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Development of the Manual of Good Practices for the Production and Recycling of Waste Electrical and Electronic Equipment (WEEE)

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Summary: The development of the Manual of Good Practices for the Production and Recycling of Waste from Electrical and Electronic Equipment arises from the need to improve the sector's production processes, promoting efficiency in the use of resources such as time, water and electricity, and reducing the generation of waste. Aimed at manufacturers of electronic components, engineers and technicians, environmental and quality managers, as well as research and development institutions, the manual is a technical and environmental guide. It was prepared with the collaboration of companies specializing in the assembly of printed circuit boards (PCBs), based on Portuguese legislation, European standards and sector-specific regulations. The relevance of this manual is reinforced by the strategic growth of microelectronics and the lack of consolidated guidelines for waste management, recovery of materials, and their efficient reintegration into the production chain. The document seeks to fill these gaps, promoting sustainable practices in line with the principles of the circular economy.

Keywords: Waste from Electrical and Electronic Equipment (WEEE), Printed Circuit Boards (PCBs), Circular Economy, Legislation, Waste Management.

1. Introduction

The microelectronics sector plays a central role in today's technological development, feeding critical value chains ranging from consumer devices to high-precision industrial and medical systems [1]. However, this accelerated evolution has led to significant environmental impacts, namely through the high consumption of natural resources and the growing generation of Waste from Electrical and Electronic Equipment (WEEE) [2-4], a specific waste stream, whose origins are transversal to various sources or sectors of activity, including components, subassemblies, and consumable materials that are an integral part of the product at the time it is discarded.

The lack of clean production practices and the poor structuring of the end-of-life management of this type of equipment compromises environmental sustainability, economic efficiency and the public image of the sector.

The volume of WEEE has been increasing exponentially, making it one of the fastest growing categories of waste worldwide [1-4]. This waste is often neglected due to the complexity of its composition and the lack of practical guidelines linking efficient production with material recovery and environmentally responsible disposal [5]. European legislation, although comprehensive, lacks operational instruments that translate regulatory principles into concrete actions in industrial and training contexts [5].

In this context, this work presents the development of a Manual of Good Practices for the Production and Recycling of WEEE, designed to guide technicians, engineers, environmental managers and trainers in adopting sustainable practices throughout the life cycle of equipment. The manual is the result of a collaboration between academic bodies and companies in the electronics and microelectronics sector, incorporating national and international standards, as well as empirical contributions gathered in real production environments. The aim is to provide a technical training tool that contributes to process efficiency, the reduction of hazardous waste, and the promotion of the circular economy in the electronics sector.

2. Methodology

The writing of the Manual of Good Practices for the Production and Recycling of WEEE followed an approach based on the identification and

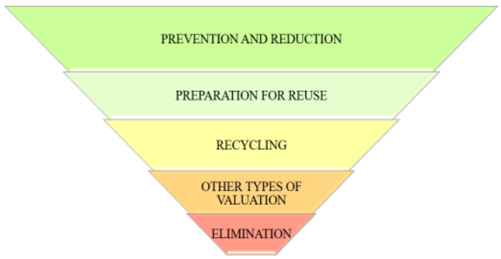

Fig. 1. Hierarchy of waste management operations.

systematization of concepts, regulatory frameworks, operational practices and assessment tools applicable to the microelectronics sector. The methodology adopted was based on a detailed analysis of national and European legislation, the incorporation of internationally recognized environmental and quality standards, and the integration of practical tools for implementing and monitoring good practices.

Firstly, fundamental concepts and principles were defined, such as the hierarchy of waste management operations (Fig.1), extended producer responsibility and flow management systems, establishing a common basis for technical and regulatory understanding. This was followed by a survey of the main regulations in force – namely Directives. 2008/98/EC on waste, 2012/19/EU on WEEE, 2011/65/EU (RoHS Directive) and Regulation (EC) 1907/2006, concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) - and the ISO 14001 and ISO 9001 standards, in conjunction with the legal requirements applicable to companies (Table 1**Table** 1).

Table 1. Restricted Substances and Maximum Concentrations values tolerated (by weight) in homogeneous materials, 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

Based on this reference, good practices have been mapped and organized by stage of the production process, from planning and design to waste management – Design for Circular Disassembly (DfCA) (Fig. 2).

3. Outcome

Starting with the principles devised in the methodology presented above, we developed the "Manual of Good Practices for the Production and Recycling of Waste from Electrical and Electronic Equipment" aiming at guiding technicians, engineers, environmental managers and trainers in adopting sustainable practices throughout the life cycle of equipment. The manual is the result of a collaboration between academic bodies and companies in the Portuguese microelectronics sector, incorporating national and international standards, as well as empirical contributions gathered in real production environments. The aim is to provide a technical training tool that contributes to process efficiency, the reduction of hazardous waste, and the promotion of the circular economy in the electronics sector.

