CIRCULAR ECONOMY THINKING TO DEVELOP SUSTAINABLE ELECTRONIC PRODUCTS, BUSINESS MODELS AND DESIGNS

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ABSTRACT: Driven by the UN's Sustainable Development goals, which has identified the issue of electronic waste growing significantly and the challenges of recycling/reusing electronic components, there is a need to research new possibilities in sustainable and recyclable printed electronic devices. The change in business models and industry and consumer device flows will also have implications. The circular model puts more emphasis back onto producers who have more knowledge to make an impact on the sustainable use of electronic devices than traditional waste management companies. This study, carried out in conjunction with the Arm-ECS Research Centre, explores the intersection of design and the circular economy. The paper identifies circular economy opportunities in the electronics sector via a review of both academic and grey literature and an accompanying SWOT analysis, with a focus on electronic components and the boards/packages (whole sub-systems, parts, materials) that make up electronic systems, and circular business models. Challenges to be addressed and overcome in order to implement a transition to circularity for the electronics sector are identified and discussed.

Keywords: Circular economy; sustainability; electronic products; circular business models.

1. INTRODUCTION

So-called Circular Economy (CE) thinking is becoming mainstream in society today. Various industries are beginning to adopt policies with circularity in mind. Natural resources have been consumed at an unprecedented rate since the Industrial Revolution. Since 1970, global use of resources has tripled, and this continues to escalate exponentially. It is estimated that the demand for resources occurs at a rate of 50% quicker than they can be replenished; at such a rate, the demand for resources by 2030 will require over two planets' worth of natural resources if they are to be met (Esposito et al., 2018).

The prevailing, dominant, so-called 'Linear Economy' (i.e. take, make, dispose) has contributed to massive changes in climatic conditions and biodiversity loss. The former has manifested in form of increased heat, ferocious and persistent wildfires, prolonged droughts in different parts of the world (PWC, 2021). Such unfettered linearity, if unchecked, could result in a further deterioration of natural ecosystems as well as posing a significant risk to the supply of resources and value chains. Linear economic models also result in production of huge amounts of waste. Recent estimates show that only 8.6% of resource usage is circular, meaning that over 90% of resources are not in a closed loop (PwC, 2021). This has led to the calls for models that will help to promote the decoupling of economic growth from the consumption of virgin resources (Esposito et al., 2018).

Consumer products, in recent years, have been designed for quick replacement cycles. This is particularly common with consumer electrical and electronic products such as laptops, smartphones and tablets. A study by the European Environment Bureau (2019) estimated that a savings of over 4 million tonnes of CO_2 emissions would be made by extending the lifetime of consumer electronics by a year. These products are designed to be easily ‘disposable’, putting further strain on primary raw materials used in their manufacture. In addition, there is a growing stock of hibernating devices with a significant reuse and resource value, especially small consumer electronics (Ongondo et al., 2015; Wilkinson & Williams, 2019; Shittu et al 2021).

1.1 Circular Economy and sustainability

The subject of sustainability has been of global interest since the landmark Brundtland 1987 report (Hajian & Kashani, 2021). While a significant number of sustainability models promote doing more using fewer resources, the CE goes further by being restorative and regenerative by design (Esposito et al., 2018). The discourse on CE continues to gain more traction amongst businesses, policymakers and academia. There are moves being made globally to transition from a linear economy model to that which prioritises closed production and consumption systems (Figure 1.1) (Korhonen et al., 2018).

