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Furniture Wood Waste Management Towards the Circular Economy

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Abstract: Wood waste (WW) from the furniture industry is a material that deserves special attention, given that it is still relatively unexplored in manufacturing industries. Therefore, this study aims to elaborate guidelines for decision-making in the furniture industry's wood waste, focusing on the north–central region of the state of Espírito Santo, Brazil, as a spatial outline of the research. The SWOT matrix is the main methodology for this stage of analysis, based on the previous study of Life Cycle Assessments (LCAs), the calculation of the Material Circularity Index (MCI), and the field research conducted in the industries. The obtained results show promising recycling scenarios over energy recovery, and the studied guidelines indicate this path. The three basic guidelines include discouraging the disposal of wood waste potentially usable as raw material into landfills; encouraging the use of wood waste based on the concept of industrial symbiosis; and promoting the creation of a market for the use of WW as a raw material in new products. Finally, with the proposed guidelines, it will be possible to contribute to the decision-making process on the management of wood waste from the furniture industry, reduce the amount of wood waste discarded in landfills, and increase the recycling rate. All of this being covered by a market created and maintained for the adequate management of wood waste. Furthermore, despite focusing on a Brazilian region for analysis, this paper intends to contribute to future research in the field, to be conducted in other locations.

Keywords: LCA; industrial symbiosis; SWOT matrix; circularity index; sustainable management

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1. Introduction

The history of humanity has undergone major changes with the phenomenon of economic growth, which began in the middle of the 18th century [1]. Thus, the day-to-day life of people was modified. For a long time, the linear model of production, in which the depletion of natural resources and the accumulation of waste are typically ignored, was determinant in the global economy [2,3].

The waste management systems adopted by the majority of communities result from a vision that perceives natural resources as endless. However, the era of this production model is coming to an end, necessitating a shift towards a circular model that incorporates a comprehensive understanding of all stages of the product life cycle [4]. Therefore, for an adequate transition towards the Circular Economy (CE), public and private managers need to make assertive decisions about waste management.

Within this context, the wood waste from the furniture industry is a material that deserves special attention, considering that it is still relatively unexplored in manufacturing industries, despite the existence of many proven studies guaranteeing a wide portfolio of products for incorporating said material as a raw material [5]. This unexpressive use occurs mainly due to the lack of efficiency in classifying these materials [6,7]. In Brazil, the vast majority of furniture industries utilize this wood waste either by burning it in ovens for heat and energy production or by sending it to landfills. Therefore, to better understand the dynamic of this sector, this research focused on the north–central region of the state of Espírito Santo, where timber residue is also often used for energy production [8].

Regarding the direct destination for burning, the cascade use of wood, which is an extremely widespread concept in the European Union, encourages the utilization of wood waste as a raw material at all possible stages, to be later used for energy recovery through burning. Thonemann and Schumann [9] highlighted that, in a multi-stage cascade, wood is processed into a product and this product is used at least once more in material form, before disposal or recovery for energy purposes. Adding to this, the cascade use and multiple uses of materials and resources, before their conversion into energy, has been identified as a strategy to improve resource efficiency and contribute to the Circular Economy, extending the lifespan of the wood resource [10].

In the study conducted by Pinho et al. [8], the recycling scenarios, mainly for the manufacturing of panels, were quite promising regarding the results of the comparative Life Cycle Assessment (LCA), conducted in the five proposed scenarios in the north–central regions of the state of Espírito Santo, Brazil. This also corroborates the concepts of the cascading use of wood. For a more effective contribution within this context, stakeholders must be guided on the best ways to dispose of the wood waste from the furniture industry. This can be accomplished through guidelines, strategies, and goals to achieve an adequate management towards the Circular Economy.

As far as it is known, to date, no other work has addressed the creation of guidelines for decision-making on the management of wood waste in the furniture industry, having as its main basis an LCA study of the projected scenarios. Furthermore, this research steps forward by studying the circularity index of the proposed products.

In this sense, there exists a scientific gap of studies that associate the LCA results with the concepts of Circular Economy, transforming them into guidelines to assist decision-making on the management of furniture waste.

In this way, acknowledging the importance of applying LCA combined with the concepts of CE for adequate waste management, this study aimed to develop guidelines for decision-making on the management of wood waste from the furniture industry in the north–central region of the state of Espírito Santo. Furthermore, despite adopting a region for analysis, this paper intends to contribute to future research in the field, to be developed in other locations.

2. Materials and Methods

Figure 1 presents the methodologies applied to achieve the proposed objective in this research. A previous study, which included a bibliographic review on Life Cycle Assessment applied to wood waste management systems, was the starting point in the first stage [5].

Subsequently, field research was conducted using a field journal, which served as a fundamental tool for recording relevant observations [11]. The field journal can be utilized by researchers to document activities, events, and conversations, capturing ideas, strategies, and thoughts [12]. Marconi and Lakatos [13] highlighted that field research aims to “obtain information and/or knowledge about a problem, for which an answer is sought, or a hypostasis that one wants to prove, or even discover new phenomena or relations between them." The technical visits took place in Colatina, Linhares, Pinheiros, São Roque do Canaã, and in Grande Vitória, Espírito Santo, Brazil, in the years 2019, 2020, 2022, and 2023.

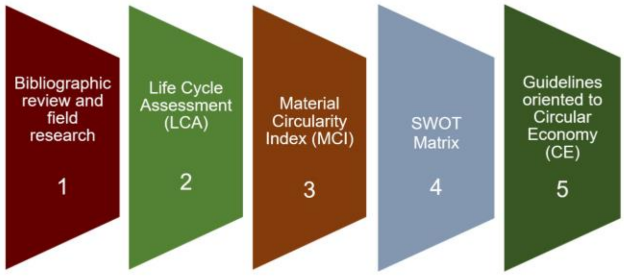

Figure 1. Methodological stages in the creation of guidelines for managing wood waste from the furniture industry.

In the second stage, the environmental performance of the proposed scenarios was evaluated based on the Life Cycle Assessment study carried out by Pinho et al. [8]. The attributional LCA conducted in the previous study was based on ISO 14040 [14] and ISO 14044 [15]. The use and final destination phases are not included within the scope of this study due to difficulties in tracking the use and final destination of the product. The adopted system boundary was from cradle-to-gate.

