for a Circular Electronics Value Chain together with Sofies and the GSMA.

In 2021, the theme of IEWD is the key role of consumers in the circular economy. Around the world, awareness raising activities will be taking place (ranging from conferences and webinars to school collections and social media campaigns) that focus on the crucial role each of us has in making circularity a reality for EEE.

For more information, visit **www.internationalewasteday.com.**

About the GSMA:

The GSMA is a global organization unifying the mobile ecosystem to discover, develop and deliver innovation foundational to positive business environments and societal change. Our vision is to unlock the full power of connectivity so that people, industry, and society thrive. Representing mobile operators and organizations across the mobile ecosystem and adjacent industries, the GSMA delivers for its members across three broad pillars: Connectivity for Good, Industry Services and Solutions, and Outreach. This activity includes advancing policy, tackling today's biggest societal challenges, underpinning the technology and interoperability that make mobile work, and providing the world's largest platform to convene the mobile ecosystem at the MWC and M360 series of events.

For more information, visit **www.gsma.com**.

About ITU:

The International Telecommunication Union (ITU) is the specialized United Nations agency for information and communication technologies (ICTs), driving innovation in ICTs together with 193 Member States and a membership of over 900 companies, universities, and international and regional organizations. Established over 150 years ago in 1865, ITU is the intergovernmental body responsible for coordinating the shared global use of the radio spectrum, promoting international cooperation in assigning satellite orbits, improving communication infrastructure in the developing world, and establishing the worldwide standards that foster seamless interconnection of a vast range of communications systems. From broadband networks to cutting edge wireless technologies, aeronautical and maritime navigation, radio astronomy, oceanographic and satellite-based earth monitoring as well as converging fixed mobile phone, Internet and broadcasting technologies, ITU is committed to connecting the world.

For more information, visit **www.itu.int.**

About Sofies:

Sofies Group is a B-corp certified international sustainability project management and consulting firm. Leveraging scientific methodologies and robust processes, Sofies supports clients from both public and private sectors in their efforts to become more sustainable. We develop solutions for integrating sustainability into governance and operational frameworks, and tackle a range of issues including climate change, circular economy, land use and regenerative economy.

For more information visit, **www.sofiesgroup.com.**

About the WEEE Forum:

The WEEE Forum is a Brussels-based for-impact, not-for-profit international association representing forty-five producer responsibility organizations across the globe. Together with our members, we are at the forefront of turning the extended producer responsibility principle into an effective electronic waste management policy approach through our combined knowledge of the technical, business and operational aspects of collection, logistics, de-pollution, processing, preparing for reuse and reporting of e-waste. It is the biggest organization of its kind in the world. Our mission is to be the world's foremost e-waste competence centre excelling in the implementation of the circularity principle. The PROs are based in Europe, the Americas, Africa, Oceania and Asia. In 2020, its member organizations reported collection and proper de-pollution and recycling of 2,8 Mt of WEEE.

For more information visit, **www.weee-forum.org**.

1. Introduction

On average, the global consumption (excluding photovoltaic panels) of electrical and electronic equipment (EEE) increases annually by 2.5 million metric tons (Mt) in parallel with higher levels of disposable income, urbanization and industrialization.[1] This rise in consumption has led to increasing quantities of waste electrical and electronic equipment (e-waste), making one of the fastest growing waste streams globally. The annual production of e-waste is expected to reach 74.7 million metric tons (Mt) by 2030.[2]

E-waste or waste electrical and electronic equipment (WEEE) is *"electrical or electronic equipment that is waste, including all components, sub-assemblies and consumables that are part of the equipment at the time the equipment becomes waste".*[3]

E-waste contains hazardous substances and toxic additives that can be dangerous to health and have adverse consequences for the environment if not managed properly. The increasing vulnerability of critical material supply chains adds extra value on e-waste as an 'urban mine'. EEE components have a high potential of material recovery at the end-of-life stage. In 2019, the value of raw materials such as iron, copper, and gold in e-waste was estimated to be approximately USD 57 billion, of which only USD 10 billion was recovered.[4]

With a growing awareness and understanding of the environmental impact and scarcity of resources that stem from unchecked growth in linear economies, the need for a shift towards a circular economy is apparent. In parallel, rapid innovation in digital technologies and their growing applications is transforming public and private operations and re-shaping the daily lives of citizens around the world. Digitalisation is increasingly regarded as one of the key enablers of the circular economy, and at the intersection of digitalisation and the circular economy could lie an opportunity for the electronics value chain to transition to a circular system.

A ***circular economy*** economy aims to minimize the input of primary materials and prevent wastage, with the ideal scenario being to reuse all waste as raw material. CE strategies close the loop between different life cycles through the design phase and incorporate decisions to enable recycling and reuse to optimize the use of raw materials, goods and waste.[5]

Digitalisation describes the growing applications of digital technologies across the economy, in fields such as robotics, smart vehicles, sensors, mobile app, smart tracking and autonomous mechanisms.[6]

Digital solutions in the electronics value chain refer to applications of digital technologies to enable a transition from a linear to a circular system or economic model.

Background

The current linear economic model is highly unsustainable and vulnerable to economic shocks from the disruption of resources as seen during the COVID-19 pandemic.[7,8] A systemic transformation towards a circular electronics value chain entails converting the current "take-make-waste model" into one that integrates circularity throughout the value chain. The movement towards a circular economy has gained prominence in the last few years and is regarded as a key enabler to help achieve the Sustainable Development Goals (SDGs).[9]

Today, digital transformation is at the heart of strategic planning of private and public institutions, particularly in their potential to catalyse the improvement of quality of life with a focus on low- and middle-income countries (LMICs) in line with the SDGs.[10] In the shift towards circularity, digital technologies can support the transparency, efficiency, ease and accountability in existing economic systems. Digital solutions not only enable a more efficient flow of information, but also leverage the flow of products, components and materials.

The widespread adoption of digital technologies has a twofold effect on e-waste management systems. New and upcoming technologies provide digital solutions and innovations that enable the transition of the electronics value chain towards a circular model. Yet, by their very nature, this also results in more devices employed, that are more widely dispersed, which exacerbates an already growing e-waste challenge.

Given the growth of e-waste generation and the potential of digital solutions in the electronics value chain, there is a need to map the current state of digitalisation in the sector and look ahead at emerging technologies that could accelerate the transition to a circular electronics value chain. However, as the space is developing with many major digital solutions still at early stages or applied on a small scale, there is limited research and evidence to make judgements on the effectiveness and scalability of digitalisation to enable a circular economy for EEE. Additionally, e-waste management systems vary in their set-up and level of formalization across regions, which is coupled with varying levels of digital capacity (infrastructure and skills) and penetration of digital solutions in the economy. Thus, this paper does not seek to make a conclusion on the need and necessity of digitalisation to enable a transition to a circular electronics value chain but seeks to explore its applicability.

The International Telecommunication Union (ITU), the WEEE Forum, GSM Association (GSMA), and Sofies Group have prepared this thought paper to explore the current applicability and scope of digital technologies in enabling the transition to a circular electronics value chain. The paper maps out major digitalisation trends and highlights use cases of digital technologies in the electronics value chain, from raw material production and EEE manufacturing to post-consumer e-waste collection, logistics and treatment.

Examples are drawn from both established and emerging digital solutions, whilst case studies provide a deeper understanding of blockchain, artificial intelligence and cloud computing applications in the electronics value chain. In addition, the paper discusses the implications of digitalisation and considerations that stakeholders looking to harness digital technologies for a circular electronics value chain should take into account, including equal access to digital infrastructure and digital skills, financial viability of digital solutions, and the opportunity for public-private cooperation in regulating digital applications.

Methodology

The thought paper is based on desk research and consultations. The research included academic literature, reports and papers on digital solutions in e-waste, as well as parallel waste streams and initiatives such as those including plastics and solid waste. The consultations were in the form of individual discussions and focus groups with producers, recyclers, WEEE Forum member and non-member producer responsibility organizations (PROs), as well as standards organizations and GSMA members. These consultations occurred over video conference and email exchange with guided questions and free discussions. Some outcomes of the consultations and focus groups are presented as case studies and act as examples of functioning digital technology applications in the electronics value chain.

2. A circular electronics value chain

A circular approach in the electronics value chain is widely accepted as the system transformation needed to move away from today's linear model of consumption.[11,12] "A New Circular Vision for Electronics" produced by PACE and the World Economic Forum in collaboration with the United Nations E-Waste Coalition, outlined three objectives for the circular economy for electronics:[13]

1. New products use more recycled and recyclable content.
2. Products and their components are used for longer.
3. End-of-use products are collected and recycled to a high standard.

Extended producer responsibility (EPR) is a *"policy principle to promote total life cycle environmental improvements of product systems by extending the responsibility of the manufacturers of the product to various parts of the entire life cycle of the product, and especially to the take-back, recycling and final disposal of the product".*[14]

On the policy and regulatory side, the last two decades have seen the formalisation of e-waste management systems, often based on the extended producer responsibility (EPR) principle. By October 2019, 78 countries were covered by some form of policy, legislation or regulation governing e-waste, yet many of these frameworks are not legally-binding.[15] In the context of e-waste, many countries have developed laws, mandating that take-back, collection, dismantling, treatment, recycling and recovery are undertaken with due diligence for a positive social, economic and environmental impact. In addition, international standards also provide guidance and the framework to implement circularity across the electronics value chain.[16]

Challenges in the electronics value chain

In 2019, only 17.4 per cent of total e-waste generated globally was documented as formally collected and recycled.[17] Even countries with relatively mature e-waste systems have low collection rates. For instance, Europe despite having the highest collection and recycling rate is only at 42.5 per cent.[18] The push towards a circular economy has provided stakeholders across the value chain with an impetus to initiate systemic improvements and invest in infrastructure and awareness raising. Yet, on-ground implementation challenges are holding back stakeholders from creating a more efficient and circular system. Some of the challenges faced by stakeholders in the value chain are highlighted below.

Challenge 1: Insufficient and unreliable data on stocks and flows of e-waste

Accurate data about e-waste import, export, generation, collection and recycling is critical for the definition of fair and effective regulation and policies, realistic collection targets and tailored e-waste management programmes. Having the right data allows regulators to set informed targets and better monitor national e-waste management efforts over time. A UNITAR and WEEE Forum study finds that European Union member countries have unreliable data on the quantities of WEEE that are mixed with metal scrap, thrown in the general bin or exported.[19] It is critical to account for such missing e-waste flows when designing appropriate measures to improve collection and set realistic targets.[20]

Good data also reveal the business case for recycling, which in turn leads to the potential for integrating digital solutions in this sector. Visibility across the electronics value chain supports effective monitoring and enforcement that is imperative for a fair and effective e-waste management system. The existing reporting and monitoring frameworks in developing systems are often based on physical paperwork and lead to low national data gathering due to cost and efficiency.[21] Current processes, such as the tracking and reporting of e-waste flows in the value chain, are prone to fraud and manipulation due to a lack of integrated and secure systems of reporting.[22]

According to research in the 2017 Global E-waste Monitor, only 21 per cent of all countries collect data for indicators such as e-waste generation and collection.[23] The Global E-waste Statistics Partnership (GESP) was established to help countries compile data and statistics on e-waste flows using an internationally harmonized measurement framework.

Challenge 2: Information asymmetry and limited trust

According to the consultations undertaken for this research, information asymmetries, such as those between producers and recyclers on product compositions, or repairers and recyclers on product components, are a prominent issue. This can occur due to lack of designated and secure channels as well as concerns from producers on the confidentiality of their product information.[24] While some formal systems provide mitigative measures in the form of registered recyclers, asset disposition firms and the use of bill of materials, such measures mostly cater to large corporations in high and upper middle-income economies.

With the myriad of e-waste management stakeholders, information collected in the value chain (producers, recyclers, PROs and aggregators) is usually stored in isolated databases and systems, creating organizational silos.[25] This leads to limited visibility of EEE flows and difficulty in identifying trends across the sector. In addition, it can create inefficiencies in the system with repetitive and inefficient information exchange between stakeholders. Even when the information is shared, legitimacy of the data can still be a concern as the data is created and validated internally, often without mechanisms to verify the data by external parties. This is particularly concerning in weakly enforced systems where fraud is commonplace.[26]

Challenge 3: Informal and illegal material flows

In many economies where e-waste management systems are not fully developed, or absent altogether, common in LMICs, the informal sector primarily manages the e-waste. This leads to unsound and ineffective e-waste treatment and a loss of vital data on e-waste recycling as e-waste management is not regulated (leading to lack of governmental records).[27]

A rampant and unregulated sector can pose severe risks to the health of informal sector workers and the community due to the lack of health and safety conditions. Informal methods such as burning, leaching, and melting e-waste to extract raw materials is not only inefficient, it damages the environment through air, soil and water pollution and exposes the community to toxic fumes and particles.[28] In addition, informal sector workers often receive inadequate compensation and have unfair working conditions.[29]

With the majority of e-waste being undocumented, a significant amount (estimated to be 7 to 20 per cent) is moved across borders illegally or under the pretences of reuse or scrap metal, particularly from developed to developing economies, which further exacerbates informal sector issues and the economy.[30] Notably, the United States Environmental Protection Agency (EPA) calculated that exporting e-waste to Asia was ten times cheaper than treating it in the United States given the guidelines.[31] To address illegal border movements of e-waste, the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal has developed technical guidelines on transboundary movements of electrical and electronic waste and used electrical and electronic equipment, in particular the distinction between waste and non-waste.[32]

Legal and regulatory obligations of EEE sector especially under the EPR principle require producers to have visibility over and report where their raw materials came from and where products end up. However, this supply chain complexity is reported as an important exposure point for producers, as the provenance of materials is increasingly difficult to identify.[33] In the consultations, producers also raised a concern that company led take-back initiatives poses a risk if e-waste is found to end up somewhere unsanctioned, causing damage to the reputation of the company.[34]

Challenge 4: Insufficient consumer participation

Consumers play a key role in e-waste management as they determine the use phase of EEE and if/how it is diverted into proper end of life channels, for instance by returning it to the producer or dropping it off at a municipal e-waste bin. Low worldwide collection and formal recycling rates indicate that barriers to consumer participation exist in developed and developing e-waste management systems alike.

Research identifies convenience, financial cost and incentives, as a large determinant of consumer participation, alongside knowledge and awareness.[35] In regions with a thriving informal sector, the convenience of kerbside pickup and buy-back from informal collectors is an attractive formal sector alternative.[36] In such systems, formal recyclers can then face supply constraints with lack of significant volumes to make compliant recycling profitable.[37] This is exacerbated further by the tendency of consumers to stockpile electronics at home due to lack of awareness of proper disposal channels and concern over personal data.[38,39] Financial or material incentives have also been found to be effective incentives for consumers to set more sustainable habits.[40]

Challenge 5: Inefficient e-waste management processes

Current e-waste management processes from collection to end of life treatment can be costly and complicated as more EEE product types are introduced in the market. The World Bank finds that lower income countries experience significant difficulty in recovering solid waste operations costs.[41] In particular, transportation poses a significant cost burden to the reverse logistics operation as large volumes of e-waste have to be transported up the value chain from the collection of e-waste to its transport to a temporary warehouse or recycler as well as the delivery of secondary materials to producers.[42]

As e-waste flows from collection to recycling and the eventual sale of recovered value, profit is largely dependent on e-waste quantity and the recovery of materials and reusable components. Introducing secondary materials into production can alleviate the burden on primary sources and provide a business incentive for e-waste stakeholders, however closing the loop through a sustainable business model requires higher recovery efficiencies.[43] During recycling, critical raw materials that have little economic value are often permanently lost as recyclers prioritize the recovery of higher value materials, and therefore divert output material fractions towards those treatments.[44]

The consultations also revealed that due to lower profit margins, it is imperative for resources such as human and physical capital to be maximized, and logistical process optimized for businesses to be financially viable, especially those with lower e-waste flows.[45]

3. Digitalising the electronics value chain for circularity

Rising Internet access, network connectivity and fixed and mobile penetration around the world are supporting the growth of digital solutions as tools to catalyse circular economy goals. Globally, 93 per cent of the population have access to mobile network connectivity, with 4G network connectivity now covering 85 per cent of the population.[46] During the COVID-19 pandemic, international bandwidth usage was estimated to have grown by 38 per cent, exceeding previous growth rates by 6 per cent. Internet connectivity and network access serve as a fundamental backbone to digital solutions as the underlying architecture that enables information exchange and access to digital technologies. The various groups of digital technologies do not exist in isolation, but rather interact with and build on each other, and it is their convergence and integration that makes them disruptive and transformational.

To understand the landscape of established and emerging digital solutions in the electronics value chain, it is important to look at every part of the process. The following section explores the application of digital technologies to strengthen and support the transition to a circular electronics value chain. Within each step of the value chain, the major digitalisation trends are mapped out along with the applications and examples of relevant solutions. Case studies are included to provide a deeper look into examples of these applications.

