

WEEE management of tinting machines in the context of industrial ecology and the circular economy in Brazil

ABSTRACT

Marcelo Angelo Taparello de Souza

Universidade do Vale do Rio dos Sinos (UNISINOS), São Leopoldo, Rio Grande do Sul, Brasil.

marcelotaparello@edu.unisinos.br

Janiel Rodrigo Zaro

Universidade do Vale do Rio dos Sinos (UNISINOS), São Leopoldo, Rio Grande do Sul, Brasil.

janielraro@gmail.com

Carlos Alberto Mendes Moraes

Universidade do Vale do Rio dos Sinos (UNISINOS), São Leopoldo, Rio Grande do Sul, Brasil.

cmoraes@unisinos.br

The evolution of the tinting system, from its introduction in the 1970s in the USA and Europe to its arrival in Brazil in 1992, transformed paint commercialization and offered growth potential, although it represents less than 20% of the Brazilian architectural paints sector. Simultaneously, environmental challenges emerge from increasing electronic equipment production, requiring strategies such as industrial ecology and circular economy. Anchored in the Science, Technology, and Society (STS) perspective and aligned with the Sustainable Development Goals (SDGs), this study addresses Waste Electrical and Electronic Equipment (WEEE) management in tinting machines, presenting component details, business scenarios, and WEEE generation estimates over 50 years to support decision-making. Results indicate that rental, by enabling reuse, remanufacturing, and recycling, can reduce WEEE generation by up to 87.5% compared to linear sales, underscoring the importance of circular business models to mitigate impacts and foster sustainability in electronic waste management.

KEYWORDS: WEEE, Industrial Ecology, Circular Economy, Tinting, Product-Service System

INTRODUCTION

The improvement of the tinting system marked a revolution in the architectural paints market, replacing the old marketing methods based on ready-made line colors with a dynamic and customizable system. Originated in the 1970s in the United States and Europe, this system arrived in Brazil in 1992 by Tintas Coral, transforming stores into production units capable of offering thousands of colors with reduced stocks. This method, using tinting machines to create colored architectural paints at the point of sale, currently represents less than 20% of the Brazilian architectural paint sector, showing a vast space for growth and implementation (Análise, 1998; Linhares, 2018; Monfardini, 2013; Zaparolli, 2009).

Along with the innovation of the tinting system, significant environmental challenges have emerged more recently, including the management of WEEE, the waste category of these machines. With the global growth of electronics production, the accumulation of these wastes has become a serious environmental concern. The European Commission defines WEEE as waste from electrical devices and household appliances, representing a problem due to the hazardous materials contained, such as mercury, lead, and cadmium, as well as the decrease in the availability of valuable metals contained in this equipment on the market (Pouyamanesh et al., 2023).

Industrial ecology, since the 1980s, has been brought in its concepts to restructure industrial production, aligning it with natural cycles, with the aim of integrating industries to reuse waste as raw materials and thus minimize waste and optimize resources. The circular economy emerges as a restorative and regenerative industrial system, emphasizing the preservation of natural capital, the optimization of resources and the elimination of waste. Therefore, it promotes a paradigmatic change by replacing the traditional concept of end of life with an emphasis on the restoration and circularity of resources.

Both approaches, industrial ecology, and circular economy, stand out as promising solutions to environmental and resource efficiency issues. The circular economy, for example, highlights the transition from product-oriented to service-oriented models, seeking to maximize the useful life of products and promote resource efficiency. In the context of WEEE of tinting machines, implementing reuse, remanufacturing and recycling strategies based on these approaches promote significant sustainable development in the environment and economy, moving the WEEE industry towards a more complete life cycle. This results in minimizing environmental impacts and maximizing the utility and value of products, driving a more holistic and efficient approach to dealing with these resources.

In this way, the integration of the concepts of industrial ecology and circular economy offers a viable path to mitigate environmental challenges, boost resource efficiency and promote a more sustainable economic model in the tinting machines of architectural paints sector and their respective WEEE.

In this context, the debate on WEEE from tinting machines must also be situated within the broader field of Science, Technology, and Society (STS), which highlights the social and political implications of technological choices. Linking this issue to the Sustainable Development Goals (SDGs), particularly SDGs 9, 11, 12, and 13, underscores that adopting circular business models in the paint sector is

not only an industrial strategy, but also part of a wider societal transition toward sustainability.

LITERATURE REVIEW

In the paint industry, the architectural paint tinting system has revolutionized production, allowing the instant creation of diverse colors and reducing logistical costs. Meanwhile, industrial ecology and the circular economy have emerged as environmental and economic solutions, aiming to reduce environmental impacts and optimize resource use. Together with strategies of reuse, remanufacturing, and recycling for waste electrical and electronic equipment (WEEE), these approaches also connect with broader debates in Science, Technology, and Society (STS), reinforcing their role in promoting sustainable development and contributing to the Sustainable Development Goals (SDGs).

Architectural paint tinting system

Before the tinting system's arrival, paint manufacturers relied on a "ready mix" model, offering a limited range of pre-made colors for retailers (Rose et al., 2019). This method was costly in terms of transportation, stocking, and unsold inventory. The tinting system, developed in the US and Europe in the 1970s, was introduced in Brazil in 1992 by Tintas Coral. It transformed retailers into small manufacturing units capable of producing thousands of colors on demand, minimizing inventory and enhancing product availability (Análise, 1998; Lin, 2021; Linhares, 2018; Monfardini, 2013; Zaparolli, 2009).

The system consists of two machines: a dispenser and a mixer. The dispenser doses colorants with high precision, controlled by software, while the mixer homogenizes the paint after colorant dosing by shaking the can (Linhares, 2018; Marcelo, 2013; Zaparolli, 2009). Paint is a key industry for Brazil, the world's fifth-largest producer, reaching USD 4.28 billion in sales in 2012 (Souza et al., 2018). In 2022, the country sold 1.647 billion liters of paint, with 82.5% being architectural paints (ABRAFATI, 2022). However, less than 20% of architectural paints in Brazil are produced using tinting machines, compared to over 80% in the US and Europe, highlighting significant growth potential for the system across the country (Van Beeck, 2019).

Waste of Electrical and Electronic Equipment (WEEE)

The rise in industrialization and competitiveness has increased electronic product consumption, leading to a significant environmental issue (Neto et al., 2017). WEEE refers to discarded consumer electronics such as smartphones, tablets, computers, and household appliances (Kangas and Seibel, 2018; Pouyamanesh et al., 2023). Hazardous substances like mercury and lead in WEEE can cause severe environmental damage, while valuable materials such as gold and silver are lost if not recycled (Pan et al., 2022). WEEE presents challenges in separating hazardous and valuable materials due to complex electronic components, such as printed circuit boards (PCB), which are widespread in electronics (Neto et al., 2017).

In 2019, 53.6 million tons of WEEE were generated globally, with only 17.4% being collected and properly recycled (Pan et al., 2022). In Brazil, less than 1% of WEEE receives proper treatment (Guarnieri et al., 2016). Effective WEEE management requires reverse logistics, where manufacturers, distributors, retailers, and consumers share responsibility for recycling (Ottoni et al., 2020). Brazil's National Solid Waste Policy (Law No 12,305/2010) sets ambitious goals for WEEE recycling, aiming to recycle 17% of all electronics sold (Guarnieri et al., 2016).