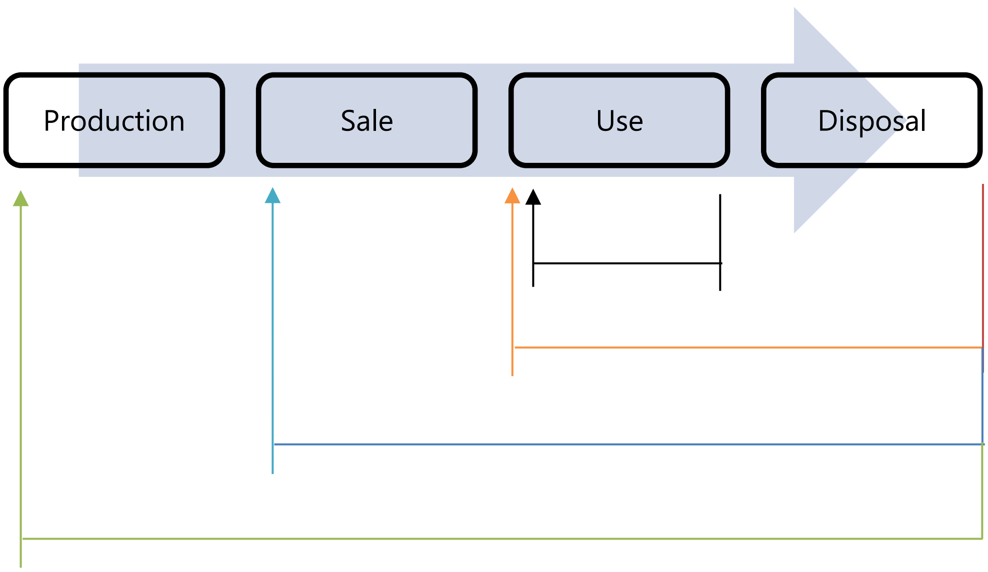

Figure 1. The Circular Economy. Thick arrow indicates the linear economy; coloured arrows indicate circular economy routes; green arrow is recycling; blue arrow indicates product refurbishment/remanufacture; orange arrow indicates product reuse and black arrow indicates extended product usage and/or dematerialization.

The CE has been characterized as having a technical and a biological cycle (Bocken et al., 2017). Both cycles involve the flow of materials and/or products in a loop; biological cycles involve materials from biological sources (Hagman et al., 2019) whereas synthetic materials intended to be used multiple times while maintaining intrinsic value are contained in technical cycles (Bocken et al., 2017). In essence, the CE enhances and promotes the reuse, refurbishment, repair, upgrade of materials and products as well as utilization of energy derived throughout a product/material value chain (Korhonen et al., 2018). Application of the CE, therefore, aims to slow, close and regenerate resource cycles thereby minimizing extraction of virgin materials and production of waste (Kanda et al., 2021; PwC, 2021). A modern definition of the CE is that it is an alternative to a traditional linear economy in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life.

1.2 The E-waste challenge

Rapid advances in technology have resulted in a proliferation of electrical and electronic equipment. Consumerism has contributed to the high levels of turnover of devices with a consequent generation of huge amounts of waste electrical and electronic equipment; global estimates show 54 million tonnes was generated in 2019 (Forti et al., 2020). Before 1990, discarded electrical and electronic equipment (EEE or e-product) was generally comingled with general waste. In reality, electronic waste (e-waste) is chemically and physically distinct from other forms of municipal or industrial waste as it contains both valuable and hazardous materials that require special handling and recycling methods to avoid environmental contamination and detrimental effects on human health. Recycling can readily recover reusable components and selected base materials, especially plastics and metals like copper (Cu), although it is much more challenging and not currently technically feasible to recover many precious and rare earth metals. However, factors such as a lack of infrastructure, prohibitive labour costs, and environmental regulations has led to a movement of e-waste from developed countries to poorer countries, where it may be recycled using primitive techniques with little or no regard for worker safety (Osibanjo & Nnorom, 2007; Ongondo et al., 2011, Balde et al., 2017; Forti et al., 2020). This presents a significant problem as less than 20% is formally collected and processed via formal channels (Balde et al., 2017; Forti et al., 2020). This evident lack of circularity has resulted in loss of materials as well as resource inefficiency (Pierron et al., 2017; Shittu et al., 2021). Several studies on the subject (e.g. Ongondo et al., 2015; Balde et al., 2017; Pierron et al., 2017; Wilkinson & Williams, 2019; Forti et al., 2020; Shittu et al., 2021) conclude that a shift from linearity is required to divert and recover WEEE, which possess inherent material value, destined for landfill. The studies suggest that relevant interventions will be required to tackle the E-waste challenge.

