

Developing Guidelines for Sustainable Electric and Electronic Equipment Production and Recycling

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Abstract: The microelectronics industry is a strategic pillar of global technological progress, yet its rapid growth has amplified environmental and resource-efficiency challenges, particularly regarding the increasing generation of Waste from Electrical and Electronic Equipment (WEEE). Although regulatory frameworks, especially in Europe, provide guidelines for sustainable management, the lack of operational tools to support implementation in industrial and training contexts remains a critical barrier. This work presents the development of a Manual of Good Practices for the Production and Recycling of WEEE, created through a collaborative effort between academia and microelectronic-sector organizations. The manual consolidates regulatory requirements, international standards, and empirical insights from real production environments to promote sustainable practices across the equipment life cycle. Its purpose is to support technicians, engineers, environmental professionals, and trainers by providing practical guidance that enhances process efficiency, reduces hazardous waste generation, and strengthens circular-economy principles in the electronics sector. The expected outcome is a structured and accessible tool that bridges the gap between legislative objectives and real-world industrial practice, fostering responsible production and sustainable end-of-life management of electronic components.

Keywords: Waste from Electrical and Electronic Equipment (WEEE), Printed Circuit Boards (PCBs), Circular economy, Legislation, Waste management, Life Cycle Assessment (LCA).

1. Introduction

The microelectronics sector plays a pivotal role in contemporary technological advancement, underpinning critical value chains ranging from consumer electronics to high-precision industrial, medical, and communication systems [1]. As societies become increasingly digital and interconnected, the demand for electronic components continues to grow exponentially, driving innovation in semiconductor design, manufacturing processes, and material engineering. However, this rapid technological evolution has also intensified environmental pressures, particularly in terms of energy

consumption, use of scarce resources, and the accelerated generation of Waste Electrical and Electronic Equipment (WEEE) [2-4]. The sector's reliance on highly specialised materials – including rare earth elements, precious metals, and hazardous substances – further amplifies its environmental footprint and highlights the need for responsible production and end-of-life practices.

Despite the critical importance of electronics in modern society, sustainable management of their life cycle remains a persistent challenge. WEEE has become one of the fastest-growing waste streams worldwide, driven by shortened product life cycles, rapid technological obsolescence, and consumer

demand for continuous innovation [1-4]. The complexity and heterogeneity of WEEE – encompassing plastics, metals, glass, ceramics, and hazardous chemical compounds – hinder efficient recovery and recycling processes. Moreover, improper disposal contributes to environmental pollution, loss of valuable materials, and human-health risks, particularly in regions where informal recycling practices prevail [5].

Although global and European frameworks have established ambitious strategies for circularity, resource efficiency, and extended producer responsibility, the translation of these regulatory principles into operational industrial practices remains limited [5]. Many organisations lack clear and practical guidance on how to implement sustainable production methods, optimise resource use, and ensure environmentally responsible end-of-life management. This gap is particularly evident in the microelectronics sector, where fast-paced innovation coexists with complex production chains and highly regulated environments.

In response to these challenges, this work presents the development of a Manual of Good Practices for the Production and Recycling of WEEE [8], intended to bridge the gap between regulatory frameworks and their practical implementation. The manual aims to support technicians, engineers, environmental managers, and training professionals in adopting sustainable practices that span the entire equipment life cycle – from design and manufacturing to disposal and recycling. Developed through collaboration between academic institutions and industrial partners in the microelectronics sector, the manual incorporates national and international standards as well as empirical observations derived from real production settings. Its ultimate goal is to provide a technical and educational instrument that enhances processing efficiency, reduces hazardous waste, improves material recovery rates, and promotes circular-economy values within the electronics industry.

2. Methodology

To define a structure for the Good Practices Manual for the Production and Recycling of Waste Electrical and Electronic Equipment, it was necessary to carry out an extensive review of the key concepts and terminology used in the microelectronics industry, the national and European legal frameworks, and the best practices in product design and reuse/recycling.

The process began with defining the concepts used in the sector and the main fundamental principles of waste management, such as the Waste Hierarchy, Extended Producer Responsibility, and the distinction between the two waste management systems – individual and collective. Establishing these concepts and principles provides a foundation for the sector's technical and regulatory knowledge.

Next, research was conducted on the main legislation applicable both to eco-design, from an

early-stage product-development perspective, and to end-of-life management. Among the directives and international standards studied are:

- Regulation (EC) No. 1907/2006 of 18 December 2006, concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH);
- Directive 2008/98/EC of 19 November 2008 on waste;
- Directive 2009/125/EC of 21 October 2009 establishing the ecodesign requirements for energy-related products, commonly known as the Ecodesign Directive;
- Directive 2011/65/EU of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, known as the RoHS Directive;
- ISO 9001, the international standard that sets out the requirements for organizations to provide products and services that meet customer needs while complying with applicable legal requirements;
- ISO 14001, the international standard that defines requirements to help organizations manage their environmental responsibilities.