Key Technologies

Artificial intelligence (AI) is a "computerized system that uses cognition to understand information and solve problems".[47] With the development of machine learning, AI is now even more intelligent and independent, as it enables "computational systems to understand data and gain knowledge from it without necessarily being explicitly programmed".[48]

Big data analysis refers to "scrutiny performed on massive volume of data with the purpose of obtaining meaningful results, such as trends or preferences".[49]

Blockchain is a "peer to peer distributed ledger based on a group of technologies for a new generation of transactional applications which may maintain a continuously growing list of cryptographically secured data records hardened against tampering and revision".[50]

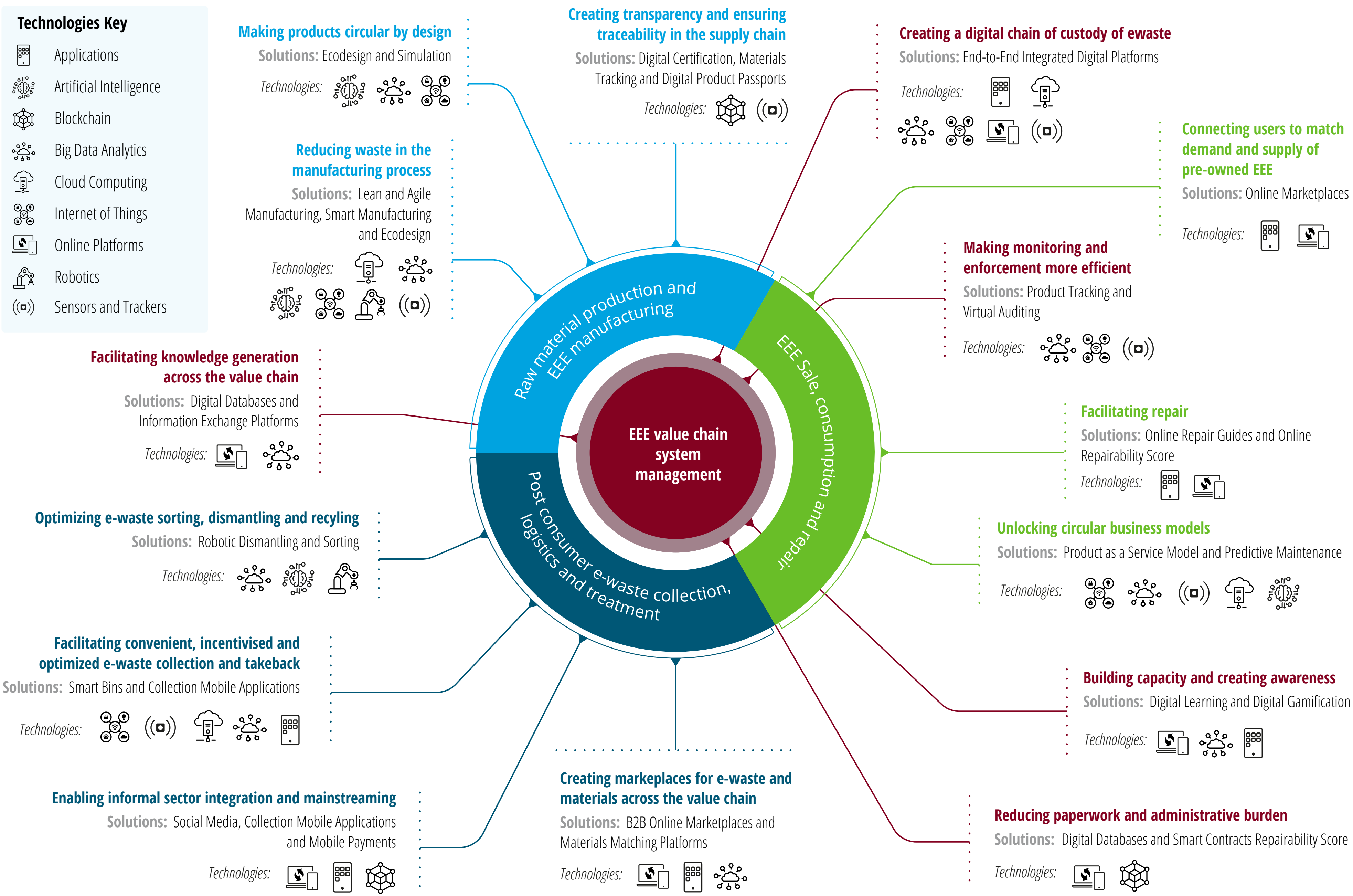
Cloud computing enables "network access to a scalable and elastic pool of shareable physical or virtual resources with self-service provisioning and administration on-demand".[51]

Internet of things (IoT) is a "global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies".[52]

Robotics entails the use of programmable machines called robots alongside complementary computer systems to control and receive feedback.

Sensor refers to an "electronic device that senses a physical condition or chemical compound and delivers an electronic signal proportional to the observed characteristic".[53]

Figure 1: **Digital solutions for a circular electronics value chain**



Raw material production and EEE manufacturing

Macro trends in digitalisation

Industry 4.0 or smart manufacturing aims to optimize manufacturing and provides an opportunity to integrate circular economy principles into the electronics value chain through digital solutions.[54] The use of data and digital technology applications is poised to deliver advances in manufacturing processes, products and related services to improve and innovate designs and materials, accelerate efficiency gains in the supply chain, reduce errors and stoppages, and increase transparency and traceability.[55] The European Commission estimates that the digitalisation of manufacturing could add approximately USD 130 billion per year to industry.[56]

Industry 4.0 the current phase of industrialisation revolution that leverages technologies such as Internet of Things (IoT) and smart cyber-physical systems using computer-based algorithms to monitor and control physical things including machinery, robots, and vehicles.[57]

This digitalisation of raw material production and manufacturing is leading to a 'data-driven revolution' where industries are increasingly generating, collecting, sharing and analysing information across networks to produce manufacturing intelligence.[58] Smart manufacturing or smart factories integrate the 'physical' and 'digital' sides of a factory by deploying technologies such as artificial intelligence (AI), big data analytics, cloud computing and industrial IoT.[59] Digitalisation is also supporting the transition from the traditional resource-intensive, waste-generative, fixed-production manufacturing to more flexible and leaner production processes.

With the growing importance of supply chain visibility and raw material sourcing, blockchain-based provenance tools are now being used to store and present data on product origin. These tools can provide information on product content and condition to stakeholders across the value chain. The EEE sector use of provenance tools includes digital product passports (DPPs) through which product information can be accessed by stakeholders along the value chain. DPPs are now gaining visibility and support in the EEE sector through recent policy developments such as the Green Deal[60] and Circular Economy Action Plan[61] in the European Union. International organizations, including the ITU-T Study Group 5 focus on environment, climate change and circular economy, have already taken the initiative to study the standardization requirements for a digital product passport. These requirements include identifying a set of product characteristics that are relevant to the management of an information and communication technology (ICT) product throughout its lifecycle while taking into consideration circular economy principles.

A ***digital product passport*** is a set of data on the composition, materials, and chemical substances of a product as well as information on its repair, spare parts and end of life disposal.[62]

Applications of digital technologies

1. Reducing waste in the manufacturing process

Digital solutions can strengthen lean manufacturing production processes that aim to maximise productivity while simultaneously minimise waste within manufacturing operations. Sensors, big data, AI and specialised software can combine to provide data-driven production management, inspection and control, and a digitally enabled workforce. Lean manufacturing can reduce waste during EEE production by preventing product defects, overproduction, processing waste, and reducing raw material inventory.

Lean manufacturing, maximising productivity and minimising waste, has the potential to improve the productivity and quality of EEE manufacturing by 23 per cent compared to traditional manufacturing processes.[63,64,65] Digitalisation can help lean manufacturing enhance flexible and autonomous maintenance, improve data-driven production management and self-inspection, and support capacity building of workers – all of which would help minimize manufacturing waste.[66] Manufacturers can implement digital technology to train workers through human-computer interfaces that have the ability to deliver on-the-spot learning to prevent and avoid errors.[67]

Digitalisation also offers the opportunity to increase the flexibility in EEE manufacturing processes in responding to variations in market demand (also known as agile manufacturing), thereby avoiding overproduction and other waste. Through the implementation of machine learning in 'smart' plug-and-play or plug-and-produce models (models that allow users to easily change input parameter values to run processes, without needing reconfiguration), it is possible to foresee demand, delivery time, and the number of warehouses or intermediaries required.[68] These technologies improve the responsiveness, efficiency and material visibility of the manufacturing sector.

2. Making products circular by design

Eco-design is considered an important enabler of a circular economy. It entails increasing EEE product lifespans by building in durability, reparability and recyclability, and reducing waste by design to make products more circular from inception. The EU WEEE Directive includes an article covering eco-design in EEE production that refers to the dismantling and recovery of components and materials when product end-of-life is reached. The "right-to-repair" policy is also being advocated globally to make producers design products that can be easily repaired and make repair more accessible through the availability of spares and repair services. However, there is scope for eco-design principles to be better integrated in EEE manufacturing globally.[69]

Digital technologies in the form of AI, big data and IoT used at the manufacturing stage can help improve product design, better visualise complex EEE production systems, increase resource efficiency, and reduce waste generation. Research on the use of AI for eco-design has shown that it can help designers to select materials based on recyclability and disassembly.[70] For instance, from 2011 to 2016, the EU Accelerated Metallurgy project used AI algorithms to analyse big data to design new alloy formations[71] and produce and store 14 000 specimens in a 'virtual alloy library'. The alloys that showed promise in line with circular economy principles (e.g., longer lifespans, non-toxic) were further tested by 20 end users.

Data collected throughout a product lifecycle can also be used to inform eco-design principles. Fairphone, a Dutch mobile phone company, leases devices to businesses for a monthly fee that includes maintenance, updates and guaranteed take-back.[72] Fairphone outlines data and connectivity as a key element of its model, where the collected data about device condition is used to identify causes of failure, which can then inform and improve the design process. Following circular design principles, Fairphone products feature modular design that prioritize repair, reuse and life extension of products and parts, in order to achieve high usage before end-of-life (or e-waste) management.[73]

3. Creating transparency and ensuring traceability in the supply chain

EEE supply chains are expansive and complex, with products being designed, manufactured and sold globally. An increasing number of companies are using tagging or track and trace technology solutions such as radio-frequency identification (RFID) tags, blockchain, quick response (QR) codes to increase transparency and traceability along the supply chain.

Blockchain in particular has been recognized for its potential to place all value chain stakeholders in a secure and immutable information chain, making it possible to verify individual transactions at the touch of a smartphone. Digital certification technologies based on blockchain allow the tracing of raw materials used in EEE production. The mining industry, for example, has introduced digital certification technologies to increase accountability.[74] In the Democratic Republic of the Congo, Dorae Inc. are piloting a blockchain-based supply chain tracking system for the cobalt and coltan (high demand conflict minerals) mined from three mines. This tracking system provides end-users with reliable information on the source of the raw materials thereby increasing the transparency of the mining methods applied.[75] A similar effort is being undertaken by battery material supplier, Umicore, alongside multiple mining companies to ensure cobalt used in electric vehicles is traceable and responsibly sourced.[76]

CASE STUDY:

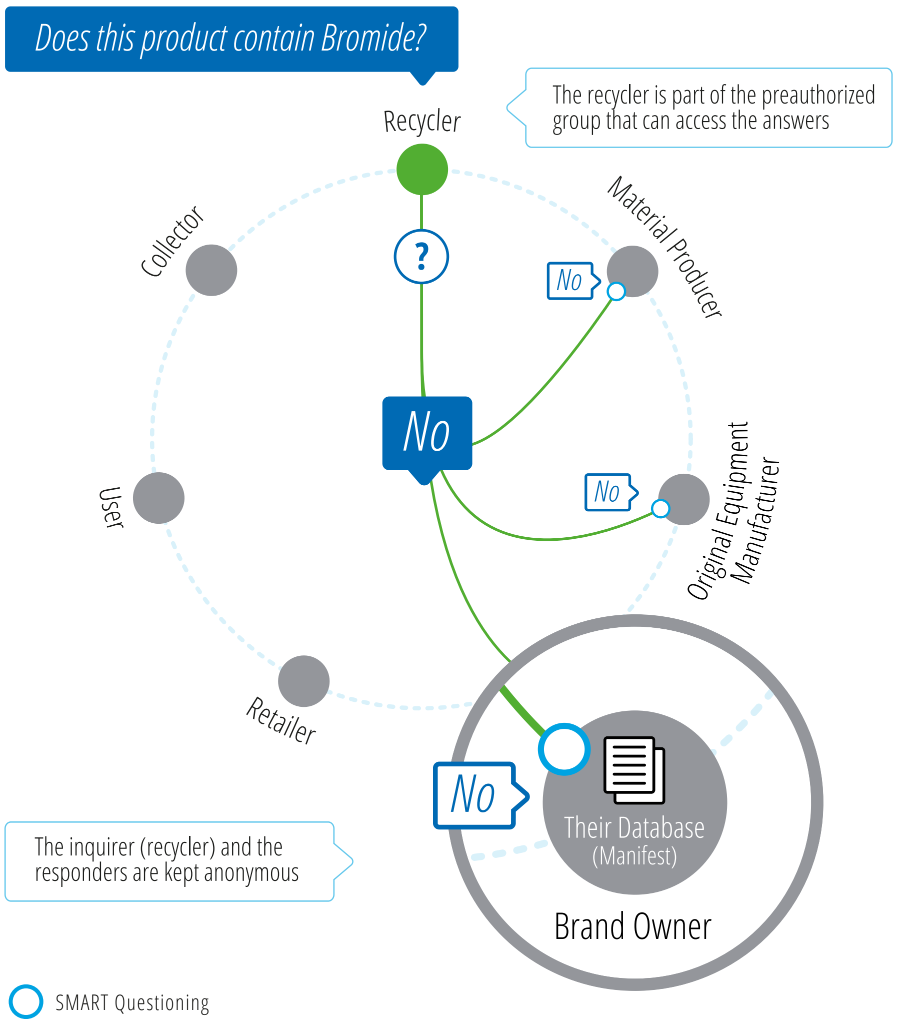
Circularise - Smart Questioning to facilitate information exchange [77]

Circularise, a Dutch start-up, is using a blockchain platform to bridge the information gap across chemical and plastic supply chains without risking confidentiality. With its patented Smart Questioning technology, the platform addresses two concerns about information exchange in the value chain – loss of control and ownership over the data, and reliability of unverified the data in terms of accountability and complexity of value chains. To achieve this, Circularise creates a digital twin of the physical value chain and members of the value chain update data in the software (through their manifests) to mirror the activities of the actual supply chain. Manifests are collections of information on the platform owned by stakeholders such as original equipment manufacturers or producers. Manifests link to other manifests. For instance, the manifest of a tablet producer links to the manifest of the supplier of a component of the tablet. Barcodes or QR (quick response) codes on labels help connect the physical devices to their digital twins.

To exchange information securely and anonymously, the platform contains the smart questioning protocol based on blockchain and zero-knowledge proofs. Stakeholders can pose push or pull questions on the public blockchain. Push questions are pre-answered questions that are encrypted on the blockchain, that can be accessed by preauthorized group members such as a trusted set of recyclers (e.g. Does the tablet contain mercury?). Pull questions are questions that have not been answered yet and is decided on a case-by-case basis if the actor wishes to answer (e.g. How much mercury does the tablet contain?).

The trustworthiness of the data is ensured by auditing. The immutable and verifiable nature of the platform means that auditors can access and verify the information. Participants, while anonymous, are also encouraged to provide correct information as their answers can be traced back to their real identities by the auditor.

Figure 2: **Circularise - Smart questioning technology**



EEE sale and consumption

Macro-trends in digitalisation

In 2020, retail e-commerce sales worldwide amounted to USD 4.28 trillion and are projected to grow to USD 5.4 trillion by 2022.[78] E-commerce has become more attractive for consumers, with the global share of online retail growing by 3 per cent from 2019 to 2020.[79] In 2020, computers and consumer electronics represented the largest share of retail e-commerce sales in the United States of America,[80] while in Europe, home electronics was the second most bought product category online.[81] Even during the COVID-19 pandemic, when the global EEE sector saw a decline (around 5 per cent in high income countries while as high as 30 per cent in LMICs through first three quarters of 2020), some EEE products such as mobile phones, laptops and gaming equipment registered a growth in sales (in high income countries while in LMICs there was a minimal decline).[82]

The used good digital marketplaces are booming and estimated to increase to 20% of new good sales by 2025 from 5% in 2015.[83] Studies on customer behaviour in resale markets show that consumer electronics are among the most resold products, especially in online markets. Research has shown consumer appetite to sell, or exchange used EEE exists, and is dependent on factors such as price, payment time and flexibility.[84] Digital marketplaces are enabling consumer access to a large re-commerce market facilitating the sale of stagnant electronics. However, digital marketplaces also have several challenges, such as the practice of "free riding", where products are sold in another country through the online marketplace to avoid EPR fees. There is little data on the scale of the issue, but it is estimated that EPR fees are unpaid for between 5 and 10 per cent of EEE placed on the market in the 38 OECD member countries due to this practice.[85]

Product life extension, combined with the increasing acceptance of leasing rather than ownership of products is a growing trend. Product-as-a-service (PaaS) and asset sharing increases the longevity of EEE as it passes through several consumers before its end-of-life is reached.[86] This approach to business is enabled in part by the rising proliferation of IoT sensors, allowing businesses to track EEE usage.

Product-as-a-service (PaaS) model entails selling the service provided by the product rather than the product itself. The customer in this case pays for the use of the product, and ownership remains with the provider.

Applications of digital technologies

1. Connecting users to match demand and supply of pre-owned EEE

The resale market faces various concerns such as perceptions of inferiority and risk of malfunction, which can discourage the buying of second-hand and refurbished EEE, particularly from unfamiliar sources.[87] By acting as intermediary standards enforcers, online marketplaces can combine the guarantee of a pre-vetted seller alongside other inherent advantages of wider choice, convenience and accessibility. Online business-to-consumer (B2C) marketplaces also provide agency and convenience to individual consumers to participate in re-commerce.[88] Various marketplaces such as eBay and Olx have long offered a channel for individuals to directly sell used devices[89] while e-commerce platforms such as Flipkart and Amazon have also introduced refurbished products as a vertical. Many online marketplaces apply stringent quality check protocols, such as Back Market, an online marketplace for refurbished electronics, where only one-third of refurbishers pass the approval process. Moreover, continuous standards checks and in-house grading systems provides their five million customers with access to quality refurbished electronics.[90]

Original equipment manufacturers (OEMs) are also participating in the resale market by offering both takeback options for functional pre-owned EEE and selling refurbished products online. These second-hand products are tested, refurbished and packed in official packaging by the manufacturer or authorized affiliates, lending legitimacy to the products.[91] Here, data transparency plays a vital role in creating consumer trust in products to drive online sales of refurbished products.[92] Notably, studies show that consumers are increasingly choosing third parties such as NextWorth and Gazelle for resale of electronics over OEMs, due to benefits such as payment flexibility and better online customer feedback to consumers.[93]

2. Facilitating repair

Repair is an important aspect of EEE life extension. For many products, the bulk of greenhouse gas (GHG) emissions arise from the manufacturing stage, and therefore by extending product lifetimes, the demand for more products to replace non-functioning products is reduced. In the European Union, approximately 4 Mt CO_{2eq}[1] could be saved annually by 2030 from extending the lifetime of washing machines, smartphones, notebooks and vacuum cleaners by one year.[94] Research has shown that ease of access to services and the quality of repair play an important role in influencing consumer decisions.[95] Therefore, policy makers in the United States and European Union are implementing the "right-to-repair" through legislation.[96,97] It should be noted, however, that the repair ecosystem depends on a variety of factors such as access to genuine spare parts and repair know-how. Digital technologies such as online platforms and mobile applications are able to facilitate this ecosystem by providing access to repair know-how, services, and genuine parts.