1.3 Project aim and objectives

A major question often asked in the discourse on CE centres on its framing to encourage its inclusion and incorporation. This will involve a gradual but seismic change in current economic models across entire value chains. While CE concepts and approaches are well-known, there is a gap in knowledge of pragmatic procedures towards its implementation; this is particularly true for the electronics industry. The aim of this study is to address some of these gaps. The study was carried out in conjunction with Arm, an electronics design company best known for the design of microprocessors used in mobile phones, computers and smart TVs. With over 200 billion Arm chips in different electronic devices (Arm, 2021), it holds a market dominance in the electronics industry.

This piece of work forms the first phase of a wider study that aims to provide an overview of the circular economic drivers, opportunities, technologies (especially chiplets), manufacturing techniques, licencing, product/open industry standards and likely future standards for Arm Electronics and its up- and down-stream business partners. The first phase aims to identify circular opportunities in the electronics sector and will involve a literature review of both academic and grey literature and an accompanying SWOT analysis, with a focus on electronic components and the boards/packages (whole sub-systems, parts, materials) that make up electronic systems. The study outline is illustrated in Figure 2.

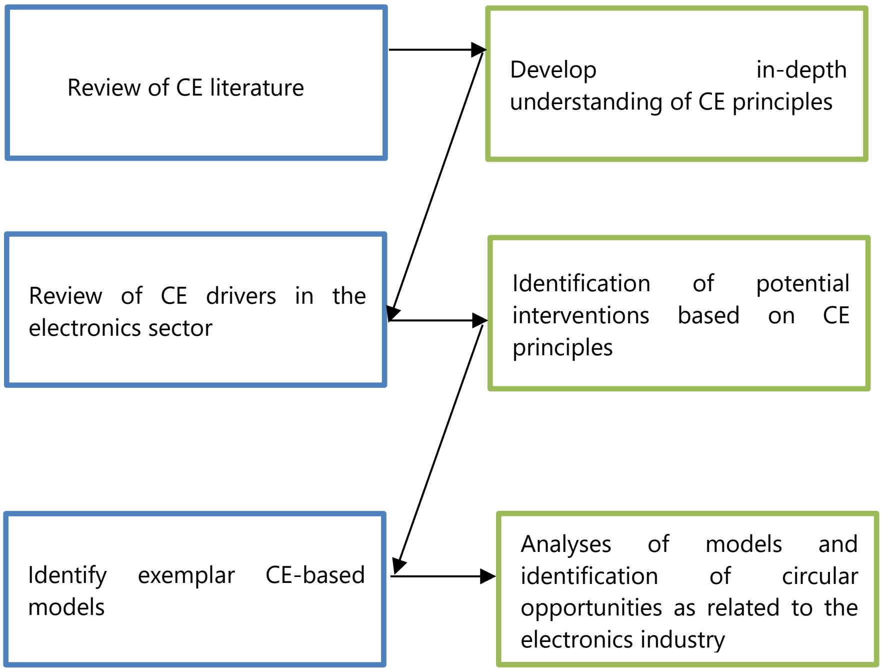

Figure 2. Project workplan. Blue boxes indicate steps; green boxes indicate outcomes.

2. OPPORTUNITIES FOR CIRCULARITY IN THE ELECTRONICS SECTOR

2.1 Circular Economy Principles and Circular Business Models (CBM)

Pathways exist to exit from the prevailing take-make-dispose linear model, to one based on the principles of a CE. A circular economy is an approach that involves gradually detangling economic activity from over-exploitation of finite resources while aiming to eliminate waste and, rather than just reducing negative impacts, concentrates on regenerating economic, human and natural capital.

The pathway towards circularity is broadly based on 3 principles:

- *Design out waste and pollution*: A circular economy reveals and designs out the negative externalities that cause damage to human health and natural systems. These costs include: the release of greenhouse gases and hazardous substances; the pollution of air, land and water; and structural waste, such as underutilised buildings and cars.
- *Keep products in use for longer*: A circular economy favours activities that preserve value in the form of energy, labour and materials. This means designing for durability, reuse, remanufacturing and recycling to keep products, components and materials circulating in the economy.
- *Regenerate natural systems*: A circular economy avoids the use of non-renewable resources where possible and preserves or enhances renewable ones, for example by returning valuable nutrients to the soil to support natural regeneration.