Additionally, the circularity (MCI) and linearity (LFI) indicators calculated for the proposed products in the third stage. These results were used to construct comparative tables, followed by the application of the SWOT matrix technique. The fifth stage was the development of guidelines for decision-making on the disposal of wood waste from the furniture industry.

2.1. Proposed Scenarios

A comparative LCA was conducted in Pinho et al. [8], in which was projected 5 scenarios for the disposal of wood waste from the furniture industry in the Linhares and Colatina furniture hubs, in the state of Espírito Santo, Brazil. The studied scenarios include the use of uncoated boards of Medium-Density Fiberboard (MDF), produced with 20% w/w of wood waste; uncoated boards of Medium-Density Particleboard (MDP), with 20% w/w of wood waste incorporation; production of solid ceramic brick with 11% w/w wood of waste incorporation; and heat production in ceramic industries (current practice) and disposal in landfills. Furthermore, the products and the energy generation were compared with the predominant scenarios in the market that utilizes virgin sources.

Regarding the percentages of recycled materials, some studies have adopted up to 100% recycled material for the manufacture of MDF [16] and MDP [17,18]. However, other authors have stated that for MDF, a replacement of 33% of fresh fibers by recycled fibers resulted in a decrease in the physical and mechanical properties of the boards [19,20]. The Brazilian study by Teixeira [21] highlights that with a 20% proportion of recycled material, new MDP boards can be produced without changing technology or compromising their quality.

Pinho et al. [8] found that scenarios that included wood waste as a raw material for manufacturing products appeared promising. Therefore, this study focused on 3 projected scenarios for the production of MDF, MDP, and ceramic brick. Subsequently, the calculation of the circularity indicator for the products was performed for the Scenarios 1, 2, and 3, which were analyzed using the SWOT matrix. Figure 2 illustrates the products considered for the insertion of wood waste.

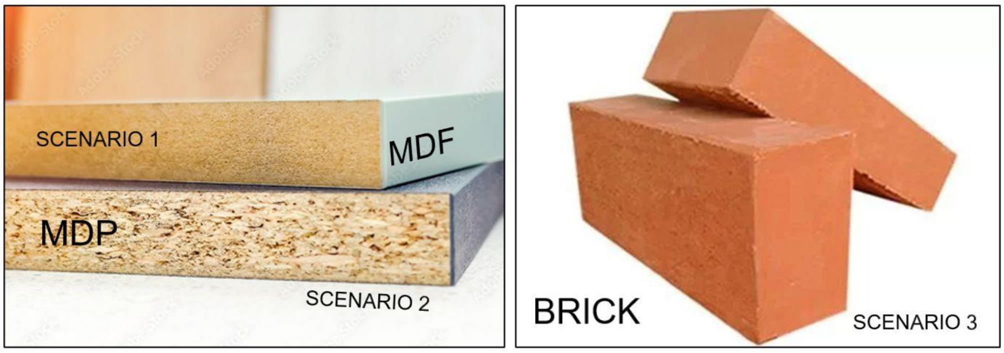

Figure 2. Scenarios 1–3 were studied for the disposal of wood waste from the furniture industry in the state of Espírito Santo.

2.2. Circularity Indicator

The Material Circularity Indicator (MCI) was developed to quantify the circularity of products individually. The MCI expresses the extent to which the linear flow is reduced and the restorative flow is maximized for the materials comprising it. It also considers the duration and intensity of its use compared to similar products manufactured on an industrial scale [2].

The MCI was utilized to quantify the circularity of the proposed products in Scenarios 1, 2, and 3. The MCI takes into account the amount of virgin raw material (V) used in manufacturing, the amount of irrecoverable waste (W) associated with the product and the utility factor (X) which considers the duration (lifespan) and intensity of use (functional units) [2]. Table 1 presents the parameters for calculating the MCI, and Table 2 shows the input data for computing the circularity and linearity indices of the products from Scenarios 1–3.

Table 1. Parameters for calculating the MCI.

Symbol	Definition
M	Mass of a product
FR	Fraction of mass of a product's feedstock from recycled sources
FU	Fraction of mass of a product's feedstock from reused sources
FS	Fraction of a product's biological feedstock from Sustained Production. Biological material that is recycled or reused is captured as recycled or reused material, not biological feedstock.
V	Material that is not from reuse, recycling or, for the purpose of this methodology, biological materials from Sustained Production.
CC	Fractionof mass of a product being collected to go into a composting process
Cg	Fraction of mass of a product being collected for energy recovery where the materials satisfies the requeriments of inclusion.
CR	Fraction of mass of a product being collected to go into a recycling process
CU	Fraction of mass of a product going into component reuse
EC	Efficiency of the recycling process used for the portion of a product collected for recycling
EE	Efficiency of the energy recovery process for biological materials satisfying the requirements for inclusion
EF	Efficiency of the recycling process used to produce recycled feedstock for a product
BC	The carbon content of a biological material, by defaut a value of 45% is used unless supported evidence to the contrary
W	Mass of unrecoverable waste associated with a product

Table 1. *Cont.*

Symbol	Definition
WO	Mass of unrecoverable waste through a product material going into landfill, waste to energy and any other type of process where the materials are no longer recoverable
WC	Mass of unrecoverable waste generated in the process of recycling parts of a product
WF	Mass of unrecoverable waste generated when producing recycled feedstock for a product
LFI	Linear Flow Index
$F(X)$	Utility factor built as a function of the utility X of a product
X	Utility of a product
L	Actual average lifetime of a product
Lav	Average lifetime of an industry-average product of the same type
ER	Recovery energy
HHV	Higher heating value
MB	Mass of biological material
U	Actual average number of functional units achieved during the use phase of a product
Uav	Average number of functional units achieved during the use phase of an industry-averege product of the same type
MCIp	Material Circularity Indicator of a product

Table 2. Input data for computing the circularity indicator from Scenarios 1–3.

Input Data for MCI				
Factor	**Unity**	**MDF**	**MDP**	**Brick**
M	kg	690	630	1
FR	%	0.172	0.170	0.1045
FU	%	0.00	0.00	0.00
Fs	%	0.688	0.680	0.00
Cc	%	0.00	0.00	0.00
CE	%	0.05	0.05	0.12
CR	%	0.95	0.95	1.00
CU	%	0.00	0.00	0.00
EC	Factor	0.95	0.95	0.95
EF	Factor	0.95	0.95	0.95
Bc	%	0.45	0.45	0.00
MB	kg	593.4	535.5	0.110
F(x)	Factor	0.9	0.9	0.9
L	years	20	20	40
LAV	years	20	20	40
U	qtt	0.80	0.80	1.00
UAV	qtt	0.80	0.80	1.00

The calculation of the Linear Flow Index (LFI) and MCI was conducted using the software Microsoft Excel 2016, following the script presented in *"Circularity Indicators Methodology"*, published by the Ellen MacArthur Foundation [2].

