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Measuring Waste Circularity: Moving Towards a Circular Economy

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Abstract: The linear production model, which extracts raw materials and discards products, is reaching its limits. Therefore, it is necessary to find solutions to prevent waste. Circular economy advocates the idea of keeping materials in use for as long as possible; one of its principles is eliminating waste. This study aimed to measure the circularity of waste in a flat glass manufacturing industry through an indicator that compared different scenarios within the company. Comparisons were made between the company's real scenario and its worst and best-case scenarios. The indicator measured the company's waste circularity and proved useful for implementing improvements based on waste reuse. The indicator calculation implied that the company achieved 83% of the ideal scenario, where all waste is reused.

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Introduction

Industrialization has brought numerous benefits to society; however, it has also caused various environmental impacts, such as pollution of rivers, seas, and air and climate change, among others, due to current production and consumption patterns (TSENG *et al.*, 2018). This can lead to the depletion of natural resources (MICHELINI *et al.*, 2017).

The current socioeconomic model is based on a linear economy, in which companies produce goods and consumers use and discard them (MICHELINI *et al.*, 2017), rooted in the unequal distribution of wealth concentrated in more developed regions (SARIATLI, 2017).

In the linear production model, one of the main consequences is the generation of waste resulting from the extraction of raw materials, production, consumption, and disposal, accelerated by economic development, whose end products not only have a short lifespan but are also disposed of at the end of it (FELLNER *et al.*, 2017).

With increasing population and rapid economic development, the linear production model is reaching its limits, and problems such as material waste are becoming more common, leading to resource depletion (ELLEN MACARTHUR FOUNDATION, 2013).

The circular economy emerges as an alternative to the linear economy, with a cyclic flow model aimed at reducing material waste and negative environmental impacts through the reuse of materials, remanufacturing, renovation, repair, and, in the last case, recycling (KORHONEN; HONKASALO; SEPPÄLÄ, 2018). For this reason, proposals to enable the rational use of resources have increased, focusing on the transition to a circular production model (SWAR *et al.*, 2011).

The concept of the circular economy is increasingly seen as a solution to many challenges, such as waste generation, resource scarcity, and sustained economic benefits (LIEDER; RASHID, 2015). The transition to circular business models aims to optimize the flow of goods and materials, considering their cyclical nature at all stages of production (SEROKA-STOLKA; OCIEPA-KUBICKA, 2019).

To identify potential solutions for improvement in both economic and environmental aspects, this study aimed to conduct an analysis of the waste generated by a flat glass production industry, including identifying the types of waste, the quantity generated annually, and the disposal methods for each type. In this context, the tools that assist in waste management are indispensable, as they streamline the decision-making process. Circularity metrics are useful for empirically assessing the effects of a circular economy in terms of profitability, value creation, and environmental impacts (LINDER; SARASINI; VAN LOON, 2017).

The study aimed to quantify the circularity of waste from a flat glass manufacturing industry through an indicator, based on the logical-mathematical Analytic Hierarchy Process which proved useful for the company to implement improvements based on waste reuse. Comparisons were made between the company's actual scenario and its worst and best-case scenarios, where, in the worst-case scenario, none of the waste is reused, and, in the best-case scenario, all waste is reused.

The indicator used is a quantitative tool that identifies waste circularity, assisting in the decision-making process for implementing policies to promote the circular economy.

Circular Economy and Circularity

The use of finite resources economically and rationally, aiming to reduce or eliminate waste, is the essence of the circular model. This requires rethinking concepts rooted in society's practices related to consumption and production, to reduce negative environmental impacts (LATOUCHE, 2012) and improve sustainable practices, which implies that organizations adopt new production practices, taking into account social and environmental aspects (LIEDER; RASHID, 2015). The concept of circular economy is not attributed to any specific author and was developed from a multidisciplinary perspective, involving various fields such as engineering, economics, ecology, design, and business (PRIETO-SANDOVAL; JACA; ORMAZABAL, 2018). It considers creating value through the rational use of resources and minimizing environmental impacts at all stages of the product lifecycle (SEROKA-STOLKA; OCIEPA-KUBICKA, 2019).