Industrial Ecology

Industrial ecology, developed in the 1980s, aims to reduce environmental impacts and foster economic growth through inter-industry collaboration. It proposes using waste from one industry as raw material for another, imitating the symbiotic relationships in natural ecosystems (Al-Thani and Al-Ansari, 2021; Motta and Carijó, 2013). Industrial ecology encourages life cycle thinking, where products are designed to be reused, remanufactured, or recycled (Yu and Zhang, 2021). The approach contrasts the traditional "cradle to grave" linear dynamic with a "cradle to cradle" circular model (Kangas and Seibel, 2018).

Key principles include integrating industries into ecosystems, closing material loops, and minimizing environmental impacts (Lowe, 2001). This strategy applies on various scales, from individual industries to regional or global levels. Tools for its practical application include material flow analysis, life cycle assessment, and cleaner production practices (Ruiz, 2013). Industrial ecology's key challenges include waste recovery, minimizing dispersion, dematerialization of the economy, and decarbonization, which promote more efficient use of natural resources and reduce waste generation (Erkman, 2001).

Circular economy

The circular economy responds to the increasing depletion of natural resources by redesigning production systems to be restorative and regenerative (CETEM, 2023). It prioritizes resource preservation, optimized use, and waste minimization through better product and system design. The circular economy emphasizes extending product lifespans through reuse, remanufacturing, and recycling, supported by business models such as product-service systems (PSS) and urban mining (Blomsma et al., 2018; Michelini et al., 2017).

Circular economy and industrial ecology both view waste as a resource and aim to minimize resource use while maximizing outputs (Al-Thani and Al-Ansari, 2021). However, while industrial ecology tends to focus on minimizing resource use, the circular economy seeks to restore and regenerate materials. The PSS approach, encompassing rental and sharing models, is a key part of this strategy, encouraging product longevity and efficient resource use (Martin et al., 2021).

Both concepts offer sustainable solutions for WEEE management by closing the product life cycle, minimizing pollution, and maintaining the value of materials and products (Pan et al., 2022). These strategies have significantly promoted sustainable development by encouraging reuse, remanufacturing, and recycling in the WEEE industry.

Science, Technology and Society (STS) and the Sustainable Development Goals (SDGs)

The relationship between science, technology and society (STS) has been fundamental to understanding how scientific and technological development is connected to contemporary social challenges. Far from being a neutral process, technological advancement is embedded in economic, political, and cultural contexts that shape both its direction and its impacts. In this context, STS studies have emphasized that the production of scientific knowledge and the diffusion of technological innovations must also be analyzed considering their social, environmental, and distributive effects (DAGNINO; BRANDÃO; NOVAES, 2004; GODIN, 2006).

Technological innovations, although often associated with increased production efficiency and economic competitiveness, can also reproduce inequalities or generate new environmental liabilities if not accompanied by mechanisms of social governance (SILVA; BOLSON, 2018). The STS perspective therefore highlights the need to evaluate technologies not only for their technical or economic viability, but also for their capacity to promote social inclusion, sustainability, and collective benefits.

In recent years, the Sustainable Development Goals (SDGs), defined by the 2030 Agenda of the United Nations (UN, 2015), have become a global framework that synthesizes this articulation between science, technology, and society. The SDGs provide a common language to align scientific, technological, and business practices with the most urgent social and environmental demands, such as promoting sustainable production and consumption patterns (SDG 12), strengthening sustainable infrastructure and innovation (SDG 9), building resilient cities and communities (SDG 11), and climate action (SDG 13). In this sense, the SDGs constitute a strategic reference for understanding the role of technology in transition processes toward sustainability (SANTOS et al., 2023; SILVA et al., 2025).

In the field of waste management, the STS–SDG interface is particularly relevant. The literature shows that the way societies organize the disposal of solid waste, including WEEE, reflects not only technical treatment capacities but also political, cultural, and social choices (SILVA; BOLSON, 2018; SILVA, 2018). Analyses of public policies aimed at the circular economy in Brazilian municipalities demonstrate, for example, that decisions on investments in recycling or landfilling involve trade-offs between immediate costs and long-term benefits, highlighting the socio-technical character of the issue. Recent studies also reinforce this perspective by showing how participatory processes for constructing the SDGs in Brazil have sought to integrate science, public policy, and social demands, emphasizing the importance of democratic governance in defining sustainable urban development goals (SILVA et al., 2025).

Similarly, research that applies geotechnologies and environmental indicators to diagnose regional vulnerabilities demonstrates how technical instruments are not neutral, but instead express methodological and political choices that directly affect territorial management and public policy design (SILVA; COSTA, 2025). These experiences strengthen the STS perspective that technology, when articulated with social policies, can promote productive inclusion and local development (SILVA; BOLSON, 2018).

In summary, STS and the SDGs offer a robust theoretical framework for understanding the social and environmental impacts of technologies, as well as the challenges and opportunities associated with the circular economy and waste management. This framework will be mobilized throughout the research to interpret scenarios of WEEE generation from tinting machines and to discuss the extent to which different business models can align technological innovation, sustainability, and social demands.

METHODOLOGY

The adopted methodology seeks to identify potential improvements in the management of WEEE of tinting machines used in architectural paints, facilitated by a Product-Service System (PSS) business model. This approach promotes a circular economy by prioritizing the rental of machines over sales, leveraging principles of industrial ecology.

Estimated WEEE inventory of tinting machines

The life cycle inventory is one of the stages of the Life Cycle Assessment (LCA), an industrial ecology tool belonging to the group of the firm or inter-firm, with methodologies that make it possible to rationalize and quantify. However, in this work, through a qualitative approach, the preparation of an estimated inventory of WEEE from automatic dispensers and gyroscopic mixers, which are the set of tinting equipment that the store owner needs to produce architectural paint colors, makes it possible to identify the list of components to familiarize yourself with their structure and composition to understand their main operating characteristics. Therefore, decision-making regarding reuse, remanufacturing, recycling, and adequate disposal of hazardous waste can be implemented.

The inventory was generated from a traditional set of tinting machines from the Brazilian brand Percolore, which manufactures them in its country, which are the AD-D8 Automatic Dispenser, which performs tinting colorant dosing, and the MX-NPE Gyroscopic Mixer, which promotes the homogenization of the paint, or base, after the addition of tinting colorants. The list of these components was provided by the manufacturer's engineering department, responsible for their project, and contains a brief description of each main item, its unit quantity and mass.

Flowchart of tinting machines business models in Brazil

The development of process flowcharts of business models for tinting machines presents a practical view of how they are sold in the country, as a product or as a service. The flowcharts, both for the linear sales economy and the circular rental economy, were designed based on business information from the manufacturer Percolore, which practices both modalities, due to the cultural demand of the market, but which has as its focus and priority the rental model.

