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I am a PhD Scholar in the Department of Design, IIT Guwahati. My research focusses on creating a design support for assessing and designing products for environmentally sustainable end-of-life performance. I have done my Master's degree in Microelectronics and VLSI Design and a Bachelor's degree in Electronics and Communication Engineering from NIT Silchar. In the past, I served as a Project Associate at Tezpur University's Technology Enabling Centre, focusing on facilitating the development, deployment, and diffusion of technology.

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Sustainable Product Design and End-of-Life Management

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5.1. Motivation

The continuous development of technology has changed the way we live, introducing a plethora of technological goods into our everyday life. From smart gadgets to alternative energy sources, electronics are everywhere. However, the boom in technological innovation poses considerable hurdles, notably in terms of sustainability and end-of-life (EoL) management.

As electronics advance at an unprecedented rate, adding complicated components and cutting-edge capabilities, our current mechanisms for managing their end-of-life stages struggle to keep up. The rising misalignment between the complexity of electronic devices and the capability of current EoL management systems necessitates a paradigm shift. As researcher, I seek to bridge this gap, create creative techniques, and imagine a future in which sustainability is seamlessly incorporated throughout the whole lifespan of electrical and electronics devices. The complexity of these devices require a more effective and proactive approach to their design, taking into account the end-of-life consequences from the beginning.

Furthermore, as worldwide awareness of environmental concerns rises, legislative bodies are responding. Directives from the European

Union, for example, emphasise responsible disposal of electronic and electrical equipment, highlighting the need of sustainable product design and end-of-life management.

5.2. Environmental Assessment in Product Design

The process of designing or developing a product is collaborative and appealing to a wide range of competencies. It has an influence on all of a company's actions that involve introducing a new product to the market. It often involves the design, marketing, and production divisions in the organisation. Pahl and Beitz outline the design process as a sequence of four primary phases: requirement clarification, conceptual design, embodiment design, and detail design. This progression aims to transition from defining functional needs to realizing a tangible physical form (Rio et al., n.d.).

Product lifespans in industrialised cultures have significantly fallen over the last decade. This has resulted in greater material consumption and waste. As a result, the environmental consequences of material manufacturing and processing are increasingly becoming critical. Material efficiency, or developing goods with less materials, is addressed in most design projects since it reduces costs and is considered good business practice. However, most design processes do not systematically address product life extension (via prolonged product life, refurbishment, and remanufacturing) or product recycling(Bakker et al., 2014).

Assessing sustainable product design involves a multi-criteria decision-making (MCDM) challenge encompassing customer needs, enterprise constraints, and available resources. Experts must consider a range of factors and constraints in the early stages of product design to make optimal decisions. The solution methods can be categorized into two main classes: 1) synthetic assessment approaches, such as weighted sum, analytical hierarchy process (AHP), technique for order performance by similarity to ideal solution (TOPSIS), VlseKriterijumsko KOmpromisno Rangiranje (VIKOR), AHP and evidential reasoning (ER), AHP and TOPSIS, and fuzzy synthetic evaluation, and 2) approaches based on life cycle assessment (LCA) (Tian et al., 2016).

Environmental concern has led to the emergence of life cycle design (LCD) in environmental engineering. LCD symbolises a comprehensive design approach that spans the full product lifespan, or "cradle-to-grave". The LCD relies on proven approaches such as life cycle assessment (LCA) and life cycle cost (LCC) to quantify performance in terms of both the environment and economics(Kiling et al., 2021). The goal of LCA is to reduce the environmental impact of product manufacturing, usage, and disposal(S. G. Lee et al., 2001). LCA has been frequently utilised in product design to quantify the environmental implications of products throughout their lifespan. However, LCA is sometimes inefficient in early design phase owing to a lack of data, the intensity of labour and time, and the urgency to make quick decisions. Thus, it needs to be simplified to drive rapid judgements by product developers, especially those who are not knowledgeable in LCA(Kiling et al., 2021). LCA also necessitates thorough product development data, which may not be available during the first conceptual stage of product design. To address this issue, eco-design principles and standards are developed to assist designers in improving the environmental consequences of their goods through better early design decisions(Chiu & Chu, 2012). Product environmental information is vital to the success of sustainable product development. Good product information is needed for successful implementation to enhance the product's environmental performance(H. M. Lee et al., 2014).

