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RESEARCH ON DESIGN IN THE CIRCULAR ECONOMY

Abstract: *Circular design represents a key pillar in the transition towards a sustainable economy. This article examines the current state of research and application of circular design in key industries such as textiles, packaging, electronics, and construction. The main methodologies used—Life Cycle Assessment (LCA), ecodesign, biomimicry, and the analysis of renewable materials—are discussed alongside concrete examples and relevant European initiatives. Current challenges and innovation opportunities are highlighted, emphasizing the role of design as a strategic tool for waste reduction, increased product durability, and achieving climate neutrality.*

Key words: *circular economy, ecodesign, sustainability, climate neutrality, reuse, renewable materials, durability, modular design.*

1. INTRODUCTION

In the context of natural resource depletion, increasing waste volumes, and accelerating climate change, circular design emerges as a fundamental strategic tool in the reconstruction of current economic systems. More than an aesthetic or functional approach, circular design proposes a paradigm shift in how products are conceived: from linear use to regenerative use, extending material life cycles and reducing environmental impact. By integrating circular principles from the design phase, innovative solutions can be developed that directly contribute to the European Union's objectives on climate neutrality and sustainable economic development.[1] [2]

2. INFORMATION

2.1. The Concept of Circular Design

Circular design is a design model grounded in the principles of the circular economy, aiming to reduce environmental impact and ensure efficient resource use.

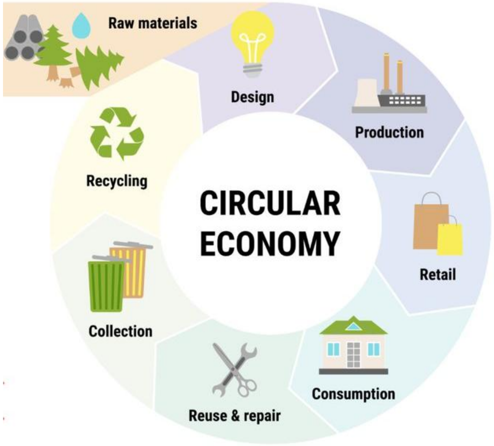

Figure 1 Circular economy[8]

Aesthetic, Functional, and Technical Criteria of Circular Design, Integrated with Ecological and Social Responsibility:

It involves the creation of products and systems in such a way that all components can be:

- reused, by integrating them into a new life cycle without loss of functional value;
- repaired, through easy access to spare parts, modular construction, and durability-focused design;
- refurbished or remanufactured, enabling their reintegration into the economic cycle with minimal intervention on core materials;
- efficiently recycled, by ensuring material separability and eliminating compounds that hinder full recyclability.

This approach eliminates the concept of waste from the design phase and promotes the development of circular material flows within a regenerative economic system.

Circular design merges aesthetic, functional, and technical criteria with ecological and social responsibility, fostering innovation at the intersection of sustainability and competitiveness. [3]

2.1.1. Aesthetic Criteria

These relate to the visual and symbolic perception of the product:

- visual simplicity and clarity of form, which facilitate repairability and disassembly;
- timeless design, avoiding passing trends and encouraging long-term use;
- material transparency, often expressed through the exposure of raw materials to suggest authenticity and sustainability;
- a visual identity aligned with circular values, conveying durability, naturalness, and regeneratively. [4]

2.1.2 Functional Criteria

These refer to the product's usefulness and performance over extended life cycles:

- modularity: the product can be easily disassembled and components replaced individually;
- durability: the product is designed to resist wear, shocks, and changes in usage context over time;

- multifunctionality: the product can adapt to multiple uses, extending its relevance;
- accessibility and ergonomics, ensuring ease of use and maintenance by the end user.

2.1.3 Technical Criteria

These are engineering conditions that ensure performance and circular compatibility:

- selection of recyclable or biodegradable materials, non-hazardous to health or the environment;
- material compatibility: avoiding combinations of materials that are difficult to separate;
- optimization of manufacturing processes to reduce waste and emissions;
- design for disassembly and maintenance, in accordance with recognized technical standards (e.g., ISO 14006 for eco-design). [5]

2.1.4 Ecological and Social Responsibility

These include:

- reduction of environmental footprint across the entire life cycle (production, use, end-of-life);
- supply chain traceability and preference for ethical suppliers
- creation of local value (e.g., through repair, collection, or local recycling services);
- social accessibility: products that are affordable and easy to understand/use across diverse social groups;
- user engagement: design that educates or encourages sustainable behaviour (e.g., returnability, repair incentives, transparent material information). [6]

These criteria are not isolated but interdependent and are applied in an integrated manner throughout the design process to support the transition toward a regenerative economic model.