Online digital platforms provide easily accessible repair solutions through specific guides or at-home repair services, enabling consumers to repair instead of replacing products. iFixit is an e-commerce and wiki-based digital platform that provides consumers freely accessible repair manuals[98] and sells specific components for fixing products.[99] To raise consumer awareness about repairability options for electronics, iFixit has also developed a semi-qualitative method for scoring the repairability of laptops, smartphones and tablets. Such solutions can normalize self-repair and bolster confidence in the quality of spare parts by building a culture of repair.

Standardising repairability metrics can also push producers to make their products more repair compatible. This has been applied in France, where EEE retailers are required to display a repairability score online since 2021.[100] The score is calculated by entering relevant parameters on a spreadsheet provided by the Ministry of Environment.[101]

3. Unlocking circular business models

IoT devices can unlock circular business models such as PaaS by enabling cost effective, continuous and non-invasive (remote) monitoring of product usage and conditions. This incentivizes service providers and producers to optimize use and better plan maintenance, as well as create long lasting products that are easily repaired and refurbished.[102] For example, Bundles, a Dutch company, offers consumers a pay-per-use or rental model for home appliances. Rather than owning the product, customers subscribe to high quality appliances such as washing machines and dishwashers, paying a monthly subscription or paying according to their usage. The company deploys IoT technologies to track appliance usage of water and energy and to optimize maintenance to best support this product-as-a-service (PaaS) offering.[103]

Papillon is a project launched in Belgium, through a collaboration between Bosch Home and Samenlevingsopbouw West-Vlaanderen, a social enterprise company. The project was launched to analyse the potential of a sustainable appliance rental model in low-income families through replacement of outdated appliances with newer models under a PaaS scheme.[104] Through Papillon, low-income households are able to rent an appliance for ten years at around nine euros a month with service and maintenance provided by Bosch. During the project, Bosch also started offering refurbished appliances for rent, making the value chain more circular.[105]

[1] CO_2 equivalent is used to standardize the global warming effects of greenhouse gases using CO_2 effects as a comparison.

Predictive maintenance is a set of activities that detect changes in the physical condition of equipment to carry out the appropriate maintenance work for maximizing the service life without increasing the risk of failure.[106]

Information derived from IoT systems can be analysed to enable predictive maintenance. Circular business models leverage predictive maintenance to take pre-emptive actions to avoid failure and maximize product life through techniques such as failure prediction and fault diagnosis. Swiss coffeemaker, Thermoplan, uses a cloud based IoT platform to store, communicate and analyse data collected from thousands of coffee machines, and by using machine learning techniques to predict maintenance needs and ensure timely repair, it saves costs in redundant maintenance checks.

Recognizing the importance of sustainable circularity, the C-Servees project in Europe works on the development, testing and validation of circular economic business models based on services such as eco-leasing, product customization and improvement of WEEE management.[107] The project identifies digital technologies such as IoT and RFID tags as a key driver of these models and is looking at incorporating emerging technologies such as AI and blockchain.[108]

Post-consumer EEE collection, logistics and treatment

Macro-trends in digitalisation

The growing integration of digitalisation in sustainable urban planning has led to the rise of the smart sustainable city (SSC) concept, where digital technologies form an active component in urban service design and delivery. This concept considers waste management to be a key area of intervention. A 'smart' waste management system can support process optimization while minimizing operational costs, when compared to traditional waste collection mechanisms.[109] Smart waste management applies various technologies such as GPS tracking, identification technologies such as RFID tags, sensor-based data acquisition through IoT devices and big data analytics, leveraging mobile communication networks to transmit data securely and in real-time. The waste management sector is adopting technology and deploying digital tools that help optimize resource use right through the post-consumer journey of end-of-life electronics to bring them back into circulation as products, components and secondary materials.

A ***smart sustainable city*** is 'an innovative city that uses ICTs and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social, environmental and cultural aspects'.[110]

Blockchain-based smart contracts take predetermined actions when predefined conditions are met. One transaction triggers the next, for instance automating payments or issuing certificates.[111] Examples of smart contract applications can include checking for pre-programmed sustainability metrics for transaction approvals[112] or pre-defining acceptable toxicity levels to assess performance of waste minimization activities.[113] With its blockchain interface, smart contracts automate transactions and make them traceable and irreversible, requiring minimal human intervention in an already decentralized system.[114] In using smart contracts, mobile money and fintech apps on smartphones are being used to transfer incentives to consumers to segregate and dispose of waste in a responsible manner in return for digital rewards.[115]

At the treatment and processing stage, there is scope for emerging technologies such as AI and robotics to optimize sorting, dismantling and recycling. Such technologies with the use of image recognition and machine learning can create more homogeneous waste streams through automatic sorting. This can help to overcome efficiency and precision shortfalls of manual and mechanical processing. In particular, AI-assisted robots are being used to identify e-waste and its components with increased accuracy and speed during the sorting and dismantling and recycling processes.[116]

E-waste management systems in LMICs are commonly dominated by the informal sector. In countries where both formal and informal stakeholders are present, their activities are usually interlinked and interdependent. However, informal sector workers are usually at a higher risk of exposure to toxic materials present in e-waste.[117] As per a report by the International Labour Organization, integration of the informal sector with the formal system requires technology transfer, and a balance among efficiency, social compliance (including job creation) and economic viability.[118] There is also a growing recognition that digitalisation could be better employed to support the transition of informal sector workers to the formal system by building capacity and introducing disruptive business opportunities that enable social innovation.

Applications of digital technologies

1. Facilitating convenient, incentivised and optimized e-waste collection and takeback

In conventional waste management systems, waste generated by households or businesses is collected in bins, which are emptied by refuse vehicles that are either operated by the municipalities or by private service providers. These vehicles typically follow predetermined schedules and collect and transport waste to recycling centres or other disposal facilities. There is little inspection of the bin contents as it is resource intensive (more labour, time and cost), thus any improper segregation that takes place is difficult to track. Moreover, the collection frequency and routes of these vehicles are not informed by usage patterns.

Volumetric sensors, IoT devices connected through mobile communication networks, collect and transmit data from 'smart' bins that can detect when bins are full, and accordingly send alerts to schedule collection. IoT-based systems and sensors collect data on variables such as bin capacity and geo-location, which can help optimize the time and date of pickup and assign a pickup vehicle. The use of smart bins enables emptying based on demand. Tailoring the routes that vehicles take to collection requests can improve the efficiency of collection and create a more sustainable logistic system whereby collection happens as and when necessary.[119,120] Strategic location of smart bins and route optimization of refuse vehicles are also making the e-waste collection process more convenient and often incentivized (through the use of digital rewards), which is essential to bring end-of-use products and materials back into circulation. This optimization of collection can lead to greater efficiency, lower labour cost, lower fuel consumption, and lower pollution levels from vehicles.[121,122]

InnoWEEE, an EIT Climate-KIC project, tested the use of smart bins for e-waste collection in Italy and the United Kingdom. In their Cava de' Tirreni pilot, users received an "ecological receipt" which was used for discounts in designated commercial entities when they disposed of their e-waste and logged it through a digital user recognition system.[123] In July 2021, Singapore introduced 300 smart bins for e-waste collection, which are available in public areas such as town centres, shopping malls, government buildings, residents' committee centres, community centres, supermarkets and retail outlets.[124,125] This system awards points that can be redeemed for shopping vouchers.[126]

Mobile apps can also be used to optimize collection due to their user-friendly and ubiquitous nature, providing an opportunity to bridge the gap between consumers, collectors and PROs by providing 'matchmaking' services. These apps are built for convenience, allowing consumers to schedule waste pickups according to their availabilities. Many of these apps also attract users by providing incentives such as online tokens or discounts on future purchases. A variety of user-friendly e-waste collection apps such as E-Tadweer in Egypt[127] and Uzed in India,[128] have been launched to incentivise and improve formal e-waste collection.

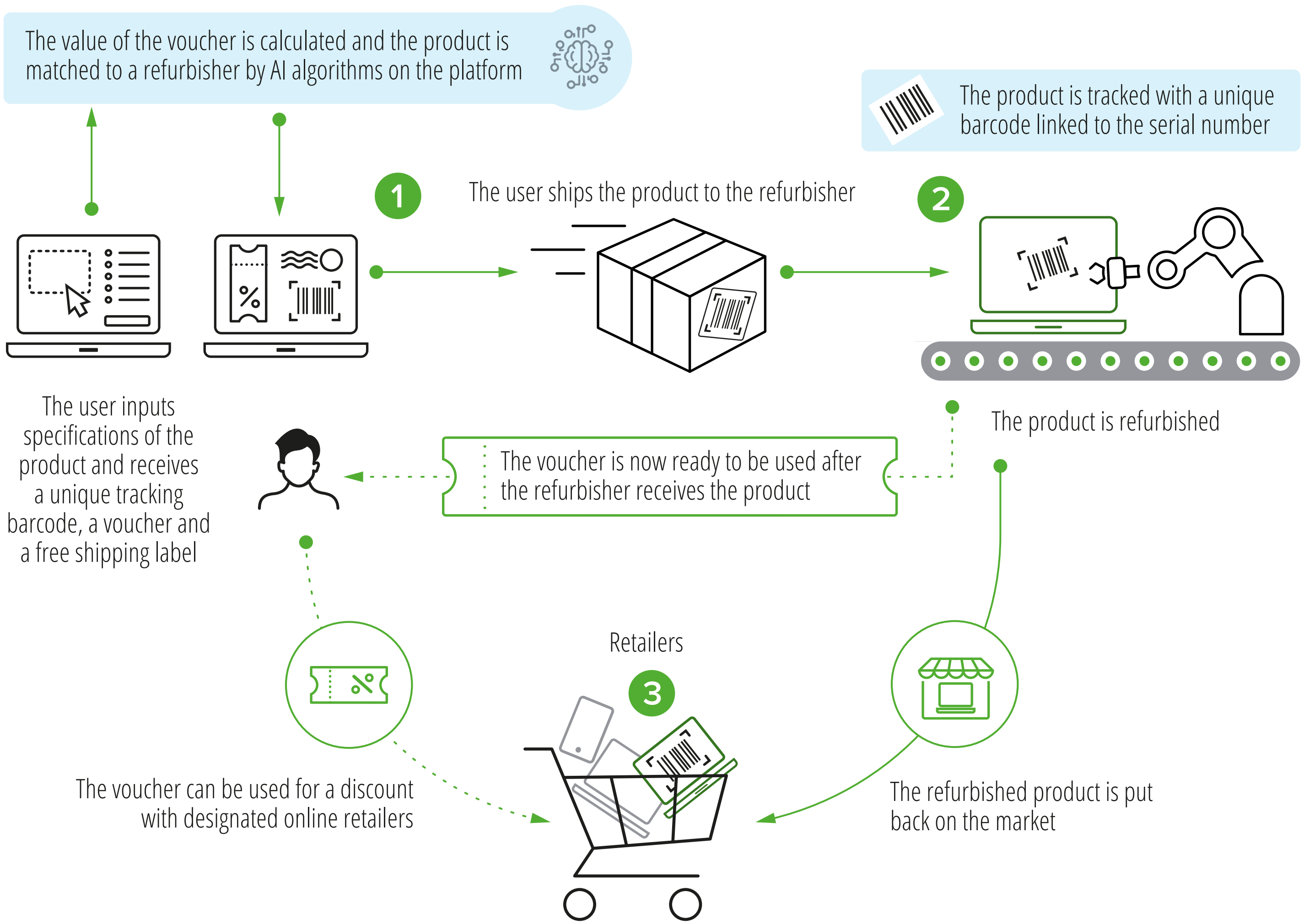
Under EPR, producers are also looking into ways to take back their devices to make their value chains circular. Digital solutions can be leveraged to enable take back by providing consumers with easy and incentivized mechanisms to return or trade in their old devices. Today, consumers can find the value of their old devices and start the take back process from the comfort of their own homes.

CASE STUDY:

Case study: Circular Brain – Facilitating take back [129]

Circular Brain is a start-up in Brazil that builds digital solutions for the circular economy. The company is currently working with INTEL in Brazil to develop a digital trade-in platform. The online platform allows consumers to register a used desktop or laptop to return. The platform generates a barcode to track the product after all the relevant information is provided by the consumer. A voucher is generated to be used in one of the registered retailers alongside a free shipping label to return the device (cost is covered by the operator that buys the product for refurbishment). The value of the voucher is calculated by an AI algorithm that factors in the costs/value of refurbishment. The returned device is matched to the most suitable recycler by an automatic algorithm that considers distance, performance and reputation to choose the best recycler/refurbisher to receive the product in the Circular Brain network. The voucher is only available for use after the operator receives the product and validates the information in the operation/traceability system.

Figure 3: **Circular Brain - Streamlining take-back**



2. Optimizing e-waste sorting, dismantling and recycling

Manual disassembly and separation of e-waste usually leads to the high recovery of materials but is very labour and time intensive and some processes can also be hazardous to health.[130] Other methods of e-waste separation such as mechanical shredding are faster but destructive, resulting in poor recovery of precious materials.[131] When e-waste is pre-processed mechanically, approximately 20 per cent of precious metals can be lost to non-recoverable side stream outputs.[132] Smaller devices and components such as IoT devices are not compatible with traditional shredders, leading to very low material recovery. The recovery of base materials is also not prioritized due to limited financial value and an inefficient recovery process.[133]

New and customized robots are not only able to sort, dismantle and effectively recover materials and parts, but are able to do so quickly and safely. Daisy, an Apple Inc. proprietary disassembly robot, can take apart 200 iPhones per hour and sort components to recover high quality materials that are often lost in existing treatment and processing.[134]

E-waste comes in different shapes, sizes, colours and material varieties and types of designs per product, therefore proper identification, dismantling, and material recovery is increasingly difficult. The development of artificial intelligence has allowed robots to identify electronic waste and its components with added accuracy and speed, enabling more efficient dismantling and recovery. The use of AI has also paved the way for smart robots that are able to self-learn with each new product or design it encounters.[135] Based in Japan, AMP Robotics has developed an AI-enabled e-waste sorting system that uses robotic arms and cameras to sort products. The photographs are run through AI image recognition software that sorts 80 items per minute with 99 per cent accuracy.[136] Better quality sorting at scale can unlock extra revenue through the recovered components.

CASE STUDY:

Case study: Recupel – A self-learning AI tool to identify e-waste[137]

Recupel is the only producer responsibility organization (PRO) in Belgium that organizes the collection and processing of discarded EEE under EPR regulation. Together with ID Lab, the IMEC research group, Recupel has developed an AI-based smart recognition system for use in their sampling centre to randomly sample EEE flowing through the PRO. As well as collecting data on the type of EEE recorded, the sampling results are used to set prices for the producers.

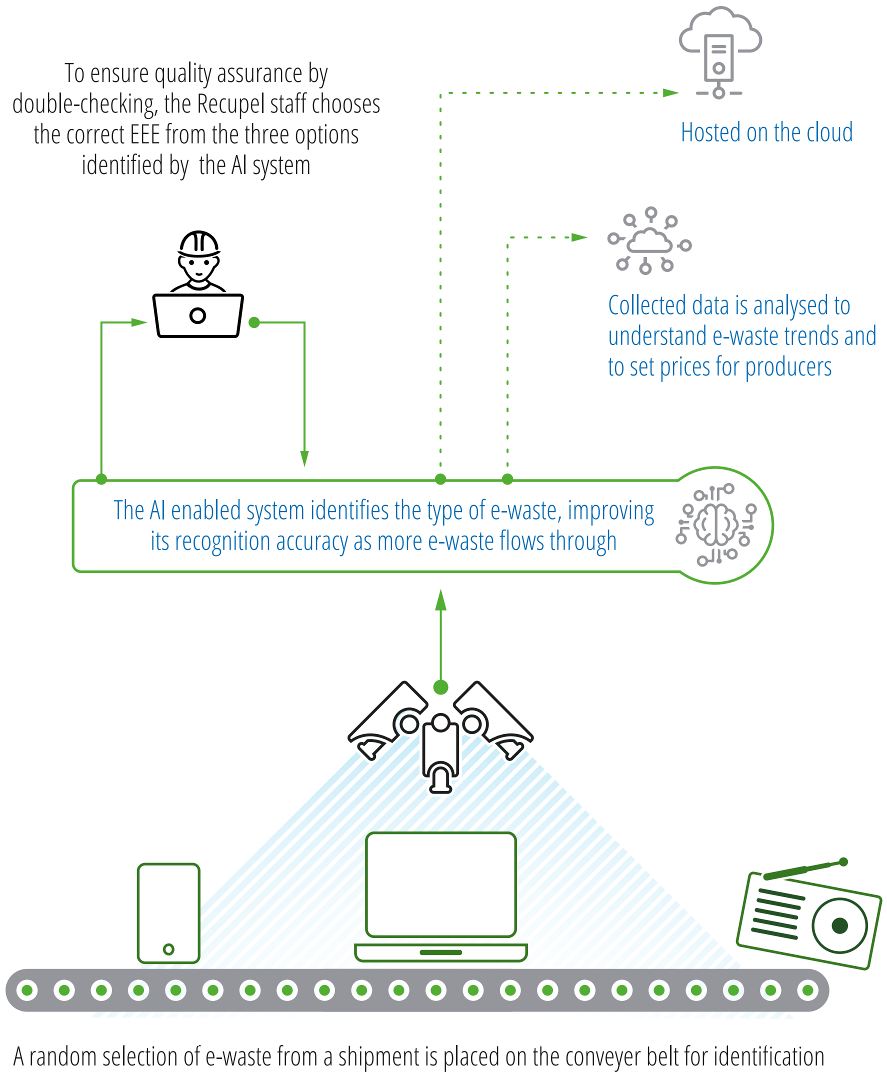
Initially, the sampling system involved a worker taking photos from a small webcam and manually identifying the type of EEE. The new AI enabled system uses a weighing scale, a computer, and six high quality cameras that can identify 116 EEE types with 96 per cent accuracy. For quality assurance, a worker will select the type of EEE between the three identified by the software.

