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# Methodology to Assess the Circularity of Industrial Processes

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***Abstract*—**The EU Circular Economy action plan, launched in 2020, is one of the major initiatives to promote the transition into a more sustainable industry. The circular economy is a popular concept used by many companies nowadays. Some industries are better forwarded to this reality than others, and the tannery industry is a sector that needs more attention due to its strong environmental impact caused by its dimension, intensive resources consumption, lack of recyclability, and second use of its products, as well as the industrial effluents generated by the manufacturing processes. For these reasons, the zero-waste goal and the European objectives are further being achieved. In this context, a need arises to provide an effective methodology that allows to determine the level of circularity of tannery companies. Regarding the complexity of the circular economy concept, few factories have a specialist in sustainability to assess the company's circularity or have the ability to implement circular strategies that could benefit the manufacturing processes. Although there are several methodologies to assess circularity in specific industrial sectors, there is not an easy go-to methodology applied in factories aiming for cleaner production. Therefore, a straightforward methodology to assess the level of circularity, in this case of a tannery industry, is presented and discussed in this work, allowing any company to measure the impact of its activities. The methodology developed consists in calculating the Overall Circular Index (OCI) by evaluating the circularity of four key areas -energy, material, economy and social- in a specific factory. The index is a value between 0 and 1, where 0 means a linear economy, and 1 is a complete circular economy. Each key area has a sub-index, obtained through key performance indicators (KPIs) regarding each theme, and the OCI reflects the average of the four sub-indexes. Some fieldwork in the appointed company was required in order to obtain all the necessary data. By having separate sub-indexes, one can observe which areas are more linear than others. Thus, it is possible to work on the most critical areas by implementing strategies to increase the OCI. After these strategies are implemented, the OCI is recalculated to check the improvements made and any other changes in the remaining sub-indexes. As such, the methodology in discussion works through continuous improvement, constantly reevaluating and improving the circularity of the factory. The methodology is also flexible enough to be implemented in any industrial sector by adapting the KPIs. This methodology was implemented in a selected Portuguese small and medium-sized enterprises (SME) tannery industry and proved to be a relevant tool to measure the circularity level of the factory. It was witnessed that it is easier for non-specialists to evaluate circularity and identify possible solutions to increase its value, as well as learn how one action can impact their environment. In the end, energetic and environmental inefficiencies were identified and corrected, increasing the sustainability and circularity of the company. Through this work, important contributions were provided, helping the Portuguese SMEs to achieve the European and UN 2030 sustainable goals.

***Keywords*—**Circular economy, circularity index, sustainability, tannery industry, zero-waste.

## I. Introduction

SUSTAINABILITY is one of the most debated topics in the scientific community today. The symbiosis between production and its self-regeneration in terms of materials and consumption, leading to a decrease in the economic expenses of the company, is a common goal for companies that want to become self-sustaining to reduce their ecological footprint [1]. Thus, one of the steps towards a sustainable future is the application of the circular economy in the industry world, since this is one of the largest demands responsible for the depletion of natural resources and environmental pollution. Modern circularity is based on the technological progress of companies and political decisions focused on meeting the sustainability principles set by the EU such as increasing recycled content in products, enabling remanufacturing and high-quality recycling and improving product durability, reusability, upgradability and reparability [2]. The EU needs to speed up the transition to a regenerative model of growth – one that gives more back to the planet than it takes from it [2]. The Circular Economy (CE) is an idea that suggests a way of planning production and consumption processes to create closed loops of materials, with the aim of preventing waste and preserving resources within the system while minimizing the economy's environmental impact and resource demands [3]. A CE is synonymous with more efficient and affordable materials for the average citizen, which have a longer duration and are designed and built to be reused, repaired, and recycled [4]. Thus, investing in the planning of circularity is betting on a more sustainable future in which the control and control measures of production are more rigid. The European Circular Economy Plan (CEAP 2020), to be implemented by 2030, proposes several measures to increase CE, being one of them the deconstruction of all the elements necessary to manufacture a product, recognize the use of harmful chemicals, and bet on their reduction replacing by other compounds more sustainable [5]. Another measure is to invest in producers and local businesses, to limit the volume of transport of materials, and to enrich the community in which they are inserted, in order to reduce gas emissions. Thus, a shift of attention from production to research and consequent improvement of the production process can lead to the

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reduction of company costs and increased sustainability. It would be ideal if we could recycle 65% of municipal waste by 2030, and if waste derived from packaging could constitute 75% of the total [3]. In addition, landfills should not represent more than 10% of municipal waste by 2030 [3]. Missing the application of these measures will reduce the possibility to achieve EU sustainable goals, meaning that industries will suffer penalties reducing the probability to enter or keep its activity into the market. In this context, this work intends to provide an effective solution to the tannery industry that allows to assess the circularity of a company.