2.2 Current Research Methodologies

Current research on circular design employs several scientifically validated methodologies that enable the assessment of environmental impact, the integration of sustainability criteria into the design process, and the identification of regenerative solutions. The most important include:

2.2.1 Life Cycle Assessment – LCA

This is a standardized method (ISO 14040/44) for assessing the environmental impact of a product, process, or service throughout its entire life cycle – from raw material extraction to end-of-life.

The steps of this method are: goal and scope definition, life cycle inventory (LCI), impact assessment (LCIA), and interpretation of results.

As applications, can be used: comparison of design alternatives, material selection, packaging optimization, carbon footprint reduction. As relevance, LCA is the analytical foundation for all circular design decisions. [1]

2.2.2 Eco design

Eco design is a design methodology that integrates environmental considerations in the early stages of product development, aiming to minimize the product's life cycle impact.

The principles of the method are: resource efficiency, selection of recyclable/biodegradable materials, design for disassembly and repair.

The regulation is supported by the EU Eco-design Directives applicable to energy-related products (e.g., appliances, IT equipment).

As working tools, the following are used: Ecodesign Checklists, pilot toolkits, eco-efficiency matrices.

As relevance, Eco design is directly applicable in industry to ensure compliance with EU sustainability standards. [1]

2.2.3 Biomimicry Design Thinking

Biomimicry is the practice of emulating nature's designs and processes to solve human challenges, promoting sustainability and innovation. This is a design method inspired by nature, where time-tested biological solutions are emulated to create sustainable innovations, having as stages: observing nature, extracting functional principles, translating them into technical solutions.

Examples can be: self-cleaning surfaces inspired by lotus leaves; load-bearing structures inspired by turtle shells; natural ventilation modeled after termite mounds.

As a relevance, supports the development of innovative, resource-efficient, and ecologically adaptive design solutions. [1]

2.2.4 Renewable Materials Analysis and Closed-Loop Material Cycles

It consists of the evaluation of materials from the perspective of renewability, availability, biodegradability, and their capacity to re-enter biological or technical cycles.

As working tools, the following are used: Material Circularity Indicator (MCI), Circularity Assessment Tools, Granta MI for material selection.

As applications, can be used: selection of bio-based materials, recyclability testing, designing compostable polymers, FSC-certified wood, and regenerated cellulosic fibers.

As relevance, this supports material choices aligned with both biological and technical circularity models. [1]

2.3 Circular Design in Key Industries

The applicability of circular design is expanding across key industries, driven by legislative pressure, shifting consumer expectations, and the urgent need to reduce environmental impact.

Circular design proves most effective in sectors where:

- product lifespan can be extended through repair, reuse, or remanufacturing;
- materials are valuable or difficult to regenerate;
- there is significant environmental impact throughout the value chain;

- production cycles allow interventions at the design stage. [4]

Below are five relevant sectors, each with concrete examples:

2.3.1 Textile Industry

Textile waste is among the most problematic forms of post-industrial and post-consumer waste, with over 5 million tons generated annually in Europe. Most discarded garments are landfilled or incinerated, while only a small fraction is effectively recycled. The main challenge lies in mixed fiber compositions (e.g., polyester-cotton blends), which are difficult to separate and recycle, and in the lack of dedicated collection and sorting infrastructure. Circular design solutions in this sector include the use of monomaterials (e.g., 100% cotton, pure wool), modular design for easy repair (e.g., detachable zippers, accessible seams), and smart labeling to ensure traceability of materials. Brands such as *Patagonia* and *Filippa K* exemplify circular strategies, offering take-back and repair programs, and designing garments for disassembly and closed-loop recycling. [6]

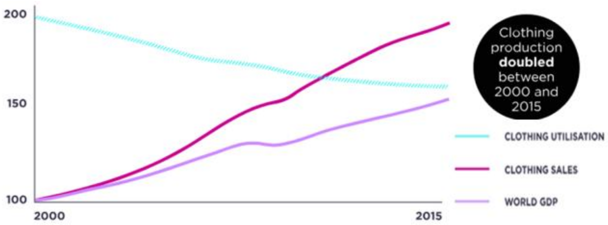

Figure 3 Clothing production [8]