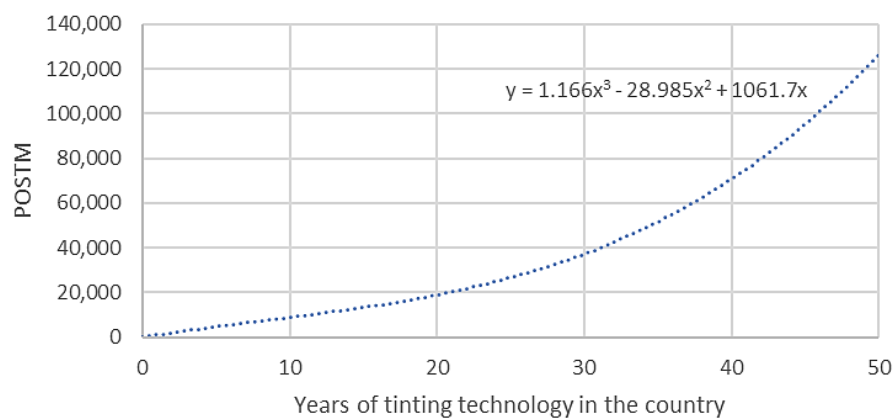
Extrapolation of inventory data can generate a current estimate of WEEE generation from this equipment, as well as the sector's growth perspective, to understand, from a macro view, at a national level, the opportunity to improve the management of this waste.

For the estimate, marketing data from the paint sector in Brazil and worldwide were considered. According to ABRAFATI and ANAMACO, architectural paints, at the retail level, are sold in specialized paint and construction materials stores in general, which in 2022 totaled around 150 thousand points of sale (POS) and that approximately 20% of them have tinting equipment, defined in this study as POSTM, since this technology arrived in Brazil in 1992. (ABRAFATI, 2022; ANAMACO, 2023; Van Beeck, 2019). Furthermore, it is known that, currently, in countries where the technology emerged, the presence of machines at points of sale represents 80%.

According to these data, we considered, in a hypothetical way, the constant of there being 150 thousand POS in Brazil, disregarding any type of growth or retraction in the sector, and varying only the percentage growth of POS, which are the POS that implemented the tinting machines. Considering linear growth, from 1992 to 2022, POSTM increased at a rate of 1000 POSTM/year, to reach 20% of total POS. From 2022 to 2042, they would grow by around 4500 POS/year, reaching 80% of the total POS, like the behavior occurring in the countries where the technology originally emerged. From the total data, year by year, of the two linear growths of POSTM admitted, sale and rental, presented in Table 1, a 3rd order polynomial equation, Equation (1), was found that best fit the results. This behavior is illustrated by Figure 1.

According to information from the manufacturer Percolore, which collaborates with the study, based on its experience and relationship with customers since 2004, the estimated useful life of the equipment is 5 years, both for the dispenser and the mixer. According to Percolore, it is approximately at the end of this period that the equipment undergoes more relevant maintenance or presents a technological or productivity gap that means that, in some cases, owners opt to purchase a new one instead of repairing it. Furthermore, the company, a pioneer in the PSS model for renting these machines in Brazil, uses this same time parameter to replace its equipment for the costumers. Equation (3) returns the number of equipment changes each year.

Figure 1: PDVT growth curve according to Equation 1.



Source: Authors.

Table 1: Curve fitting data by 3rd order polynomial equation.

	Year	Linear growth	Equation-Adjusted Growth
1991	0	0.00	0.00
1992	1	1,000.00	1,033.88
1993	2	2,000.00	2,016.79
1994	3	3,000.00	2,955.72
1995	4	4,000.00	3,857.66
1996	5	5,000.00	4,729.63
1997	6	6,000.00	5,578.60
1998	7	7,000.00	6,411.57
1999	8	8,000.00	7,235.55
2000	9	9,000.00	8,057.53
2001	10	10,000.00	8,884.50
2002	11	11,000.00	9,723.46
2003	12	12,000.00	10,581.41
2004	13	13,000.00	11,465.34
2005	14	14,000.00	12,382.24
2006	15	15,000.00	13,339.13
2007	16	16,000.00	14,342.98
2008	17	17,000.00	15,400.79
2009	18	18,000.00	16,519.57

2010	19	19,000.00	17,706.31
2011	20	20,000.00	18,968.00
2012	21	21,000.00	20,311.64
2013	22	22,000.00	21,744.23
2014	23	23,000.00	23,272.76
2015	24	24,000.00	24,904.22
2016	25	25,000.00	26,645.63
2017	26	26,000.00	28,503.96
2018	27	27,000.00	30,486.21
2019	28	28,000.00	32,599.39
2020	29	29,000.00	34,850.49
2021	30	30,000.00	37,246.50
2022	31	34,500.00	39,794.42
2023	32	39,000.00	42,501.25
2024	33	43,500.00	45,373.98
2025	34	48,000.00	48,419.60
2026	35	52,500.00	51,645.13
2027	36	57,000.00	55,057.54
2028	37	61,500.00	58,663.83
2029	38	66,000.00	62,471.01
2030	39	70,500.00	66,486.07
2031	40	75,000.00	70,716.00
2032	41	79,500.00	75,167.80
2033	42	84,000.00	79,848.47
2034	43	88,500.00	84,765.00
2035	44	93,000.00	89,924.38
2036	45	97,500.00	95,333.63
2037	46	102,000.00	100,999.72
2038	47	106,500.00	106,929.65
2039	48	111,000.00	113,130.43
2040	49	115,500.00	119,609.05
2041	50	120,000.00	126,372.50

Source: Authors.

Eight different scenarios were created, four types of sale and four types of rentals, to test the sensitivity of WEEE generation, and its extrapolation, regarding possible business variables: reuse, remanufacturing, recycling, and disposal. The scenarios were created with the help of the manufacturer Percolore through its skill acquired from experience, mainly in the rental business, to list in a qualitative way the probability of such scenarios occurring and their real feasibility. In addition, certain efficiencies were admitted in the remanufacturing and recycling processes. Considerations for each scenario are shown in Tables 2 and 3.

Table 2: Sales scenarios.

Scenario	% Reuse	% Remanufacturing	η Remanufacturing	% Recycling	η Recycling	% Disposal	Probability
Sale Type 1	0%	0%	50%	0%	50%	100%	High
Sale Type 2	10%	10%	50%	5%	50%	75%	High
Sale Type 3	20%	20%	50%	5%	50%	55%	Moderate
Sale Type 4	30%	30%	50%	5%	50%	35%	Low

Source: Authors.

Table 3: Rental scenarios.

Scenario	% Reuse	% Remanufacturing	η Remanufacturing	% Recycling	η Recycling	% Disposal	Probability
Rental Type 1	80%	10%	50%	5%	50%	5%	High
Rental Type 2	65%	20%	50%	5%	50%	10%	High
Rental Type 3	50%	30%	50%	5%	50%	15%	Low
Rental Type 4	35%	40%	50%	5%	50%	20%	Low

Source: Authors.

In the rental model, as it is a closed cycle business, it presents higher percentages of reuse, remanufacturing, and recycling, as the equipment necessarily returns to its original manufacturer. While on sale, this equipment may be traded in exchange, when accepted, for new to any manufacturer or dealer. When returning to the original manufacturer and the compatibility of parts is extremely high for reuse, remanufacturing is facilitated by knowledge of the technology and experience with the respective component. Finally, recycling is

more efficient due to knowing the construction form and assembly process of the equipment, which, consequently, helps in the disassembly and adequate separation of materials.