The manual includes recommendations on design for circular disassembly, application of tools such as

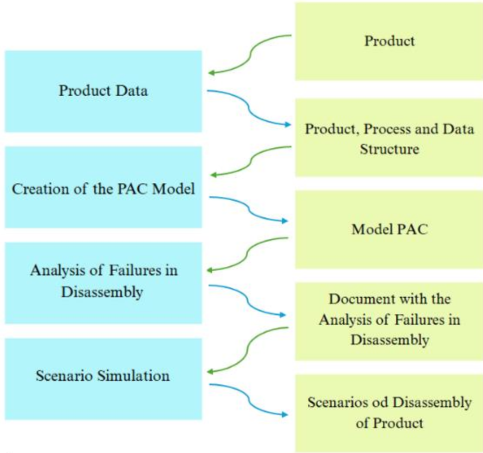

Fig. 2. DfCD Application (adapted from [6])

Life Cycle Assessment (LCA), efficient use of materials, reuse of by-products and continuous improvement through digitalization and traceability. Sustainable practices in logistics, packaging and waste separation were also considered, with an emphasis on integration with the circular economy.

In addition, the manual included guidelines for defining performance indicators, carrying out audits and drawing up compliance reports, as well as proposals for training and environmental awareness actions. Finally, the methodological approach was strengthened by collecting and documenting success stories and practical examples of waste reduction and efficiency increase in real contexts.

After the Introduction, the Manual addresses the basic concepts and definitions in Waste Management, focusing on the concepts of the Hierarchy of Waste Management, and Extended Producer Responsibility. Then it addresses the topic of Waste Stream Management Systems. The complexity of these systems, particularly in the case of Integrated Management Systems, involving a plethora of players with different responsibilities and roles, can be confusing and daunting to newcomers and those that are not dedicated in full-time to waste management and, in our opinion, constitutes a major barrier to the implementation of these systems in technological companies, most notably in the case of SMEs. As such, the method described in the Manual should adopt a pedagogical orientation, helping staff in technological companies to understand the rationale behind these systems.

Terminology is another topic that interferes in the communication between the Electronics technology and production community, that develops circuits and defines manufacturing processes, and the community of Environmental Engineers and specialists. As such, we felt that a section in the Manual dedicated to explaining the terms involved in Waste Stream Management would provide helpful information for those involved. As in many other activities, it is important to break barriers between different communities, where each expert remains siloed in her or his area of expertise (Electronics, Manufacturing, Sustainability, …), focusing on specific parts of the problem. Only by addressing the sustainability of Electronic Production processes as a whole, by all parts involved, will we be able to reach efficient and effective solutions. Currently, in the EU, less than 40% of WEEE is properly recycled. However, the generation of this waste stream is on the rise due to consumerism. Therefore, the EU has taken measures and established standards to combat this problem.

Chapter 3 of the Manual presets the main regulations in force, that is summarized in the table 2. The principle of extended producer responsibility states that the costs of managing waste resulting from the production and end-of-life of a given product should be borne by its producer. This principle is a realization of the polluter-pays principle in the area of waste management and aims to hold the economic operator that places the product on the market accountable for the environmental impact resulting from the production process, use, and its future waste and management. This waste management responsibility can be assumed directly by the producer, but it can also be transferred to an integrated WEEE management system, bearing the cost of management carried out by this system. Figure 3 presents the caracteristics of these two management alternatives.

Fig. 3 - Waste Streams Management Systems

Chapter 4 of the Manual addresses a set of good practices that are proposed to the Electronics sector companies. A fundamental aspect of these good practices is that they must consider a holistic view of the electronics production process and integrate the complete lifecycle of products and goods, including marketing, product conception and requirement elicitation, distribution, … In many cases, the recyclability of an electronics product is hindered by options that were taken in the initial design phases [7], such as choosing a particular type of component (e.g., a capacitor) that may contain chemical elements that are difficult to process in the product end-of-life. These good practices encompass aspects such as DfX (Design for Disassembly, Design for End of Life, Design for Manufacturability, Design for Environment, Design for Circular Disassembly…), the PAC (Parent-Action-Child) [6] model for the explicit description of the disassembly process and LCA (Life Cycle Analysis). Digitalization, and in particular the concept of DPP (Digital Product Passport), are fundamental tools to bring traceability and transparency into the product value chain. DPP will provide extensive information about the product's origin, materials, environmental impact, and end-of-life procedures.