Example of a solution: *Patagonia* is a pioneer in this field, integrating the principle of functional durability into its product design and launching the Worn Wear program, which enables customers to repair or return used garments for reuse or recycling [7]. Additionally, the Swedish brand *Filippa K* offers collections based on biodegradable materials, with fully traceable life cycles and a design philosophy focused on functional minimalism. On the technological front, companies like *Renewcell* are advancing chemical recycling processes for cellulosic fibers, converting worn cotton and viscose clothing into sheets of recycled material—branded as *Circulose*—which are then used in the production of new garments.

2.3.2 Packaging Industry

Plastic waste is ubiquitous and difficult to manage due to the diversity of resin types, contamination, and the non-recyclable nature of many packaging formats. In a circular economy, packaging design must prioritize monomaterials, eliminate plastic-aluminium composites, and avoid opaque colorants. Circular solutions include Deposit Return Schemes (DRS), reusable packaging systems such as *Loop by TerraCycle*, and chemical recycling technologies like pyrolysis or depolymerization. Recycled plastics can be repurposed in road construction, urban furniture, or even the textile industry (e.g., recycled PET yarns used by Adidas or Decathlon). Circular design in this sector also entails a shift from single-use packaging to reusable or refillable systems. [8]

Example of a solution: *Loop by TerraCycle* is a functional example of a reusable packaging system implemented in France, the US, and the UK, where products from brands like Nestlé and Unilever are delivered in durable, returnable containers that are cleaned and refilled. In parallel, companies such as *Ecovative Design* manufacture mycelium-based compostable packaging, already adopted by IKEA and Dell as a replacement for expanded polystyrene. In Nordic countries, PET return systems have achieved collection rates over 90%, driven by recycling-compatible design and economic incentives. [9][10]

2.3.3 Electronics Industry

Electronic waste (e-waste) is the fastest-growing waste stream globally, with over 50 million tonnes generated annually and less than 20% effectively recycled. These devices contain high-value components—such as rare metals (gold, cobalt, tantalum), technical plastics, and hazardous substances (lead, mercury). The core challenge lies in poor disassembly design, excessive miniaturization, and planned obsolescence. Transitioning this sector toward circularity begins with modular design, enabling easy repairs, replaceable parts, and easily dismantled casings.

Example of a solution: *Fairphone*, a Dutch start-up, produces fully modular smartphones designed for easy user repairs, where components can be replaced individually without technical expertise. Similarly, *Framework Laptop* offers a fully repairable, upgradeable laptop, addressing the issue of planned obsolescence directly through its architecture. At the policy level, the European initiative Right to Repair, already implemented in France and supported by the European Commission, mandates that manufacturers provide spare parts and repair information, encouraging design that prioritizes accessibility and transparency.[11][12][13]

Figure 4 Framework Laptop [12]

2.3.4 Construction Industry

The construction sector generates over 30% of the EU's solid waste, making it the largest waste-producing industry in Europe. Construction and demolition waste (CDW) includes materials such as concrete, brick, metal, wood, and glass, largely resulting from renovation, demolition, and infrastructure projects. The main challenge lies in material contamination and the lack of on-site separation. In a circular system, CDW can be valorized through the design of buildings for disassembly, using modular, easily detachable components. Crushed concrete can be reused as aggregate in roads or prefabricated elements. Recovered materials (e.g., doors, beams, facades) can be resold through urban material hubs, such as *Rotor Deconstruction* in Belgium, which collects, cleans, and reintegrates architectural components into new production cycles. [14]

***Example of a solution**:* A firm in the Netherlands designs buildings from salvaged materials (doors, glass, steel) recovered from demolition sites. *The Circular Building* (London, 2016) is a demonstrative project that allows complete disassembly, using screws instead of adhesives or welding. The *Circl Pavilion*, developed by ABN AMRO Bank in Amsterdam, is an emblematic example: every component is detachable, reusable, and digitally documented, resulting in an extremely low carbon footprint. In parallel, the *Rotor Deconstruction* initiative in Belgium salvages materials from old buildings (doors, facades, parquet), refurbishes them, and reintegrates them into new projects, promoting reversible architecture and the reuse of existing resources.[15] [16]

Figure 5 Refactory [17]

2.3.5 Automotive waste

This represents a complex and voluminous flow, originating from end-of-life vehicles as well as from production, repair, and maintenance activities. A typical vehicle contains over 20,000 components, many of which—such as steel, aluminum, glass, rubber, plastics, and textiles—are technically recoverable. The key challenge is to integrate circularity from the design phase, enabling efficient disassembly, component reuse, and material recycling at the end of the product's life.