LCC assesses the overall cost incurred during the product's lifespan. An LCC analysis can help product developers understand the link between costs and design parameters by identifying cost factors. Nonetheless, its analysis in Product design have traditionally been carried out in fixed scenarios, assuming a static product lifespan. Accurately estimating the lifespan of a product during the early stages of design is challenging. This static approach may lead to discrepancies between LCC-driven and actual costs, resulting in inaccurate cost estimations. Therefore, it is imperative to ensure accurate LCC calculations during the design phase to guide product developers in specifying cost distributions across the product lifecycle. It's worth noting that Life Cycle Assessment (LCA) faces a similar challenge in dealing with dynamic product lifespans(Kiling et al., 2021).

5.3. Circular Economy and Challenges

The circular economy (CE) paradigm proposes for the transition of our economies from linear to circular models, in which waste and recycled materials are transformed into resources. It has intentions to halt or decrease human-caused environmental harm to our planet, as well as to preserve its future habitability and the wellbeing of people(Reuter et al., 2019). The circular approach stands in opposition to the conventional linear business model, which involves the production, consumption, and disposal of goods. Unlike the linear model, circular business models prioritize deriving profits from the continuous flow of materials and products over time rather than simply selling artifacts. This shift allows for economically sustainable practices by

promoting the ongoing reuse of products and materials, with an emphasis on utilizing renewable resources when feasible. It was observed that Circular Economy (CE) is frequently associated with sustainability. The significant connection, particularly with environmental sustainability, underscores that CE, when applying its principles, provides practical solutions to alleviate the human impact on natural ecosystems. (Bocken et al., 2016).

One of the greatest obstacles to attaining a 'closed' loop of materials from consumer goods, especially electrical and electronic products, is a lack of effective collection and recycling infrastructure. Furthermore, the complex architecture of modern items complicates end-of-life (EoL) treatment procedures. Recycling technologies are surpassed by evolving complex and elementally varied products. This is making resource recovery increasingly challenging (Parajuly et al., 2016).

Scholars' engagement with Circular Economy (CE) is intimately tied to sustainability, with a predominant emphasis on environmental aspects often combined with economic evaluations. However, the relationship between CE and sustainable development remains a subject of lively debate among academics, lacking clear and defined boundaries. Some argue that CE transcends sustainable development, suggesting that the latter is constrained by linear thinking strategies, and the circular approach could provide a remedy for sustainability shortcomings. Conversely, others position CE within the broader sustainability movement, considering it a tool to implement sustainable development principles effectively. While sustainability seeks to integrate environmental, economic, and social dimensions, CE predominantly focuses on environmental concerns, presenting a targeted approach to addressing them. One possible explanation for

this focus is that CE is situated in an industrial context, typically not addressing social issues. When connecting Circular Economy (CE) to the broader concept of sustainability, there is a tendency to overlook the social consequences of a circular system. Nevertheless, CE demonstrates a positive correlation, particularly with intergenerational considerations, as a decrease in natural resource consumption creates more prospects for future generations. Hence, there is a growing need to enhance the integration of the social aspects of the CE framework (Merli et al., 2018).

5.4. Design for End-of-Life (DfEoL)

At the conclusion of its functional lifespan, a product has various end-of-life options, including reuse, remanufacturing, primary or secondary recycling, incineration, or disposal in a landfill. The decision hinges on whether the goal is to minimize environmental impact or address resource deficits (or maximize surpluses) (S. G. Lee et al., 2001). Given the present issues of environmental waste effect and landfill saturation, selecting an appropriate end-of-life (EOL) destination for discarded items is becoming more critical for most produced products. To solve these concerns, a product's design must be optimised with the goal of implementing an ecologically sustainable end-of-life scenario that respects economic and statutory restrictions (Remery et al., 2012). Thus, for design engineers, it is very important to proactively plan for product retirement(S. G. Lee et al., 2001). It is well known that combining product design with suitable end-of-life (EoL) processing may significantly increase resource recovery from electronic devices (Parajuly et al., 2016).

Design for End-of-Life (DfEoL) is a component of a novel design approach known as 'design for environment' (DfE). Its objective is to

enhance a company's overall environmental performance by minimizing the impact generated at each stage of the product life cycle, while maintaining key aspects like quality, functionality, and cost (Parajuly et al., 2016). It aims to improve the environmental performance of goods throughout their life cycles by systematically incorporating environmental components of the EoL stage into product design. In simple terms, it is to create a product with 'an end in mind'. Since the 1990s, there have been research initiatives in the domain of DfEoL spanning from design for disassembly, recovery timeframes, EoL methods for diverse goods, and design for recycling methodologies. However, no one incorporates all element of EoL (H. M. Lee et al., 2014)

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