Finally, Equation (4) was developed, which calculates the amount of WEEE generated annually since the introduction of the technology in the country. The sum of these quantities over the years corresponds to the total WEEE generated during the entire period.

$$POSTM_n = (1.166n^3 - 28.985n^2 + 1061.7n) \quad (1)$$

$$NPOSTM_n = POSTM_n - POSTM_{n-1} \quad (2)$$

$$repl_n = NPOSTM_{n-5} + repl_{n-5} \quad (3)$$

$$WEEE_n = [(reman * (1 - \eta_{reman})) + (rec * (1 - \eta_{rec})) + (1 - re - reman - rec)] * m_{inv} * repl_n \quad (4)$$

Where:

$POSTM_n$: number of points of sale with tinting machines after n years of technology in Brazil.

$NPOSTM_n$: number of new points of sale with tinting machines in year n of technology in Brazil.

$repl_n$: number of tinting machines replaced in year n of technology in Brazil.

$WEEE_n$: mass of WEEE from tinting machines generated in year n of technology in Brazil.

re : % of WEEE reuse from replaced tinting machines.

$reman$: % of WEEE remanufacturing of replaced tinting machines.

rec : % of WEEE recycling from replaced tinting machines.

η_{reman} : remanufacturing efficiency.

η_{rec} : recycling efficiency.

m_{inv} : total mass of the WEEE inventory of tinting machines by POSTM.

RESULTS AND DISCUSSION

The results were obtained in accordance with the methodology adopted. Therefore, the WEEE inventory of tinting machines is presented to later serve as a basis for estimating generation over the years for each business model.

Estimated WEEE inventory of tinting machines

Tinting machines contain several electrical and electronic components to control its operation. The results presented come from Percolore brand equipment.

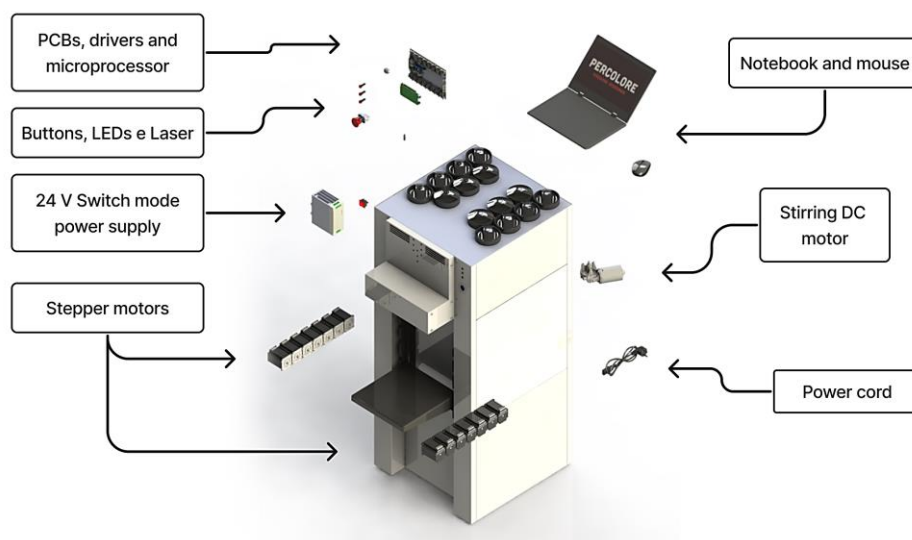
In automatic dispensers, the main objective of the system is to control, with precision and accuracy, pumps driven by stepper motors, through a PCB, powered by a switch mode power supply, which transforms the alternating current, at the input, into direct current of 24 V, at the output. The PCB receives instructions through a connection to a computer, in this case a notebook, which stores the paint formula database. In addition, other peripheral components are part of the set, such as a stirring motor, wires, buttons, cables, LEDs, etc. Table 4 presents the complete inventory, containing all components of the automatic dispenser, their quantities and respective masses, and Figure 2 displays the main components of the inventory, moved from their original positions, to assist in understanding the equipment and its operation.

Table 4: WEEE inventory of an Automatic Dispenser, model AD-D8, Percolore brand.

Component	Type / Material	Unit mass (kg)	Quantity	Unit	Total mass (kg)
Emergency button	220 V	0.1	1	unit	0.10
Power cord	220 V / 10 A	0.5	1	unit	0.50
Seesaw switch	220 V / 10 A	0.05	1	unit	0.05
Limit switch	Percolore	0.1	2	unit	0.20
Driver	Percolore	0.05	16	unit	0.80
220V Circuit Wires	5 mm	0.015	5	meters	0.08
24V Circuit Wires	4 mm	0.01	3	meters	0.03
Switch mode power supply	24 V / 10 A	1.0	1	unit	1.00
Laser	5 V Cross	0.1	1	unit	0.10
Led	24 V Red	0.1	3	unit	0.30
Microprocessor	Percolore	0.2	1	unit	0.20
DC Motor	24V Bosch	1.2	1	unit	1.20
Mouse	Multilaser	0.2	1	unit	0.20
Stepper motor	NEMA 23	1.2	14	unit	16.80
PCB (Printed Circuit Board)	Percolore	0.4	1	unit	0.40
Notebook	Multilaser	1.2	1	unit	1.20
Structure/fairing	Steel	50.0	1	unit	50.0
Pump and components	POM	0.1	14	unit	1.40
Canisters	POM	0.8	14	unit	11.20
Total					85.76

Source: Authors.

Figure 2: Main electrical and electronic components of an Automatic Dispenser, model AD-D8, Percolore brand.



Source: Authors.

The inventory for the automatic dispenser totals a mass of 85.76 kg, dominated by three main components: the steel structure/fairing, which alone accounts for over 58% of the total weight, the 14 NEMA 23 stepper motors, comprising nearly 20%, and the POM canisters, making up approximately 13%.

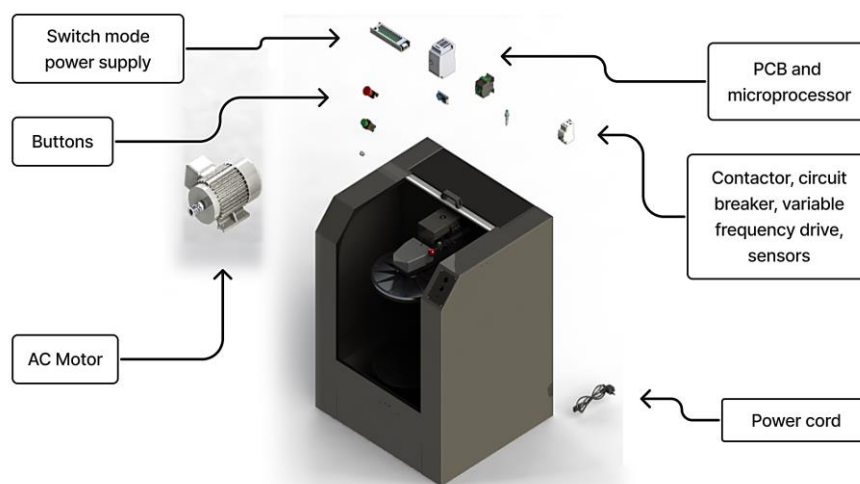
Mixers are tinting machines produced to homogenize the mixture of neutral base and colorants, after the dosing process in the dispenser, until reaching the final color. To do this, it has a mechanism driven by an alternating current motor, starting controlled by a variable frequency drive, which receives timing instructions from a PCB and microcontroller, powered by a switch mode power supply. Other peripherals make up the complete electronic system, such as cables, buttons, sensors, contactor, circuit breaker, among others. Table 5 displays the complete inventory, containing all components of the gyroscopic mixer, their quantities, and respective masses. Figure 3 shows some of the main components of the inventory, moved from their original assembly positions, to assist in understanding the equipment and its operation.