***Example of a solution**:* In the automotive sector, Renault ReFactory Flins (France) is the first European industrial center dedicated to circular economy in mobility. Built on the site of a former assembly plant, ReFactory comprises four divisions: Re-Trofit (vehicle refurbishment),Re-Cycle (component and battery recycling),Re-Energy (renewable energy generation), and Re-Start (open innovation and upskilling). Its goal is to extend vehicle life cycles and reintegrate materials into production, with a target of 120,000 vehicles refurbished annually by 2030. [17]

2.4 European Regulations on Climate Neutrality

The European Union has adopted a coherent legislative framework to support the transition to a circular economy and the achievement of climate neutrality. Key strategic documents and objectives include:

2.4.1 Circular Economy Action Plan (2020)

Part of the European Green Deal, this is the EU's second comprehensive strategy on the circular economy. It focuses on sustainable product design, extended product lifespans, reparability, and efficient recycling. Priority sectors include textiles, electronics, packaging, batteries, construction, vehicles, and plastics.

The concept of a Digital Product Passport is introduced to enhance traceability and transparency across the supply chain. The Right to Repair for consumers is promoted. [2]

2.4.2 European Green Deal (2019)

It sets the overall goal of achieving climate neutrality by 2050.by 2050. It identifies the circular economy as a central tool for reducing emissions and conserving natural resources. It includes wide-ranging measures across energy, industry, mobility, agriculture, and biodiversity. [2]

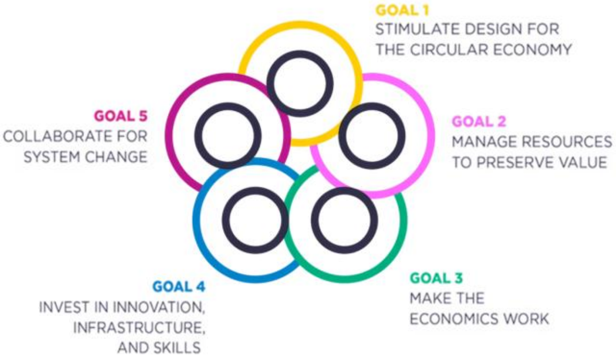

Figure 6 Universal Circular Economy Policy Goals [8]

2.4.3 European Climate Law (Regulation EU 2021/1119)

It legally enshrines the objective of climate neutrality by 2050, establishing as a binding intermediate target: a minimum 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels. [2]

2.4.4 Sustainable Products Regulation (proposed 2022)

It establishes the legal basis for the Eco-design for Sustainable Products Regulation (ESPR), requiring that all products placed on the EU market meet circular design criteria: durability, reparability, recyclability, and efficient use of resources. [2]

2.5 Functional International Solutions

The Netherlands is recognized as a European leader in nationwide circular design implementation. The government's strategy, *"Nederland Circular in 2050"*, aims to achieve a fully circular economy by 2050 through partnerships between authorities, industry, and academic institutions. A flagship project is the Circle Pavilion in Amsterdam—a building designed for disassembly, constructed almost entirely from reclaimed materials, with all components digitally registered for future reuse. Additionally, initiatives such as Blue City in Rotterdam host a community of start-ups developing circular products within an urban innovation ecosystem supported by local policies. [18]

France has embedded circular design into national legislation through the Anti-Waste Law for a Circular Economy (2020), requiring manufacturers to improve product reparability, reduce single-use packaging, and support reuse. A key tool is the Repairability Index, displayed on electronic devices, which mandates transparent, modular design. Concrete applications include the Envie network, which refurbishes old household appliances while providing employment to vulnerable groups. France is also one of the first countries to ban the destruction of unsold clothing, thereby promoting reuse and recycling in the fashion industry. [19]