Beyond the different circularity methodologies, Material Circularity Indicator (MCI) [6] is the state of the art, regardless of the area in which the assessment is conducted. The methodology assigns a score between 0 and 1 to the company's products in question to understand how linear or restorative the product life cycle is and how harmful or beneficial the company's product is compared to related products from similar industries. This means that the overall low circularity score indicates a big need for better-implementing circularity strategies [7]. Three product attributes are essentially combined to create the MCI: the mass V of virgin raw material used in the product's creation, the mass W of unrecoverable waste associated with the product, and a utility factor X that considers the duration and intensity of the product's use. Prior to this methodology, another has emerged to meet the needs of circularity. Life Cycle Assessment (LCA) [8] is carried out in four main phases: Goal and Scope Definition; Inventory Analysis; Impact Assessment; and Interpretation. The ISO standard for LCA includes the following sub-phases: Impact category definition; Classification; Characterization; Normalization; Grouping; and Weighting. MCI and LCA are general methodologies, not specific to any industry but that can be adapted for any circularity index calculation. Using the above methodologies, numerous ones with different applications and dimensions emerged. The combination of these two methodologies gives rise to new circularity methodologies that combine the basis for the MCI indicators and the LCA phases, with adaptation for specified industries and with the update that the sustainability measures require. The different methodologies, created by different countries, initiated by comparison in areas such as industrial competitiveness, sustainable development, globalization, and innovation [9] differ in the application of the same, following different methodologies and lines of thought. For example, the index proposed in Sustainable Circular Index (SCI) [10] is for an individual company and not for a supply chain. The construction of the SCI is formed by four dimensions (Economic, Social, Environment, and Circularity) and focuses on a linear methodology followed step-by-step. The next five phases are followed to reach the proposed SCI: Phase 1 – Selection of sustainability and circularity indicators; Phase 2 – Weighting of indicators; Phase 3 – Normalization; Phase 4 – Aggregation method for index construction – Simple Addictive Weighting Method; Phase 5 - Index Construction. Thus, by refining the phases of the methodology, specifying a little more than the LCA, the calculation of the circularity index becomes more objective and can be adapted to all industries, thus being an upgrade to the original methodology. However, there is another divergent methodology that proposed a Circularity Measurement Toolkit (CMT) [11] which enables the assessment of the degree of circularity in manufacturing SMEs. This methodology is divided into three phases: 1) Development of the Framework for the proposed CMT; 2) Verification and 3) Validation. This methodology is important to organize the focus of the company back into environmental measures and to organize data. There is still another methodology focused on SMEs that offers another perspective and encourages the change in basic assumptions in enterprises. The work's goal is to create a model for calculating a Composite Sustainable Development Index ($I_{CSD}$) so that integrated data on the company's social, environmental, and economic performance can be tracked over time [12]. The study shows that an integrated approach to sustainable development assessment is feasible and can yield useful recommendations for policymakers. Focusing on linear methodologies, the goal of a study formulated in 2022 is to create a thorough methodology for CE assessments that can evaluate the circularity of products and processes across many different sectors and businesses [13]. The established framework includes a step-by-step approach for selecting indicators that encompasses the micro, meso, and macro-CE levels of implementation, allowing for a thorough assessment. The framework provides for both subjective and objective methods for allocating weight to the indicators based on stakeholder preferences, which slightly changes the initial perspective that all indicators had the same. Thus, assigning different weights is possible, some factors are more important than others for the construction of an industry's sustainability.