Circularity strategies encompass reuse, repair, refurbishment, remanufacturing, repurposing, and recycling (BOCKEN *et al.*, 2017). They are directly linked to the concept of circular economy design, which aims to create products that facilitate reuse and recycling, extend their lifespan, reduce excessive material use, and prevent the depletion of natural resources (CLARK *et al.*, 2016).

A key component of an industrial ecosystem is enhancing resource efficiency through material circulation (HAUPT; VADENBO; HELLWEG, 2017) and closing the loop, which represents one of the pillars of the circular economy. This involves reintegrating waste into the production cycle and recovering energy to drive the entire material management and recovery chain (TOMIĆ; SCHNEIDER, 2018), aiming for significant cost and environmental impact savings (LINDER; WILLIANDER, 2017).

To extend the lifespan of resources, it is necessary to change production practices and analyze all stages of the production process, from resource extraction to final disposal, taking into account the lifecycle management of each product (SWAR *et al.*, 2011).

A strategy that can be employed in proposing a new vision for sustainable production and consumption is the creation of return flows, where a product that would otherwise be discarded is used to feed other cycles, thus extending its lifespan and reducing the waste of scarce resources (SVENSSON; FUNCK, 2019).

Materials and Methods

To calculate the circularity of the waste, the industrial symbiosis indicator proposed by Felício (2016) was used as a reference, based on the waste associated with the company's production sector, which represented over 90% of the total waste.

Innovatively, the indicator was applied to a flat glass production company to analyze in detail the waste associated with its production and quantify the circularity of the waste, based on the principles of the circular economy.

The tool aims to show the evolution of waste reuse by relating the amount of circulating impact to the amount of output impact. Circulating impact refers to waste that is used, and output impact refers to waste that is discarded (MANTESE; AMARAL, 2016).

$$ISI = \frac{QCI}{(1+QOI)} = \frac{\Sigma(QCW \times DCW)}{1+\Sigma(QWO \times DWO)} \qquad \text{Equation 1}$$

Where:

QCI: Quantity of circulating impact

QOI: Quantity of output impact

QCW: Quantity of circulating waste

QWO: quantity of waste output

DCW: Degree of circulating waste

DWO: Degree of waste output

For the calculation of the indicator, information such as types of waste, the quantity of each waste, and the amounts of waste reused and discarded were obtained through questionnaires.

According to Felicio (2016), the quantity of circulating impact is obtained by multiplying the quantity of reused waste by its respective degree. The quantity of output impact is obtained by multiplying the quantity of discarded waste by its respective degree.

The degree of the waste is based on its significance according to an environmental impact assessment. The degree is determined using several evaluation criteriaincluding: legislation, waste class, use or disposal, and problems or risks.

Given that waste has different classifications in environmental terms according to its significance and hazardousness (ABNT NBR 10004), it is necessary to evaluate each one individually and determine its priority level relative to others.

To calculate the degree of each waste, it is necessary to determine the weight of each criterion and the assessment of each waste within each criterion. The weight of each criterion is identified using a matrix of judgments from experts.

For calculating the degree of circularity waste, the criteria used are legislation, waste class, and waste use. For calculating the degree of waste output, the criteria are legislation, waste class, and waste disposal, which is why the values for these are divergent.

After determining the criteria, weights are assigned according to the importance of each, obtained through the Analytic Hierarchy Process (AHP). Subsequently, the variables for the degree of circularity waste (DCW) and the degree of output waste (DOW) are calculated for each criterion, and then the quantities for circulating impact and output impact are computed (FELICIO et al., 2016).

The calculations for the degree of circulating waste and waste output can be obtained using Equations 2 and 3, respectively.

$$DCW = criterion\ weight \times criterion\ assessment \qquad Equation\ 2$$

$$DOW = criterion\ weight \times criterion\ assessment \qquad Equation\ 3$$

After determining the degree of waste, multiply this by the quantity of each waste and repeat for all circulating and outgoing waste. The sum of each multiplication will be the impact (dimensionless).

Finally, once all the necessary variables have been determined, simply substitute them into Equation 1, calculating the indicator and observing circularity as a function of waste. Perfect circularity occurs when all the waste is reused, i.e. when the amount of output waste is zero.

Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a well-established decision-making technique used for analyzing complex problems. Developed by Thomas L. Saaty in 1971 and refined in 1973, the method involves creating a comparison matrix of criteria to reflect priorities and preferences.