Table 5: WEEE inventory of an Automatic Dispenser, model AD-D8, Percolore brand.

Component	Type	Unit mass (kg)	Quantity	Unit.	Total mass (kg)
Emergency button	220 V	0.1	1	unit	0.10
General button	220 V	0.1	1	unit	0.10
Power cord	220 V / 10 A	0.5	1	unit	0.50
Limit switch	Micro Switch Z-15gqb 220 V	0.1	1	unit	0.10
Contactor	660 V / 18 A	0.4	1	unit	0.40
DR circuit breaker	4000 A	0.3	1	unit	0.30
220V Circuit Wires	5 mm	0.015	3	meters	0.05
24V Circuit Wires	4 mm	0.01	3	meters	0.03
Switch mode power supply	220 V / 12 V	0.5	1	unit	0.50
Fuse	10 A	0.1	1	unit	0.10
Variable frequency drive	Three-phase / 220 V / 1 hp	0.5	1	unit	0.50
PCB and Microprocessor	Percolore	0.4	1	unit	0.40
AC Motor	Three-phase / 380 V / 1 hp	20	1	unit	20.00
Potentiometer	10000 K	0.1	1	unit	0.10
Inductive sensor	220 V	0.1	1	unit	0.10
Timer	5 min / 120 W 5/220 V	0.2	1	unit	0.20
Structure/fairing	Steel	100.0	1	unit	100.0
Gyroscopic mechanism	Steel and aluminium	75.0	1	unit	75.0
				Total	198.48

Source: Authors.

Figure 3: Main electrical and electronic components of a Gyroscopic Mixer, model MX-NPE, Percolore brand.



Source: Authors.

The inventory for this machine totals a mass of 198.48 kg, with most of the weight concentrated in two primary components: the steel structure/fairing, which makes up over 50% of the total mass, and the gyroscopic mechanism, contributing around 38%. The AC motor, at 20 kg, also plays a significant role, accounting for about 10% of the overall weight.

Flowchart of tinting machines business models in Brazil

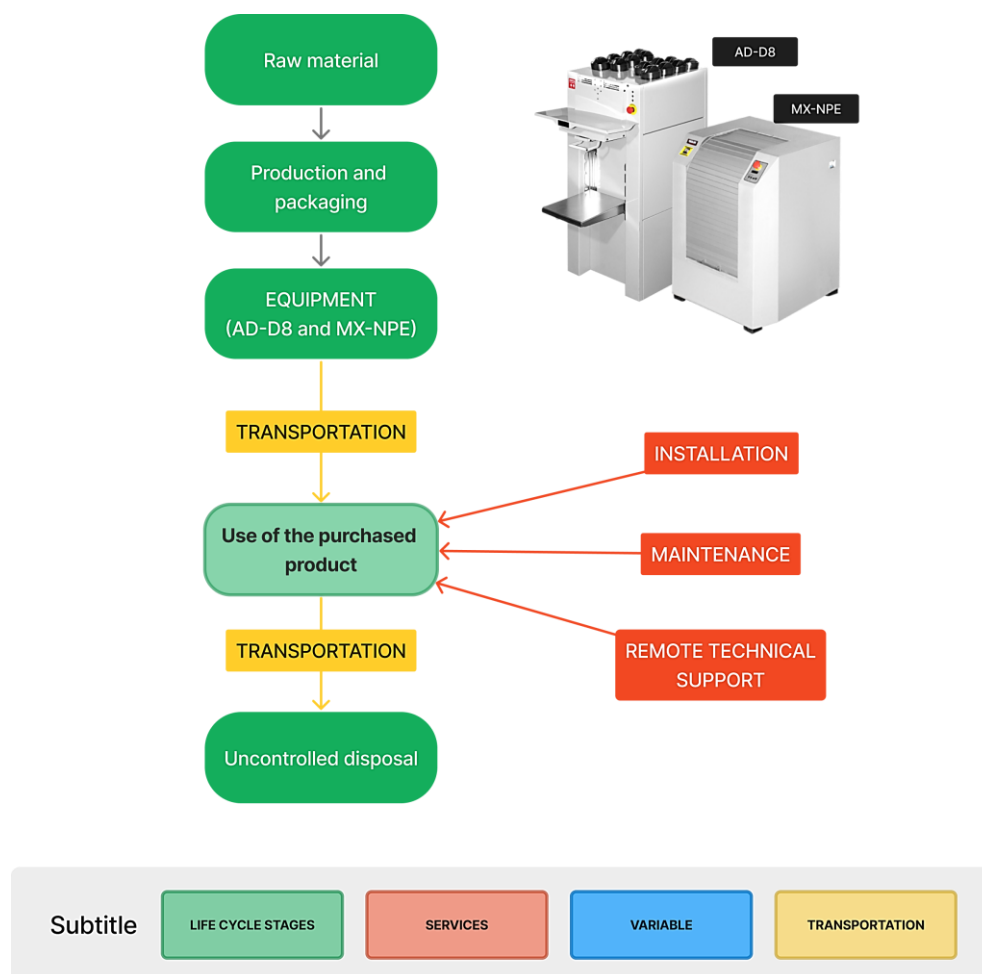
The sales process flowchart is traditionally a linear economic concept, in which the product is purchased for use and to be discarded at the end of its life, when, in most cases, it is replaced by a new one. The process flowchart of the PSS rental model is a circular economy concept. The product is purchased as part of a service system, where the company is responsible for delivery, installation, maintenance, technical support, and replacement when there is a production or technological lag. Figures 4 and 5 show the flows of these processes for tinting machines, from the Percolore brand, sold in Brazil.

Tinting machines, after purchase or rental and when replaced or discarded, have the particularity of requiring installation and uninstallation by a specialized technician, like that of a home or industrial air conditioner. Particularities like these, for this type of equipment, were reported by the Brazilian manufacturer Percolore.