The application of these principles in the design, manufacture and usage of electronic products requires innovation in areas such as design, business models and reverse logistics. This is especially critical in the upstream phase i.e. the design of products is critical to enabling the economic reuse of products, as well as their components and materials. However, this will only go so far if product users continue to landfill their products after the first use or simply store them in a closet in perpetuity, the impact of better design is limited. Therefore, it is essential to incorporate and adopt downstream interventions that will involve adopting new business models and deploying effective reverse cycles to achieve greater product circularity.

A Circular Business Model (CBM) is one that incorporates the CE principles. According to Geissdoerfer et al. (2020), a circular business model can be defined as a model that aims to cycle, extend, intensify and/or dematerialize material and energy loops for the purpose of reducing the input of resources and leakage of waste/emissions. The definition includes four key components that are important strategies for CBMs: *cycle, extend, intensify and dematerialise* (See Figure 3) The *Cycle* component of a circular business model involves the recycling of materials and energy within a system and this can be achieved via reuse, remanufacturing, repair/refurbishing and recycling; *Extend* component entails the design for longevity ensuring that the usage phase of a product is extended. This is closely linked with the *Intensify* component of a CBM which involves the identification and incorporation of protocols or ancillary services that ensure the intensification of a product's usage period. The 4th component of a CBM is *Dematerialise* which involves the substitution/servitization of physical hardware through provision of software and services.

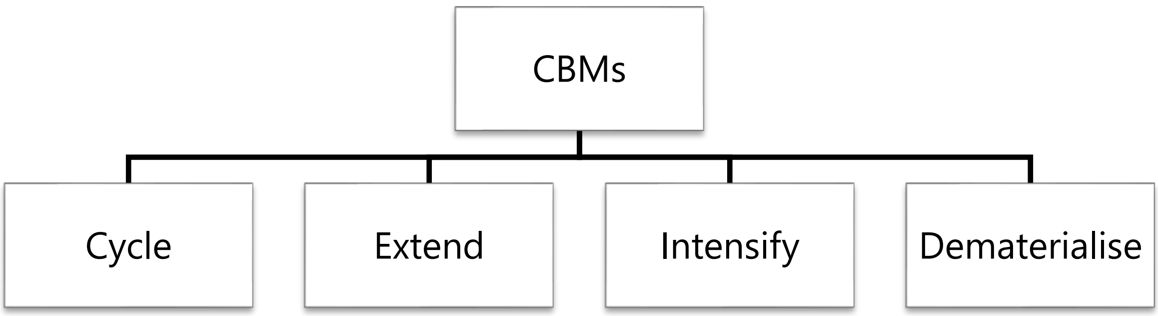

Figure 3. Strategies of a Circular Business Model (adapted from Geissdoerfer et al., 2020).

A shift from a linear to a circular business model will require innovative approaches which can be described as Circular Business Model Innovation (Geissdoerfer et al., 2020); this can be described as the conceptualisation and delivery of circular business models. This, as highlighted in Table 1 could comprise the creation of circular start-ups, diversification into circular business models, acquisition of circular business models or the transformation of a business model into a circular one.

Table 1. Types of Circular Business Model (CBM) Innovation (adapted from Geissdoerfer et al., 2020).

Circular Business Model Innovation	Definition
CBM Transformation	Current business model transformed to one that can be described as circular
CBM Diversification	Addition of a CBM alongside current business model
Circular Start-up	Creation of a new CBM
CBM Acquisition	Identification and acquisition of an existing CBM that is then integrated into organisation

2.2 Towards circularity in the electronics sector

The ideal scenario for circularity of electronics is for products to be in use for extended periods, having multiple usage cycles by being reused after refurbishment and then valuable constituents are used for remanufacturing and recycled. End-of-life management of electronics after their use is a crucial part of a circular economy though are equally crucial. An understanding of these processes is essential to plot the path towards circularity. However, the transition to a circular economy requires holistic planning. According to Leipold et al. (2021), this requires answering a number of policy-related questions including the following:

- How can policies be designed and integrated to increase material resource efficiency at every stage of the life cycle of electronic products and services?
- How can a better understanding of the relationship between the formal and informal industrial and service sectors be leveraged to generate a just transition to a circular economy?
- What are suitable indicators to measure progress towards circularity and to assess the sustainability of the emerging circular society?
- How to allocate social, environmental and economic costs in circular supply chains from extraction through design, manufacture, retail, use and disposal to recycling?
- How can life-cycle oriented sustainability assessment be translated into policy in a circular economy context, given that no supply chain is under the control of a single government or a single sector?