The AI system was developed using a growing dataset of photographs accumulated by the new sampling setup. The AI technology is unable to identify certain types of EEE due to its lack of frequency in the waste stream, but as more types of EEE pass through the machine learning algorithm, accuracy will increase as it is trained and becomes familiar with more products.

Recently, the team has also trialled a prototype of the conveyer belt system to further automate the process and speed up identification. Using the same AI technology, similar precision levels have been reached on this conveyor belt in only three months of development.

As the infrastructure required is not extensive nor costly, and the technical skills needed are relatively basic, Recupel believes that the system is highly replicable and might be useful for both emerging and established e-waste management systems.

Figure 4: **Recupel - AI enabled EEE recognition**



3. Creating marketplaces for e-waste and materials across the value chain

Much like digital marketplaces that exist for resale of electronics, they also exist for end-of-life (i.e. e-waste management) phase of electronic products. Digital marketplaces are helping to connect different stakeholders in the e-waste value chain by facilitating discovery, purchase and sale. Business-to-business (B2B) marketplaces connect businesses with potential vendors and service providers for compliance and assurance to companies that need to dispose of their IT assets securely. These marketplaces leverage cloud infrastructure to handle large volumes of data as well as integrate with other applications such as payment gateways (online portals that facilitate digital payment) and logistics providers to make transactions across the value chain seamless. For instance, Recykal Marketplace brings together bulk e-waste generators, aggregators and recyclers from across India using an online platform.[138] Sellers have access to online pick up scheduling and reliable pricing, as well as the possibility of compliance support and waste traceability through the platform. Aggregators can find recyclers and use the platform to review market trends. Recyclers can post requirements and get matched to aggregators by their algorithm.

Digital platforms can also create opportunities for recyclers to connect with downstream buyers. Through marketplaces, sellers and buyers of e-waste can easily tap into a large partner base to seek the best value and volume. This helps reduce the search and transaction costs, thereby enabling recycled materials to compete more effectively when compared with virgin material prices.[139] By making information more transparent and available faster, online marketplaces can also facilitate more stable and competitive recycling markets.[140]

In providing platforms for traceable and transparent transactions for e-waste and secondary resources, digital marketplaces are facilitating the achievement of some core circular economy principles, such as use of waste as a resource and minimising the consumption of virgin materials.

Excess Materials Exchange is a B2B digital platform that matches the excess materials from organizations to its highest value match, enabling reuse. The platform provides a digital identity for waste through the use of resource passports, capturing information such as product origin and composition. Tags such as barcodes and QR codes are then used to follow the material throughout the supply chain.[141]

4. Enabling informal sector integration and mainstreaming

In many countries, specially LMICs, the informal sector dominates the collection and processing of e-waste. However, the unregulated, purely market-driven nature of the informal sector prioritizes material recovery – often at the cost of worker health. Digital technologies, aided by mobile connectivity and affordable access to data, are being leveraged to fast track the mainstreaming of the informal sector. In particular, smart phone apps allow users to build greater digital literacy through technologies that can help transform day-to-day businesses, such as mobile payments. Karo Sambhav, an e-waste PRO in India, has established a wide network of partners (originally from the informal sector) by building trust through financial transactions. They helped workers establish bank accounts and register their tax information - the first step towards setting up a 'formal' business- and consider digital payments. Since mobile payments allow bank accounts to be credited immediately, the workers could be relieved from the stress of security risks and having to carry large sums of cash on their person.[142]

At the collection stage, social media and other platforms such as Facebook and WhatsApp are playing a vital role in connecting informal waste collectors and recyclers with different stakeholders and customers. These apps are leveraged by various types of informal businesses and have been shown to help them 'protect, stabilize, and augment' their income in an increasingly competitive world through advertisements and direct contact with consumers.[143] Specifically in waste collection, social media is being used innovatively to connect consumers to arrange collections, exchange market information on prices and expand their network, for example in the case of Malawi where informal collectors reach out to consumers and arrange for door-to-door collection of e-waste through Facebook.[144]

The use of digital media to incorporate informal workers into the formal system has seen some success in Ghana. At a pilot effort by GIZ in Kumasi, Ghana, for incentivized refrigerator collection and processing, the local informal sector association used WhatsApp to document the refrigerator dismantling process, where photographs and videos were used to negotiate payment with GIZ who, in turn, were able to achieve almost real time remote verification.[145] In Agbogbloshie, Ghana, mobile payments are being used for the sale of cables, which has led to an almost fully digital data management system, and enhanced traceability of finance and e-waste flows.[146]

There are also numerous examples of social innovation-oriented non-governmental organizations and companies that use digital technology at the core of their business strategy. Kabadiwalla Connect in India helps local scrap dealers and waste pickers respond to requests for collection, which in turn creates transparency in the value chain using IoT and QR codes.[147] Kabadiwalla Connect has also installed smart bins in the city of Chennai, which directly alerts local scrap dealers on when they need to be emptied.[148] Recykal, through the Uzed app and marketplace, also include 'kabadiwalas' or individual informal waste collectors, who collect the waste when alerted by the app.[149] Through such a mechanism, they can skip the middlepersons and earn an extra 10 to 20 per cent. Coliba, in the Ivory Coast, is formalizing the informal plastic waste collection sector by employing workers for door-to-door collection, in response to requests raised by customers on mobile apps.[150] Customers are awarded 'points' for using the app, which can be converted to mobile credit.[151]

Electronics value chain system management

Macro-trends in digitalisation

Digitalisation of production, communication and business process management can result in faster transactions, higher reliability in terms of quality and security, and an upgrade of existing management frameworks.[152] In particular, digitalisation is able to provide the following advantages from a system management perspective: autonomous control over products and processes, greater opportunities for collaboration and cooperation, integrated systems and network over the value chain, and enhanced adaptation, flexibility, connectivity and cognition.[153]

With greater digitalisation and tracing of waste flows into and out of the e-waste value chain system, the waste management sector is producing vast volumes of digital data. Increasingly, big data analytics are being applied to identify patterns, extract pertinent information and discover trends.[154] In particular, big data analytics can play a crucial role in the working of automated mobilization of waste collection vehicles, sensor data evaluation in automated sorting plants, and automated logistic systems.[155]

Globally, many e-waste management systems have one or more processes that can be carried out online. Registration of key sector players, such as producers, dismantlers and recyclers with either the government or the PROs in operation, is usually an important component of an e-waste management system. Digital registration is especially common in mature e-waste systems, although emerging e-waste legislation for example in the case of Jordan, are instituting a digital platform for registration from the establishment of the system itself.[156] Integrated platforms for data sharing, business management, enhanced transparency and stakeholder cooperation are also gaining popularity.

Smart information exchange and smart contracts coupled with automated reporting alternatives are reducing paper-based transactions and providing more security. As mentioned previously, digital technologies make it possible to automatically generate electronic invoices and contracts, linking with payments and signatures in order to close the administrative process. The shift to online monitoring and virtual auditing in response to COVID-19 are making way for greater efficiency and effectiveness in remote monitoring of systems and processes.[157]

Applications of digital technologies

1. Facilitating knowledge generation across the value chain

Internationally, effective generation, collation and analysis of e-waste data has become increasingly important. Digitalisation is supporting such endeavours through technologies such as digital databases that can integrate large volumes of data and make it accessible and amenable to analysis. Online platforms and databases are being designed to collect information about e-waste with the aim of building knowledge in the sector.

Digital platforms can be leveraged to share insights on the availabilities of e-waste in a region, their flows, and the opportunities that exist in their usage. The Urban Mine Platform (UMP), a key deliverable of the EU financed ProSUM project, is an open-access web portal that hosts information on key parameters of EEE in Europe, such as the number and type of products placed on the market, in-stock (in use and hibernated) and generated as waste; composition of EEE, batteries and vehicles in terms of components, materials and elements; and waste flow data for small batteries and EEE products. The UMP has an easy to update, user-friendly and data-centric nature and can generate dynamic data charts for analysis and understanding.[158] The ProSUM project was launched in 2015 with the aim of creating a regional 'information network' that allows partners to develop an inventory of waste streams that had a high potential to serve as a source of critical raw materials.[159] Such digital platforms and databases can help in building networks and facilitating peer-to-peer exchange and co-learning.

The circularity benefit in this context comes largely from the availability of valuable knowledge, that would otherwise require the consumption of various resources (including, time, cost, travel) to be obtained. For example, the WEEE Forum LibraWEEE database is an outcome of an EU-funded Countering WEEE Illegal Trade (CWIT) project. This database consists of information compiled from various sources such as previous work undertaken by CWIT partners and other platforms similarly to the compliance and risks knowledge platform, C2P.[160,161] This open-access database consists of studies and initiatives focused on understanding the dynamics of the e-waste industry particularly illegal movement of e-waste. The WEEE Forum also has a dedicated platform where members can share their experience from the e-waste collection process such as best practices, innovative policies, technological information, experience of running successful collection campaigns, etc. The collection platform enables knowledge sharing and peer-to-peer learning at a global scale.[162]

Another relevant platform is the Information for Recyclers Platform (I4R), created by the WEEE Forum, APPLiA and DIGITALEUROPE, which allows recyclers to access recycling information at product category level. I4R allows EEE producers to comply with Article 15 of Directive 2012/19/EU on WEEE, which requests producers to provide information free of charge about preparation for re-use and treatment in respect of each type of new EEE placed for the first time on the EU market. The platform offers a convenient communication tool that aims to further increase the recycling results in the electrical and electronic sector while reducing compliance cost for both manufacturers and recyclers.[163]

2. Reducing paperwork and administrative burden

The use of digitalisation can help streamline the administrative aspect of the electronics value chain. Apart from the direct benefits such as reducing paperwork, record keeping, contracting, and human error, digitization efforts in the e-waste management sector will improve the accessibility of practical information in the field of e-waste, which is the basis of sound monitoring and decision making.

Circular Brain, for instance, offers a cloud-based Think Circular platform that helps small and medium recyclers to manage logistical processes and environmental requirements.[164] Traceability information is integrated in the Think Circular software linking environmental authorities and required documentation, such as the generation of official waste transportation manifests. Traceability data are logged into a blockchain that triggers reverse logistic credits (digital certificates) that confirm responsible disposal of e-waste. These digital certificates are traded back to producers to fulfil their EPR targets.

The WEEE Forum reporting tool (WF-RepTool) database is another example of an application that determines and documents treatment and depollution results and monitors downstream fractions for e-waste that are transparent, traceable and comparable, in accordance with EN 50625 European standards requirements. The key feature of this calculation model is that classification is based on the use of individual components (fractions) in final treatment processes. E-waste PROs and treatment operators in Europe, for example, use the WF-RepTool application to construct their own flowcharts covering the whole chain of e-waste treatment processes in one click.[165]

As mentioned previously, the use of smart contracts can also be seen in the sector, for example in the case of WEEE Ireland, which has adopted automated contract signing and certification, doing away with paper contracts and thereby making the process friction free and more efficient.[166]

The administrative requirements of transboundary shipments of used EEE are largely paper based, requiring original notification documents to be signed in hardcopy and posted to competent import, export, and transit country authorities for approval. In its 2022–2023 workplan, the Basel Convention secretariat has set out a working group to explore electronic approaches to notification and movement documents.[167]

3. Creating a digital chain of custody of e-waste

Multiple layers of logistics, administration and approval processes go into an efficient and effective e-waste management system. Technologies and methods such as cloud computing, scanning and identification and automated validation and document verification technologies are helping the e-waste value chain system managers to better collect data and record activities, improve chain of custody visibility and control of in-built management systems. PROs for instance, depending on their role, need to manage and monitor downstream e-waste flows, and collect information that can be reported back to regulatory authorities and their membership.

Chain of custody is a process that tracks EEE and those responsible for e-waste during its end-of-life management.

Digital platforms build on the computerisation that started with traditional enterprise resource planning (ERP) software. Recent advances in software and hardware architecture have made it possible to have easily accessible digital platforms that integrate several user-friendly business functions in a single, convenient computerized system. E-waste stakeholders can use the platform to digitalize operations to provide credible chain of custody, manage inventories and issue recycling certificates. These platforms allow the automation of processes such as financial calculations, settlements, and report creation for compliance purposes.

CASE STUDY:

Case study: Karo Sambhav – Enabling optimized end-to-end tracking of e-waste[168]

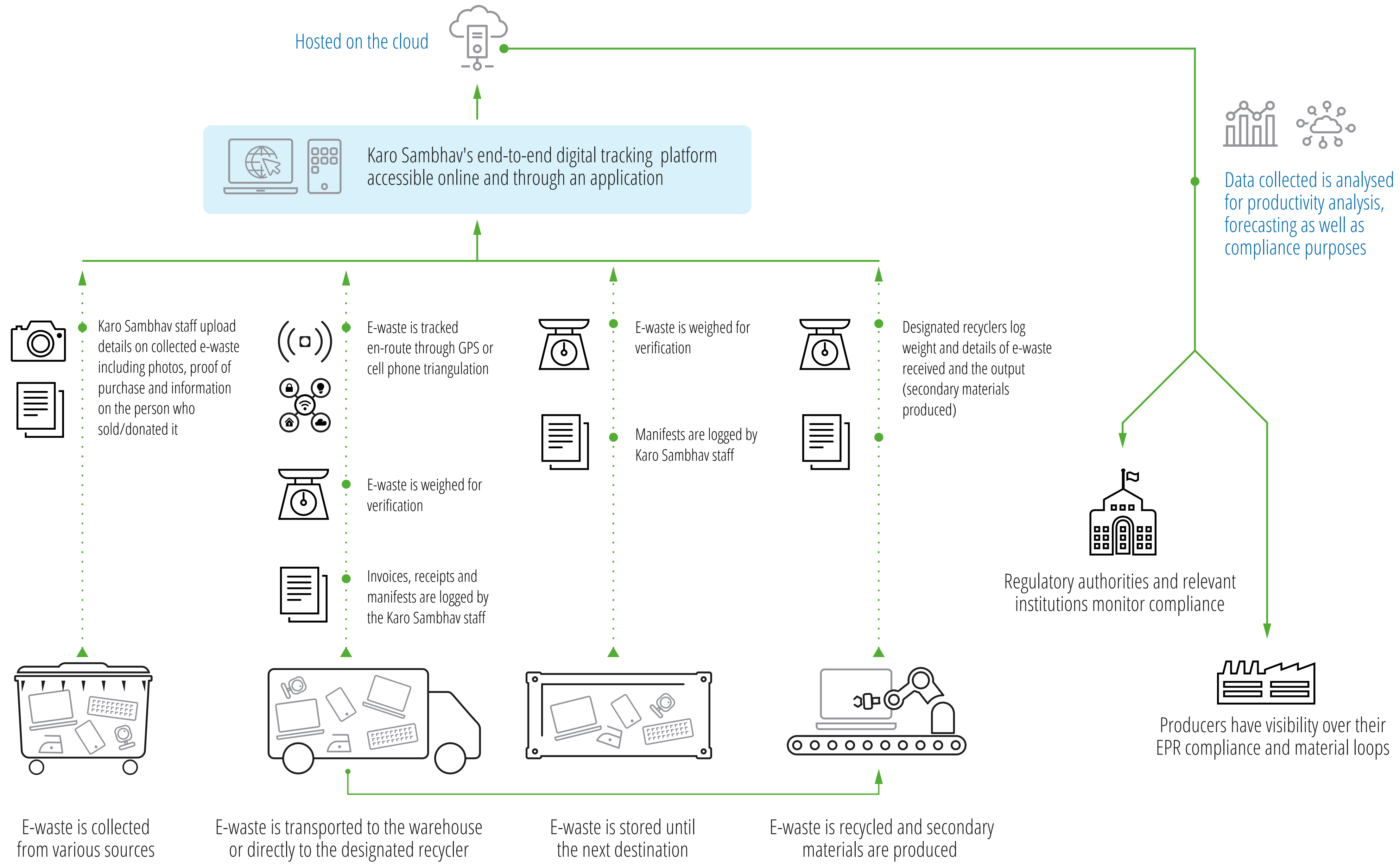
Karo Sambhav is a producer responsibility organization (PRO) in India that has developed an integrated digital platform hosted on the cloud and accessed through a smartphone app to enable end-to-end tracking and traceability of their operations. The mobile app tracks e-waste flows into the system from collection to disposal by a recycler, including time-stamps, geo-locations, photographs, receipts and other documentation such as invoices, e-way bills and shipment manifests.

From the moment e-waste is acquired from waste pickers, drop-offs, aggregators, bulk generators or auctions, staff members record proof of collection that includes purchase invoices, photographs, and details of the person who sold it. The information is updated while the e-waste travels to a warehouse or directly to a recycler.

The cloud platform allows extensive analysis such as heat map generation, mapping costs, productivity indicators as well as forecasting and predictive analysis. The platform is especially helpful for automating compliance and reporting to the regulatory authorities. The end-to-end tracking simplifies internal and external audits such as tracking e-waste flows and ensuring that the same waste is not allocated multiple times.

Despite large volumes of e-waste and the numerous touch-points along the value chain, Karo Sambhav ensures traceability using flexible cloud architecture.

Figure 5: **Karo Sambhav - End-to-end tracking digital platform**



4. Making monitoring and enforcement more efficient

The increase in connectivity of EEE through technologies, such as sensors and IoT tags (QR codes, RFID tags, GPS trackers etc.), supports the live tracking of e-waste flows and activities, which in turn enables effective monitoring and enforcement. As part of the e-trash transparency project, the Basel Action Network (BAN) placed GPS trackers on used consumer electronics to track disposal methods. In Europe they found that out of the 314 used EEE that were tracked, 19 were exported, 11 of which were sent to developing countries such as Ghana, Nigeria, Pakistan, Tanzania, Thailand, Ukraine and the Hong Kong Special Administrative Region, China. This shows an export rate of 6 per cent compared to 34 per cent in the United States and 12 per cent in Canada.[169]

At the national level, digital solutions are also being employed in customs to log trade flows, especially in the imports of new and used electronics. Many LMICs where the illegal import of e-waste has been a concern, Rwanda and Zambia for example, have strengthened their type-approval through an online platform to log imports into the country.[170] Only on getting approval through this digital platform can an importer bring products into the country. The digital system not only helps maintain a digital record of all EEE products but also makes it easier to enforce e-waste import bans. High resolution x-ray screening technologies combined with AI and machine vision allow automated container inspections by customs and enforcement agencies.