AHP transforms a complex decision problem into a hierarchical structure through pairwise comparisons of criteria. Experts are asked to provide their judgments on the relative importance of one criterion over another to determine its significance in achieving a specific objective (GARBUZOVA-SCHLIFTER; MADLENER, 2016).

AHP models assume unidirectional relationships between elements at different decision levels within the hierarchy, with no correlations among elements within each cluster or between clusters. Therefore, AHP is not suitable for models that specify interdependent relationships within the structure (CHENG; LI, 2007).

A typical application of the AHP method begins with defining the problem, identifying the goal to be achieved, comparing pairs of components relative to the criteria, and constructing a hierarchical structure that serves as a logical and organized representation of the problem (KHAIRA; DWIVEDI, 2018).

The importance of each criterion relative to the others is measured on an intensity scale from 1 to 9, where 1 indicates equal importance between the two criteria and 9 represents the absolute importance of one criterion over the other. In constructing the matrix, the most important element in the comparison is always assigned an integer value on the scale, while the less important element is assigned the reciprocal of this value (SILVA, 2007). The comparisons are based on the fundamental scale proposed by Saaty (1990), which is described below.

Intensity 1: The two criteria contribute equally to the objective (Equal Importance).

Intensity 3: One criterion is slightly more important than the other (Moderate Importance).

Intensity 5: One criterion is strongly more important than the other (Strong Importance).

Intensity 7: One criterion is much more important than the other (Very Strong Importance).

Intensity 9: One criterion is absolutely more important than the other (Absolute Importance).

Intensities 2, 4, 6, and 8: represent intermediate values between the defined levels of importance

After completing the decision matrix, it is necessary to normalize the values by summing the values in each column of the matrix and dividing each entry in the matrix by the sum of the values in its respective column. Next, the average of each row in the normalized matrix is calculated to estimate the weight of each criterion, resulting in the weight vector (BERTAHONE; BRANDALISE, 2017).

Subsequently, the relative weights of the elements are determined by calculating the arithmetic mean of each row in the normalized matrix, thereby forming the weight eigenvector (BERTAHONE; BRANDALISE, 2017). The Consistency Ratio (CR) indicates the consistency of the judgments with threshold values based on the number of judgments. Equations 4 and 5 show how to obtain the CR value (HERNÁNDEZ, 2010)

Where:

CR: Consistency Ratio

RI: Random Consistency Index

$$CR = \frac{\lambda - n}{n-} . RI \qquad Equation\ 4$$

n: Number of Criteria

λ: Maximum Eigenvalue

The Random Consistency Index (RI), also known as the Random Index, is a tabulated standard value proposed by Saaty (1990), which depends on the number of criteria (n). The values of RI can be observed in Figure 1.

Figure 1 - Random Consistency Index

n	1	2	3	4	5	6	7	8	9	10	11	12
IR	0	0	0,58	0,9	1,1	1,24	1,3	1,41	1,45	1,49	1,51	1,48

Font: Saaty, 1990

For 3x3 matrices, the accepted limit is 0.05; for 4x4 matrices, the limit is 0.08; and for larger matrices, the limit is considered 0.1 (CHENG; LI, 2007).

The weight eigenvector (P) defines the priority of the judgments and is obtained through the calculation of the priority vector. This involves normalizing the values by summing the components of each column, dividing each component by this sum, and then calculating the average of the normalized values, resulting in the priority vector for each criterion (ARUEIRA, 2014).

The eigenvalue (λ) indicates the consistency of the values presented and is calculated by multiplying the comparison matrix of judgments by the priority vector. The average of the values obtained in each row of the resulting matrix is then computed, yielding the maximum eigenvalue (ARUEIRA, 2014).

Equation 7 is used for calculating the maximum eigenvalue.

$$A^t . P^t = \lambda max . P^t \qquad Equation\ 5$$

Where:

A: Comparison Matrix

P: Weight Eigenvector

λ_{max}: Maximum Eigenvalue

The AHP method is used to identify the best path among various options. In this study, it was employed to calculate the waste degree, and subsequently used for calculating the indicator.

Calculation of Waste Degree

For the calculation of the indicator, information was collected on the types of waste, the amount of each type of waste produced in the year 2020, and the quantities of waste reused and discarded. This information was gathered through questionnaires directed at the responsible personnel. Additionally, the waste directly associated with production was identified and subsequently used in the indicator calculation.

