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A FRAMEWORK FOR SECONDARY MATERIAL CIRCULARITY ASSESSMENT

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ABSTRACT: Recent efforts have been undertaken to structure technical standards that define related concepts and regulate circular economy practices in recovering value from post-consumer products and materials. Some challenges emerged during the process and motivated the consolidation of definitions and synergy between the interested parties regarding the high level of importance guaranteeing the supply of critical raw material. The potential of recovery of secondary material from waste stream is also evaluated. The diversity of materials and products represents one of the main issues during the standard elaboration process. Therefore, aiming to contribute technically to the structuring of a framework for material circularity analysis, it is proposed a comparative analysis of the circularity potential of different waste streams, enabling weighted results between countries or regions according to different dimensions evaluated.

Keywords: circular economy, waste streams, circularity potential

1. INTRODUCTION

The vision of a circular economy is to provide adequate solutions for the reduction, efficient, and effective use of virgin resources, and to prevent harmful releases, losses and environmental degradation when meeting consumption needs. Therefore, the International Standard Organization (ISO) has been responsible for structuring six technical standards that will be published by the end of 2024. Among the standards, concepts such as the definitions of waste, resources, efficiency, secondary materials and subsistence, along with others, are proposed. One of the main contributions for the development of these standards is the alignment and adoption of definitions which makes it possible to harmonize concepts between standards and, subsequently, contributing with regulations in different countries.

The type and sequence of activities and processes related to resources recovery are defined as the recovery pathway. The motivation for the decision making about one specific pathway is based on economic, social, technical or regulation requirements. The chosen recovery pathway can be considered more or less intensive in terms of costs, energy consumption or logistical routes according to the available infrastructure, suppliers, market prices and the reverse network of agents.

The waste management stages rely on different agents that work directly or indirectly with the collected materials. Another relevant aspect is the need to manage the environmental and social risks inherent to waste management. Waste categories confer a greater or lesser degree of occupational risk due to their properties or the way in which they are collected, stored, sorted or handled. Among the agents whose activities are directly related to waste handling are collection and sorting, which deserve greater attention in terms of establishing procedures to consider hazardous substances care or risk.

The wide variety of waste streams still remain an important challenge for the consolidation of regulations and standards related to circular economy. The ISO definition for organization reunite individual and collective instances such as sole-traders, companies, corporations, public and private organizations, NGO's. These organizations can be specialized in waste streams management according to regional characteritics or regulatory requirements. However, the circularity potential of waste streams as recoverable resources is not well established.

Since the elaboration of specific policies are being proposed in order to guarantee the supply of critical material, secondary material is emerging as a potential solution for resources shortage. In this article we discuss the aspects related to the management of different waste streams and propose a framework for secondary material assessment as a tool for supporting the decision making at different levels, regions and countries, as a contribution for circular economy principles.

2. MATERIAL MANAGEMENT AND CIRCULAR ECONOMY

2.1 Circular economy concept

Circular economy is defined in the FDIS version (ISO/FDIS 59004, 2024), as the "economic system that uses a systemic approach to maintain a circular flow of resources by recovering, retaining or adding to their value, while contributing to sustainable development." The use of virgin resources shall be kept as low as possible and the waste, losses and releases minimization as premises of circular economy definition. Additionally, waste streams are considered as recoverable resources kept in both stocks and flows through the value chain.

Previous concepts such as industrial symbiosis and industrial ecology were the root of the circular economy, since they first considered the use of waste streams as potential resources. Recently, the end-of-waste concept, introduced in Europe, also inspired important discussions related to the waste definition and the value assignment transition to waste streams and feasible secondary resources.

In a nutshell, identifying and analyzing the potential of waste streams along value chains is a challenge that requires information from economic and technical data and regulatory requirements. This alignment differs depending on the environment, countries and regions of the world. It adds greater complexity to the decision-making process that will support the installation of secondary material processing units.

2.2 Secondary materials

Secondary materials or resources are defined in the FDIS version of ISO 59004:2024 as recovered resources, which means, those resources that were "obtained from one that has already been processed or used". Other important contribution in the standard is that waste definition imply that the recovered resource may provide no value to the holder.

This definition elevates the position of the holder as the one who will define, in the first instance, the destination of waste. However, most of the time, the holder, whether small or large consumer, is unaware of the legal obligations or technical implications of inappropriate waste disposal. As an example, data on the disposal of e-waste shows that only 17% of this category of waste is correctly allocated and documented worldwide (Forti et al., 2020).

Relevant concepts likewise consider that non-destructive processes are intended for the recovery of parts, components and co-products through reuse, repair, reconditioning and remanufacturing. On the other hand, destructive processes aim to recover materials through recycling techniques, for the most part, and there is no concern with maintenance of functionality. According to Lingyu Sun et al. (2016), pollutants released by hydrometallurgy processes can contaminate the environment by the wastewater and gases emissions, thus requiring appropriate mitigating measures.