A waste transportation project collaboration between the Netherlands and Belgium governments uses blockchain technology to track various waste streams as they cross international borders. The solution streamlines communication and coordination between different government entitles involved. As information is stored on a transparent online channel, border controllers can also reliably verify permits digitally with random on the spot checks.[171]

Another application of digital technologies includes virtual monitoring and auditing processes. Audits, previously carried out in person, are now conducted virtually, through a combination of video conferencing, digital file sharing and remote access to video feeds. The COVID-19 pandemic has made virtual audits more commonplace, with the standards bodies such as SERI providing advisories for the necessary checks and balances to conduct remote audits . These digital audits[172] are also helping auditors overcome the stress of continuous physical audits.[173]

5. Building capacity and creating awareness

Digital technologies can be leveraged for capacity building in the e-waste management sector, as well as creating awareness on EEE use and proper disposal. The rising popularity of digital learning, especially during the COVID-19 pandemic, has led to development of virtual training programmes, massive online open courses (MOOCs), conferences and discussions, and e-waste has become an important topic for sector stakeholders and the public. In early 2020, ITU, together with the Basel, Rotterdam and Stockholm Conventions, the European Institute for Innovation and Technology Climate Knowledge and Innovation Community (EIT Climate-KIC) and other key stakeholders, released the first MOOC on e-waste management. The MOOC provides insights and knowledge on how policymakers, industry leaders, academics and consumers can address e-waste.

Gamification – turning the learning of important topics into a game – has also shown an increase in activities in topics such as recycling and sorting.[174] Many governments, particularly through websites and environment agency initiatives, are disclosing e-waste management data, statistics, and performance indicators to increase the transparency of the sector. In addition, as organizations improve not only the amount of data they capture, but also how they combine data from different sources and use that data will continue to affect how organizations interact with people to drive behaviour change (Internet of behaviour).[175]

Digital technologies are able to support positive behaviour changes, such as appropriate handling of e-waste as well as good practices in EEE use and disposal, which in turn help inculcate a positive attitude towards circularity.

4. Implications and considerations

The digital technologies discussed in this thought paper vary in their level of complexity and function. The technologies range from online platforms that require relatively minimal intervention to emerging and disruptive technologies that can require systemic change and collaboration, transforming the way in which EEE products are made, used and managed at the end of use or end of life. Such wide-ranging and often deep changes, especially as the technologies evolve can, to an undetermined extent and with the right conditions, support and strengthen the circular flow of EEE products, materials and information.

However, the application of digital technologies in the transition to a circular electronics value chain is still developing and its impact on the space is still not completely understood or expansively studied. While there is consensus on the benefits of digitalisation in accelerating circularity, it can pose negative impacts as well.[176,177] Digital solutions can amplify existing socio-economic inequalities due to uneven connectivity and access and can raise new issues of digital privacy and security as well as create additional e-waste in the process.[178]

Therefore, in assessing the role of digitalisation in the electronics value chain, it is important to understand the general and context-specific implications of applying digital solutions. The section below assesses the implications and considerations of digitalisation across the sector that are relevant while establishing a digitally enabled circular electronics value chain.

The importance of digital infrastructure

Digital infrastructure includes Internet connectivity, fixed and mobile networks and data centres as well as cloud services, software and security. The digital solutions mentioned throughout this paper are heavily dependent on infrastructure, in particular ICT infrastructure, for their delivery as most require some form of information exchange or asset connectivity. As the applications of digital technologies grow in electronics value chains, it is imperative that the digital infrastructure that supports it is robust, resilient and has extensive coverage.

With the increase in ICT usage and the consequent demand for infrastructure, the gap in network coverage is decreasing, with only 7 per cent of the world population remaining unserved by some form of mobile-broadband network.[179] The accessibility of essential mobile communication devices has also increased, and with it, greater Internet use. However, there is still a considerable usage gap between different regions and socio-economic strata. While in most regions, more than 90 per cent of citizens have access to a mobile-broadband network (3G or above), about 25 per cent of the population in least developed countries (LDCs) and land locked developing countries still lack access.[180] Technology transfer and investments in least developed countries will be critical for them to build the science, technology and innovation capacity to benefit from the opportunities of digital technologies.[181]

In the case of a digitally enabled circular electronics value chain, the implications of poor infrastructure are significant. Lack of network coverage is a barrier to efficient and timely information exchange between key stakeholders as well as EEE products (such as through sensors and tags) and exchanges that are vital for solutions such as end-to-end tracking of products and materials.[182] For instance, in tracking e-waste transport, Recykal uses cell phone triangulation, relying heavily on the coverage and connectivity of mobile networks in the absence of GPS technology.[183]

Similarly, smart waste management relies on real-time connectivity to collect data. Current 3G and 4G networks are unable to keep up with the increasing scope of mobile technologies and their applications, however, 5G is expected to withstand the present and future network demand from smart cities, industrial automation and the rising applications of IoT.[184] Although mobile-network requirements can vary and be programmed to function in specific bandwidths for energy efficiency and resource maximization, a lack of the required network bandwidth can hinder functionality and longevity. This was observed in ConnectedBin's devices, which are programmed for minimal power consumption on low bandwidth networks.[185] Lack of networks mean devices had to run on higher power networks and were replaced more than intended, increasing business costs and producing additional e-waste.[186]

With the growing network and Internet connectivity around the world, it is not surprising that ICT tools are emerging as a key solution for a circular electronics value chain. However, as there is still disparity in access to digital infrastructure globally and concepts such as smart cities and GPS tracking, which are rapidly developing in some contexts, are not an option for some regions. With more and more of the world's economic and social activity being integrated into the digital arena, lack of access brought about by poor infrastructure can isolate entire populations from the information society and associated benefits of digitalisation. In line with the SDG Target 9.c[187] and ITU Strategic Goal Nr. 2 that address ICT inclusion[188], public and private leaders and institutions have an increasing responsibility to invest in digital infrastructure particularly in low- and middle-income countries to ensure that no one is left behind.

The need for digital literacy and skills

A spectrum of digital skills, from development to operation and use, are needed to deploy, operate and interact with digital systems. ITU Facts and Figures 2020 reports that less than 40 per cent of the population possessed basic ICT skills in 32 out of 86 economies studied.[189] Effective digitalisation requires significant investment in digital literacy and skills that range from basic operation of tools and equipment to building and maintaining advanced digital solutions.

Many digital solutions require only basic ICT tools and skills with only low levels of training. For instance, in the Recupel case study, although the development of its AI software and its continuous updates required highly skilled technicians, the digital skills required to operate its AI sorting system are not difficult to learn and can be easily taught.[190] Similarly, while an end-to-end integrated digital platform for e-waste tracking requires digital expertise to maintain and develop, end-users such as recyclers and truck drivers perform less complex tasks, such as taking photos and logging receipts.

Nonetheless, even simple applications require basic ICT skills. Similar to infrastructure, digital literacy and skills also determine access to the benefits of digitalisation. For instance, while affordability and infrastructure are important, one of the main barriers to Internet use has been found to be the digital skills and awareness of citizens.[191] As digital skills are directly related to income,[192] employing digital solutions without investment in building digital skills can further amplify inequalities particularly in LMICs and LDCs where the informal sector is significant and informal workers depend on e-waste management activities for their livelihoods.

According to the ITU digital skills insights 2020 recommendations, the private and the public sector that includes governments, businesses, educational systems and society have an impetus to support continuous digital skill building that needs to evolve alongside digital technologies.[193] Policymakers and practitioners can leverage targeted data literacy programmes to promote digital inclusiveness to provide citizens with the tools to participate in the digital economy.[194]

Facilitating stakeholder coordination and cooperation

The electronics value chain includes a range of stakeholders from large-scale corporations to small sized recyclers and individual collectors. The full benefits of digitalisation are possible only with the coordination and participation of stakeholders across the lifecycle of a product. Limited awareness of potential applications of digital technologies, insufficient capacity in underlying digital infrastructure and skills, unwillingness or lack of financial incentive to participate are thus significant challenges in such coordination.[195]

In a chain of information collection, one faulty, missing or improperly recorded information can impact the reliability of data. For instance, blockchain is secure and cannot be tampered with meaning that incorrect data, once logged cannot be changed.[196] If a recycler mislabels the type of volume of a material extracted from e-waste in the blockchain, the correct information can only be updated as an additional block further complicating the chain. Similarly, the Karo Sambhav example shows that any lack of compliance or inability to properly log flows leads to the use of their own staff at pick up and drop off points to ensure information legitimacy and dependability, especially since official documents once delivered are extremely difficult to amend.[197] While this is a functional solution, ideally, all members of the value chain would be held accountable to input and process reliable data.

This coordination problem can also arise when organizations employ different digital platforms. There are many digital solutions and many forms of raw data collected from various sources and devices. Hence, digital information often cannot be simply transferred from one organization to another, and any consolidating or verifying of different databases is costly.[198] Producer responsibility organizations identified the many database solutions and the low data quality of recycler databases as prominent issues when integrating recyclers into their systems.[199] Lack of interoperability and synchronization also diminishes the potential to scale solutions.[200]

There are many organizations with e-waste management systems that use simple online databases and information exchange solutions. As these entities have already-established, albeit simple but functional legacy digital systems, there is pushback in "further complicating" such procedures. For instance, databases that are already digitized and systemized can require significant manpower reskilling and time investment to be transferred to a new digital platform.

Particularly in developing economies, organizations attempting to institute integrated digital solutions across the value chain face significant barriers in bringing stakeholders together into a common network. In settings where digital technologies and supportive infrastructure are not commonplace, solutions have to work internally and in isolation, while coordinating with external non-digital or uncomplimentary systems.[201] For example, consultees revealed that if a single operator is not on the digital platform the coordinating body needs to adjust the system, leading to additional inefficiencies.[202] While digital infrastructure and skills play a key role in building a culture and framework of digital intervention, government policy and frameworks still need to ensure that stakeholders are mandated to participate in circular EEE management, where applicable, within a digital framework (such as in blockchain product passports).

Interoperability, a crucial element in digitalisation, allows the sharing of data and enables the scaling-up of digital solutions. International standards can improve interoperability of digital systems and facilitate vibrant digital ecosystems that in turn enable seamless vertical integration, including scaling-up of digital tools for e-waste management. ITU-T Study Group 20 on IoT and smart cities & Communities has developed international standards that coordinate the deployment of IoT systems and platforms. They define the key requirements and frameworks that enable stakeholders of EEE management to coordinate digitalisation efforts.[203]

The sharing of digital solutions

The movement towards digitalisation in the electronics value chain is not currently well coordinated but rather found in isolated pockets throughout the private and the public sectors, where resources and expertise are not fully maximized.[204] Digital solutions that could be easily shared (depending on business model) amongst different stakeholders are often built from scratch rather than repurposing and customizing existing software which implies inefficient use of present expertise and resources.[205] Many new organizations are unaware of existing digital solutions and seek to create their own solution which can be expensive, time consuming and need continuous maintenance.[206]

New stakeholders acquiring an existing end-to-end digital platform and customizing it in a cloud-based software subscription model would not only allow a PRO, recycler or collector to save on development and maintenance costs but also allow them to tap into the tried-and-tested insights that can only come from experience and continuous improvement of the tool.[207] This can also apply to a solution such as the Recupel AI sampling tool. As the development of this AI technology required significant resources, Recupel notes that it would be costly and redundant for another actor to recreate the technology, as the Recupel tool is customizable and can be shared on the cloud.[208] Recupel is currently looking at ways to share its technology keeping in mind the costly and technically advanced elements such as the development, maintenance and system updates.[209]

Understanding cost and benefits according to the context

Digital technologies are often capital intensive and require upfront investments in hardware such as robots and sensors as well as software such as tracking and traceability software. In addition, the added investment in digital solutions can lead to limited benefits or even net loss as low profit margins make stakeholders dependent on economies of scale. For any e-waste management system to be sustainable, financial stability is crucial.

Upfront investment such as in AI enabled robotics for sorting and recycling only pay off over the years and can pose a financial impediment.[210] The AMP AI robots mentioned previously can cost up to USD 300 000 (USD 6 000 a month to lease).[211] The company has sold or leased about 100 of its robots since 2017 to recyclers in North America, Europe and Japan, and while expensive, savings in labour and efficiency are expected to offset this capital cost.[212]

However, in many LMICs, low e-waste volumes generated are rarely significant to be particularly lucrative for an industry of small and medium e-waste operators. Therefore, in a context where the e-waste flow is already limited, it is difficult to integrate costly digital technologies such as AI or Robotic sorting without basic public digital infrastructure in place.[213] In addition, a cost-benefit analysis is not uniform for all contexts, such as in LMICs, where dependence on the informal sector entails much lower labour costs, and elsewhere, the loss of jobs to automation is a serious concern.[214]

Costs of employing new solutions can also deter larger corporations and producers to adopt solutions without guaranteed returns. Strategic considerations lead producers to apply well established and widely used digital solutions rather than become pioneers themselves.[215] As many of these solutions are emerging and do not have adequate impact research, producers do not have the assurance to mass deploy these solutions.[216] Furthermore, since some EEE such as computers have a relatively long lifespan and are often stockpiled even after their end-of-life, the technology used to add features such as tracking and sensors can quickly become outdated by the time these products leave the consumer. Without consumers playing an active role, producers consulted outlined investment as risky.[217]

Although a cost-benefit analysis remains a significant consideration in employing any digital solution, advances in technology are making digital solutions more cost and resource effective. The emergence of cloud-based services, which allows the sharing of software and even hardware across regions, has made digital technologies more accessible. As mentioned above, the development of an AI sorting technology or an integrated end-to-end tracking and reporting platform is costly and requires continuous fine tuning. However, once it is built, such solutions can be customized for individual requirements and shared via the cloud across regions, making solutions an option for diverse financial settings and operational models.

Maintaining data security and allaying privacy concerns

Data protection and privacy is a key concern for organizations when it comes to employing digital solutions. Digital technologies that seek to bridge information gaps and promote transparency in the value chain can raise concerns of confidentiality and data leakage.[218]

In the consultations, producers shared a concern that opening transparent channels and sharing product compositions or recycling guidelines can risk leakage of proprietary information to competitors.[219] For instance, product passports can include both confidential and nonconfidential information.[220] The security of the information meant for recyclers and refurbishers remains a concern for producers. While blockchain technology with its encryption and data security technology can allow for different access rights to information on the same platform such as that seen in Circularise, data protection cannot be guaranteed from within an organization that has access to that information.[221]

Business models that depend on IoT connectivity to track product condition face concerns and mistrust from the consumer.[222] This highlights the need for a secure reputation of the service provider coupled with robust privacy protection laws.[223] The European General Data Protection Regulation (GDPR) protects the personal data of individuals with IoT information collection requiring anonymisation, pseudonymisation, encryption.[224] As each country and region have their own interpretation and forms of data privacy, this remains a key consideration in the application of technologies that are increasingly integrated into consumer lives.[225]

Digital technologies have an environmental footprint

Despite the benefits of digitalisation, its application inevitably leads to the use of more EEE and consequently e-waste and energy use. The ICT ecosystem is estimated to account for more than 2 per cent of global emissions, with electricity demand of ICTs forecasted to reach 20.9 per cent of all demand by 2030.[226]

In particular, the widespread adoption of IoT solutions have rendered IoT devices such as sensors and tags ubiquitous in our daily appliances and tools. Embedding IoT devices in electronics entails that these sensors or tags have to be removed during the material recovery process and/or dealt with as e-waste, further complicating the e-waste stream.[227] As many of these IoT embedded devices are low cost, consumers are more likely to dispose of these products than engage in proper e-waste management processes in the absence of incentives or regulation.[228]

The increase in IoT device consumption highlights the need for e-waste management operators and circular business to start thinking about the end-of-life provisions for devices that are embedded in other electronics. In general, if IoT devices are taken back and companies are responsible in their creation, IoT uses can be more beneficial than detrimental. Innovation, such as the design of 3D printable IoT devices made with wood-derived cellulose materials, can support this movement.[229]

The consumption of energy and use of digital infrastructure by technologies, such as cloud computing, are also a concern. Admittedly, the demand for data centre services is rising exponentially and the sector is projected to grow 500 per cent by 2030.[230] Increasing demand had been linked to exponential increase in energy use by data centres, however in the past years, strong improvements on energy efficiency by large-scale cloud data centres has limited the percentage of global electricity use of data centres to 1 per cent.[231]

In the case of hardware, cloud computing technology is rapidly developing in the competitive market and it is inevitable that equipment such as random access memory (RAM), printed circuit boards (PCB), central processing units (CPU) and servers in data centres are regularly replaced to stay competitive, creating more electronic waste.[232] The average lifespan of such equipment can be up to five years in its first use and ten years in its second life,[233] which means there is opportunity in refurbishing such equipment rather than recycling it at the end of its first useful life. Therefore, EEE life-span in this case needs to be maximized through refurbishing, reusing and finally recycling upon becoming waste.

Some companies are already taking significant steps to meet these sustainability goals. To design out waste, Google refurbishes old equipment and reintroduces it in machine upgrades in its data centres, leading to 19 per cent of components for machine upgrades being refurbished in 2019. The company also resells equipment such as memory modules and hard drives, 9.9 million units were sold in 2019.[234] Similarly, the Microsoft Circular Centers initiative reuses and repurposes decommissioned servers and hardware for their own use as well as buy-back from suppliers. The company is bringing together design and supply chain teams to optimize future generations of equipment and realize its goal of 90 per cent reuse of servers and components by 2025.[235]

The opportunity for public-private cooperation to enable innovation

The nature and potential of digital technologies requires innovation and an enabling environment. To achieve this, there is a need for public-private cooperation and mobilization from both sides.