In the rental model, when the contract ends or the estimated time for replacing the equipment is reached, the old equipment returns to the manufacturer, creating a closed cycle. Its return provides the possibility of reuse for a new rental contract, after cleaning and review, if the equipment still presents adequate efficiency and productivity. When reuse is not possible, other closed

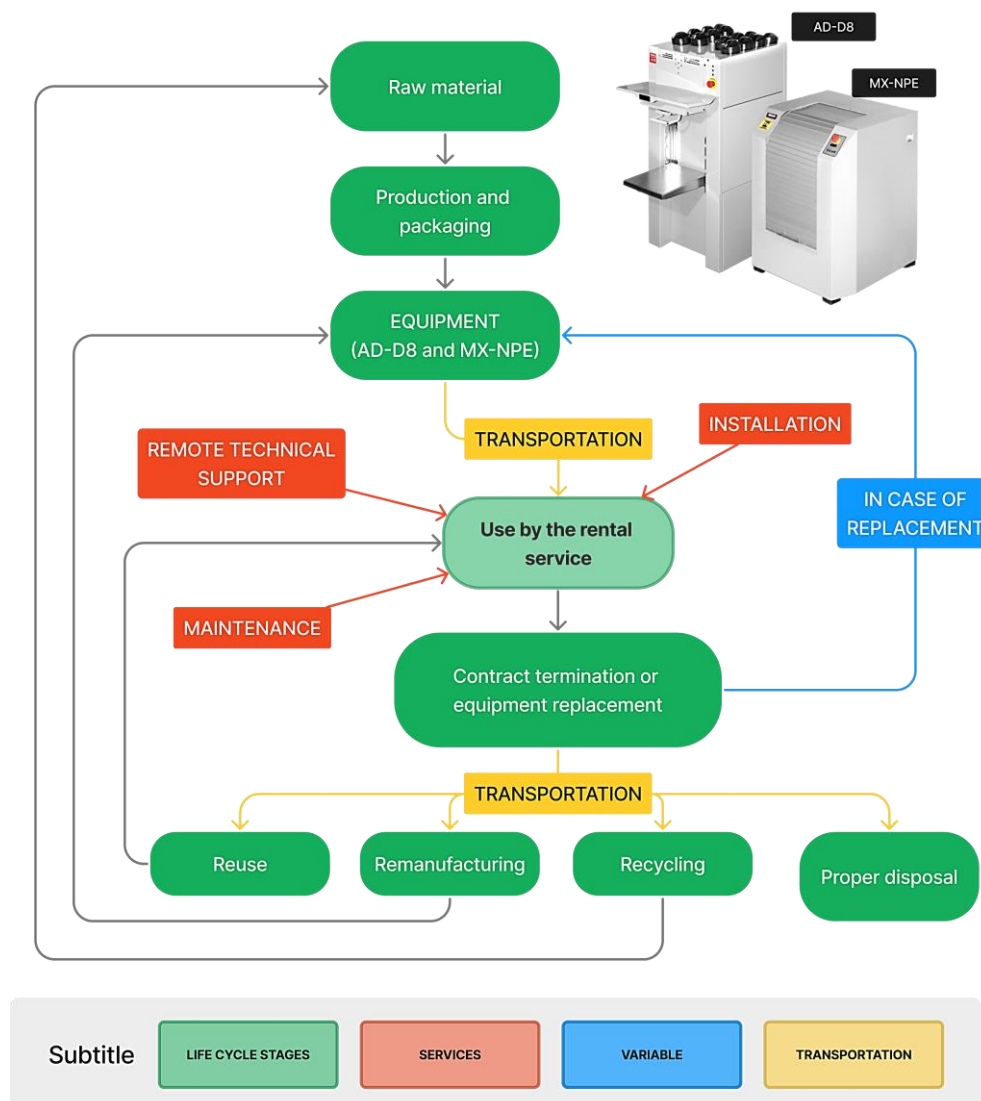
cycles include remanufacturing and, finally, recycling. In remanufacturing, the equipment undergoes repair and maintenance to be allocated again under a new contract, while in recycling it is dismantled, and its materials are separated and returned to the process as raw materials.

Figure 4: Flowchart of the tinting machines sales process.



Source: Authors.

Figure 5: Process flowchart of the tinting machines rental process.



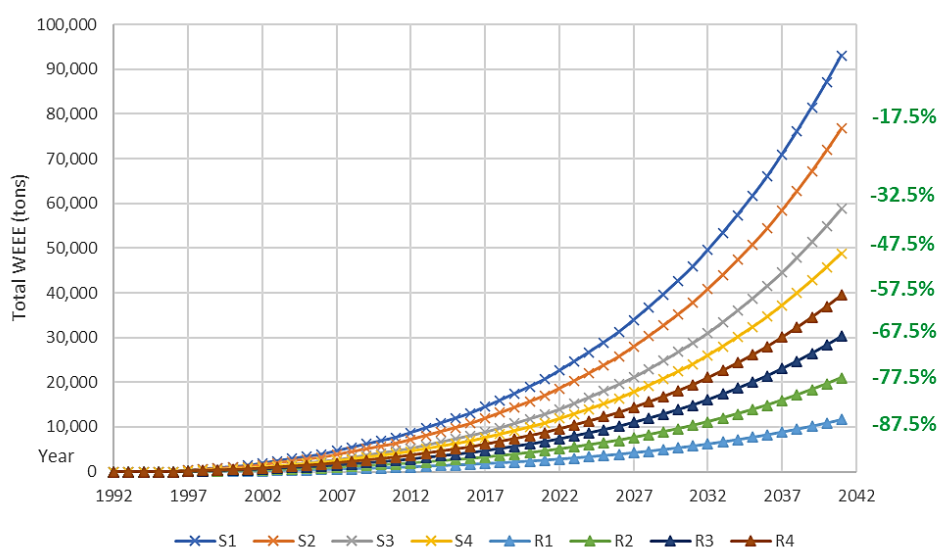
Source: Authors.

Estimated generation of WEEE from tinting machines in Brazil

The methodology adopted for the estimation made it possible to analyze the behavior of WEEE generation in the country since the introduction of tinting technology. From equation (4), the total mass of WEEE generated annually for the chosen 50-year period was found. Figure 6 illustrates the behavior. The legend represents the scenarios, where, for example, S1 refers to the Sale Type 1 scenario, R2 refers to the Rental Type 2 scenario.

The Sales Type 1 scenario represents the most traditional form of business for this equipment, in the linear economy format. Trivially, it is the scenario that represents the highest generation of WEEE, because it does not plan any percentage of remanufacturing or recycling of these components as it does not take advantage of the used equipment in exchange for new ones.

Figure 6: Total WEEE from tinting equipment over the years.



Source: Authors.

The Type 2, Type 3 and Type 4 Sales scenarios result in a reduction of 17.5%, 32.5% and 47.5% of WEEE, respectively, and a slight introduction of indices, even if small, reuse, remanufacturing, and recycling, represent an important reduction in the total mass of WEEE, especially in the perspective of growth over the years. In the Sale Type 2 scenario, which considers 10% reuse, 10% remanufacturing and 5% recycling, in the year 2042 the total WEEE could be reduced by 16,290 tons, compared to the traditional Sale Type 1 scenario which does not take advantage of the used equipment when exchanging it for new equipment.

As percentages of reuse, remanufacturing and recycling of components are inserted into the scenarios, as expected, reductions in the generation of WEEE are observed. In the case of sales scenarios, the discard percentages are higher as the modality cannot guarantee the closed-cycle standardization that is obtained in rental scenarios. There is no guarantee that the equipment will return to its original manufacturer, which would make better use of the components due to equipment compatibility. Therefore, sales scenarios, from the perspective of WEEE generation, heavily depend on consumer behavior. Every five years, consumers may choose to switch tinting equipment manufacturers, which often results in the old equipment being discarded or traded in for new equipment from the new brand.

It is also important to highlight that the consumer who contracts the rental service is not obliged to continue with the same brand over the years, throughout equipment replacements, traditionally every five years. The consumer continues to be free to choose to change equipment brands over the years if more brands offer the service. However, the great contribution of the rental service is because the equipment must be returned to the original manufacturer, who is its owner.