Based on the defined principles and the legal framework presented – and in collaboration with companies in the microelectronics industry – the best practices were mapped and organized according to each stage of production, from product planning and design, through Printed Circuit Board (PCB) manufacturing and assembly, to the management of waste generated.

Considering that this is a continuous improvement process, information was also gathered on the best methods to monitor production, minimizing waste generation, and on the most effective approach to train and empower all employees involved in the production process.

3. Outcomes

Taking into account the principles mentioned above and in light of the current European legal framework, the Good Practices Manual for the Production and Recycling of Waste Electrical and Electronic Equipment was developed, with the main objective of creating a bridge between the various entities involved in the production process in the microelectronics sector – such as technicians, engineers, environmental managers, and trainers – so that they can support the adoption and implementation of sustainable practices throughout the product life cycle.

The manual developed is the result of close collaboration between academic institutions and Portuguese companies in the microelectronics sector, incorporating both Portuguese and international standards, as well as empirical knowledge collected from real production environments.

With the objective of providing a technical training tool designed to improve process efficiency, reduce hazardous waste generation and promote the circular economy in the sector, the manual includes recommendations on product design such as Design for Circular Disassembly (DfCD), tools such as Life Cycle Assessment (LCA), efficient material use, reuse of by-products, and continuous improvement through digitalization and traceability. Sustainable practices related to logistics, packaging, and waste segregation are also included, with emphasis on integrating economically circular strategies.

Fig. 1 shows a hierarchy of waste management operations.



Fig. 1. Hierarchy of waste management operations.

In addition, the manual provides guidance on defining performance indicators, carrying out audits, and preparing compliance reports, as well as training proposals and environmental awareness actions. Finally, this methodological approach is reinforced through documentation of real case studies and practical examples of efficiency improvement and waste reduction.

The following sections present in greater detail the chapters that make up the good practices manual.

3.1. Concepts

After the introductory chapter, which addresses issues associated with the production and disposal of WEEE, defines the key objectives of the manual, and provides a brief description of its structure, the second chapter is presented.

This chapter is divided into three sections: the first introduces key definitions such as EEE, WEEE, hazardous and non-hazardous waste, and circular economy; the second describes the fundamental principles of waste management, such as the waste hierarchy (Fig. 1) (prevention, reuse, recycling, recovery, and disposal) and extended producer responsibility, which establishes that waste management is the responsibility of whoever places a product on the market, while also distinguishing between the two waste management systems (individual and collective/compliance schemes) (Fig. 2); finally, the third section presents and defines the main technical terms associated with electronic circuit assembly such as surface-mount technology

(SMT), printed circuit board (PCB), and soldering processes.

This approach allows the manual to be read and understood by a wide range of actors involved across the entire production process, facilitating topic comprehension, which in turn will lead to greater acceptance and readiness to implement measures that reduce waste generation and increase process efficiency.



Fig. 2. Waste Streams Management Systems.

3.2. Legal Framework

The third chapter extensively presents the European directives and regulations currently in force, as well as the Portuguese legislation that transposes these directives and the relevant international standards. The compilation of these documents aims to gather, in a single source, all legal documents that companies must consult (Table 2).

Two regulatory frameworks that must be considered when designing a product are the RoHS Directive and the REACH Regulation. The RoHS Directive aims to restrict the use of certain hazardous substances above specified concentration limits in order to reduce their impact on human health (Table 1). The REACH Regulation, in turn, establishes rules for the registration, evaluation, and authorization of chemical substances that may be carcinogenic, mutagenic, or present negative effects on reproduction.

In addition to ISO 9001 and ISO 14001 standards, another relevant standard is ISO 14025, which establishes principles and procedures for Type III environmental declarations. These declarations are based on Life Cycle Assessment (LCA) and aim to provide quantitative, third-party-verified environmental information regarding the environmental performance of products, enabling product comparison. This type of declaration promotes transparency and supports continuous improvement in the industrial sector. Specifically, for

the electrotechnical and electronic sector, there is an international program dedicated to environmental declarations, called PEP ecopassport®. The PEP provides detailed information on the environmental impacts of a product throughout its life cycle.