2.2.1 Circular Economy Drivers: Material Focus

Metals, minerals and natural materials have been part of our daily lives for millennia. These materials are critical to the functioning of an array of anthropogenic ecosystems including the electronics sector. Critical raw materials are essential to the functioning and integrity of a wide range of industrial ecosystems. Products of modern technology from medical to recreational are produced using an array of natural raw materials and resources.

It is generally agreed that the breakthrough in the electronics industry was brought about by the invention of the transistor in 1947 (Munchen et al., 2019). This was followed by the invention and evolution of integrated circuits (ICs), and by the 1980s, these had become miniaturised and inexpensive thereby stimulating their use in various consumer products. However, their production and usage are linked with significant environmental impacts. The consumption of resources for anthropogenic activities is exerting a huge amount of pressure on the planet some of these are highlighted in Table 2.

Table 2. Select priority materials for electronics manufacture and associated environmental/social issues associated with mining.

Material	**Primary use**	**Recycling Rate**	**Major Producers**	**Environmental/Social issues**
Cobalt	Li-ion battery, chip fabrication	**Very high**	Democratic Republic of Congo	Artisanal mining involving child labour; exposure to toxic mining dust; high CO_2 emissions
Copper	PCBs, Interconnects, on-chip wiring	**Very high**	Chile; China	Air and water contamination; artisanal mining and the associated health hazards
Gallium	Semiconductors; renewable energy tech.	**Very low**	China	Toxic spillages
Gold	Connectors; integrated circuits	**High**	China; Australia; Ghana	Informal mining often involving child labour; widespread water and soil contamination

Material	Primary use	Recycling Rate	Major Producers	Environmental/Social issues
REEs e.g. yttrium, neodymium	Speakers; Green tech.	Very low	China	Farmland contamination; air pollution

The unique physical, chemical, magnetic, luminescent properties have made rare-earth elements crucial for many technological advances, such as greater efficiency, miniaturization, speed, durability, and thermal stability. In recent years, their demand is particularly on rise in energy-efficient gadgets, which are faster, lighter, smaller, and more efficient. This has also led to concerns with supply and demand of these compounds, in recent years. For instance, a number of rare-earth metals and platinum group metals, are listed as critical raw materials (CRM) by a number of countries and regions including the USA, EU, Japan, and China. The majority of these metals are usually produced as by-products of basic metals with predictions of potential scarcity of reserves in the near future (Munchen et al., 2019).

2.2.2 Circular Strategies Framework for electronics

The route towards circularity requires carefully planned strategies that have to consider a product's entire lifecycle. This Circular Strategies Framework (Table 3) outlines the strategies to attain circularity for consumer products including electronics. It proposes a closed-loop implementation of design and manufacture of consumer products with the aim of keeping products, components and materials in use for longer.

Table 3. Circular Strategies Framework highlighting features a product must possess to achieve circularity (adapted from Meloni, 2020).

Strategy	Objective	Remarks
Design for durability	Extended usage by user with minimal intervention	Build quality that ensures resistance to wear and tear; robustness of components
Design for repair and maintenance	User-repairability with access to spares; cost-effective maintenance by technician	Time- and cost-effective replacement of components; access to components needed to maintain product performance
Design for upgradability	Adaptability of function to match requirements of a new user	Easily identifiable components; easy access to components
Design for refurbishment /remanufacturing	Restoration of product to original working condition	Easily identifiable and accessible reusable components; components with durability

Electronic product design is a key aspect towards achieving circularity and a product requires features that are necessary to make this happen (Meloni, 2020). These are choices of materials, product recyclability and software compatibility. The choice of materials requires the consideration of factors including fitness for multiple usage cycles as well as reduction of toxic substances (e.g. brominated flame retardants). The inclusion and increased percentage of recycled materials is desirable as it reduces the usage of virgin materials.