Therefore, in the rental model, the improvements are significant and reach an 87.5% reduction in the Rental Type 1 scenario, which considers 80% reuse, 10%

remanufacturing and 5% recycling, totaling a reduction of around 81,452 tons of WEEE at the end of the studied period. As the rental model offers a service, equipment can, and should, be reused without any implications, if it fulfils its function. Therefore, the percentage of reuse is very high as it is equipment designed for this type of modality. The reuse percentage represents the proportion of electrical and electronic equipment in tinting machines that can be reused after simple cleaning and review, that is, that do not require remanufacturing, repair, or any other severe maintenance. Furthermore, remanufacturing is facilitated by standardization and experience with components and recycling is optimized by knowing the best ways to disassemble equipment.

Product design is fundamental to the efficiency of the service in which it is included. In the rental model, the emphasis on reusing components is notable, as the equipment is designed from the beginning with the perspective of efficient and sustainable operation, so that its assembly and disassembly is facilitated.

CONCLUSION

The construction of a WEEE inventory of tinting machines, the mapping of its trajectory, through possible business flowcharts, both sales and rental services, together with adjusted data on market behavior, made it possible to present a hypothetical panorama of the total WEEE over a 50-year period, according to practical business scenarios.

Although the calculation basis for the total WEEE estimate uses the inventory of just one manufacturer of tinting machines, which collaborated with the research, the results, in addition to be unprecedented as it is the first study on the subject, illustrate the behavior of the sector reliability, since the technology used for tinting machines to perform its function has little fluctuation between brands, with a small variation between electrical and electronic components for a machine of similar size. Additionally, it is common for manufacturers to not want to disclose an inventory of their electrical and electronic machine design. Unlike the data obtained in this work, which were provided by the Percolore brand, directly from the equipment design data, it would be necessary to completely disassemble equipment to measure the masses in practice.

The mass of WEEE from tinting machines that equips a POSTM is relevant, reaching around 284 kg, and its potential for reuse and remanufacturing is high, as long as it has adequate reverse logistics, which in the flows designed and operated is obtained efficiently only in the business plan that includes the rental service.

Applying the STS and SDG framework to these results, it becomes clear that the evolution of tinting systems and their diffusion in the Brazilian architectural paints sector involve dimensions that go beyond technological innovation. The incorporation of tinting machines has improved efficiency and customization in paint commercialization, but it has also created new environmental liabilities related to end-of-life management. The comparative scenarios developed in this study show that the rental-based business model, by enabling greater reintegration of components and facilitating remanufacturing and recycling, directly contributes to achieving strategic SDGs. The estimated reduction of up to 87.5% in WEEE generation compared to linear sales highlights its relevance as an innovation aligned with SDG 12 (Responsible consumption and production) and

SDG 9 (Industry, innovation, and infrastructure). At the same time, the reduction of environmental impacts and the extension of equipment lifetime relate to SDG 13 (Climate action) and SDG 11 (Sustainable cities and communities). Therefore, the adoption of circular business models in the tinting sector should not be understood only as an economic strategy, but as a socio-technical innovation capable of aligning industrial practices with broader social demands.

Considering that the rental service model is generally offered only by the manufacturer Percolore, with rare exceptions, and that all other brands work in Brazil with a focus entirely on the linear sales economy, it can be believed that the total WEEE generated to date falls within a value between the Type 1 Sale or Type 2 Sale scenarios, that is, with low rates of reuse, remanufacturing or recycling of these components. Therefore, for the year 2023, an average of the accumulated WEEE of the scenarios would be approximately 22,471 tons, and by the end of 2042, if the practice of the circular economy obtained by the rental model is not introduced, it would reach around 84,942 tons. Furthermore, these values are for the total waste disposed of in an unknown manner or location.

Certainly, considering the industrial ecology strategy and a business model that guarantees circularity is crucial to mitigate environmental impact and maximize the reuse and recycling of WEEE. Effective management of reverse logistics not only allows you to significantly reduce inappropriate disposal but also helps to achieve significant potential for reuse and remanufacturing of these tinting machines through environmental tools of industrial ecology. By investing in rental strategies, the potential for minimizing the volume of WEEE discarded is visible, promoting a transition to a more sustainable and responsible circular economy. In this model, machine manufacturers and consumers create an industrial symbiosis, in which each has an important responsibility. For example, consumers are responsible for good use and maintenance of the machine to maximize its reuse after return. It is essential that more companies adopt similar practices and that consumers increasingly evaluate this type of service, consolidating a collective movement in favor of environmental preservation, the intelligent use of available resources, and the mitigation of greenhouse gas emissions.

Considering that the lack of studies and estimates evaluating the tinting scenario through the adoption of circular economy strategies implies the novelty of the work and prevents comparisons of the results, it is reasonable to admit that the promotion of the circular economy reduces the generation of WEEE through better management of resources derived from EEE. The methodology adopted thus allowed for the presentation of relevant results and highlighted this important opportunity in the sector.

ACKNOWLEDGEMENTS

The authors would like to thank CAPES and CNPq for the Ph.D. student scholarship, and CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for the Research on Technological Development DT2 grants and extend our gratitude to the team at Percolore for their extensive interest and support in completing this project.

REFERENCES

ABRAFATI – Brazilian Association of Paint Manufacturers. (2022). O setor de tintas no Brasil. Available at: <https://abrafati.com.br/setor-de-tintas/dados-do-setor>. Accessed on: December 10, 2023.

Al-Thani, N.; Al-Ansari, T. (2021). Comparing the convergence and divergence within Industrial Ecology, Circular Economy, and the Energy-Water-Food Nexus based on resource management objectives. Sustainable Production and Consumption, 27. <https://doi.org/10.1016/j.spc.2021.04.008>

ANAMACO – National Association of Construction Material Traders. (2023). About ANAMACO. Available at: <https://www.anamaco.com.br/sobre-anamaco>. Accessed on: December 13, 2023.

Análise Setorial da Indústria de Tintas. (1998). Panorama Setorial da Gazeta Mercantil. Gazeta Mercantil.

Blomsma, F.; Kjær, L.; Pigosso, D.; McAloone, T.; Lloyd, S. (2018). Exploring Circular Strategy Combinations – towards Understanding the Role of PSS. Procedia CIRP, 69, 752-757. <https://doi.org/10.1016/j.procir.2017.11.129>

BRAZIL. (2020). Decree No. 10,240, of 12 February 2020. Regulates Law No. 12,305/2010 and complements Decree No. 9,177/2017. Available at: http://www.planalto.gov.br/ccivil_03/_ato2019-2022/2020/decreto/D10240.htm. Accessed on: December 10, 2023.

CETEM – Mineral Technology Center. (2023). R3minare. Available at: <https://www.gov.br/cetem/pt-br/pesquisa-e-desenvolvimento/reminare>. Accessed on: December 13, 2023.

Dagnino, R.; Brandão, F. C.; Novaes, H. T. (2004). Sobre o marco analítico-conceitual da tecnologia social. Ciência e Cultura, 56(4), 35-38.