Japan adopts a rigorous approach to circular design, governed by the Home Appliance Recycling Law, which obliges electronics producers to collect, dismantle, and recycle their own products. Companies like Panasonic and Toshiba design appliances with color-coded parts, standardized connectors, and glue-free assembly to facilitate automated recycling. At the municipal level, Kamikatsu has become a global model for zero-waste practices, achieving over 80% recycling without incineration, through strict source separation into 45 categories and continuous community education. [20]

Sweden promotes circular design through a favorable tax framework for repairs, reducing VAT on repair services to just 12%. This directly encourages the design of maintainable and repairable products. The Ministry of Repair network connects craftspeople, repair centers, and local workshops, fostering a social reuse infrastructure. Meanwhile, IKEA has implemented a buy-back and furniture redesign program in Sweden, where old furniture is repaired, resold, or transformed into new products—aligned with the company's global goal of achieving full circularity by 2030. [21]

2.6 What are PHAs?

PHAs (polyhydroxyalkanoates) are a class of natural polyesters produced through microbiological processes, primarily by bacteria that accumulate these substances under nutrient stress conditions. Unlike conventional petroleum-based plastics, PHAs are fully biodegradable and can be produced from renewable resources such as vegetable oils, sugars, or even organic waste. Their chemical structure provides mechanical properties comparable to polyethylene or polypropylene, making them compatible with various commercial applications. [22]

Within the circular economy, PHAs are increasingly used as a substitute for single-use plastics. PHA-based packaging is bio compostable, even in marine and soil environments, and can be applied to food containers, coffee capsules, bags, films, and flexible packaging. For example, Danimer Scientific has developed PHA materials under the brand name *Nodax*, used by global companies like PepsiCo and Nestlé for compostable packaging solutions.

Another major application is in single-use products such as cutlery, straws, toothbrushes, and cup lids—all designed to be composted after use. These items can enter closed-loop biological cycles, leaving no microplastics or toxic residues, thereby supporting the principles of circular design as defined by the Ellen MacArthur Foundation. [23]

PHAs are also being used in the development of biodegradable 3D printing filaments and in circular textile experiments, contributing to the reduction of the industrial footprint of traditional production. Unlike other bioplastics, such as PLA (polylactic acid), PHAs can degrade completely under natural conditions, giving them a distinct ecological advantage. [22]

Given their ability to be produced from organic waste, their complete biodegradability, and their broad applicability across industries, PHAs offer a practical and scalable example of circular material use, fully aligned with regenerative economy principles and global strategies for plastic pollution reduction.

3. CONCLUSIONS

Circular design stands today as a pivotal discipline in the systemic reconfiguration of economic models toward sustainability. No longer limited to niche experimentation, it is now embedded within broader policy frameworks such as the EU Circular Economy Action Plan and the Green Deal, and is actively applied in industries ranging from textiles and construction to electronics and mobility. By rethinking how products are conceived—from raw material sourcing to end-of-life scenarios—circular design promotes longer lifespans, ease of repair, material separability, and biological or technical reintegration.

Among the most promising innovations supporting this paradigm is the development and integration of PHAs (polyhydroxyalkanoates)—a class of biopolymers produced from renewable or waste-based resources. Unlike petroleum-based plastics, PHAs are fully biodegradable, even in marine environments, and are increasingly used for packaging, consumer goods, and textile applications. Their compatibility with natural degradation processes makes them ideal candidates for biological cycles within the circular economy. Moreover, their production from organic waste streams supports a regenerative model where waste becomes feedstock, reducing pressure on fossil resources and minimizing the ecological footprint of materials.

Countries such as the Netherlands, France, Sweden, and Japan have demonstrated that when circular design is paired with targeted regulation, innovation incentives, and consumer education, it can lead to measurable outcomes: reduced landfill waste, lower emissions, and the emergence of new markets for sustainable materials and services. The integration of bio-based materials like PHAs, modular product architecture, and digital traceability systems (e.g., Digital Product Passports) illustrates the convergence between design, technology, and ecology.

In conclusion, circular design is not only a technical discipline but a strategic enabler of environmental stewardship and industrial competitiveness. By embedding principles such as reuse, disassembly, renewable materials, and local value creation from the earliest stages of product development, circular design becomes a driver of climate neutrality, resource resilience, and social inclusion—with materials like PHAs exemplifying the material innovations that can support this transition at scale.

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