Reused waste is termed circulating waste, while discarded waste is termed waste output.

Evaluation of the criteria

The evaluation of the criteria: legislation, waste class, waste usage, and waste disposal was carried out by the company's specialists, who assigned scores of 1, 3, and 5, as observed below.

Legislation:

1 - Good Practices

3 - General Requirement

5 - Specific Legal Requirement

Waste Class:

1 – Non-hazardous - Inert

3 – Non-hazardous – Non-inert

5 – Hazardous

Waste Usage:

1 - Waste is treated at both the donor and recipient companies

3 – Waste is treated only at the recipient company

5 - Waste is not treated

Waste Disposal:

1 – Used as fuel

3 – Recycling

5 – Landfill

Problems and Risks:

1 – Low risk (accidents and contamination)

3 – Medium risk (accidents and contamination)

5 – High risk (accidents and contamination)

The evaluation of the criteria was carried out by the company's specialists, based on the criteria proposed by Felício (2016), which are: legislation, waste class, use or disposal, problems, and risks. For circulating waste, 'use' is considered, and for discarded waste, 'disposal' is considered. After evaluating the criteria, a comparison matrix of the criteria was developed, based on Saaty's fundamental scale and the responses from the interviewed specialists, as proposed by Felício (2016), in order to determine the order of importance of each criterion and calculate its respective weight. The AHP method was used to determine the weights.

Criteria Weights

To determine the weight of each criterion, a questionnaire was distributed among representatives from the company's environmental, production, and procurement departments, as these individuals are most closely related to the subject and possess the necessary understanding and information.

After identifying the evaluation and weight of each criterion, the degree of circularity waste (DCW) was calculated according to Equation 2, and the degree of waste output (DWO) was calculated according to Equation 3.

Subsequently, a table was created for each proposed scenario by multiplying the values of the quantities of circulating and waste output by their respective degrees, resulting in the circulating and output impacts.

The values for the amount of circulating and output impacts were then substituted into Equation 1, yielding the indicator value for each proposed scenario. This value provided a basis for assessing the company's position relative to the best and worst scenarios.

Description of the scenarios

For a better analysis of the company's waste circularity level, three scenarios were considered:

- Scenario 1: Total utilization of waste – best-case scenario
- Scenario 2: No utilization of waste – worst-case scenario
- Scenario 3: The company's real scenario

Results and Discussion

An indicator is a central element for decision-making. In this study, it was used to analyze the company's actual situation by comparing it with the best-case and worst-case scenario references.

The indicator was used to measure the circularity of the company's waste.

Type of Waste

To calculate the indicator, the types of waste produced at the company in 2020 and their respective quantities were identified, as shown in Table 1.

Table 1 - Total waste generated

TYPE OF WASTE	QUANTITY (tons per year)
Glass shards	6842.92
Rubble	4.00
Styrofoam	2.11
Light bulbs	3.00
General waste	63.31
Wood	52.11
Cooking oil	102.60
Lubricating oil	7.93
Plastic	18.35
Medical waste	0.03
Lime	399.27
Metal	73.54
Paper/Cardboard	8.88
Miscellaneous waste	13.45
Total	**7591.50**

Font: Data provided by the company, 2021

According to the data provided by the company, 14 distinct types of waste were generated. These values were quantified in tons per year, with a total annual waste production of 7,591.50 tons. Notably, glass shards alone constituted 90% of the total waste generated.

For the calculation of the indicator, only waste directly associated with production was considered, representing over 95% of the total waste generated. The production-related waste categories included glass shards, lubricating oil, lime, and miscellaneous waste, which amounted to 7,263.57 tons in 2020. Among these, glass shards represented 94% of the production-related waste.

To improve the model's performance and facilitate more accessible analysis, the data were normalized to a scale ranging from 0 to 1.

This step ensures that the data are scaled consistently without altering their variability profile. The normalization of the values was achieved by dividing the quantity of each type of waste by the total sum of all waste quantities. The normalized values are as follows:

- Glass shards = 0.942
- Lubricating oil = 0.001
- Lime = 0.055
- Miscellaneous waste = 0.002

Weights of the Criteria

To calculate the degree of each residue, it is necessary to know the weight of each criterion and the evaluation of each residue within each criterion. To identify the weight of each criterion, we used the comparison matrix of the expert judgments, which can be seen in Table 2.