Equation (1) of the LFI quantifies how much material comes from virgin raw material and ends as irrecoverable waste. LFI presents a value between 0 and 1, in which 0 is a circular flow and 1 is totally linear. The same is calculated using the following equation:

$$LFI = \frac{V + W}{2M + \frac{Wf - Wc}{2}} \tag{1}$$

Equation (2) of the MCI considers the LFI and an F(X) factor, which is constructed as an F function with X utility. It is calculated using the following equation:

$$\boldsymbol{MCI = 1 - LFI \cdot F(X)} \tag{2}$$

The data collected for the LCA studies conducted in Scenarios 1 to 3 in Pinho et al. [8] served as the basis for composing the input parameters for calculating the MCI, which are presented in Table 2. The mass (M) represents the weight of each finished product, while FR represents the percentage of wood waste incorporated into MDF, MDP, and ceramic brick. FS denotes the fraction of biological raw material originating from sustainable sources. In the panels, FR and the FS were calculated considering only the final wood incorporated. It was possible to exclude the value of other raw materials contained in the product; thus, V = 148.35 kg for MDF and V = 113.40 kg for MDP. The values of 108.33 kg (20% w/w) and 433.32 kg (80% w/w) are associated with MDF, respectively, for FR and FS. Regarding MDP, 113.4 kg (20% w/w) is related to FR and 413.28 kg (80% w/w) to FS. The FR of the ceramic brick corresponds to 0.111 kg (11% w/w). For the ceramic brick, FS = 0, while clay accounts for 0.890 kg (89% w/w) of the composition. None of the products studied used raw materials from reused sources; hence, FU = 0.

At the end of its lifespan, no waste is collected for composting, so CC = 0 in the three scenarios analyzed. Given that the adopted methodology focuses on the materials present in the final product, the biological materials constituting the panels and ceramic bricks do not satisfy all the conditions required for energy recovery, and thus CE = 0 [2]. At the end of their lifespan, the products are collected for recycling. CR = 0.95 was adopted for panels and CR = 0.80 for bricks [22]. Since there is no reuse of components in any of the products, CU = 0. The recycling process was considered 95% efficient, resulting in EC = 0.95. Similarly, EF = 0.95 [23].

The utility factor X was considered to be 1, adopting the recommended average utility of the industries [2]. A duration of 20 years was assumed for the panel's lifespan and 40 years for bricks [24,25]. For the LAV referring to a similar product life, the same lifetime was considered. An average value of 0.80 for functional unit "U" was adopted for panels and similar products, accounting for losses in the furniture industries, while the value of 1.0 was used for ceramic bricks [22].

2.3. SWOT Matrix

The SWOT matrix (strengths, weaknesses, opportunities, and threats) is a strategic planning tool that aims to diagnose the strengths, weaknesses, opportunities, and threats of the object under analysis [26]. Initially formulated for the field of administration, this matrix has been applied in various fields, including research in the field of solid waste management [27,28].

The tool is typically employed to conduct scenario analysis, aiming to compile all information into a matrix and thus facilitate the visualization of the characteristics involved in the study [29]. In this research, Scenarios 1, 2, and 3 were studied, which were intended for the incorporation of WW as a raw material in the manufacturing processes of MDF, MDP, and ceramic brick. The strengths and weaknesses in the internal environment of the panel factory and the ceramic industry, which will utilize WW as a raw material, are analyzed. The strengths are variables that provide favorable conditions for integrating the product into the company's portfolio. The opportunities are listed, considering external factors that can enhance the industrialization of the proposed product. External conditions, understood as difficulties, are considered threats to the manufacturing of the studied products. Figure 3 depicts the basic design of the SWOT matrix.

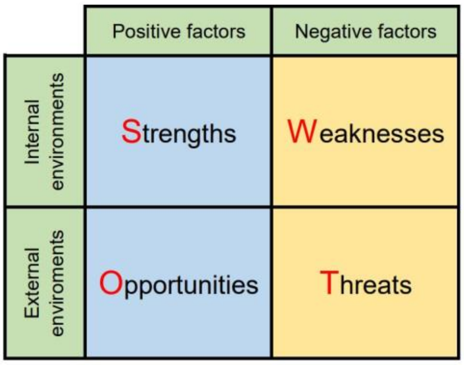

Figure 3. SWOT matrix.

3. Results and Discussion

3.1. LCA of Scenarios 1–3 and MCI of Scenarios 1–3

The results of the study by Pinho et al. [8], presented below, serve as the primary reference for preparing the SWOT matrix. Subsequently, the results from the Global Warming (GW) category were adopted as a reference to continue the analyses. Table 3 demonstrates that MDF and MDP exhibit the greatest environmental benefits per ton of waste and for the annual production of product, compared to Scenario 3. Considering the concept of the cascading use of wood, prioritizing use scenarios for manufacturing products is essential, with disposal for burning reserved as an end-of-life option [9,10,30,31].

Table 3. Comparative LCA results regarding GW (Scenarios 1–3).

Scenarios		Environmental Benefit (GW)	Annual Environmental Benefit (GW)
MDF	1	9.49×10^1	4.30×10^6
MDP	2	3.74×10^1	1.85×10^6
BRICK	3	2.90×10^1	1.70×10^4

The results of the sensitivity analysis regarding waste transport distances were also significant for this study. It demonstrates the feasibility of utilizing waste from the furniture industry throughout Grande Vitória. Only the truck modal from the southern region appears to be environmentally unviable. The modals that integrate trains and trucks show promise in all studied regions. Furthermore, considering that the amount of waste required to meet the monthly production of the projected scenarios and the estimated monthly generation of wood waste (6700 tons) in the furniture hubs of Colatina and Linhares, more than one scenario could be addressed simultaneously; however, the amount of wood waste is sensitive to market demands.