In parallel, within the scope of the European Ecodesign for Sustainable Products Regulation (ESPR), the Product Passport (PdP) is being developed. This digital tool intends to aggregate detailed information on the composition, environmental performance, maintenance, repairability, dismantling, and recyclability of a product.

Table 1. Restricted Substances and Maximum Concentrations according to RoHS.

Substance	Limit [ppm]
Lead (Pb)	<1000
Mercury (Hg)	<1000
Cadmium (Cd)	<100
Hexavalent Chromium (Cr VI)	<1000
Polybrominated Biphenyls (PBBs)	<1000
Polybrominated Diphenyl Ethers (PBDEs)	<1000
Phthalates (DEHP, BBP, DBP, DIBP)	<1000

3.3. Best Practices at Each Stage of the Production Process

This chapter presents best practices that can be applied in the microelectronics sector throughout the entire production process.

To develop a product, it is necessary to consider which components will be used and how the product will be built. On one hand, this ensures that substances classified as hazardous – such as those listed in the RoHS and REACH Directives – are not used. On the other hand, it ensures that the product's repairability (i.e., the replacement of parts), as well as its reuse and recycling, can be performed in a simple and fast way, making the process economically viable. To support this, the chapter presents several Design for X (DfX) methodologies, including the Design for Circular Disassembly (DfCD) methodology, whose objective is to design a product that can be easily dismantled at end-of-life in order to increase its circularity potential. This methodology can be modeled using a description of the disassembly process called the Parent–Action–Child (PAC) model.

Next, Life Cycle Assessment (LCA) is addressed, explaining the stages of the process and presenting software tools available to perform this evaluation. Conducting an LCA offers numerous advantages, such as supporting decision-making, allowing the selection of indicators that lead to more sustainable product development, and serving as a demonstration of environmental commitment – thus also being an effective marketing strategy.

The following subsections introduce best practices directly related to the production process itself, specifically PCB manufacturing and component assembly. Several waste-reduction measures are presented. For example, the use of solder flux can be reduced by employing a well-calibrated solder paste stencil printing process, or the flux can be reused as long as specific parameters are controlled.

Testing and inspection stages are also presented, as these contribute to improving process efficiency. Manual workstations can be used, where once non-conforming components are identified, they are replaced by trained technicians. Selective soldering can also be employed, where only specific points are reworked without affecting surrounding components. Methods for analyzing the causes of recurring failures during production are described, enabling the development of measures to reduce or even eliminate such faults.

The packaging and logistics phase is also covered, as it involves selecting appropriate materials for packaging products. The chosen materials must protect the product, reduce waste, and be economically sustainable. Product routes should also be optimized to reduce emissions.

Finally, best practices for waste management during the production process are presented, including source separation, clearly identified containers with text or images indicating the waste type and what can be disposed in each, and the establishment of partnerships with licensed operators to ensure proper treatment and valorization of the waste generated.

3.4. Monitoring and Audit

Chapter 5 discusses the importance of monitoring and auditing processes. This type of process makes it possible to identify failures throughout the entire production chain and to seek explanations for these failures, allowing the development of measures that improve the efficiency of the production process.

Through monitoring, it is possible to ensure that all the best practices previously described are having an effect and to highlight what can still be improved by defining performance indicators (KPIs). These KPIs make it possible to assess the performance of the most critical aspects, such as waste management and energy efficiency; reduce operational costs; and evaluate the efficiency of the process as a whole. Some of these indicators may include: waste generated during the process, material reuse rate, energy consumed per production unit, CO₂ emissions, and the frequency of environmental incidents.

Another tool addressed in this chapter is auditing, both internal and external. Audits play an important role in assessing environmental compliance and in the sector's continuous improvement. They enable verification of whether processes comply with legal requirements, help identify weaknesses and correct them, and serve as a key tool for identifying

opportunities for optimization and process improvement.

3.5. Education and Training

In the sixth chapter, the importance of training and empowering all employees is highlighted, so that they are aware of the environmental importance of minimizing waste generated at all stages of production. Continuous training is one of the key factors that determines compliance with legal requirements. At the same time, it contributes to minimizing operational risks and waste generation and optimizes the organization's performance.

Several training methodologies are proposed, such as face-to-face sessions, where knowledge is delivered by environmental specialists as well as specialists in production processes, who can provide guidance on process optimization, especially manual processes; the provision of e-learning platforms, where training can be carried out by employees autonomously, continuously, and flexibly; and the implementation of practical simulations, allowing assessment of whether the training is effective. This method helps evaluate both the knowledge acquired and the effectiveness of the training. Based on the results obtained, it is always possible to improve the training approach.

Table 2. EU legislation applicable to WEEE and waste management.