2.3 Exemplar Circular Economy-based models/projects

The transition towards circularity, including for the electronics industry, will require a system that takes advantage of three critical drivers: resource availability/constraints, technological development and socioeconomic opportunities. Using these key drivers, the implementation of circular economy principles can be actualized via three fundamental avenues:

- **Product design for reuse, repair, remanufacture and recycling**

This encompasses designing products with circularity strategies (as highlighted in Table 2) that allows for the retention of components and materials for extended periods. The choice of materials (responsibly sourced, recyclable, recycled) is also fundamental to circularity. Such design designs are essential as it allows for the possibility to retain products in extended use, with the potential of product circulation between different 'user types' including cutting-edge and function-focused users (Meloni, 2020). The strategy adopted will largely depend on business model and the device being manufactured. Electrolux and Fairphone are notable examples that have adopted this model by using product modularity to simplify their products enabling easy repair, reuse and refurbishment.

- **Enhancement of ancillary services including circular supply chain, reverse logistics, parts recovery and recycling**

A product design strategy is essential to achieving circularity as are other activities such as reverse logistics, repairs, remanufacturing, parts harvesting, and recycling which are crucial in achieving circularity in the entire lifecycle of a product. A circular business strategy for electronics would push for and favour the utilization of renewable and recyclable input materials over linear ones (Esposito et al., 2018).

- **Enabling favourable environment for circularity**

Prevailing conditions that enable circularity play an important role in the transition to a circular economy and can act as enablers or barriers towards circularity. Such conditions include business models, policy and user perception.

2.3.1 Product modularity

The attainment of high product repairability and reusability is inherently linked with its ability to be easily disassembled. Product modularity has the potential to support circularity in the use of resources by supporting product longevity, durability, repairability and upgradeability and it is based on a product life-extension business model. The Circular Economy Framework (Table 2.2) provides some guidance on some areas that can be focused on by product designers in the designing of circular products; such design choices will also be influenced by other factors such as technological innovation, software and hardware requirements and integration of components.

A number of manufacturers have adopted this model including Fairphone, a mobile phone manufacturer. Their devices are known to be designed for easy disassembly, allowing users to make repairs or upgrades with little or no specialist knowledge. This is supported by easy access to spare parts and an online manual to guide parts replacement and upgrade. The company aims to be e-waste-neutral by 2023 by taking back and recycling all products produced via supporting local and international e-waste takeback and recycling programs. The modularity design of their products makes it easier to attain such targets. Electrolux, which produces consumer electronics such as vacuum cleaners, has also adopted this model by using modular design as well as using sustainable materials that are responsibly sourced.

2.3.2 Unzippable electronics

The reusability and recyclability of electronic assemblies/printed circuit boards (PCBs) is largely dependent on the recyclability of the substrate materials; these are mostly manufactured using non-recyclable materials (Hunt et al., 2015). The use of alternative materials with higher recyclability enhances the prospect of recovering components from such assemblies. There have been some studies carried out on the potential for non-destructive recovery of electronic components from printed circuit boards (PCBs) for reuse. An example of this was carried out involving the use of thermoplastic substrates and special bonding agents for PCB assembly (Hunt et al., 2015). The assembly is designed to allow for easy disassembly of components using hot water to dissolve adhesives for the recovery of components on the PCB. This approach differs from the forceful and often destructive separation techniques used to recover materials from PCBs and allows for components reuse. Such ability would be particularly useful for wearable technology which is a rapidly-emerging category of consumer electronics especially in the fashion sector (Gurova et al., 2020).