In addition to the Life Cycle Assessment study, this article also considers the calculations of the circularity index (MCI) and the product linearity index (LFI). Bertani et al. [23] highlighted the importance of joining MCI with LCA in search of circular and sustainable solutions. LCA is a consolidated methodology that follows ISO standards, allowing for the study of the entire product life cycle and obtaining information on different impact categories at different stages of the life cycle, whereas, for the MCI, information about the origin of the raw material, lifespan, function, and destination after use is necessary. Another feature of MCI is to present the result in a single value.

In Table 4, it is possible to see that the MDF and MDP indicated a strong tendency towards circularity, given the fact that they presented indices close to 1 for MCI. Regarding the linearity indicator, the value is 0.1346 for MDF and 0.1173 for MDP, indicating low linearity [2]. The brick presents moderate results for MCI and LFI. Appendix A, Appendix B, and Appendix C contains the tables prepared in Microsoft Excel 2016, with the data and equations used in calculating the LFI and MCI.

Table 4. Results of the circularity and linearity index of products (Scenarios 1–3).

Scenarios		Linearity Index (LFI)	Circularity Indicator (MCI)
MDF	1	0.1346	0.8789
MDP	2	0.1173	0.8945
BRICK	3	0.5910	0.4681

3.2. SWOT Matrix of Scenarios 1–3

Based on the literature review conducted by Pinho and Calmon [5], along with field research and the findings presented in Tables 3 and 4, the SWOT matrix was developed using the scenarios of the studied products. Upon completing the diagnosis, the scenarios were analyzed in light of the strengths, weaknesses, opportunities, and threats identified in the matrix quadrants.

In Figure 4, it is possible to observe that the strengths listed positively influence the panel industry in the redesign of the MDF produced, making it more eco-efficient product. Thus, the MDF was improved with the proposal to include 20% w/w of wood waste, replacing a percentage of virgin sources. It was possible to reduce the use of urea formaldehyde resin (UF) from 14% to 13.5% of the total weight of the board, influencing the reduction in environmental loads. In relation to MDP, corporative forces encourage the company to include it in its product portfolio, since the panel factory in the state of Espírito Santo, Brazil, has its production concentrated on the manufacture of MDF. Within the study analyzed, MDP incorporates 20% w/w of wood waste in its composition, making the panel more environmentally friendly, this being a practice that does not require a complex process for recycling. In addition to the region studied, the sensitivity analysis proved that all panel manufacturing can also receive waste from the entire Metropolitan Region of Grande Vitória. The proposed redesign aimed to enhance the eco-efficiency of the panels, resulting in environmental benefits compared to products manufactured solely with wood from virgin sources. The MCI showed a strong tendency towards circularity and the LFI showed a low tendency towards linearity in the analyses of the proposed panels that incorporate the WW with raw material.

Weaknesses are variables that can create unfavorable conditions for the adoption of the products proposed by the panel company. The factories in the state of Espírito Santo, Brazil, only have MDF in their portfolio; thus, the expansion of these factories would be required to enable MDP manufacturing. A thermo-hydrolytic treatment, in which wood fibers are recovered, requires an increase in water consumption, and, as a result, wastewater generated by the MDF manufacturing process will increase, which contributes to increased environmental impacts. The factory studied uses UF resin in the manufacture of panels, which was a relevant item in accounting for environmental impacts. Furthermore, a percentage of this adhesive is added to wood fibers in the recycling process. Therefore, more environmentally friendly solutions, as already reported in the literature, should be pursued for the manufacturing of wood panels in Brazil [32].

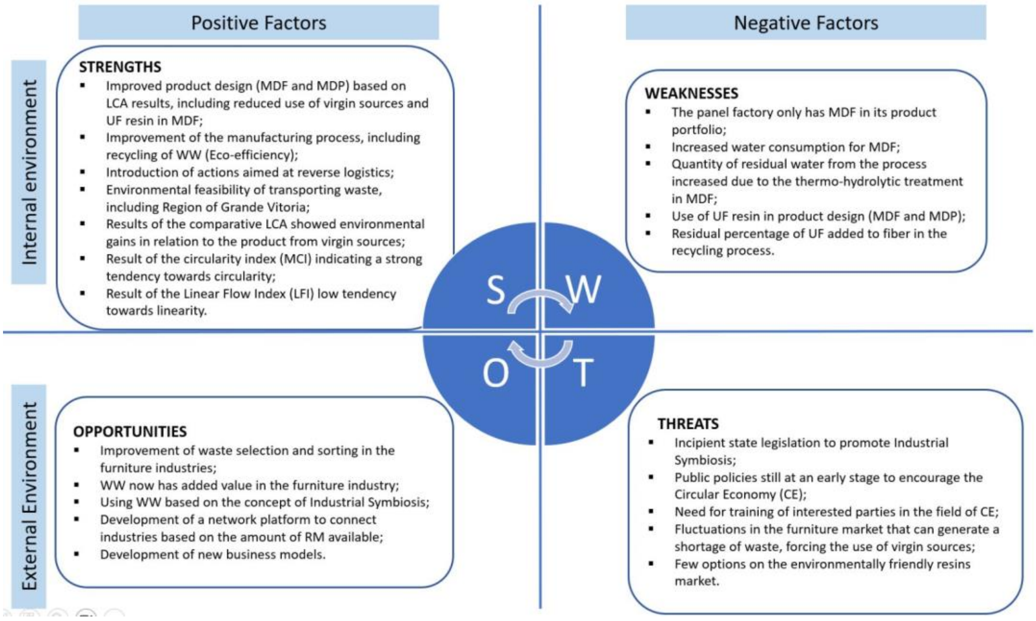

Figure 4. SWOT matrix (Scenarios 1 and 2) of the environmental performance of the production of MDF and MDP with wood waste.

Opportunities are external factors that, when worked on, positively stimulate the panel industry, in the readjustment of MDF and in the manufacture of MDP. Furthermore, they bring environmental and economic benefits to the furniture industries, also boosting CE in the state of Espírito Santo, Brazil. The selection and sorting of WW must be improved so that this material has added value and becomes raw material for the panel industry. This context is in line with the concept of industrial symbiosis, in which WW from the furniture industry is incorporated to produce new wooden panels. Therefore, it is appropriate to develop a network platform to monitor the amount of available WW. This platform will allow the panel industry to schedule its production with existing WW.