The recovery of secondary materials can significantly contribute to reducing the uncertain supply of critical and strategic materials around the world (Xavier et al., 2021). One of the success cases, for example, is the recovery of aluminum cans from the beverage retail market in Brazil, which has already reached the impressive mark of 99% in collection, recovery of recycled material and manufacturing of new cans in 2021 (Brazil, 2022). However, the lack of information to consumers about environmentally appropriate disposal, the lack of traceability of post-consumer product movement, as well as data on the risk of some waste, compromise knowledge about the recovery potential of secondary materials.

The guidance of critical and strategic materials is one of the mechanisms that can contribute to the management of secondary materials. To this end, knowledge and analysis of different waste streams can reduce the degree of complexity, support regulation and enable efficient waste management.

3. METHODS

Studies contemplating the classification and categorization of waste tend to qualify as special and non-urban waste those that demand management attention, requiring specialized and expensive treatment methods. In order to identify and classify the waste streams, it was suggested a tentative list of types of waste according to different scientific studies (Dodampegama et al., 2023; Wiśniewska et al., 2024; Kannan et al., 2024). The methodological approach was divided into three stages. The first stage consisted of identifying and grouping the types of waste most found according to consumption. The second stage consists of structuring and classifying the waste. The third and final stage consists of the circularity assessment material. All steps are detailed below. Categorization is perceived as a form of grouping in accordance with similarities between the items in each category, while classification implies the attribution of grades considering greater or lesser adherence to the analysed characteristics.

3.1. Material categorization

At this stage, 32 priority categories were identified and grouped into four levels of complexity, as follows: (i) Minimum or no complexity: single-material products or easy segregation of materials; (ii) Low to medium complexity: products with a low diversity of materials or substances and an easy level of segregation; (iii) Medium to high material complexity: products with a significant diversity of materials and a significant level of complexity for segregation; (iv) High material complexity: products with a great diversity of materials and high complexity of segregation of materials and substances.The materials grouping was based on the physical and chemical composition characteristics of the products, as well as the estimated feasibility for the segregation of materials or substances.

3.2. Material classification

The second stage consists of classifying the categories. The weights definition considered the following criteria: disassembling and/or sorting capacity level, material complexity level and technological recovery solution costs level, ranging from 1 (low level) to 4 (high level).

In the following step, the degree of impact was assigned, ranging from 1 (low impact) to 10 (high impact), according to the criteria, as follows.

Dimension	Definition
Social	Consider the impact in job creation and social commitment in separation and disposal for the material groups
Economic	Consider the economic value of material groups, balancing the market value and decontamination requirements
Environmental	Consider the environmental impact of material groups (balance between environmental impact and recyclability)

Technological	Consider the technological requirements to recover the material groups
Regulatory	Consider the regulatory requirements to recover the material groups

3.3 Circularity assessment

The circularity assessment considered both material grouping and material classification in order to enable the measurement of the degree of circularity. The proposed weighting is based on the established dimensions, namely: social, economic, environmental, technological and regulatory.

As the attribution of weights and scores consider the area of analysis (region, country or municipality), a customized analysis is possible based on the established criteria. The formula used to consolidate the value equivalent to the material circularity score (CS) is as follows (Formula 1).

CS = sum of dimension scores + (disassembling/sorting capacity index * material complexity level index * technological recovery solution costs) (1)

The matrix results in a value for each of the 32 categories, enabling comparative analysis and even scenario analysis, also considering the possibility of temporal analysis based on the consolidation of time series data.

4. RESULTS AND DISCUSSION

Waste management is carried out by a group of agents that act in a more or less integrated way, while the types of waste present a significant diversity and forms of processing. The categorization and classification of waste requires in-depth knowledge of the specificities of products and materials, as well as the influence of dimension factors, such as those considered in this study: social, economic, environmental, technological and regulatory. In this way, studies and expert opinion were considered both for the survey of the 32 categories of waste and for the attribution of weights and scores.

The results show, even at a preliminary stage of the analysis, that the degree of complexity of post-consumer products and components is related to the diversity of materials that compose them, as well as the chemical or physical diversity and complexity. Single-material products have shorter disassembly and separation times compared to multi-material products with an intricate degree of composition.

The attribution of weights and scores to the analyzed dimensions and accounting using the formula resulted in a value that suggests the degree of circularity. The evaluation can occur in a way that considers the evaluation of the same scenario over time, taking into accounts adjustments towards the enactment of regulations that may restrict or encourage a certain product or process, for example. Another analysis may consider the composition between countries or cities with the intention of identifying points of convergence or even delimiting the impact of decisions in the different dimensions analyzed.