2.3.3 Reuse network/ecosystem

A reuse ecosystem is one that allows for the multiple use and cascading of the same materials and resources, including waste, thereby reducing the dependence on extraction of virgin materials and new manufacturing. Such an ecosystem would involve a circular movement of materials and/or whole products whereby the by-products of some would constitute the raw materials for others. This ensures there is minimal waste produced with products built to last and parts/components from them can be reused to create new products or refurbish older ones. This model has been piloted in the past in the ICT sector whereby pre-owned ICT equipment are prepared for reuse using reusable components to repair and refurbish while maintaining a closed loop (Dietrich et al., 2014; Esposito et al., 2018). The model has been demonstrated successfully by Re-Tek which provides logistics and end-of-life solutions for I.T equipment. It recovers business I.T. equipment for decommissioning, repairs and refurbishment before redistributing via sales or donations. The devices recovered are mostly handheld electronics, laptops and monitors. Their operations illustrate a scenario whereby electronics cascade from high-end to lower-end applications thereby extending product and material use before they eventually get recycled. Recolight is another example of a business that has adopted this model by prioritizing reuse of light fittings including LED and fluorescent fittings.

2.3.4 Product as a Service (PaaS) model

Product-as-a-Service (PaaS) is a business model that allows customers to purchase a desired output or service rather than the product or equipment that delivers that service. Rather than selling a product, a company may adopt Product-as-a-Service (PaaS) model to create higher quality devices and more dependable revenue streams. This model is becoming widely adopted for consumer products such as smartphones, light bulbs, where a customer 'subscribes' to a plan that includes installation, maintenance and service, upgrades meaning that a consumer does not own a product. Such consumer only pays for the use of the product as opposed to outright ownership. The PaaS model can take several forms (Esposito et al., 2018):

- Pay for use—customers buy output rather than a product and pay based on use (e.g., miles driven, hours used, pages printed, or data transferred). Philips employs this model in providing lighting solutions (see below).
- Leasing—customers buy contractual rights to exclusively use a product over a longer period of time. An example of this is the LEASE-TEK model by Re-Tek.
- Rental—customers buy the rights to use a product for a short period of time. Turo, a mobility solutions firm, adopts this model.
- Performance agreement—customers buy a predefined service and quality level, and companies commit to guaranteeing a specific result.

This is the idea behind the 'Pay-per-lux' model introduced by the consumer products company Philips. The company's 'product-as-a-service' business model involves the sale of lighting as a service, providing a tailor-made service based on specific spatial requirements. The company retains ownership of the lighting equipment supplied and provides the necessary maintenance, repairs and recovery of products after use.

3. FUTURE PERESPECTIVES AND CHALLENGES

Although vast amounts of natural resources such as metals, energy and water are required for their production of electronic devices, millions of tonnes of electronic products go to waste every year with significant volumes often treated in substandard conditions. As a result, people and the environment are exposed to harmful substances from both production and after-use processing. Keeping electronic products, components, and materials in use for longer represents a significant economic opportunity and has the potential to reduce the negative environmental and health impacts of this linear electronics system. A shift from linearity to circularity helps with addressing some of these issues. However, there are challenges to be addressed and overcome in implementing the transition. Tables 4 and 5 outline some strengths and weaknesses of two circular models highlighted previously. Product modularity offers an innovative approach for circular design. However, its use is not universally practicable.

Table 4. SWOT (Strengths, Weaknesses, Opportunities, Threats) Analysis: Product Modularity.

Strengths	**Weakness**
High repairability index achievable i.e. ease of repair and availability of spare parts Materials sourced and kept within closed resource loop Waste minimisation	Not universally practicable
Opportunities	**Threats**
Right to Repair regulation Changing attitudes towards sustainability	Components compatibility Production costs Quality of used components Industry standards

Table 5. SWOT (Strengths, Weaknesses, Opportunities, Threats) Analysis: Reuse Ecosystem.

Strengths	Weakness
Closed-loop system allows for reuse of products and by-products Potentially scalable (micro to macro level) Transferability Allows for product servitization	Subject to regulatory changes
Opportunities	**Threats**
Improved product testing Right to Repair regulation	Logistics Regulatory obstacles Industry standards Consumer attitude to used/pre-owned devices

In manufacturing electronics, there is a need for consideration of material efficiency from the economic and marketing viewpoints. Currently, there are few incentives or pressures, outside environmental concerns, to incorporate measures such recyclability and design for reuse of electronic products largely due to their technological complexity. More often than not, only metals or materials of economic value such as copper, gold, silver, palladium, rare-earth elements, or fiberglass, are being recycled from e-waste (Baldé et al. 2017; Forti et al. 2020).