Threats are external variables that can create difficulties in implementing the proposed products by the panel company. To foster industrial symbiosis, it is necessary to create legislation that encourages connections between industries. In regards to the Circular Economy, there is a need for training interested parties and public policies are still incipient in this field. The availability of wood waste is sensitive to fluctuations in the furniture market, but the panel industry must be programmed to work with only virgin wood during these periods. In this context, it is important to highlight that there are still few large-scale produced options on the market to replace UF resin with more environmentally friendly products.

In relation to Scenario 3, in Figure 5, the highlighted strengths positively influence the red ceramic industry, improving the brick produced and making it a more eco-efficient product. The incorporation of 11% w/w of wood waste generates a reduction in the amount of clay, making the product lighter. The sensitivity analysis also proved that the entire manufacturing process of the proposed bricks can receive waste from the entire Metropolitan Region of Grande Vitória. Furthermore, the redesign proposal aimed at making the bricks more eco-efficient resulted in environmental gains compared to products manufactured solely with clay.

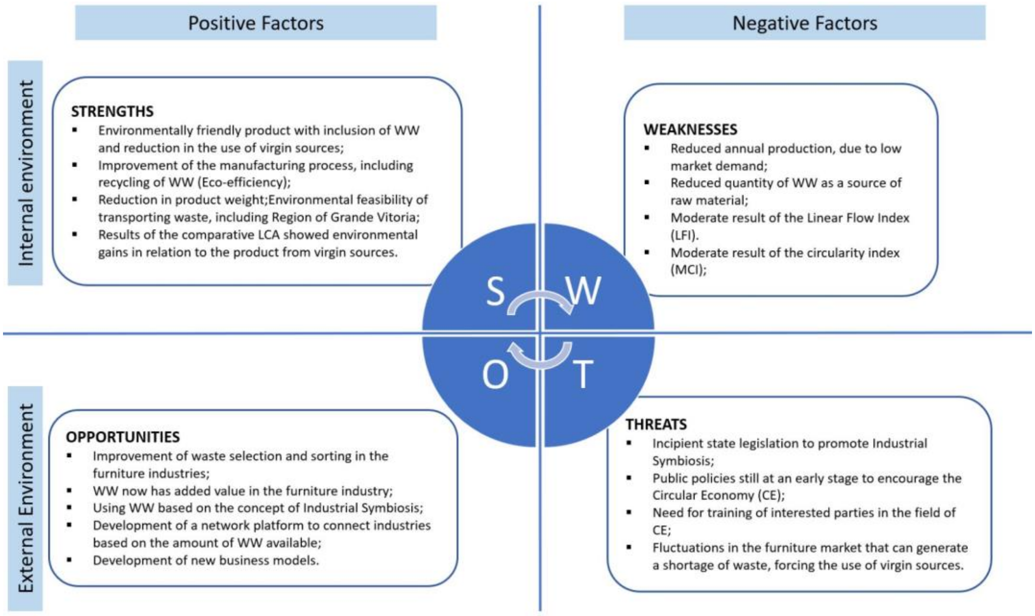

Figure 5. SWOT matrix (Scenario 3).

Weaknesses are variables that can create unfavorable conditions, particularly concerning the Material Circularity Indicator (MCI) and Linearity Flow Index (LFI), which exhibit moderate results. The production of solid brick is relatively low in the region under study, and an increase in demand could lead to greater environmental benefits compared to the current annual environmental benefit of manufacturing this product.

Opportunities are external factors that can positively stimulate the industry in the decision to improve the existing product in its portfolio. The selection and sorting of wood waste (WW) must be improved, generating added value and transforming waste into raw material for the ceramic industry, which will also lead to the qualification of labor. This proposed scenario is also in line with the concept of industrial symbiosis. Additionally, the network platform for monitoring the quantity of available WW will allow the ceramic industry to schedule its production with existing WW. In this context, there is a broad field for leveraging new sustainable business models.

Threats are external variables that can create difficulties in implementing improvements to be made to the product by the red ceramic industry, which are essentially similar to the challenges highlighted in the panel industries.

In the context of this analysis (Scenarios 1–3), it is also highlighted that this research includes an extensive phase of technical visits that took place over 4 years. It also adopts a regional scale, which enables the consideration of the positive and negative factors in the SWOT matrix. It all takes into consideration the characteristics and industrial synergies of the studied region. Furthermore, stakeholders involved in the generation and use of wood waste should collaborate to convert weaknesses and threats into strengths and opportunities.

3.3. Guidelines and Strategies

With the basis obtained through the proposed methodology, guidelines and strategies for the management of wood waste were developed, seeking to enable new cycles under the Circular Economy. This final stage was designed to support decisions for both external and internal stakeholders within the scope of industries implementing Scenarios 1, 2, and 3 as proposed.

As shown in Figure 6, the guidelines are connected to support decision-making within the scope of wood waste management in the furniture industry in Espírito Santo, Brazil. The three basic guidelines proposed are as follows:

- Guideline 1—Discourage disposal of natural wood waste (WW from virgin wood) and panels (WW from wood panels) to landfill;
- Guideline 2—Encourage the use of WW based on the concept of industrial symbiosis;
- Guideline 3—Promote the creation of a market for the use of WW as a raw material in new products, such as MDF, MDP, and ceramic brick.

Figure 6. Guidelines for WW management from the furniture industry.

The first step expressed in Guideline 1 would be to inhibit the disposal of virgin wood waste and wood panel waste to landfill, as classified by Pinho et al. [8]. The strengths and opportunities detected for the manufacture of products in Scenarios 1, 2, and 3 show promising scenarios for the allocation of WW, which justifies the first guideline. Given its availability for disposal as a raw material, it is necessary to encourage the use of WW based on the concept of industrial symbiosis, as expressed in Guideline 2. Guideline 3 supports the reinsertion of wood waste into industries that can utilize it as a raw material for their products. It should also be noted that, once the market is established, efforts must be made to sustain it efficiently. In this regard, the study proposes the partial incorporation of wood waste, as the quantity of raw material fluctuates depending on market conditions. Therefore, in a scenario of scarcity, production can be adjusted according to the available quantities of waste and virgin wood, depending on the percentage available.

The three proposed guidelines form the fundamental framework, delineating a pathway for effective wood waste management. These guidelines were formulated with the proposition of strategies, representing necessary actions to achieve the proposed objectives. Moreover, it is imperative for industries in the sector, entities associated with the furniture industry, and policymakers to establish quantifiable time-bound goals that align with the strategies outlined in each guideline. These goals should be regularly monitored to assess compliance with the proposed strategies, ensuring continual improvement of the wood waste management system in the north–central region of the state of Espírito Santo, Brazil.