Regulation	Relating to	Font size and style
COMMISSION DECISION 2014/955/EU amending Decision 2000/532/EC on the list of waste pursuant to Directive 2008/98/EC.	Established a standard list of waste materials, the European Waste Catalogue (EWC).	Wastes from electrical and electronic equipment is identified according to Chapter 16, code 16 02.
Directive 2008/98/EC of the European Parliament and of the Council, the Waste Framework Directive (WFD).	Lays down measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste and by reducing overall impacts of resource use and improving the efficiency of such use.	Waste hierarchy shall apply as a priority order in waste prevention and management legislation and policy. Extended producer responsibility, in order to strengthen the re-use and the prevention, recycling and other recovery of waste.
Directive 2012/19/EU on waste electrical and electronic equipment (WEEE).	Six categories of electrical and electronic equipment, among which: 5. Small equipment, 6. Small information technology (IT) and telecommunication equipment (no external dimension more than 50 cm).	Minimum targets applicable by category for WEEE falling within category 5 or 6: 75 % shall be recovered, and 55 % of them shall be prepared for re-use and recycled.
Directive (EU) 2018/849 of the European Parliament and of the Council amending among others, Directive 2012/19/EU.	About the electronic report of the WEEE data. The data shall be reported in the format established by the Commission.	Member States may make use of economic instruments and other measures to provide incentives for the application of the waste hierarchy
Regulation (EC) 1907/2006, (REACH)	Concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and establishing the European Chemicals Agency	Based on the principle that it is for manufacturers, importers and downstream users to ensure that they manufacture, place on the market or use such substances that do not adversely affect human health or the environment – precautionary principle.
Directive 2011/65/EU (RoHS Directive).	On the restriction of the use of certain hazardous substances in electrical and electronic equipment.	Precaution - Member States shall ensure that EEE placed on the market, including cables and spare parts for its repair, its reuse, updating of its functionalities or upgrading of its capacity, does not contain the substances listed in Annex II.

3.6. Success Stories and Practical Examples

In chapter 7, real case studies are presented, illustrating practices in production processes that cover one or more aspects discussed in Section 3.3, which refers to best practices throughout the entire process.

In order to meet the European Union's minimum targets for the recovery, reuse, and recycling of goods, as shown in Table 2, for small equipment categories (categories 5 and 6), which include the microelectronics sector, it is necessary to implement a set of best practices within the industry.

There are several success stories. One of them comes from a company with many years of experience

in the microelectronics field, focused on the production, assembly, and repair of electronic equipment for various sectors such as healthcare, aerospace, and lighting. The company has a strict waste management system based on material separation at the source. This step is extremely important for waste valorization – the better the sorting, the lower the risk of contamination and the greater the amount of material that can be recovered. Among all the waste generated by the company, the largest share comes from packaging waste, representing 85 % of total waste produced. This stream is divided into paper/cardboard, plastic, composites, and wood. Some of these materials are reused internally, while the remainder is sent for recovery. Within the waste generated in the production cycle, the following stand out:

- The company has numerous waste-separation stations, clearly identified with the type of waste and its corresponding European Waste Catalogue (EWC) code;
- Hazardous waste accounts for only 1 % of the total waste produced;
- Aluminum, iron, and steel waste is separated and sent to a licensed recycling operator;
- Electronic waste is sent to a company specialized in electronic equipment recycling, focusing on dismantling, separation, and recycling of this type of waste;
- In the wave soldering process, the flux used is reintroduced. After reintroduction, certain quality parameters of the flux are monitored;
- Some waste containing solder residues, such as PCBs and metals, has economic value and is sold to a recycling company for recovery;
- The company has an equipment repair department, which follows a standard repair procedure consisting of replacing specific components (capacitors, PCBs, connectors, and cables). Waste produced by this department represents 31 % of non-packaging waste. This waste is separated, although there is currently no recycling solution; however, the company continues to look for one, so that this waste can be diverted from landfill.

By optimizing the reuse of materials (mainly packaging and reels) and incorporating by-products into the production process, waste generation is reduced, resulting in financial benefits for the company.