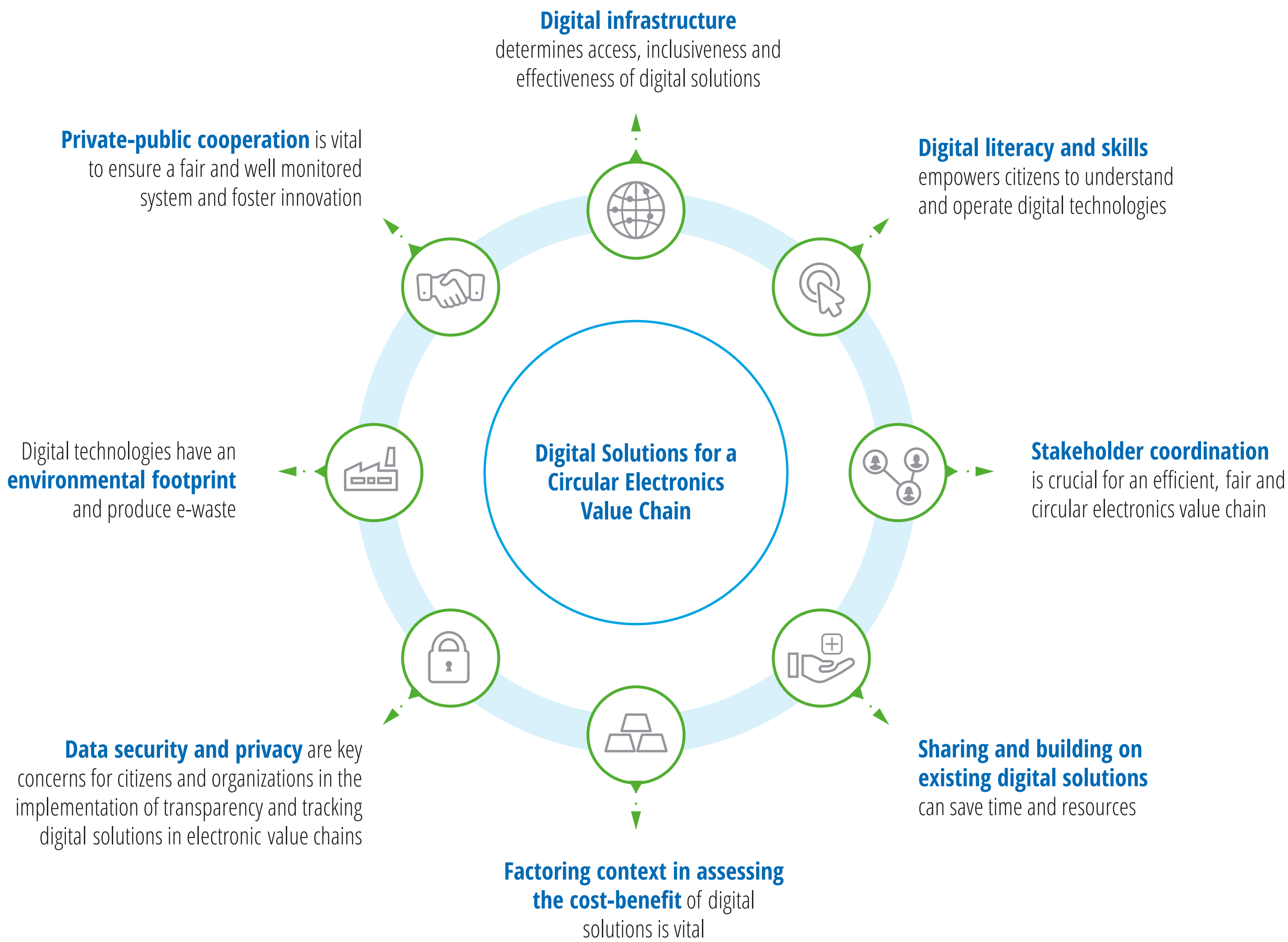
The government plays a fundamental role in facilitating and regulating a fair and effective circular electronics value chain and the relevant application of digital solutions in the following ways:

- Providing a digital foundation with equal opportunities for access (including in infrastructure and skills) can enable the development as well as the scalability of these technologies in its conception and uptake.
- Policy and regulation are also needed to ensure participation from all stakeholders in the value chain, be it through incentives or penalties.
- Government policy and regulation can also address and offset some of the major concerns with regards to digital technologies such as data privacy and security.
- Government funding and subsidies can also serve as a major boost to the innovation economy. Particularly in developed settings, governments can act as research donors and provide early-stage funding to support and scale circular initiatives.

Similarly, the private sector has already entered the sector as digitalisation service providers, both as respondents to existing needs (outlined in policies or strategies by governmental decision makers) and as innovators by creating solutions for the sector. This role of the private sector is likely to continue, indeed, it should be expected to grow with the increasing opportunities brought forth by digitalisation. The private sector can effectively be a torchbearer for digitalisation in circular electronics management, but there is a need to ensure adequate opportunities, financial incentives and freedom for innovation.

This can be brought about by concerted cooperation between the two sectors where private sector experiences and information informs government policies and guidelines, which in turn enables and facilitates private sector participation. Such coordination can address the challenges of the current system and enable an electronics value chain where the flow of materials, products and information is efficient, transparent and circular.

Figure 6: **Implications and considerations of digital solutions for a circular electronics value chain**



5. Conclusion

This paper has shown the diverse application of digital technologies across the electronics value chain, from raw material production and EEE manufacturing to post-consumer e-waste collection, logistics and recycling. Around the world, there is growing interest in digital technologies - particularly AI, robotics, cloud computing, the IoT and blockchain - as tools to strengthen and support a circular electronics value chain from operational and logistical tasks to communication. Digital solutions were found in all stages of the EEE value chain, with some in widespread use. However, globally, technologies are being applied at various scales and in a heterogenous nature. Digital solutions were also found to be largely aimed at the optimization of existing business processes for improved efficiency.

Digital solutions were found to address the challenges observed in the electronics value chain. They bridge the information gap between stakeholders by building connectivity and communication channels, as well as between devices, facilitating vital information exchange, including tracking, and monitoring of materials and e-waste flows. Digital technologies such as collection applications and online marketplaces provide consumers with the convenience and incentives to turn in their e-waste. Given the logistical requirements of the value chain and the large amount of EEE and e-waste in circulation, digitalisation leverages data analysis to maximize resources, and optimize processes by increasing efficiency and reducing costs. With the emergence of highly automated or autonomous systems, digital technologies can contribute to the improvement of worker health and safety through improved handling of hazardous materials, as well as increase the efficiency and speed of sorting large quantities of EEE and e-waste, increasing the purity of the waste stream and the amount recycled. As functionality and sophistication of digital technologies increase, solutions are more likely to be employed to access data in real time, design new products and services, and with it, transform business models towards circularity.

With the extent of digitalisation varying considerably between and within countries, as well as between private and public entities, it should be noted that digital solutions require resources and an enabling ecosystem to be effectively rolled out across the electronics value chain. Elements such as equal access to digital infrastructure and digital skills, financial viability of the digital applications, the opportunity for public-private partnerships, as well as data security and privacy provisions are important factors in the effectiveness of digital solutions. Furthermore, countries with fledgling e-waste management systems and linear electronics value chains, particularly in LMICs, need to prioritize strengthening linkages between stakeholders and creating robust and circular electronics value chains as a first step.

This paper has shown that the electronics value chain and the necessary shift towards a circular economy, can benefit from and be enabled by the use of digital solutions, especially for waste prevention, more transparent producer responsibility and supporting consumer participation. In assessing the potential of digital solutions to strengthen and support the transition towards a circular electronics value chain, it is important to note that such an evolution needs to be complemented with continuing research and efforts to understand its impact on the electronics value chain and its stakeholders, considering the most vulnerable such as those working in the informal sector. Digitalisation comes with numerous benefits, but an unregulated space can alienate some of those involved and potentially underscore inequalities, infringe on privacy and even create more e-waste. Attention should also be paid to the environmental impact of digital technology solutions, from the resources needed for device production, energy consumption during use, and e-waste generation from the solutions themselves. It is important that stakeholders adopting digital solutions consider that they are designed for longevity, taking into consideration the need of future software upgrades, and designed for efficient repair, reuse or refurbishment.

Further research is also needed to evaluate the level of investment required to instigate digital technology solutions more widely across the value chain. International standards such as those developed by ITU can provide valuable guidance to strengthen digital capability and unlock the full potential of the circular economy. There is an opportunity to bring authorities and stakeholders up to speed and engage them with digital technology providers who offer modular solutions that can be trialled and integrated into operations without significant financial and operation risk. In addition, PROs and waste management associations could support awareness raising about the benefits, barriers, and approaches to different digital technologies. The eventual goal of stakeholders looking to employ digital solutions in the value chain should be to maximize the value-added by these technologies while tracking and weighing cost and benefits and minimising their potential negative impacts.

End Notes

1 Forti, V., Baldé, C., Kuehr, R., Bel, G. (2020). The Global E-waste Monitor 2020. UNU/UNITAR and ITU. https://www.itu.int/en/ITU-D/Environment/Documents/Toolbox/GEM_2020_def.pdf.

2 Forti, V., Baldé, C., Kuehr, R., Bel, G. (2020). The Global E-waste Monitor 2020. UNU/UNITAR and ITU. https://www.itu.int/en/ITU-D/Environment/Documents/Toolbox/GEM_2020_def.pdf.

3 Technical guidelines on transboundary movements of electrical and electronic waste and used electrical and electronic equipment, in particular regarding the distinction between waste and non-waste under the Basel Convention. (UNEP/CHW.14/7/Add.6/Rev.1)

4 Platform for Accelerating the Circular Economy. (2019). A new circular vision for electronics - Time for a global reboot. http://www3.weforum.org/docs/WEF_A_New_Circular_Vision_for_Electronics.pdf.

5 Recommendation ITU-T L.1022, Circular economy: Definitions and concepts for material efficiency for information and communication technology, https://www.itu.int/ITU-T/recommendations/rec.aspx?rec=13962.

6 International Energy Agency. (2017). Digitalisation and Energy. https://www.iea.org/reports/digitalisation-and-energy.

7 Platform for Accelerating the Circular Economy. (2021). Circular Economy Action Agenda – Electronics. https://pacecircular.org/sites/default/files/2021-02/action-agenda-electronics-feb2021_FINAL.pdf.

8 Circularity Gap Reporting Initiative (2021). The Circularity Gap Report 2021. https://www.circularity-gap.world/2021#downloads.

9 Schröder , P. and Raes Jan. (2021). Financing an inclusive circular economy De-risking investments for circular business models and the SDGs. Chatham House. https://www.chathamhouse.org/sites/default/files/2021-07/2021-07-16-inclusive-circular-economy-schroder-raes_0.pdf.

10 ITU. (2019). Digital transformation and the role of enterprise architecture. ITU Publications. https://www.itu.int/dms_pub/itu-d/opb/str/D-STR-DIG_TRANSF-2019-PDF-E.pdf

11 Ellen MacArthur Foundation. (2018). Circular Consumer Electronics: An Initial Exploration. https://ellenmacarthurfoundation.org/circular-consumer-electronics-an-initial-exploration.

12 Platform for Accelerating the Circular Economy. (2019). A new circular vision for electronics - Time for a global reboot. http://www3.weforum.org/docs/WEF_A_New_Circular_Vision_for_Electronics.pdf.

13 Platform for Accelerating the Circular Economy. (2019). A new circular vision for electronics - Time for a global reboot. http://www3.weforum.org/docs/WEF_A_New_Circular_Vision_for_Electronics.pdf.

14 Recommendation ITU-T L.1021 "Extended producer responsibility - Guidelines for sustainable e-waste management". See www.itu.int/ITU-T/recommendations/rec.aspx?rec=13458.

15 Forti, V., Baldé, C., Kuehr, R., Bel, G. (2020). The Global E-waste Monitor 2020. UNU/UNITAR and ITU. https://www.itu.int/en/ITU-D/Environment/Documents/Toolbox/GEM_2020_def.pdf.

16 For examples, Recommendation ITU-T L.1023 "Assessment method for circular scoring", Recommendation ITU-T L.1021 "Extended producer responsibility - Guidelines for sustainable e-waste management". For more see https://www.itu.int/ITU-T/recommendations/index_sg.aspx?sg=5.

17 Forti, V., Baldé, C., Kuehr, R., Bel, G. (2020). The Global E-waste Monitor 2020. UNU/UNITAR and ITU. https://www.itu.int/en/ITU-D/Environment/Documents/Toolbox/GEM_2020_def.pdf.

18 Forti, V., Baldé, C., Kuehr, R., Bel, G. (2020). The Global E-waste Monitor 2020. UNU/UNITAR and ITU. https://www.itu.int/en/ITU-D/Environment/Documents/Toolbox/GEM_2020_def.pdf.

19 Baldé, C.P., Wagner, M., Iattoni, G. & Kuehr, R. (2019). In-depth review of the WEEE Collection Rates and Targets. https://weee-forum.org/wp-content/uploads/2020/11/In-depth-review_WEEE-Collection-Targets-and-Rates_UNITAR_2020_Final.pdf.

20 WEEE Forum. (2020). An enhanced definition of EPR and the role of all actors. https://weee-forum.org/wp-content/uploads/2020/11/EPR-and-the-role-of-all-actors_final.pdf.

21 J. Huisman, I. Botezatu et. Al. (2015). Countering WEEE Illegal Trade (CWIT) Summary Report.https://www.researchgate.net/publication/281344533_Countering_WEEE_Illegal_Trade_CWIT_Summary_Report_Market_Assessment_Legal_Analysis_Crime_Analysis_and_Recommendations_Roadmap.

22 Consultations carried out from April 1st to May 15th with stakeholders.

[23] Baldé, C. P., Forti, V., Gray, V., Kuehr, R., Stegmann, P. (2020). The Global E-waste Monitor – 2017. https://www.itu.int/en/ITU-D/Climate-Change/Documents/GEM%202017/Global-E-waste%20Monitor%202017%20.pdf.

[24] Consultations carried out from April 1st to May 15th with stakeholders.

[25] Consultations carried out from April 1st to May 15th with stakeholders.

[26] Consultations carried out from April 1st to May 15th with stakeholders.

[27] Forti, V., Baldé, C., Kuehr, R., Bel, G. (2020). The Global E-waste Monitor 2020. UNU/UNITAR and ITU. https://www.itu.int/en/ITU-D/Environment/Documents/Toolbox/GEM_2020_def.pdf.

[28] International Labour Union (2014). Tackling informality in e-waste management: The potential of cooperative enterprises. https://www.ilo.org/wcmsp5/groups/public/---ed_dialogue/---sector/documents/publication/wcms_315228.pdf.

[29] International Labour Union (2014). Tackling informality in e-waste management: The potential of cooperative enterprises. https://www.ilo.org/wcmsp5/groups/public/---ed_dialogue/---sector/documents/publication/wcms_315228.pdf.

[30] Forti, V., Baldé, C., Kuehr, R., Bel, G. (2020). The Global E-waste Monitor 2020. UNU/UNITAR and ITU. https://www.itu.int/en/ITU-D/Environment/Documents/Toolbox/GEM_2020_def.pdf.

[31] Lundgren, M. K. (2012, December 20). The global impact of e-waste: Addressing the challenge. Retrieved from http://www.ilo.org/sector/Resources/publications/WCMS_196105/lang--en/index.htm.

[32] Technical guidelines on transboundary movements of electrical and electronic waste and used electrical and electronic equipment, in particular regarding the distinction between waste and non-waste under the Basel Convention. (UNEP/CHW.14/7/Add.6/Rev.1)

[33] Accenture. (2014). Circular Advantage: Innovative Business Models and Technologies to Create Value in a World without Limits to Growth (https://tinyurl.com/hdu6tff).

[34] Consultations carried out from April 1st to May 15th with stakeholders.

[35] Shevchenko, T., Laitala, K., & Danko, Y. (2019). Understanding Consumer E-Waste Recycling Behavior: Introducing a New Economic Incentive to Increase the Collection Rates. Sustainability, 11(9), 2656. https://doi.org/10.3390/su11092656.

[36] Shevchenko, T., Laitala, K., & Danko, Y. (2019). Understanding Consumer E-Waste Recycling Behavior: Introducing a New Economic Incentive to Increase the Collection Rates. Sustainability, 11(9), 2656. https://doi.org/10.3390/su11092656.

[37] Consultations carried out from April 1st to May 15th with stakeholders.

[38] Rathore, P., Kota, S., & Chakrabarti, A. (2011). Sustainability through remanufacturing in India: A case study on mobile handsets. Journal of Cleaner Production, 19(15), 1709-1722. https://doi.org/10.1016/j.jclepro.2011.06.016.

[39] Ylä-Mella, J., Keiski, R. L., & Pongrácz, E. (2015). Electronic waste recovery in Finland: Consumers' perceptions towards recycling and re-use of mobile phones. Waste Management, 45, 374-384. https://doi.org/10.1016/j.wasman.2015.02.031.

[40] Shevchenko, T., Laitala, K., & Danko, Y. (2019). Understanding Consumer E-Waste Recycling Behavior: Introducing a New Economic Incentive to Increase the Collection Rates. Sustainability, 11(9), 2656. https://doi.org/10.3390/su11092656.

[41] WHAT A WASTE 2.0. (n.d.). Retrieved from https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html.

[42] Doan, L. T. T., Amer, Y., Lee, S.-H., Phuc, P. N. K., & Dat, L. Q. (2019). E-Waste Reverse Supply Chain: A Review and Future Perspectives. Applied Sciences, 9(23), 5195. https://doi.org/10.3390/app9235195.

[43] Valero, A., Valero, A., Calvo, G., & Ortego, A. (2018). Material bottlenecks in the future development of green technologies. Renewable and Sustainable Energy Reviews, 93, 178-200. https://doi.org/10.1016/j.rser.2018.05.041.

[44] Charles, R. G., Douglas, P., Dowling, M., Liversage, G., & Davies, M. L. (2020). Towards Increased Recovery of Critical Raw Materials from WEEE– evaluation of CRMs at a component level and pre-processing methods for interface optimisation with recovery processes. Resources, Conservation and Recycling, 161. https://doi.org/10.1016/j.resconrec.2020.104923.

[45] Consultations carried out from April 1st to May 15th with stakeholders.