3.3.1. Guideline 1

The strategies outlined in the first guideline aim to discourage the disposal of raw material to landfills, as it can be repurposed as a raw material for other industries. The proposed strategies include the following: training stakeholders involved in the life cycle of renewable wood; establishing high tariffs for landfill disposal as a means of promoting industrial symbiosis; and monitoring the transport of small and large generators, as shown in Figure 7.

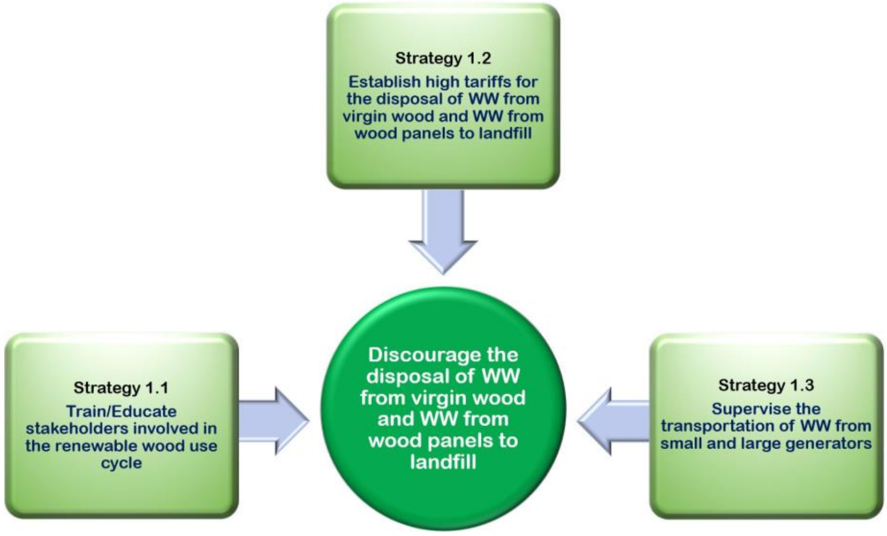

Figure 7. Guideline 1 for the management of wood waste from the furniture industry.

By discouraging the disposal of potentially usable wood waste in new cycles, a stock of raw material will be available for use in industry. In this way, Guideline 2 advances, encouraging connections between industries.

3.3.2. Guideline 2

The second guideline presented in Figure 8 concerns the need to encourage the use of WW based on the concept of industrial symbiosis. Relevant strategies include the following: the creation of legislation and standards that determine the sorting of waste based on type and quality; the creation of platforms to supply the quantity of WW available for use as a raw material in other industries; and the identification of existing synergies between generators and industries that can insert WW into the production cycle, such as the panel industry and the ceramic industry that were the subject of analysis in this study, and encourage the development of research into "eco-friendly" components for new products.

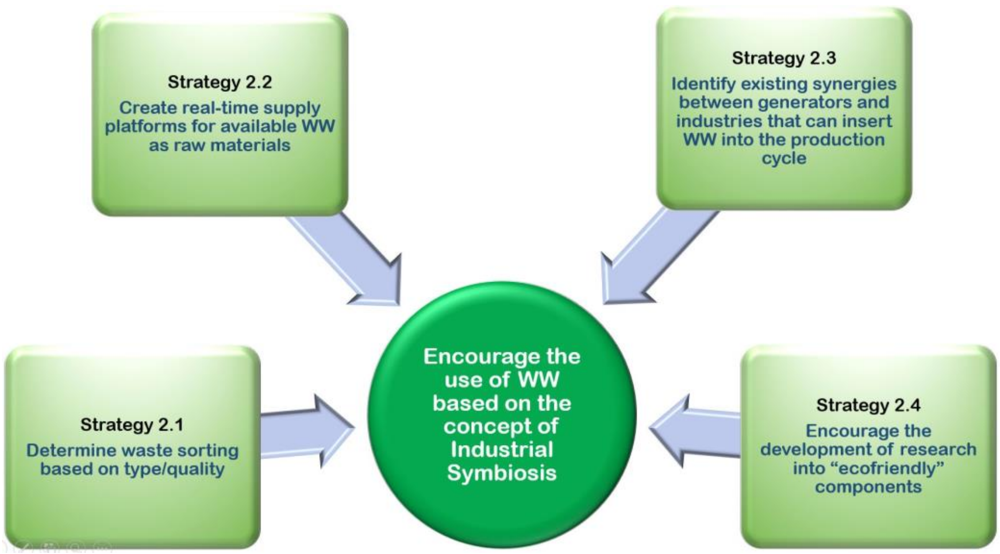

Figure 8. Guideline 2 for the management of wood waste from the furniture industry.

Based on quality, wood waste from the furniture industry can be destined for different scenarios, thus avoiding competition among them. In addition, in the study conducted by Bütün Buschalsky and Mai [16], MDF was recovered up to the third generation of panels using the thermo-hydrolytic disintegration process, and Kim and Song [33] stated that MDP can be recycled up to 16 times after the first use. This demonstrates the potential life cycle stages that these products present.

With these industries mapped and connected, with the available stock being supplied in real time, Guideline 3 deals with creating and maintaining the market so that WW management is sustainable.

3.3.3. Guideline 3

The third guideline aims to encourage the creation of a market for the use of WW as a raw material in new products. Within this proposal, the strategies include the following: the valorization of the railway modal as an alternative for WW transport, which proved to be promising in the analysis conducted for the products studied; the creation of legislation that encourages recycling as the first destination option for virgin wood waste and wood panel waste; the encouragement of new business models that use WW as a raw material in the manufacture of new products (open or closed cycles); and the drafting of legislation that encourages the use of WW in the product portfolio of companies that use virgin wood as a raw material, as shown in Figure 9.