Table 2 – Expert judgments

	LEGISLATION	WASTE CLASS	USE / DISPOSAL	PROBLEMS / RISKS
LEGISLATION	1	1/3	1/5	1/7
WASTE CLASS	3	1	1/3	1/5
USE / DISPOSAL	5	3	1	1/3
PROBLEMS / RISKS	7	5	3	1

Font: Authors, 2021

The pairwise judgments of the criteria by the company experts are presented in Table 2, following a consensus among the evaluations. It is observed that the comparison between problems/risks and legislation was assigned a weight of 7, indicating that problems/risks are significantly more important than legislation. Additionally, it was found that no pairwise comparison assigned equal importance to two distinct criteria.

The comparisons between waste class and legislation, use/disposal and waste class, and problems/risks and use/disposal were judged to be slightly more important than the other, each receiving a weight of 3. Conversely, use/disposal versus legislation and problems/risks versus waste class were deemed as more important than the other.

To enhance the visualization of the results, the data were normalized by dividing each judgment value by the sum of the weights in each column. The normalized values were scaled to a range from zero to one, as shown in Table 3.

Table 3 - Data normalization

	LEGISLATION	WASTE CLASS	USE / DISPOSAL	PROBLEMS / RISKS
LEGISLATION	0.063	0.036	0.044	0.085
WASTE CLASS	0.188	0.107	0.074	0.119
USE / DISPOSAL	0.313	0.321	0.221	0.199
PROBLEMS / RISKS	0.438	0.536	0.662	0.597

Font: Authors, 2021

After normalization, the priority vector for each criterion was calculated, with the following results: legislation had a priority vector of 0.057, waste class had a value of 0.122, use/disposal had a value of 0.263, and problems/risks had a value of 0.558.

The results indicate that the criterion with the highest priority is problems/risks, while the criterion with the lowest priority is legislation. To evaluate the consistency of the judgments and validate the results, the consistency ratio was computed.

The consistency ratio was determined by calculating the maximum eigenvalue. The calculation of the maximum eigenvalue involves relating the original comparison matrix to the weights of each criterion, where each comparison is multiplied by the weight of the corresponding column, resulting in a new matrix.

For each criterion, the sum of the values was computed and then divided by the weight of the corresponding criterion, as detailed below:

LEGISLATION: (0.057 + 0.041 + 0.053 + 0.080) / 0.057 = 4.050
WASTE CLASS: (0.171 + 0.122 + 0.088 + 0.112) / 0.122 = 4.040
USE/DISPOSAL: (0.285 + 0.366 + 0.263 + 0.186) / 0.263 = 4.182
PROBLEMS/RISKS: (0.399 + 0.610 + 0.789 +0.558) / 0.558 = 4.222

The value of the maximum eigenvalue (λ) is given by the average of the obtained values, as follows:

The value of $\lambda = 4.123$

The consistency ratio is given by:

CR = (4.123-4) / (4-1) x 0.9

CR = 0.045

Since for 4x4 matrices the threshold for the consistency ratio is 0.08, and given that 0.045 < 0.08, it is concluded that there is consistency in the judgments, and the priority vector values as described in Table 5 are considered valid.

After determining the weight vector for each criterion, the criteria for circulating and outgoing wastes were evaluated, respectively. Following the criteria assessment for each type of waste, the degree of circulating waste was calculated. The values for the degree of circulating waste (DCW) are presented below

- Glass shards = 2.36
- Lubricating oil = 3.13
- Lime = 2.411
- Miscellaneous waste = 2.411

The waste degree is determined based on the waste significance within an environmental impact assessment. Among the evaluated circulating wastes, lubricating oil was identified as having the highest degree of importance. The degree of outgoing waste for each criterion is presented below.

- Glass shards = 2.886
- Lubricating oil = 3.130
- Lime = 2.411
- Miscellaneous waste = 2.411

Among the outgoing wastes assessed, lubricating oil was identified as having the highest degree of significance.

Evaluation of the Criteria

The calculation of the waste degree involves multiplying the weight of each criterion by the evaluation of each waste within that criterion. The evaluations for the criteria of circulating and outgoing wastes are as follows, where 5 represents the worst condition and 1 represents the best.