In Circularity Indicators Project Methodology (CIP) [14], the focus is on circularity indicators, and the following indicators are proposed: a main indicator, the MCI, is a metric that assesses the restorative nature of material flows associated with a product or company. It is complemented by additional indicators that enable the consideration of additional impact and risks. The restorative aspect of a product's material flow is defined as the proportion that originates from reused or recycled sources and is restored through reuse or recycling, which is one of the most interesting perspectives of circularity methodologies regarding sustainable production and cadence of virgin material use. In addition to the rate of use of the material for production, methodologies that consider the sustainability of all other components adjacent to production were established. Circularity GAP Report (CGR) methodological approach [15] for the qualification and tracing of material, energy, and waste flows through the socioeconomic system, is based on the economy-wide monitoring framework of the CE as developed by previous studies but adapted for the assessment of the global socioeconomic system and tracking material flows for our Circularity Indicator framework. Still in the combination of all components of production for a combination of them for an increase in CE, a paper developed in 2021 by Arneu Gonzalez and his team employed a ratio-based approach to assess the circularity of flows in three key areas: energy, water, and materials construction. This ratio is then combined with an assessment of the social and economic value added throughout the entire activity's life cycle [16]. The rationale is to maximize the circular flows, i.e., the reuse/recycling of materials or the energy self-generation; the circularity of Business Model (BM) proposed to guarantee the CE principles are respected to a major extent. Also, the use of renewable energy sources together with the characteristics of the production process positively affects the Circularity Indicators for Energy ($ECI_p$) value, which is the main objective of all these methodologies [17]. Being GHG emissions still the single biggest contributor to climate change [18], carbon emissions must be considered too to evaluate the sustainability of a company, using for example methodologies such as cradle-to-grave, cradle-to-site [19]. Under optimized conditions, the packaging of the products that follows some strategies such as promoting cross-sectoral valorization of plastic wastes, or improving recycling efficiency of wastes can reach a positive balance in terms of GHG emissions [20]. Extending the methodologies to a more informatic vein, the BILIMOD method combined self-partitioning algorithm for the static component and a gradient-based optimization method for the dynamic component [21]. The proposed method reaches the desired set point faster and with fewer setpoint changes, which implies that the overall economic cost is less. Focusing on the social aspect of calculating the circularity indicator, a knowledge map of the CE, an examination of social features within the CE, and the theories/frameworks used to assess the social impact of the CE are the three primary outcomes of yet another review [22]. This study sheds light on the potential social effects of CE implementation and emphasizes the significance of the social dimension in the fields of CE and policymaking, which way facilitated the transition of CE towards sustainable development. In addition to this series of steps, the implementation of S-LCA to assess CE concepts, and which additional training and education (for employees) were found to be relevant indicators that should be considered [23]. It has already been proven that consumer health and safety rank highest among the social factors that matter most to CE professionals [24], bringing a better understanding of CE monitoring. Ecopyme [25] operationalizes the preceding theory by developing it for a series of steps that are based on the importance of the social component. These steps have two key criteria that must be included in the process: the creation of value within the firm is contingent upon the implementation of a CE and the commitment of senior management to all employees [26]. The identification of interactive relationships among the KPIs will assist managers and decision-makers in incorporating effective and sustainable policies in this kind of industry. This will highlight the power that choosing the right KPIs can have in the development of a company. Although there are already numerous methodologies based on the MCI and LCA, theorizing a linear method for calculating circularity in SMEs, the practical component is still lacking insofar as the applicability of the methodologies is not yet being put into practice, leaving some gaps in the subject of circularity. While MCI indicates how much a product's materials circulate, it neither considers what these materials are nor does it provide information on other impacts of the product, and since it is the basic methodology and can be applied to different circularity calculations applied to different industries, it cannot go too deeply into a specific area in terms of circularity indicators. However, the MCI has corrected some shortcomings in the LCA in terms of the amount of data required in this methodology which, in some cases, may not be suitable for the company. The methodology developed in this work article, being applied to a specific industry, manages to go further when it comes to circularity indexes, customizing those same indexes for the company under study. On the other hand, SCI does not offer a reformulation to improve the circularity index, i.e., it is calculated and that is the end of the methodology. It does not consider a circular methodology that reformulates the index, correcting the previous steps to be a methodology that allows the company to constantly evolve. Another identified gap is the non-combination of one or more circularity factors. The lack of precise combination of these factors leads to an excess of unnecessary data and does not consider that, in companies, the components are interconnected with each other leading to one depending on the other. Thus, it is important to combine several factors into one circularity index so that it resembles reality and the true circularity index as much as possible. In addition to the complexity of the indicators, it is also important to consider the complexity of the products themselves, making it possible to adjust indicators accordingly. To reduce the complexity of the indicators' calculation, it is important to deconstruct the production process so that the various elements in it are separated into categories and grouped together in the most efficient way so that the indicators do not repeat themselves and are not calculated more than once. Another factor to consider is the weight of the circularity indicators and how the determination of this weight is accurate. As the circularity index is calculated from the average of the values of the circularity indicators in each section of the company, it should be taken into account that not all indicators can have the same weight regarding the company's sustainability. Thus, poor determination of the weight of the indicators can lead to an incorrect circularity index that cannot be improved in the right way. As far as circularity indicators are concerned, there is no consensus in the selection of the framework as sometimes indicators are subjective, and the company is not able to provide an effective and representative value. Finally, circularity indicators on the sustainability of the company at the environmental level are not built in the sense of heading to a positive indicator that brings benefits to the company but rather as a negative indicator that lowers the circularity index. Therefore, strategic planning of indicators is required to enhance the global circularity index's performance.