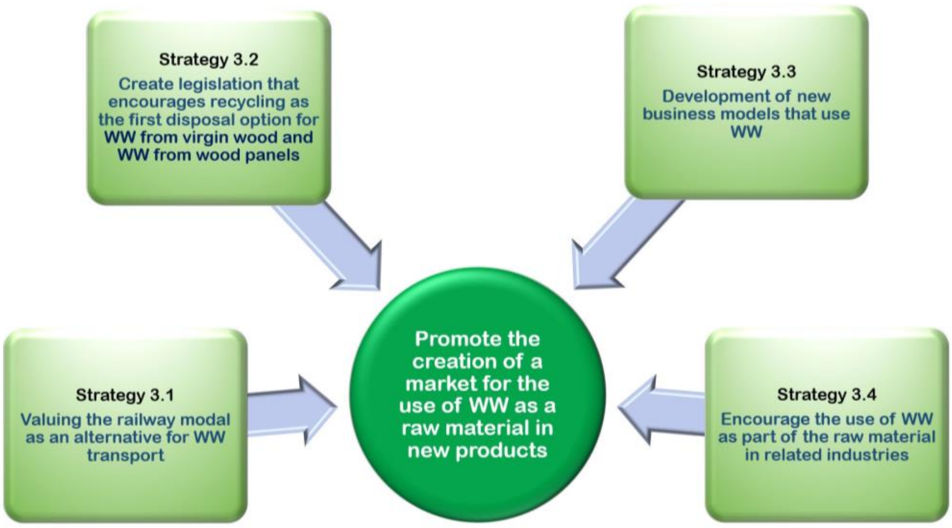

Figure 9. Guideline 3 for the management of wood waste from the furniture industry.

Using the proposed guidelines, it will be possible to reduce the amount of wood waste discarded in landfills and increase the recycling rate, all of this being covered by a market created and maintained for the adequate management of wood waste. It should also be noted that, after the possibility of recycling has been exhausted, the waste can be used for energy production, as long as the mixing proportion with panel waste is within the limits established by law, as presented in Pinho et al. [8] for the ceramic industry.

4. Conclusions and Prospects for Future Work

This article was based on studies published by Pinho and Calmon and Pinho et al. [5,8]. In the first article, an in-depth review of the literature of works related to LCA was conducted for the management of WW in the period from 2011 to 2021. Furthermore, a guiding proposal was presented, which highlights the main points to be considered for better LCA practice. In the second study, a comparative LCA was conducted to analyze the environmental aspects and impacts of various management scenarios of wood waste generated in the furniture industries of Espírito Santo, with a focus on the north–central region of the state. Thus, this work aimed to develop guidelines to support decision-making on furniture waste management, based on the association of three distinct methodologies applied from the perspective of the Circular Economy.

Based on the findings of Pinho et al. [8], which included the calculation of the circularity index and field studies, the achieved results were analyzed in relation to the strengths, weaknesses, opportunities, and threats proposed in the SWOT matrix methodology. This final stage was developed to support decision-making for both external stakeholders, concerning the creation of legislation and incentive/support programs, and internal stakeholders within the industries adhering to the proposed Scenarios 1, 2, and 3.

As the results found show the recycling scenarios as promising, prior to energy recovery, the guidelines studied indicate this direction. These basic pillars are connected to support decision-making in the management of wood waste from the furniture industry in Espírito Santo, Brazil. The three basic guidelines proposed are as follows:

- Guideline 1—Discourage the disposal of natural wood waste and wood panel waste to landfills;
- Guideline 2—Promote the utilization of wood waste under the principles of industrial symbiosis;
- Guideline 3—Foster the establishment of a market for the utilization of wood waste as a raw material in the manufacturing of new products, such as MDF, MDP, and ceramic bricks.

The guidelines were outlined with the proposition of strategies, which are essential for achieving the proposed objectives. Additionally, industries, furniture sector entities, and policymakers need to establish measurable time-bound goals that align with the strategies outlined in each guideline. These goals should be measured regularly to assess compliance with the proposed strategies, thereby ensuring continuous improvement of the wood waste management system designed for the north–central region of the state of Espírito Santo.

Finally, with the guidelines outlined in this research, it will be possible to reduce the amount of wood waste discarded in landfills and increase the recycling rate, all of this being covered by a market created and maintained for the adequate management of wood waste. It should also be noted that, after the possibility of recycling has been exhausted, the waste can be used for energy production. Additionally, an economic analysis of the projected scenarios must be incorporated into the decision-making process regarding the management of wood waste from the furniture industry, considering the region studied.

From the analysis performed, several perspectives have been identified for future studies. The most relevant ones are summarized and highlighted below:

- Faced with environmental emergencies, the demand for information regarding the life cycle is growing exponentially. Consequently, increasing scalability in conducting LCA studies is essential for companies aiming to grow sustainably. This is facilitated by the rising use of sensors, controllers, and digitization of processes in the context of Industry 4.0, which generate data that can be used in LCA. Therefore, new studies that address this objective should be encouraged.
- Future studies should also explore, through a consequential LCA, the impact of the increased use of wood waste across various production sectors.
- Studies that integrate methodologies with fuzzy membership could be beneficial and offer valuable insights. Therefore, it is a study field that should be further explored.
- Since the use and final destination phase are not included within the scope of this study, future research should investigate the use and final disposal phase of bricks and panels (cradle-to-grave or cradle-to-cradle).

- Wood panels with coatings were not discussed in this paper. Therefore, they require further study.
- Within this research field, there are few studies that explore how the efficiency of transportation is affected when the wood waste is shredded before being sent to the panel factory. Consequently, its effects should be investigated further.

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Appendix A

CIRCULAR ECONOMY FACTORS—MDF			
FACTOR	DEFINITION	VALUE	UNITY
M	Mass of a product.	690	kg
Fr	Fraction of mass of a product's feedstock from recicled sources.	0.1570	%
Fu	Fraction of mass of a product's feedstock from reused sources.	0.00	%
Fs	Fraction of a product's biological feedstock from Sustained Produc-tion. Biological material that is recycled or reused is captured as recycled or reused material, not biological feedstock.	0.6280	%
V	Material that is not from reuse, recicling or, for the purpose of this methodology, biological materials for sustained production.	**148.35**	kg
Cc	Fraction of mass of a product being collected to go into a composting process.	0.00	%
Ce	Fraction of mass of a product being collected for energy recovery where the materials satisfies the requiriments for inclusion.	0.00	%
Cr	Fraction of mass of a product being collected to go into a recycling process.	0.95	%
Cu	Fraction of mass of a product going into componet reuse.	0.00	%
Ec	Eficiency of the recycling process used for a portion of a product collected for recycling.	0.95	
EE	Eficiency of the energy recovery process for biological materials satisfing the requiriments for inclusion.	**0.0000**	
EF	Eficiency of the recycling process used to produce recycled feedstock for a product.	0.95	