Chapter 5 discusses the importance of monitoring and auditing processes to ensure the effectiveness of the good practices implemented and compliance with the norms and standards applicable to the microelectronic industry. Through the collection of data in the form of Key Performance Indicators (KPI) and their analysis, it is possible to identify opportunities for improvement, reduce operational costs and evaluate the effectiveness of processes. Some of these indicators are defined as: waste produced in the process, index of reusability of the materials, energy consumed per unit of production, CO_2 emissions and environmental accident frequency.

Another tool covered in this chapter is audits, both external and internal. Audits play an essential role in assessing environmental compliance, operating effectively, and continuous improvement in the microelectronics sector. They enable the verification of whether processes comply or not with regulatory standards and quality requirements. They are also helpful for identifying opportunities for optimization and improvement.

Chapter 6 highlights training and environmental awareness as strategic tools for consolidating effective waste management systems in this sector. The continuous training of employees emerges as a determining factor in ensuring compliance with regulatory frameworks. At the same time, it contributes to the mitigation of operational risks, the minimization of waste, and the optimization of organizational performance.

Diversified training methodologies are proposed—face-to-face, digital, workshops, and practical simulations—which favor both the transfer of technical knowledge and the development of applied skills, promoting safer and more sustainable work environments. At the same time, environmental awareness is presented as an essential cultural vector, based on internal campaigns, incentive programs, thematic events, and daily eco-efficiency practices. This integrated approach promotes the active involvement of employees, reinforces collective responsibility, and contributes to the incorporation of an organizational culture oriented towards sustainability and continuous improvement.

In order to achieve the minimum European targets for recovered, prepared for reuse and recycled goods, as set out in Table 2, for the categories of small equipment (categories 5 and 6), which include waste from the microelectronics sector, it is necessary to implement a set of good practices in the industry

Table 2 – European regulation in the field of WEEE

Regulation	Relating to	Specification
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 % 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,	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.

There are some successes cases. One of them is a company with extensive experience in the electronics industry, specializing in the production, assembly, and repair of innovative electronic solutions for various sectors, from electronics and telecommunications in general, to healthcare, aerospace, and lighting. The company has a rigorous internal waste management system, which is based on the separation of materials, which is essential to enable material recovery. Of all the waste generated by the company, packaging waste represents 85% and the remainder is waste from the production cycle. The packaging is sorted into paper/cardboard, plastic, composites and wood. Some of the packaging is reused internally and the rest are sent for recovery. Among the waste generated in the production cycle, the following stand out:

- Within the company, there are numerous waste separation stations, clearly identified by the type of waste using the EWC code.
- The hazardous waste representes just 1% of the total.
- Metal, aluminum, iron, and steel waste is separated and sent to a licensed recycling operator.
- Electronics waste is sent to a company specializing in the recycling of computer scrap and other smart equipment, focusing on the decomposition, separation, and recycling of technological waste.
- In the wave soldering process, used solder flux is reintroduced, optimizing this flux by monitoring quality parameters.
- Some waste, which still contains solder residue, PCBs, and metals, has some economic value and is sold to a recycling company for further recovery.
- The company has integrated a repair department for telecommunications equipment, following a standard repair procedure that involves replacing certain components of the equipment (capacitors, PCBs, connectors, and cables)), representing 31%

of non-packaging waste. These are separated to be sent for recovery, even if the recycling market does not yet receive them. In this situation, they seek a solution to avoid their disposal in landfills.

Optimizing the internal reuse of materials (mainly packaging and spools) and incorporating by-products into the production process allows for less waste, which translates into financial gains for the company.

The Manual is still a Work-in-Progress and has not been yet extensively applied. As such, there are no quantitative results that allow us to estimate its impact on the companies' processes.

4. Conclusions

The Manual of Good Practices for the Production and Recycling of WEEE represents a significant step toward bridging the gap between environmental legislation and practical implementation in the microelectronics sector. Developed through a collaborative effort between academia and industry, the manual provides a structured and accessible tool for promoting sustainable practices across the entire life cycle of electronic equipment.

By consolidating technical guidelines, regulatory requirements, and practical tools, the manual offers concrete support to manufacturers, engineers, technicians, and environmental managers in improving resource efficiency, reducing waste generation, and facilitating the recovery and reintegration of valuable materials. Its alignment with national and European legislation and international standards, ensures its applicability in diverse industrial contexts.

The integration of circular economy principles – particularly through recommendations on eco-design, material reuse, and lifecycle analysis – reinforces the manual's relevance in a sector marked by rapid growth and increasing environmental pressure. Furthermore, the inclusion of real-world case studies and performance evaluation mechanisms enhances its value as a training and decision-support tool. The Manual is a Work-in-Progress, and it will now start to be applied to a larger scale. This will allow collecting KPIs that can be used to assess the impact of the Manual, providing insight into the effectiveness of this proposal. In this sense, future work will focus on assessing both the impact of the Manual in the outcome of manufacturing processes, and the usability or easiness of use of the Manual.

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