Another case is related to product design. A company in the automotive lighting sector, which produces rear lights for trucks, trailers, and tractors, placed on the market in 2005 a product whose lighting was entirely composed of LEDs. This product was designed to be modular – each function (turn signal, tail/brake light, fog light, etc.) had its own PCB and power source, allowing easy access and replacement in case of failure. The idea was well received by

stakeholders; however, despite being an environmentally sustainable solution, it did not translate into sales of individual components. That is, whenever one of the products failed, customers purchased an entirely new light, even though the option to replace only the damaged component was available. By not taking advantage of the modular light's full potential, the product became uncompetitive in the market. The company then decided to design a light with a single PCB containing all functions and fully sealed. Although this may seem like a step backwards, this design change allowed the company to reduce the amount of glue used to protect PCBs in the modular light (as it was not sealed), and also to reduce plastic usage by approximately 13 %. Another relevant point is the possibility of recycling the PCB, since it does not contain any glue; in the modular light, recovery of electronic components was difficult due to the need to use glue to protect the PCBs from moisture. At present, an LCA comparison between the two types of lights is being carried out and will later be included in the manual.

Although the LCA is not yet fully completed, it is already possible to present and discuss preliminary results that highlight clear trends in the environmental performance of the modular and non-modular tail lights. The partial outcomes illustrated in the Fig. 3 reveal consistent differences between the two configurations across all assessed impact categories.

In the Climate Change (kg CO₂eq per unit) category, the non-modular tail light shows more than double the carbon footprint of the modular design. This suggests that the integrated PCB configuration relies on more energy-intensive or material-intensive production processes, resulting in higher greenhouse gas emissions.

The most pronounced difference appears in Energy Resources (MJ per unit). The non-modular version requires more than twice the energy consumed by the modular alternative, indicating that modularity reduces material requirements and streamlines manufacturing steps, consequently lowering the embodied energy of the product.

For Eutrophication (mol N-Eq per unit) and Material Resources (kg Sb-Eq per unit), although the absolute values are smaller, the pattern remains the same: the non-modular solution exhibits higher impact values. This reinforces the notion that the modular design enables more efficient use of critical materials and generates fewer emissions associated with nutrient pollution.

A similar tendency is observed in Water Use (m³ world-eq deprived per unit), where the modular taillight requires significantly less water during production. This reduction further highlights the resource efficiency benefits associated with modular design.

Overall, even at this preliminary stage of the LCA, the results consistently demonstrate that the modular taillight achieves lower environmental impacts across all analysed categories. The most substantial advantages are observed in energy consumption and

carbon emissions, but relevant reductions are also evident in material usage and water demand. These early findings already position the modular design as

a more sustainable alternative, aligned with principles of eco-efficiency and circular product development.

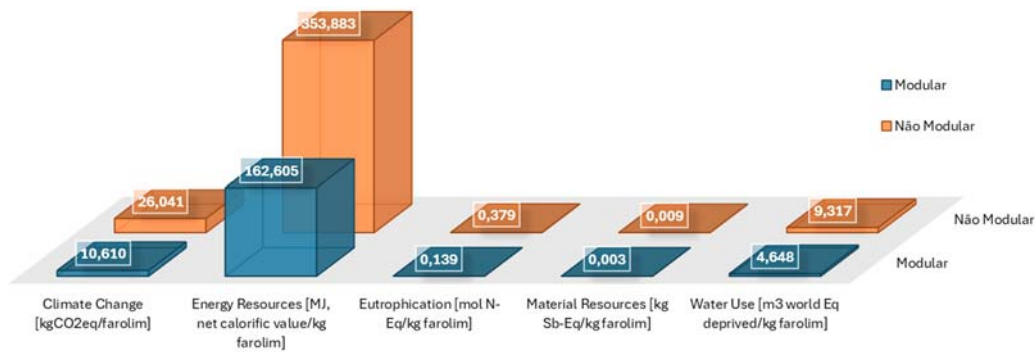


Fig. 3. Life Cycle Assessment Comparison of Modular vs. Non-Modular Taillight Designs.

This analysis aims to show that each company, each production process, and each product must be evaluated case-by-case, since what sometimes appears to be an economically and environmentally sustainable solution may not actually be one.

4. Conclusions

The development of the Manual of Good Practices for the Production and Recycling of WEEE constitutes a significant contribution to strengthening sustainability practices within the microelectronics sector. By integrating legislative requirements, international standards, and empirical insights gathered from real industrial environments, the manual provides a practical and accessible tool to support the implementation of clean-production strategies, efficient resource management, and responsible recycling practices.

This work highlights that the transition towards circular-economy models in the electronics industry demands not only comprehensive regulation, but also operational instruments capable of facilitating technical training and standardised procedures. As such, the manual enhances the capacity of organisations to reduce hazardous waste, optimise production processes, and align with circular-economy principles, contributing to a more sustainable, competitive, and socially responsible electronics sector.

Future work will focus on continuous validation of the manual across diverse industrial contexts, integrating performance indicators, and expanding the framework to other critical technology-intensive sectors in response to evolving regulatory and technological demands.

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