The complexity of electronics has been on the rise since the invention of the transistor and will continue to do so as hybrid materials as well as advanced manufacturing technologies are used for more sophisticated electronics. Hence, there is a critical necessity for high-level multidisciplinary competencies and the development of new solutions, which can be crucial factors in renewing the global manufacturing industry. Electronics manufacture in the current industrial system is very complex, and most of the material cycles are multifaceted and interconnected in terms of material sourcing. This potentially makes the reuse of by-products or metals from recycling to develop new products very complicated due to the already pre-existing and well-established linear-economy logistics. The change needs to be implemented right at the design and material-development stage to facilitate material circularity. The aim is to include life-cycle thinking of complex materials in the design and development phases and integrate recycling and sustainability perspectives into decision making at strategic, management, and production levels.

Supply of microprocessor chips was severely impacted by the COVID-19 pandemic, disrupting supply chains and resulted in global microchip shortage. This has had a profound effect on the manufacture of new consumer electronics and automobiles. Despite this, the demand for chips continues to rise. The manufacture of microprocessors has huge environmental impacts; the power consumption of a factory with capacity to manufacture 50,000 silicon platforms monthly is approximately 1 Terawatt hours per year. Despite this, a typical microprocessor is generally underused over its expected lifetime. Therefore, it is imperative that the reuse of microprocessors is considered. This comes with challenges, both from a technical and economic point of view. On the technical side, it has been shown that measures to facilitate reusability of chips are largely dependent on the microprocessor's utilisation and power requirements. This means that microprocessors with lower specifications and computational requirements have higher reusability in comparison to high-end, top-of-the-line versions. From an economic point of view, the reuse of microchips will likely reduce the profitability of chip manufacturers though this may be offset by actively being involved in the recovery and resale of the processors.

The attainment of circular and sustainable electronics will require innovative techniques and models. The lack or shortage of natural resources and raw materials needed in the production phase can become a strong driver for promoting a circular economy. It is well known that the linear economy model's is unsustainable and it is estimated that the enormous demand for natural resources will result in a shortage of 8 billion tons of raw material supply (Esposito et al., 2018). The first step of promoting a circular economy is extending the product's life cycle by using durable materials and making long-life products that can be repaired and reused at the end of their life cycles. In some cases, a product or component can be designed to be used for another purpose without chemical or mechanical modifications. This reduces or eliminates the need for further processing of the product which would require extra energy or new raw materials (Pajunen & Holuszko., 2021). It is also essential to make sure that non-hazardous substances are used in composite materials as this could potentially hinder recirculation and cause the materials to become and/or treated as hazardous waste. Waste and losses can be reduced in many ways and will require the participation of all relevant stakeholders in the product's life cycle.

4. CONCLUSIONS AND FUTURE WORK

This study has focused on the circular economy principles and the role of circularity thinking when making electronic devices that are circular. The transition towards a non-carbon intensive circular economy and sustainability in small electronics is possible due to the opportunities lying in the recovery of valuable components and the desire to build resilient manufacturing industries that will promote eco-design and the principles of circular economy.

Sustainability is all about living within the planet's natural boundaries and physical means, maintaining the planet's vitality and keeping the extracted resources and products made from these natural resources in circular use as long as possible. Adopting the circular economy model requires the electronics industry to initiate and develop disruptive technology and business concepts that focus on product longevity, renewability, reuse, repair, upgrade, refurbishment, servitization, capacity sharing, and a shift towards dematerialisation. Although there are estimated economic and environmental benefits to be found in transitioning to a circular economy, the challenges to both businesses and policymakers are diverse; they must consider how to deal with the stakeholders who lose out in the circular economy and must create organisational designs that facilitate adoption of the circular model.

The next phase of this work will involve an in-depth assessment of material and economic costs of electronics manufacture, particularly consumer electronics and their wider impact on the environment. The outcome of the research is expected to have a wide policy impact in the transition to a circular economy for electronics and the electronics sector.

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