Erkman, S. (1997). Industrial ecology: An historical view. Journal of Cleaner Production, 5, 1-10. [https://doi.org/10.1016/S0959-6526\(97\)00003-6](https://doi.org/10.1016/S0959-6526(97)00003-6)

Godin, B. (2006). The linear model of innovation: The historical construction of an analytical framework. Science, Technology, & Human Values, 31(6), 639–667.

Guarnieri, P.; Camara e Silva, L.; Levino, N. A. (2016). Analysis of electronic waste reverse logistics decisions using Strategic Options Development Analysis methodology: A Brazilian case. *Journal of Cleaner Production*, 133, 1105-1117. <https://doi.org/10.1016/j.jclepro.2016.06.025>

Kangas, P.; Seibel, G. (2018). An industrial ecology teaching exercise on cycling e-waste. *Ecological Modelling*, 371. <https://doi.org/10.1016/j.ecolmodel.2017.12.008>

Linhares, H. (2018). 16 melhores sistemas tintométricos do Brasil: Máquinas tintométricas mais vendidas no Brasil. Available at: <http://sohelices.com.br/16-melhores-sistemas-tintometricos-do-brasil>. Accessed on: December 20, 2023.

Lin, R. W. A. (2021). The Development of a Universal Dispersant For Organic and Inorganic Pigments In Waterborne Coatings. Scholar Bank at NUS Repository.

Lowe, E. (2001). *Eco-Industrial Park Handbook for Asian Developing Countries*. Indigo Development.

Marcelo, C. P. (2013). Optimização da aprovação de produtos para afinação nas tinting machines. Available at: <https://run.unl.pt/handle/10362/10805>

Martin, M.; Heiska, M.; Björklund, A. (2021). Environmental assessment of a product-service system for renting electric-powered tools. *Journal of Cleaner Production*, 281, 125245. <https://doi.org/10.1016/j.jclepro.2020.125245>

Micheline, G.; Moraes, R.; Nobre da Cunha, R.; Costa, J.; Ometto, A. (2017). From Linear to Circular Economy: PSS Conducting the Transition. *Procedia CIRP*, 64, 2-6. <https://doi.org/10.1016/j.procir.2017.03.012>

Monfardini, L. (2013). Sistemas Tintométricos e Colorantes: Automatização consolidada. *Revista Paint & Pintura*, 179, 70-71. Available at: <https://www.paintshow.com.br/edicao/paintpintura/179/files/assets/basic-html/page70.html>. Accessed on: December 20, 2023.

Motta, J. P. S. P. de; Carijó, R. de S. (2013). Simbiose Industrial: Um estudo de caso para a indústria de cosméticos no município do Rio de Janeiro. Available at: <http://hdl.handle.net/11422/9084>

Neto, G. O.; Correia, A.; Schroeder, A. (2017). Economic and environmental assessment of recycling and reuse of electronic waste: Multiple case studies in Brazil and Switzerland. *Resources, Conservation and Recycling*, 127, 42-55. <https://doi.org/10.1016/j.resconrec.2017.08.011>

United Nations (UN). (2015). Transforming our world: The 2030 Agenda for Sustainable Development. New York: UN.

Ottoni, M.; Dias, P.; Xavier, L. H. (2020). A circular approach to the e-waste valorization through urban mining in Rio de Janeiro, Brazil. *Journal of Cleaner Production*, 261, 120990. <https://doi.org/10.1016/j.jclepro.2020.120990>

Pan, X.; Wong, C.; Li, C. (2022). Circular economy practices in the waste electrical and electronic equipment (WEEE) industry: A systematic review and future research agendas. *Journal of Cleaner Production*, 365, 132671. <https://doi.org/10.1016/j.jclepro.2022.132671>

Pouyamanesh, S.; Kowsari, E.; Ramakrishna, S.; Chinnappan, A. (2023). A review of various strategies in e-waste management in line with circular economics. *Environmental Science and Pollution Research*, 30, 1-29. <https://doi.org/10.1007/s11356-023-29224-y>

Rose, E.; Nikam, P.; Joshi, A. (2019). Effect of ingredients of accent base on shade development in point of sale tinting. *Color Research & Application*, 45. <https://doi.org/10.1002/col.22439>

Ruiz, R. H. (2013). *Ecologia Industrial: Avaliação do Ecopolo Industrial de Santa Cruz, no Rio de Janeiro*. UFRJ. Available at: <http://hdl.handle.net/11422/9305>

Santos, G. O. et al. (2023). Concretos sustentáveis à luz da ciência, tecnologia e sociedade. *Revista Tecnologia e Sociedade*, 20(51).

Silva, C. L. (2018). Proposal of a dynamic model to evaluate public policies for the circular economy: scenarios applied to the municipality of Curitiba. *Waste Management*, 78, 456–466.

Silva, C. L.; Bolson, C. (2018). Public Policy for Solid Waste and the Organization of Waste Pickers: Potentials and Limitations to Promote Social Inclusion in Brazil. *Recycling*, 3(40).

Silva, J. L. B.; Costa, F. R. (2025). Diagnóstico ambiental da região geográfica imediata de Cajazeiras-PB: aplicação de geotecnologias e indicadores ambientais. *Revista Tecnologia e Sociedade*, 21(65), 304-331. <https://doi.org/10.3895/rts.v21n65.19507>

Silva, N. V. C. et al. (2025). Processo participativo para construção dos Objetivos de Desenvolvimento Urbano Sustentável no Brasil. *Revista Tecnologia e Sociedade*, 21(65), 35-59. <https://doi.org/10.3895/rts.v21n65.19502>

Souza, A.; Gianezini, M.; Watanabe, M. (2018). Panorama do setor de tintas no Brasil: mercado, gestão e tecnologias para o segmento de tintas imobiliárias. *Revista Gestão Inovação e Tecnologias*, 8, 4430-4446. <https://doi.org/10.7198/geintec.v8i3.1110>

Van Beeck, A. (2019). A transformação do setor de material de construção. Available at: <https://mercadoeconsumo.com.br/01/10/2019/artigos/a-transformacao-do-setor-de-material-de-construcao/>. Accessed on: December 13, 2023.

Yu, X.; Zhang, Y. (2021). An Economic Mechanism of Industrial Ecology: Theory and Evidence. *Structural Change and Economic Dynamics*, 58. <https://doi.org/10.1016/j.strueco.2021.03.008>

Zaparolli, D. (2009) Sistema tintométrico - preço e despreparo dos lojistas dificultam crescimento das vendas. Accessed on December 19, 2023. Available at: <https://www.quimica.com.br/sistema-tintometrico-preco-e-despreparo-dos-lojistas-dificultam-crescimento-das-vendas>

Recebido: 24/09/2025

Aprovado: 30/09/2025

DOI: 10.3895/rts.v21n66.20905

Como citar:

SOUZA, Marcelo Angelo Taparello de; ZARO, Janiel Rodrigo; MORAES, Carlos Alberto Mendes. WEEE management of tinting machines in the context of industrial ecology and the circular economy in Brazil. *Revista Tecnologia e Sociedade*, Curitiba, v. 21, n. 66, p. 273-296, seção temática, 2025. Disponível em:

<https://periodicos.utfpr.edu.br/rts/article/view/20905>

Acesso em: XXX.

Correspondência:

Direito autoral: Este artigo está licenciado sob os termos da Licença Creative Commons-Atribuição 4.0 Internacional.