[46] International Telecommunication Union (ITU). (2020). Measuring digital development Facts and figures. Available from: https://www.itu.int/en/ITU-D/Statistics/Documents/facts/FactsFigures2020.pdf.

[47] Recommendation ITU-T M.3080 "Framework of artificial intelligence enhanced telecom operation and management (AITOM)", https://www.itu.int/itu-t/recommendations/rec.aspx?rec=14590.

48 Recommendation ITU-T M.3080 "Framework of artificial intelligence enhanced telecom operation and management (AITOM)", https://www.itu.int/itu-t/recommendations/rec.aspx?rec=14590.

49 Recommendation ITU-T Y.2244 "Service model for a cultivation plan service at the pre-production stage". https://www.itu.int/rec/T-REC-Y.2244/en.

50 Recommendation ITU-T Y.4464 "Framework of blockchain of things as decentralized service platform", https://www.itu.int/ITU-T/recommendations/rec.aspx?rec=14167.

51 Recommendation ITU-T Y.3500 "Information technology - Cloud computing - Overview and vocabulary". https://www.itu.int/rec/T-REC-Y.3500-201408-I.

52 Recommendation ITU-T Y.2060 "Overview of the Internet of Things". https://www.itu.int/rec/T-REC-Y.2060-201206-I.

53 Recommendation ITU-T Y.2221 "Requirements for support of ubiquitous sensor network (USN) applications and services in the NGN environment". https://www.itu.int/rec/T-REC-Y.2221/en.

54 Platform for Accelerating the Circular Economy. (2019). Harnessing the Fourth Industrial Revolution for the Circular Economy Consumer Electronics and Plastics Packaging. http://www3.weforum.org/docs/WEF_Harnessing_4IR_Circular_Economy_report_2018.pdf.

55 Björkdahl, J. (2020). Strategies for Digitalisation in Manufacturing Firms. California Management Review, 62(4), 17–36. https://doi.org/10.1177/0008125620920349.

56 European Commission. (2016). Digitising European Industry Reaping the full benefits of a Digital Single Market. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52016DC0180&from=EN.

57 What Is Industry 4.0? - SAP Insights. (2021). Retrieved from https://insights.sap.com/what-is-industry-4-0/.

58 Yang, F., & Gu, S. (2021). Industry 4.0, a revolution that requires technology and national strategies. Complex & Intelligent Systems, 7(3), 1311–1325. https://doi.org/10.1007/s40747-020-00267-9.

59 Deloitte University Press. (2017). The smart factory Responsive, adaptive, connected manufacturing. https://www2.deloitte.com/content/dam/insights/us/articles/4051_The-smart-factory/DUP_The-smart-factory.pdf.

60 A European Green Deal. European Commission - European Commission. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en.

61 Circular economy action plan. (n.d.). https://ec.europa.eu/environment/strategy/circular-economy-action-plan_en.

62 "CIRCULAR ECONOMY." (2021), https://joinup.ec.europa.eu/collection/rolling-plan-ict-standardisation/circular-economy.

63 Venkat Jayanth, B., Prathap, P., Sivaraman, P., Yogesh, S., & Madhu, S. (2020). Implementation of lean manufacturing in electronics industry. Materials Today: Proceedings, 33, 23–28. https://doi.org/10.1016/j.matpr.2020.02.718.

64 Lorenz, R., Buess, P., Macuvele, J., Friedli, T., & Netland, T. (2019). Lean and Digitalisation: Contradictions or complements? Advances in Production Management Systems. Production Management for the Factory of the Future IFIP WG 5.7 International Conference, APMS 2019, Austin, TX, USA, September 1–5, 2019, Proceedings, Part I, 566, 77–84. https://doi.org/10.3929/ethz-b-000353437.

65 Buer, S.-V., Semini, M., Strandhagen, J. O., & Sgarbossa, F. (2021). The complementary effect of lean manufacturing and digitalisation on operational performance. International Journal of Production Research, 59(7), 1976–1992. https://doi.org/10.1080/00207543.2020.1790684.

66 Trstenjak M, Cosic P. LEAN PHILOSOPHY IN THE DIGITALISATION PROCESS. (2018). https://www.bib.irb.hr/950193/download/950193.Lean_Manufacturing_in_The_Digitalization_Process.pdf.

67 Trstenjak M, Cosic P. LEAN PHILOSOPHY IN THE DIGITALISATION PROCESS. (2018). https://www.bib.irb.hr/950193/download/950193.Lean_Manufacturing_in_The_Digitalization_Process.pdf.

68 Guzman, S. C., Cabal, M. D. C., Regidor, F. M., & Virgos, L. A. (2019). Cyber-Physical System Architecture for Minimizing the Possibility of Producing Bad Products in a Manufacturing System. In Industry 4.0—Impact on Intelligent Logistics and Manufacturing. IntechOpen. https://doi.org/10.5772/intechopen.88461.

69 X. Zenga, H. Duanb, F. Wang, and J. Li. (2017). Examining environmental management of e-waste: China's experience and lessons, Renewable and Sustainable Energy Reviews, Volume 72, 2017,Pages 1076-1082, https://doi.org/10.1016/j.rser.2016.10.015.

70 Rojek, I., Dostatni, E., & Hamrol, A. (2018). Ecodesign of Technological Processes with the Use of Decision Trees Method. In H. Pérez García, J. Alfonso-Cendón, L. Sánchez González, H. Quintián, & E. Corchado (Eds.), International Joint Conference SOCO'17-CISIS'17-ICEUTE'17 León, Spain, September 6–8, 2017, Proceeding (pp. 318–327). Springer International Publishing. https://doi.org/10.1007/978-3-319-67180-2_31.

71 Accelerated Metallurgy - the accelerated discovery of alloy formulations using combinatorial principles. (n.d.). Retrieved from https://cordis.europa.eu/project/id/263206.

72 From ownership to service: A new Fairphone pilot just for companies. (2020, December 17). www.fairphone.com/en/2018/01/08/from-ownership-to-service-new-fairphone-pilot-for-companies.

73 Fairphone. (2020). FAIRPHONE'S IMPACT 2020 A challenge to the industry. Fairphone. Retrieved from https://www.fairphone.com/wp-content/uploads/2021/07/Impact-Report-2020-Fairphone.pdf.

74 Dadhich, S., Bodin, U., & Andersson, U. (2016). Key challenges in automation of earth-moving machines. Automation in Construction, 68, 212–222. https://doi.org/10.1016/j.autcon.2016.05.009.

75 Baker McKenzie. Blockchain and Cryptocurrency in Africa. (2018). https://www.bakermckenzie.com/-/media/files/insight/publications/2019/02/report_blockchainandcryptocurrencyreg_feb2019.pdf.

76 Reuters. (2021). Glencore, Umicore to trace battery cobalt with blockchain technology. https://www.reuters.com/business/energy/glencore-umicore-trace-battery-cobalt-with-blockchain-technology-2021-05-20/.

77 Email consultation with Circularise.

78 Chevalier, S. (2021, July 07). Global retail e-commerce market size 2014-2023. Retrieved from https://www.statista.com/statistics/379046/worldwide-retail-e-commerce-sales/.

79 United Nations Conference on Trade and Development (UNCTAD). (2021). Global e-commerce jumps to $26.7 trillion, COVID-19 boosts online sales. https://unctad.org/news/global-e-commerce-jumps-267-trillion-covid-19-boosts-online-sales.

80 Ecommerce Powers Consumer Electronics Sales. (2020). Insider Intelligence. https://www.emarketer.com/content/consumer-electronics-sales-powered-by-ecommerce.

81 Postnord. (2020). E-commerce in Europe 2020. https://www.postnord.se/siteassets/pdf/rapporter/e-commerce-in-europe-2020.pdf.

82 Laptops, Cell Phones, eGames Defied Slump as COVID-19 Dented 2020s Electronics Sales: UN. (2021). Retrieved from https://unitar.org/about/news-stories/news/laptops-cell-phones-egames-defied-slump-covid-19-dented-2020s-electronics-sales-un.

83 World Economic Forum (WEF). (2016). Digital Transformation of Industries Consumer Industries. Retrieved July 30, 2021, from http://reports.weforum.org/digital-transformation/wp-content/blogs.dir/94/mp/files/pages/files/dti-consumer-industries-white-paper.pdf.

84 Esenduran, G., Hill, J. A., & Noh, I. J. (2020). Understanding the Choice of Online Resale Channel for Used Electronics. Production and Operations Management, 29(5), 1188–1211. https://doi.org/10.1111/poms.13149.

85 McCarthy, A. and P. Börkey (2018), "Extended Producer Responsibility (EPR) and the Impact of Online Sales", OECD Environment Working Papers, OECD Publishing, Paris, http://dx.doi.org/10.1787/19970900.

86 Accenture. (2014). Circular Advantage: Innovative Business Models and Technologies to Create Value in a World without Limits to Growth. https://www.accenture.com/t20150523T053139__w__/us-en/_acnmedia/Accenture/Conversion-Assets/DotCom/Documents/Global/PDF/Strategy_6/Accenture-Circular-Advantage-Innovative-Business-Models-Technologies-Value-Growth.pdf.

87 Ellen MacArthur Foundation. (2018). Circular Consumer Electronics: An Initial Exploration. Ellen MacArthur Foundation. https://ellenmacarthurfoundation.org/circular-consumer-electronics-an-initial-exploration.

88 Deloitte. (2016). Used smartphones: the $17 billion market you may never have heard of. https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Technology-Media-Telecommunications/gx-tmt-prediction-used-smartphones.pdf.

89 Esenduran, G., Hill, J. A., & Noh, I. J. (2020). Understanding the Choice of Online Resale Channel for Used Electronics. Production and Operations Management, 29(5), 1188–1211. https://doi.org/10.1111/poms.13149.

90 Dillet, R., & Lunden, I. (2021, May 18). Back Market raises $335M for its refurbished device marketplace, now valued at $3.2B. Retrieved from , https://techcrunch.com/2021/05/17/back-market-raises-another-335-million-for-its-refurbished-device-marketplace/.

91 Certified Renewed. (n.d.). https://www.backmarket.com/e/certified-renewed.

92 Ravichander, P. (2021). Council Post: The Digital Marketplace: A New Paradigm Requiring Digital Twins And Digital Trust. Forbes. https://www.forbes.com/sites/forbestechcouncil/2021/03/03/the-digital-marketplace-a-new-paradigm-requiring-digital-twins-and-digital-trust/.

93 Ravichander, P. (2021). Council Post: The Digital Marketplace: A New Paradigm Requiring Digital Twins And Digital Trust. Forbes. https://www.forbes.com/sites/forbestechcouncil/2021/03/03/the-digital-marketplace-a-new-paradigm-requiring-digital-twins-and-digital-trust/.

94 EEB. (2019). Cool products don't cost the earth–Full report. www.eeb.org/coolproducts-report.

95 Chang, M.-Y., Chen, K., Pang, C., Chen, C.-M., & Yen, D. C. (2013). A study on the effects of service convenience and service quality on maintenance revisit intentions. Computer Standards & Interfaces, 35(2), 187–194. https://doi.org/10.1016/j.csi.2012.08.002.

96 S Svensson, S., Richter, J. L., Maitre-Ekern, E., Pihlajarinne, T., Maigret, A., & Dalhammar, C. (2018). The Emerging 'Right to Repair' legislation in the EU and the U.S. Going Green CARE INNOVATION 2018. https://portal.research.lu.se/portal/en/publications/the-emerging-right-to-repair-legislation-in-the-eu-and-the-us(34ca32eb-5148-4b33-b82a-d7cfca46c672).html.

97 Mdepypere. (2021, February 3). The French repair index: challenges and opportunities. Right to Repair Europe. https://repair.eu/de/news/the-french-repair-index-challenges-and-opportunities/.

98 iFixit: The Free Repair Manual. (n.d.). Retrieved July 30, 2021, from https://www.ifixit.com/.

99 Lepawsky, J. (2020). Planet of fixers? Mapping the middle grounds of independent and do-it-yourself information and communication technology maintenance and repair. Geo: Geography and Environment, 7(1), e00086. https://doi.org/10.1002/geo2.86.

100 Repair is Better Than Replace: France's New Reparability Index for Electronic Products. https://www.sgs.com/en/news/2021/03/repair-is-better-than-replace-frances-new-reparability-index-for-electronic-products.

101 Mdepypere. (2021, February 3). The French repair index: challenges and opportunities. Right to Repair Europe. https://repair.eu/de/news/the-french-repair-index-challenges-and-opportunities/.

102 Ellen MacArthur Foundation. (2018). Circular Consumer Electronics: An Initial Report. https://ellenmacarthurfoundation.org/circular-consumer-electronics-an-initial-exploration.

103 Internet enabled pay-per-wash: A model offering multiple benefits. (2017). Retrieved July 30, 2021, from https://ellenmacarthurfoundation.org/circular-examples/a-model-offering-multiple-benefits-for-multiple-electronic-products.

104 Circular economy meets social commitment. (n.d.). Bosch Global. https://www.bosch.com/stories/papillon-project/.

105 Papillon. (n.d.). Vlaanderen Circulair. https://vlaanderen-circulair.be/en/cases/detail/papillon.

106 March, S. T., & Scudder, G. D. (2019). Predictive maintenance: Strategic use of IT in manufacturing organizations. Information Systems Frontiers, 21(2), 327–341. https://doi.org/10.1007/s10796-017-9749-z.

107 European Commission. (n.d.). Activating Circular Services in the Electric and Electronic Sector | C-SERVEES Project | H2020 | CORDIS | European Commission. https://cordis.europa.eu/project/id/776714.

108 Díaz, A. I. & Arnaiz, S. (2019). Framework for setting up and running the demonstrations. C-SERVEES. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c8e28ed1&appId=PPGMS.

109 Hannan, M. A., Arebey, M., Basri, H., & Begum, R. A. (2010). Intelligent Solid Waste Bin Monitoring and Management System. Undefined. https://www.semanticscholar.org/paper/Intelligent-Solid-Waste-Bin-Monitoring-and-System-Hannan-Arebey/bd98985b9278b4ec0af9f514dfe20ad561d54c18.

110 Recommendation ITU-T Y.4900/L.1600 "Overview of key performance indicators in smart sustainable cities".

111 Dindarian A, Chakravarthy S. Chapter 7: Traceability of Electronic Waste Using Blockchain Technology. In: Electronic Waste Management. 2019:188-212 https://doi.org/10.1039/9781788018784-00188.

112 Saberi, S., Kouhizadeh, M., Sarkis, M., and Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. Int. J. Prod. Res. 57, 2117–2135. https://doi.org/10.1080/00207543.2018.1533261.

113 Kouhizadeh, M., and Sarkis, J. (2018). Blockchain practices, potentials, and perspectives in greening supply chains. Sustainability 10:3652. https://doi.org/10.3390/su10103652.

114 Frankenfield, J. (2019). Smart Contracts. Investopedia. https://www.investopedia.com/terms/s/smart-contracts.asp.

115 Swachhcoin. (n.d.). from http://swachhcoin.com/.

116 Robots put to work on e-waste. (2014, November 14). Retrieved from phys.org/news/2014-11-robots-e-waste.html.

[117] Soaring e-waste affects the health of millions of children, WHO warns. (2021). https://www.who.int/news/item/15-06-2021-soaring-e-waste-affects-the-health-of-millions-of-children-who-warns.

[118] International Labour Union (2014). Tackling informality in e-waste management: The potential of cooperative enterprises. https://www.ilo.org/wcmsp5/groups/public/---ed_dialogue/---sector/documents/publication/wcms_315228.pdf.

[119] Nowakowski, P., Szwarc, K., & Boryczka, U. (2018). Vehicle route planning in e-waste mobile collection on demand supported by artificial intelligence algorithms. Transportation Research Part D: Transport and Environment, 63, 1–22. https://doi.org/10.1016/j.trd.2018.04.007.

[120] Haque, K., Zabin, R., Yelamarthi, K., Yanambaka, P., & Abdelgawad, A. (2020). An IoT Based Efficient Waste Collection System with Smart Bins. https://doi.org/10.36227/techrxiv.12455936.

[121] Medvedev, A., Fedchenkov, P., Zaslavsky, A., Anagnostopoulos, T., & Khoruzhnikov, S. (2015, August 1). Waste Management as an IoT-Enabled Service in Smart Cities. https://doi.org/10.1007/978-3-319-23126-6_10.

[122] Kedia, P. (2016). BIG DATA ANALYTICS FOR EFFICIENT WASTE MANAGEMENT. IJRET: International Journal of Research in Engineering and Technology, 5(10). https://ijret.org/volumes/2016v05/i10/IJRET20160510034.pdf.

[123] The rewarding system of Cava de' Tirreni pilot. (n.d.). www.innoweee.eu. http://www.innoweee.eu/rewardingsystemCava.

[124] Tan, A. (2021, July 1). More than 300 bins placed islandwide to collect e-waste. The New Paper. https://www.tnp.sg/news/singapore/more-300-bins-placed-islandwide-collect-e-waste.

[125] ALBA E-Waste Singapore – Singapore E-Waste Collection & Recycling Program. (n.d.). Retrieved August 1, 2021, from https://alba-ewaste.sg/.

[126] News Releases. (2021, June 4). Retrieved from https://www.nea.gov.sg/media/news/news/index/nea-and-alba-to-soft-launch-e-waste-recycling-bins-ahead-of-start-of-e-waste-management-scheme.

[127] UNDP. (2021, April 13). Launch of E-Tadweer for e-waste management: UNDP in Egypt. Retrieved from https://www.eg.undp.org/content/egypt/en/home/press-center/pressreleases/2021/launch-of-e-tadweer-for-e-waste-management-.html.

[128] Uzed. (n.d.). Exchange your old stuff ! Retrieved from https://uzed.in/.

[129] Email consultation with Circular Brain.

[130] How can we automate the valuation of e-waste? (n.d.). Retrieved from https://www.cambridgeconsultants.com/insights/vlog-how-can-we-automate-valuation-e-waste.

[131] How can we automate the valuation of e-waste? (n.d.). Retrieved from https://www.cambridgeconsultants.com/insights/vlog-how-can-we-automate-valuation-e-waste.