The analysis is based on the items evaluated for a delimited area and allows comparison, for example, between countries, cities or regions. In this way, the tool proves to be versatile in the sense of allowing customizations and contributing to support the decision-making process as the comparative analysis makes it possible to identify drivers for better scores and assign penalties for lower scores.

			Material and products categories																		
			Minimum or no complexity										Low to medium complexity								
Products			Cork	Paints and vanishes (aromatic compounds)	Glass (flat)	Glass (tempered)	Plastics	Fiber Products (cartons & paper)	Styrofoam board	Oil / Cooking oil	Soil (sand, clay, etc)	Scrap Steel		Leather	Batteries (all types)	EoL Vehicles	Solar Panels	Lamps	Beverage bottles	Masks	Monitors and flat panels
Weight	assembling and/or sorting capacity (1-4)		1	2	1	2	1	1	2	2	1	2		3	2	2	3	2	1	2	3
	Material complexity level (1-4)		1	3	1	3	3	1	3	1	2	1		2	3	3	3	3	3	4	2
	hnological recovery solution costs (1-4)		2	1	1	2	2	3	2	1	2	1		3	1	3	4	3	2	2	3
Dimension (1-10)	Social	1	3	7	2	13	7	4	13	3	5	3	2	20	8	20	38	20	8	18	20
	Economic	2	4	14	3	14	8	5	14	4	6	4	4	22	10	10	40	22	10	20	22
	Environmental	1	3	13	2	13	7	4	13	3	5	3	6	24	12	12	42	24	12	22	24
	Technological	2	4	14	3	14	8	5	14	4	6	4	4	22	10	10	40	22	10	20	22
	Regulatory	2	4	14	3	14	8	5	14	4	6	4	6	24	12	12	42	24	12	22	24
	CIRCULARITY SCORE		**18**	**62**	**13**	**68**	**38**	**23**	**68**	**18**	**28**	**18**		**112**	**52**	**64**	**202**	**112**	**52**	**102**	**112**

Figure 1. Material circularity assessment framework simulation.

The findings suggest that products coding is an important step of traceability that can support circularity analysis through the mass balance equation. To exemplify, the product HS code 6404.11.00 (Training Shoes) is related to the following materials HS codes: 4004.00.00 (Rubber Sole Chips), 6310.00.00 (Textile Upper Chips) and 4115.20.00 (Leather Upper Chips). Tracing these materials along the value chain it is possible to amplify the circularity level assessment.

Improving the tool with the inclusion of HS codes can enable a more accurate analysis and, at the same time, result in indicating the potential for improving processes and products in order to comply with the principles of the circular economy through materials management. The creation of new HS codes for secondary materials instead of these being classified as waste, parings or rags will be essential for upgrading their status in the value chain.

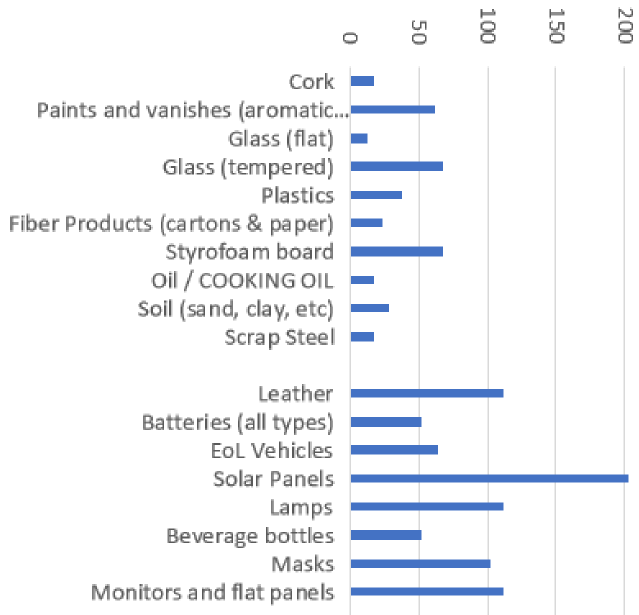

Figure 2. Material circularity scores simulation.

5. CONCLUSIONS

The definition of critical and strategic materials has been prioritized in public policy in different countries as a way of guaranteeing supply and mitigating the economic impact on resource management for production processes. In this way, the recovery of secondary resources is considered as an important resolution, but it lacks reliable consolidated information to support the decision. The purpose of assigning degrees of circularity to processes and products is to enable the understanding of the potential to comply with the principles of circularity and, in this way, highlight best practices. However, little attention has been shown in the literature to the recoverable materials or resources that will effectively be the basis for capturing value according to the principles of the circular economy.

Finally, the proposal and simulation of the circularity assessment framework proves to be a tool that enables the comparative analysis of materials as a way of identifying best practices and also products or materials that need to be monitored and require processes to improve the degree of circularity. Future studies may refine data input, considering, for example, the specification of encodings, the relationship between products and materials based on mass balance and the consideration of the importance of dimensions in different economic blocs or regions.

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