Assessment of Criteria for Circulating Wastes

The evaluation of criteria for circulating wastes, as provided by the company's experts, is detailed below.

A) Glass Shards
Legislation: 1
Waste Class: 3
Waste Use: 1
Problems and Risks: 3

B) Lubricating Oil
Legislation: 1
Waste Class: 5
Waste Use: 3
Problems and Risks: 3

C) Lime
Legislation: 3
Waste Class: 3
Waste Use: 5
Problems and Risks: 1

D) Miscellaneous Waste
Legislation: 3
Waste Class: 3
Waste Use: 5
Problems and Risks: 1

The values presented represent the evaluations of circulating wastes within each criterion, assuming that all wastes are classified as circulating. Subsequently, the same evaluation was conducted for the outgoing wastes, as detailed below.

A) Glass Shards
Legislation: 1
Waste Class: 3
Waste Use: 3
Problems and Risks: 3

B) Lubricating Oil
Legislation: 1
Waste Class: 5
Waste Use: 3
Problems and Risks: 3

C) Lime
Legislation: 3
Waste Class: 3
Waste Use: 5
Problems and Risks: 1

D) Miscellaneous Waste
Legislation: 3
Waste Class: 3
Waste Use: 5
Problems and Risks: 1

Calculation of the Indicator

After identifying the values, the indicator was calculated for the three described scenarios in Table 4.

Table 4 - Calculation of the indicator in the described scenarios

SCENARIO 1						
TYPE OF WASTE	**QRC**	**GRC**	**QRC X GRC**	**QRS**	**GRS**	**QRS x GRS**
Glass Shards	0.942	2.36	2.22	0	2.886	0
Lubricating Oil	0.001	3.13	0	0	3.13	0
Lime	0.055	2.411	0,13	0	2.411	0
Miscellaneous Waste	0.002	2.411	0	0	2.411	0
		QIC	2.36		**QIS**	0
					ISI	2.36
SCENARIO 2						
TIPO DE RESÍDUO	**QRC**	**GRC**	**QRC X GRC**	**QRS**	**GRS**	**QRS x GRS**
Glass Shards	0	2.36	0	0.942	2.886	2.72
Lubricating Oil	0	3.13	0	0.001	3.13	0
Lime	0	2.411	0	0.055	2.411	0.13
Miscellaneous Waste	0	2.411	0	0.002	2.411	0
		QIC	0		**QIS**	0
					ISI	0
SCENARIO 3						
TIPO DE RESÍDUO	**QRC**	**GRC**	**QRC X GRC**	**QRS**	**GRS**	**QRS x GRS**
Glass Shards	0.942	2.36	2.223	0	2.886	0
Lubricating Oil	0.001	3.13	0.003	0	3.13	0
Lime	0	2.411	0	0.055	2.411	0.13
Miscellaneous Waste	0	3.884	0	0.002	2.411	0
		QIC	2.226		**QIS**	0.14
					ISI	1.96

Font: Authors, 2021

The results presented in Table 4 indicate that the optimal value for the scenario is 2.36, which assumes no output residues. The worst-case scenario is represented by a value of zero, signifying no utilization of residues. In contrast, the company's actual scenario (Scenario 3) achieved a value of 1.96, reflecting a situation where some residues are discarded while others are reused. This result suggests that increased efforts are needed to enhance residue utilization to approach the optimal reference.

The indicator effectively quantified the company's residue utilization performance, providing insight into the effectiveness of waste circularity in comparison to other stakeholders. A result closer to zero indicates higher waste levels, suggesting that residues are not being used as inputs.

This circularity indicator is directly related to the second principle of the circular economy, which focuses on maintaining products and materials in use. This involves reducing the quantity of output impact (QOI) and increasing the quantity of circulating impact (QCI), thereby enhancing effectiveness through residue reuse.

Favorable enabling and systemic conditions include collaborative actions among stakeholders, the establishment of environmental regulations, agile leadership, and public policies that promote material reuse and increased resource productivity as common practices.

In the context of rational resource use and residue reuse, implementing reverse cycles is a crucial strategy for advancing a circular economy. This approach involves reintegrating materials into the production system and requires coordinated efforts across various areas, including supply chain logistics, separation, storage, risk management, energy generation, and the reduction of output residues. Such comprehensive efforts reinforce the principles of circular design.