[132] How can we automate the valuation of e-waste? (n.d.). Retrieved from https://www.cambridgeconsultants.com/insights/vlog-how-can-we-automate-valuation-e-waste.

[133] Rujanavech, C., Lessard, J., Chandler, S., Shannon, S., Dahmus, J., Guzzo, R. Liam - An Innovation Story. Apple, 2017. https://www.apple.com/environment/pdf/Liam_white_paper_Sept2016.pdf.

[134] Apple adds Earth Day donations to trade-in and recycling program. (2021, August 06). Retrieved from https://www.apple.com/newsroom/2018/04/apple-adds-earth-day-donations-to-trade-in-and-recycling-program/.

[135] Kedia, P. (2016). BIG DATA ANALYTICS FOR EFFICIENT WASTE MANAGEMENT. IJRET: International Journal of Research in Engineering and Technology, 5(10). https://ijret.org/volumes/2016v05/i10/IJRET20160510034.pdf.

[136] Cai, K. (2020, November 17). Rise Of The Recycling Robots. Retrieved from https://www.forbes.com/sites/kenrickcai/2020/11/12/rise-of-the-recycling-robots/?sh=6f8ed87465f9.

[137] Consultation with Recupel on 2nd July 2021

[138] Consultation with Recykal on 1st July 2021.

[139] Berg, Holger, et al. (2021). European Environment Agency Digital Waste Management. www.eionet.europa.eu/etcs/etc-wmge/products/etc-reports/digital-waste-management.

[140] International Solid Waste Association. (2019). How Industry 4.0 transforms the waste sector. https://www.iswa.org/?eID=tx_iswaknowledgebase_download&documentUid=5235&v=8bc2afe7028c.

[141] Van Maaren, C. (n.d.). Excess Materials Exchange. Uplink. Retrieved August 10, 2021, from https://uplink.weforum.org/uplink/s/uplink-contribution/a012o00001OSdnIAAT/excess-materials-exchange.

[142] Hinchliffe, D., et al. (2020). Case studies and approaches to building Partnerships between the informal and the formal sector for sustainable e-waste management. SteP Initiative. Retrieved from https://step-initiative.org/files/_documents/publications/Partnerships-between-the-informal-and-the-formal-sector-for-sustainable-e-waste-management.pdf.

143 Bhattacharya, R. (2019). ICT solutions for the informal sector in developing economies: What can one expect? The Electronic Journal of Information Systems in Developing Countries, 85(3), e12075. https://doi.org/10.1002/isd2.12075.

144 Based on previous ITU consultation, https://www.facebook.com/.groups/2193034550925048.

145 Hinchliffe, D., et al. (2020). Case studies and approaches to building Partnerships between the informal and the formal sector for sustainable e-waste management. SteP Initiative. Retrieved from https://step-initiative.org/files/_documents/publications/Partnerships-between-the-informal-and-the-formal-sector-for-sustainable-e-waste-management.pdf.

146 Hinchliffe, D., et al. (2020). Case studies and approaches to building Partnerships between the informal and the formal sector for sustainable e-waste management. SteP Initiative. Retrieved from https://step-initiative.org/files/_documents/publications/Partnerships-between-the-informal-and-the-formal-sector-for-sustainable-e-waste-management.pdf.

147 Indian firm's digital solution for urban waste pickers. (n.d.). Retrieved August 5, 2021, from https://www.itu.int:443/en/myitu/News/2021/07/29/16/51/Digital-solution-India-waste-pickers-Kabadiwalla-Connect.

148 Kannadasan, A. (2018, July 12). Kabadiwalla Connect: Going the e-way for waste management. The Hindu. https://www.thehindu.com/society/deal-with-that-scrap/article24399239.ece.

149 Consultation with Recupel on 2nd July 2021

150 Coliba. (2020, September 18). https://coliba.ci/.

151 Meet our portfolio start-ups: Coliba, Côte d'Ivoire. (2019, June 7). Mobile for Development. https://www.gsma.com/mobilefordevelopment/blog/meet-our-portfolio-start-ups-coliba-cote-divoire/.

152 Kerpedzhiev, G. D., König, U. M., Röglinger, M., & Rosemann, M. (2021). An Exploration into Future Business Process Management Capabilities in View of Digitalisation. Business & Information Systems Engineering, 63(2), 83–96. https://doi.org/10.1007/s12599-020-00637-0.

153 Kayikci, Y. (2018). Sustainability impact of digitization in logistics. Procedia Manufacturing, 21, 782–789. https://doi.org/10.1016/j.promfg.2018.02.184.

154 Gu, F., Ma, B., Guo, J., Summers, P. A., & Hall, P. (2017). Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management, 68, 434-448. https://doi.org/10.1016/j.wasman.2017.07.037.

155 Gu, F., Ma, B., Guo, J., Summers, P. A., & Hall, P. (2017). Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management, 68, 434–448. https://doi.org/10.1016/j.wasman.2017.07.037.

156 Ministry of Environment, Government of Jordan. (2021). Instructions for managing electrical and electronic waste for the year 2021. http://moenv.gov.jo/AR/List/%D8%A7%D9%84%D8%AA%D8%B9%D9%84%D9%8A%D9%85%D8%A7%D8%AA

157 Eulerich, M., Wagener, M., & Wood, D. A. (2021). Evidence on Internal Audit Effectiveness from Transitioning to Remote Audits Because of COVID-19 (SSRN Scholarly Paper ID 3774050). Social Science Research Network. https://doi.org/10.2139/ssrn.3774050.

158 Urban Mine Platform.(n.d.). Retrieved July 30, 2021. http://www.urbanmineplatform.eu/homepage.

159 About the project | ProSUM. (n.d.). Retrieved July 30, 2021. http://www.prosumproject.eu/about-project.

160 LibraWEEE | WEEE Forum. (2019, June 13). https://weee-forum.org/libraweee/.

161 LibraWEEE | WEEE Forum. (2019, June 13). https://weee-forum.org/libraweee/.

162 WEEE Forum Collection Platform | WEEE Forum. (2019, June 13). https://weee-forum.org/collectionplatform/.

163 Information 4 Recyclers | WEEE Forum. (2019, March 12). https://weee-forum.org/information-4-recyclers/.

164 Email consultation with Circular Brain.

165 WF-RepTool | WEEE Forum. (2019, March 12). https://weee-forum.org/wf-reptool/.

166 WEEE Ireland. (2020). WEEE IRELAND ANNUAL ENVIRONMENTAL REPORT TWENTY NINETEEN. http://www.weeeireland.ie/wordpress/wp-content/uploads/pdfs/WEEE-Ireland-environmental-report-2019.pdf.

167 Fifteenth Meeting of the Conference of the Parties to the Basel Convention. Matters related to the implementation of the Convention: work programme of the Open-ended Working Group for the period 2022–2023. Document symbol: UN/CHW.15/19. Accessed from: http://www.basel.int/TheConvention/ConferenceoftheParties/Meetings/COP15/tabid/8392/Default.aspx.

168 Consultation with Karo Sambhav on 5th July 2021.

169 Puckett, J., Brandt, C., and Palmer, H., Holes in the Circular Economy - Leakage from Europe. Basel Action Network. https://www.ban.org/trash-transparency.

170 E-waste Policy Toolkit. (2021). ITU. from https://www.itu.int:443/en/ITU-D/Environment/Pages/Toolbox/WEEE-Africa-Toolkit.aspx.

171 LTO Network—Use case—Waste transport on Blockchain (ILT). (n.d.). Retrieved July 30, 2021, from https://www.ltonetwork.com/use-cases/waste-transport-on-blockchain/.

172 SERI COP. (2021). Advisory No. 23: Remote Auditing for Surveillance Audits. https://sustainableelectronics.org/wp-content/uploads/2021/03/Advisory-23-for-Remote-Surveillance-audits-Version-1.pdf.

173 Leif, D. (2020, July 30). Pandemic upends certification audit sector. E-Scrap News. https://resource-recycling.com/e-scrap/2020/07/30/pandemic-upends-certification-audit-sector/.

174 Happonen, A., Santti, U., & Auvinen, H. (2019). Digitalisation Boosted Recycling: Gamification as an Inspiration for Young Adults to do Enhanced Waste Sorting. 2233. https://doi.org/10.1063/5.0001547.

175 Gartner Top Strategic Technology Trends for 2021. (n.d.). Retrieved August 1, 2021, from www.gartner.com/smarterwithgartner/gartner-top-strategic-technology-trends-for-2021/.

176 Sipka, S., & Hedberg, A. (2020). The circular economy: Going digital. https://www.epc.eu/en/publications/The-circular-economy-Going-digital~30c848.

177 Consultations carried out from April 1st to May 15th with stakeholders.

178 Guterres, A. (2020). Report of the Secretary-General Roadmap for Digital Cooperation. https://www.un.org/en/content/digital-cooperation roadmap/assets/pdf/Roadmap_for_Digital_Cooperation_EN.pdf.

179 GSMA. (2020). The State of Mobile Internet Connectivity. https://www.gsma.com/r/wp-content/uploads/2020/09/GSMA-State-of-Mobile-Internet-Connectivity-Report-2020.pdf.

180 ITU. (2020). Measuring Digital Development - Facts and Figures. ITU Publications https://www.itu.int/en/myitu/Publications/2020/11/30/09/32/Facts-and-Figures-2020.

181 Technology Bank for the Least Developed Countries |. (n.d.). www.un.org. https://www.un.org/technologybank/.

182 Consultations carried out from April 1st to May 15th with stakeholders.

183 Consultation with Recykal on 1st July 2021.

184 5G - Fifth generation of mobile technologies. (n.d.). www.itu.int. https://www.itu.int/en/mediacentre/backgrounders/Pages/5G-fifth-generation-of-mobile-technologies.aspx.

185 Climate KIC. (2018). Digitalisation – unlocking the potential of the circular economy. https://www.climate-kic.org/wp-content/uploads/2018/08/ClimateKICWhitepaperFinalDigital_compressed.pdf.

186 Climate KIC. (2018). Digitalisation – unlocking the potential of the circular economy. https://www.climate-kic.org/wp-content/uploads/2018/08/ClimateKICWhitepaperFinalDigital_compressed.pdf.

187 SDG Indicators — SDG Indicators. (n.d.). Unstats.un.org. from https://unstats.un.org/sdgs/metadata/?Text=&Goal=9&Target=9.c.

188 ITU. (2018). Strategic plan for the Union for 2020-2023. https://www.itu.int/en/council/planning/Documents/ITU_Strategic_plan_2020-2023.pdf.

189 ITU. (2020). Measuring Digital Development - Facts and Figures. ITU Publications https://www.itu.int/en/myitu/Publications/2020/11/30/09/32/Facts-and-Figures-2020.

190 Consultation with Recupel on 2nd July 2021.

191 ITU. (2019, June 18). Why digital skills training is so important if we are serious about closing the digital divide. ITU News. https://news.itu.int/why-digital-skills-training-is-so-important-if-we-are-serious-about-closing-the-digital-divide/.

192 International Telecommunication Union (2020). Digital Skills Insights. https://academy.itu.int/sites/default/files/media2/file/Digital%20Skills%20Insights%202020.pdf.

193 International Telecommunication Union (2020). Digital Skills Insights. https://academy.itu.int/sites/default/files/media2/file/Digital%20Skills%20Insights%202020.pdf.

194 International Telecommunication Union (2020). Digital Skills Insights. https://academy.itu.int/sites/default/files/media2/file/Digital%20Skills%20Insights%202020.pdf.

195 Consultations carried out from April 1st to May 15th with stakeholders.

196 Turpitka, D. (2020, September 28). Council Post: Five Challenges To Prepare For When Using Blockchain For Supply Chain Operations. Retrieved from http://www.forbes.com/sites/forbestechcouncil/2020/09/29/five-challenges-to-prepare-for-when-using-blockchain-for-supply-chain-operations/?sh=209dd484b40f.

[197] Consultation with Karo Sambhav on 5th July 2021.

[198] Consultations carried out from April 1st to May 15th with stakeholders.

[199] Consultations carried out from April 1st to May 15th with stakeholders .

[200] Climate KIC. (2018). Digitalisation – unlocking the potential of the circular economy. https://www.climate-kic.org/wp-content/uploads/2018/08/ClimateKICWhitepaperFinalDigital_compressed.pdf.

[201] Consultations carried out from April 1st to May 15th with stakeholders.

[202] Consultations carried out from April 1st to May 15th with stakeholders.

[203] More on ITU-T Study Group 20 digital and interoperability standards https://www.itu.int/en/ITU-T/studygroups/2017-2020/20/Pages/default.aspx.

[204] Consultation with Karo Sambhav on 5th July 2021.

[205] Consultation with Karo Sambhav on 5th July 2021.

[206] ECERA European Circular Economy Research Alliance. 2020. Digital circular economy as a cornerstone of a sustainable European industry transformation. https://www.era-min.eu/sites/default/files/publications/201023_ecera_white_paper_on_digital_circular_economy.pdf.

[207] Individual consultations carried out from July 1st to July 15th with stakeholders.

[208] Consultation with Recupel on 2nd July 2021.

[209] Consultation with Recupel on 2nd July 2021.

[210] Berg, Holger, et al. (2021). European Environment Agency Digital Waste Management. www.eionet.europa.eu/etcs/etc-wmge/products/etc-reports/digital-waste-management.

[211] Cai, K. (2020, November 17). Rise Of The Recycling Robots. Retrieved from https://www.forbes.com/sites/kenrickcai/2020/11/12/rise-of-the-recycling-robots/?sh=54210a4c65f9.

[212] Cai, K. (2020, November 17). Rise Of The Recycling Robots. Retrieved from https://www.forbes.com/sites/kenrickcai/2020/11/12/rise-of-the-recycling-robots/?sh=54210a4c65f9.

[213] Berg, H,. et al. (2021). Digital Waste Management. www.eionet.europa.eu/etcs/etc-wmge/products/etc-reports/digital-waste-management.

[214] Consultations carried out from April 1st to May 15th with stakeholders.

[215] Consultations carried out from April 1st to May 15th with stakeholders.

[216] Climate KIC. (2018). Digitalisation – unlocking the potential of the circular economy. https://www.climate-kic.org/wp-content/uploads/2018/08/ClimateKICWhitepaperFinalDigital_compressed.pdf

[217] Consultations carried out from April 1st to May 15th with stakeholders.

[218] Consultations carried out from April 1st to May 15th with stakeholders.

[229] Consultations carried out from April 1st to May 15th with stakeholders.

[220] Adisorn, T., Tholen, L., & Götz, T. (2021). Towards a Digital Product Passport Fit for Contributing to a Circular Economy. Energies, 14(8), 2289. https://doi.org/10.3390/en14082289.

[221] Consultations carried out from April 1st to May 15th with stakeholders.

[222] Consultations carried out from April 1st to May 15th with stakeholders.

[223] European Commission. (2018). The EU data protection reform and big data. https://op.europa.eu/en/publication-detail/-/publication/51fc3ba6-e601-11e7-9749-01aa75ed71a1.

[224] Bastos, D., et al. (2018). GDPR Privacy Implications for the Internet of Things.

[225] ECERA European Circular Economy Research Alliance. 2020. Digital circular economy as a cornerstone of a sustainable European industry transformation. https://www.era-min.eu/sites/default/files/publications/201023_ecera_white_paper_on_digital_circular_economy.pdf

[226] Andrae, A. S., & Edler, T. (2015). On global electricity usage of communication technology: trends to 2030. Challenges, 6(1), 117-157. https://doi.org/10.3390/challe6010117.

[227] ITU. (2020). Internet Waste: A thought paper for International E-Waste Day. ITU and WEEE Forum. https://www.itu.int/en/ITU-D/Environment/Documents/Publications/2020/Internet-Waste%202020.pdf?csf=1&e=iQq5Zi.

[228] ITU. (2020). Internet Waste: A thought paper for International E-Waste Day. ITU and WEEE Forum. https://www.itu.int/en/ITU-D/Environment/Documents/Publications/2020/Internet-Waste%202020.pdf?csf=1&e=iQq5Zi.

[229] Collaboration sparks sustainable electronics manufacturing breakthrough. (n.d.). Retrieved from http://www.sfu.ca/sfunews/stories/2019/02/collaboration-sparks-sustainable-electronics-manufacturing-break.html.

[230] Andrews, D., & Whitehead, B. (2019). Data Centres in 2030. Retrieved from https://openresearch.lsbu.ac.uk/item/8675q.

[231] Iea. (2020, June 01). Data Centres and Data Transmission Networks – Analysis. Retrieved from https://www.iea.org/reports/data-centres-and-data-transmission-networks.

[232] ITU. (2020). Internet Waste: A thought paper for International E-Waste Day 2020. ITU and WEEE Forum, https://www.itu.int/en/ITU-D/Environment/Documents/Publications/2020/Internet-Waste%202020.pdf?csf=1&e=iQq5Zi.

[233] ITU. (2020). Internet Waste: A thought paper for International E-Waste Day 2020. ITU and WEEE Forum, https://www.itu.int/en/ITU-D/Environment/Documents/Publications/2020/Internet-Waste%202020.pdf?csf=1&e=iQq5Zi.

[234] Google. Environment report. (2020). https://www.gstatic.com/gumdrop/sustainability/google-2020-environmental-report.pdf.

[235] Microsoft commits to achieve 'zero waste' goals by 2030.(2020). Retrieved from https://blogs.microsoft.com/blog/2020/08/04/microsoft-direct-operations-products-and-packaging-to-be-zero-waste-by-2030/.

International Telecommunication Union

Telecommunication Development Bureau
Place des Nations
CH-1211 Geneva 20
Switzerland

www.itu.int/climate

Contact ITU:
eetmail@itu.int

GSM Association:

www.gsma.com

Contact GSMA:
info@gsma.com

Sofies Group

Quai du Seujet 28, CP 2091
1211 Geneva 1
Switzerland

www.sofiesgroup.com

Contact Sofies Group:
india@sofiesgroup.com

WEEE Forum a.i.s.b.l.

BluePoint Conference and Business Centre
Boulevard Auguste Reyerslaan 80
B-1030 Brussels, Belgium
Transparency register: ID 702397445-73

www.weee-forum.org

Contact WEEE Forum:
info@weee-forum.org

ISBN: 978-92-61-35251-6

9 789261 352516