Bc	The carbon content of a biological material, by default a value of 45% is used unless supported by evidence to the contrary.	0.45	%
ER	Recovered energy.	0.00	Mj
HHV	Higher heating value.	0.00	Mj
MB	Mass of biological material.	0.00	kg
W	Mass of unrecoverable waste associated with a product.	**38.0477**	kg
Wo	Mass of unrecoverable waste through a product's material going into landfill, waste to energy and other type of process where the materials are no longer recoverable.	**34.5000**	kg
Wc	Mass of unrecoverable waste generated in the process of recycling parts of a product.	**1.3939**	kg
Wf	Mass of unrecoverable waste generated when producing recycled feedstock for a product.	**5.7016**	kg
LFI	Linear flow index	**0.1346**	
F(X)	Utility factor built as a function of the utility **X** of a product.	0.90	
X	Utility of a product.	**1.00**	
L	Actual average lifetime of a product.	20	years
Lav	Average lifetime of an industry-average product of the same type.	20	years
U	Actual average number of functional units achieved during the use phase of a product.	0.80	qtt
Uav	Average numbers of functional units achieved during the use phase of a industry-average product of the same type.	0.80	qtt

	OUTPUT		
MCIp	**Material circularity Indicador of a product.**	**0.8789**	(0 to 1)
	☐ Input Data		

Appendix B

CIRCULAR ECONOMY FACTORS—MDP			
FACTOR	DEFINITION	VALUE	UNITY
M	Mass of a product.	630	kg
Fr	Fraction of mass of a product's feedstock from recicled sources.	0.16	%
Fu	Fraction of mass of a product's feedstock from reused sources.	0.00	%
Fs	Fraction of a product's biological feedstock from sustained prodution. Biological material that is recicled or reused is captured as recicled or reused material, not biological feedstock.	0.66	%
V	Material that is not from reuse, recicling or, for the purpose of this methodology, biological materials for sustained production.	**113.40**	kg
Cc	Fraction of mass of a product being collected to go into a composting process.	0.00	%

Ce	Fraction of mass of a product being collected for energy recovery where the materials satisfies the requiruments for inclusion.	0.00	%
Cr	Fraction of mass of a product being collected to go into a recycling process.	0.95	%
Cu	Fraction of mass of a product going into componet reuse.	0.00	%
Ec	Eficiency of the recycling process used for a portion of a product collected for recycling.	0.95	
EE	Eficiency of the energy recovery process for biological materials satisfing the requiruments for inclusion.	**0.000**	
EF	Eficiency of the recycling process used to produce recycled feedstock for a product.	0.95	
Bc	The carbon content of a biological material, by default a value of 45% is used unless supported by evidence to the contrary.	0.00	%
ER	Recovered energy.	0.00	Mj
HHV	Higher heating value.	0.00	Mj
MB	Mass of biological material.	0.00	kg
W	Mass of unrecoverable waste associated with a product.	**34.8496**	kg
Wo	Mass of unrecoverable waste through a product's material going into landfill, waste to energy and other type of process where the materials are no longer recoverable.	**31.5000**	kg
Wc	Mass of unrecoverable waste generated in the process of recycling parts of a product.	**1.3939**	kg
Wf	Mass of unrecoverable waste generated when producing recycled feedstock for a product.	**5.3053**	kg
LFI	Linear flow index	**0.1172**	
F(X)	Utility factor built as a function of the utility **X** of a product.	0.9	
X	Utility of a product.	**1.0000**	
L	Actual average lifetime of a product.	20	years
Lav	Average lifetime of an industry-average product of the same type.	20	years
U	Actual average number of functional units achieved during the use phase of a product.	0.80	qtt
Uav	Average numbers of functional units achieved during the use phase of a industry-average product of the same type.	0.80	qtt
	OUTPUT		
MCIp	**Material circularity Indicador of a product.**	**0.8945**	(0 to 1)
	☐ Input Data		

Appendix C

CIRCULAR ECONOMY FACTORS—BRICK			
FACTOR	DEFINITION	VALUE	UNITY
M	Mass of a product.	1	kg
Fr	Fraction of mass of a product's feedstock from recicled sources.	0.1110	%

Fu	Fraction of mass of a product's feedstock from reused sources.	0.00	%
Fs	Fraction of a product's biological feedstock from sustained prodution. Biological material that is recicled or reused is captured as recicled or reused material, not biological feedstock.	0.00	%
V	Material that is not from reuse, recicling or, for the purpose of this methodology, biological materials for sustained production.	**0.8890**	kg
Cc	Fraction of mass of a product being collected to go into a composting process.	0.00	%
Ce	Fraction of mass of a product being collected for energy recovery where the materials satisfies the requiriments for inclusion.	0.00	%
Cr	Fraction of mass of a product being collected to go into a recycling process.	0.80	%
Cu	Fraction of mass of a product going into componet reuse.	0.00	%
Ec	Eficiency of the recycling process used for a portion of a product collected for recycling.	0.80	
EE	Eficiency of the energy recovery process for biological materials satisfing the requiriments for inclusion.	**0.0000**	
EF	Eficiency of the recycling process used to produce recycled feedstock for a product.	0.80	
Bc	The carbon content of a biological material, by default a value of 45% is used unless supported by evidence to the contrary.	0.00	%
ER	Recovered energy.	0.0000	Mj
HHV	Higher heating value.	0.0000	Mj
MB	Mass of biological material.	0.00	kg
W	Mass of unrecoverable waste associated with a product.	**0.2739**	kg
Wo	Mass of unrecoverable waste through a product's material going into landfill, waste to energy and other type of process where the materials are no longer recoverable.	**0.20**	kg
Wc	Mass of unrecoverable waste generated in the process of recycling parts of a product.	**0.12**	kg
Wf	Mass of unrecoverable waste generated when producing recycled feedstock for a product.	**0.0278**	kg
LFI	Linear flow index	**0.5910**	
F(X)	Utility factor built as a function of the utility **X** of a product.	0.90	
X	Utility of a product.	**1.00**	
L	Actual average lifetime of a product.	40	years
Lav	Average lifetime of an industry-average product of the same type.	40	years
U	Actual average number of functional units achieved during the use phase of a product.	1	qtt
Uav	Average numbers of functional units achieved during the use phase of a industry-average product of the same type.	1	qtt
	OUTPUT		
MCIp	**Material circularity Indicador of a product.**	**0.4681**	(0 to 1)
	☐ Input Data		

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