The indicator enabled the quantification of the effectiveness of the company's residue utilization, facilitating a deeper understanding of waste circularity and its interaction with other stakeholders. A result closer to zero indicates greater waste, reflecting insufficient use of residues as inputs.

Proposed improvement actions for the company include seeking information about nearby companies that could become partners, creating new synergies and collaborative efforts to promote collective benefits such as cost reduction and environmental impact mitigation through material sharing and/or residue utilization.

Furthermore, it is recommended to perform a more detailed analysis of opportunities and actions for residue utilization and to increase the company's involvement in developing new projects focused on enhancing these practices. Given the proven effectiveness of residue reuse projects, exploring new business opportunities and leveraging industry collaboration as a competitive advantage is essential.

Conclusion

A study was conducted at a flat glass production company to evaluate the effectiveness of the company's waste reuse practices. To assess the effectiveness of resource circularity within the company, an innovative indicator was utilized to analyze waste circularity within the flat glass manufacturing industry.

Four categories of waste directly associated with the company's production were identified, accounting for over 95% of the total waste generated. It was determined that glass shards were the predominant type of waste, constituting more than 90% of the production waste. All glass shards are either reused within the company or repurposed externally.

The calculation of the circularity indicator, which measures the effectiveness of residue reuse, yielded a value of 1.96, representing 83% of the optimal scenario value. This indicates that the company could achieve the ideal value for production waste circularity with additional efforts.

The analyses and results offer valuable insights and serve as a reference for the company to develop a plan for improving residue reuse. The indicator demonstrated its effectiveness as a tool for monitoring, guiding, and controlling actions and could serve as a model for other companies seeking to enhance their production practices.

Furthermore, this indicator supports the implementation of policies related to the circular economy by proposing strategies for resource reuse and waste reduction. Future research should explore the application of this approach to other scenarios and consider integrating it with additional indicators related to the circular economy.

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Medindo a circularidade dos resíduos: caminhando para uma economia circular

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Resumo: O modelo de produção linear, que extrai matéria-prima e descarta produtos, está chegando ao seu limite. Por esse motivo é necessário encontrar soluções para evitar o desperdício. A economia circular defende a ideia de que os materiais continuem em uso pelo maior tempo possível e tem como um dos princípios a eliminação de resíduos. O presente trabalho teve como objetivo medir a circularidade dos resíduos de uma indústria de produção de vidros planos, através de um indicador, que comparou cenários dentro de uma empresa. Para isso foram feitas comparações entre o cenário real da empresa com o pior e melhor cenários da mesma. O indicador mediu a circularidade dos resíduos da empresa e demonstrou ser uma ferramenta útil para implementar melhorias em função do reaproveitamento de resíduos. O cálculo do indicador indicou que a empresa representou 83% do cenário ideal, onde todos os resíduos são reaproveitados.

Palavras-chave: Economia Circular, Resíduos, Circularidade, Indicador, Vidro.

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Midiendo la circularidad de los residuos: avanzando para una economía circular

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Kelly Alonso Costa

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Artículo Original

Resumen: El modelo de producción lineal, que extrae materias primas y descarta productos, está alcanzando su límite. Por esta razón, es necesario encontrar soluciones para evitar el desperdicio. La economía circular defiende la idea de que los materiales deben permanecer en uso durante el mayor tiempo posible y tiene como uno de sus principios la eliminación de residuos. Este estudio tuvo como objetivo medir la circularidad de los residuos de una industria de producción de vidrio plano, utilizando un indicador que comparaba escenarios dentro de una empresa. Para ello, se hicieron comparaciones entre el escenario real de la empresa y los escenarios peor y mejor dentro de la misma, donde en el peor escenario, ninguno de los residuos es reutilizado y en el mejor escenario, todos los residuos son reutilizados. El indicador midió la circularidad de los residuos dentro de la empresa y demostró ser una herramienta útil para ayudar en la implementación de mejoras basadas en la reutilización de residuos. El indicador se calculó en tres escenarios diferentes: dos escenarios de referencia y un escenario que representaba la situación real de la empresa. El cálculo del indicador indicó que la empresa representaba el 83% del escenario ideal, donde todos los residuos son reutilizados.

***Palabras-clave*:** Economía Circular, Residuos, Circularidad, Indicador, Vidrio.