To address the limitation associated with the circularity assessment of companies, the present methodology is applied to a practical case in order to validate its steps in the different areas of intervention. Based on the existing literature, the aspects to be noted in the construction of a sustainable and fair circularity index for the company are identified, balancing all factors and combining the complexity of production with the interconnection of product components. Regarding the needs highlighted by the EU by 2030, the methodology will also permit to identify solutions for low circular indicators so that, while increasing its circularity index, it collaborates towards European sustainability objectives. The final aspect to consider is the potential for normalization of indicators to facilitate progress in other industries. Once the efficacy of such normalization has been demonstrated, the resulting values can be employed in future calculations of circularity indicators. This could pave the way for the unification of industries, enabling a more straightforward and equitable assessment of regulatory units. Furthermore, it could foster a competitive environment where companies strive to enhance their circularity index, thereby contributing to the achievement of EU sustainable goals. In this context, this work intends to respond to two research questions:

A) Is it possible to combine different indicators based on the complexity of the product?
B) Is it possible to increase the circularity index of a company by effecting changes in the manufacturing process already defined by the use case?

## II. Methodology

The present methodology was developed in order to face up to the challenges the SME's meet in assessing and improving their circularity. By creating a simple rationale around the steps needed to be taken to improve the CE, the companies that do not have enough specialized resources to tackle this issue can work on it without much investment or research.

The methodology consists of 4 main steps: target characterization, circularity level assessment, goals definition, strategy formulation and strategy implementation, as expressed in Fig. 1. Each step that characterizes the methodology is expressed in Subsections II *A-E*.

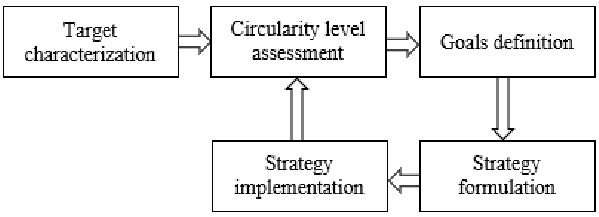


Fig. 1 Methodology Strategy Scheme.

### A. Target Characterization

First, it is necessary to define the target to assess circularity. The target could be a product, a process, a factory, a company, a whole industrial sector, etc. For example, if assessing the circularity of a product, one must address all of its life cycle from beginning to end of life, its impact and how "circular" it can be. For any of these targets, the line of thinking remains the same, which is what this methodology reflects.

### B. Circularity Level Assessment

The assessment of the circularity follows the target characterization and involves the calculation of an overall circularity index (OCI). The OCI, when applied for the first time, serves as a baseline and can be compared with future situations. The index is calculated based on a group of selected KPIs and has a value between 0 and 1, representing from a linear to a CE. The KPI's are segregated into four main domains – Environmental, Material, Economic and Social. These domains were selected since they emphasize the sustainability triple bottom-line approach, alongside the material part. Each domain will have an index on their own, also varying between 0 and 1, and the OCI consists of the average of the four circular indexes – ECI (Environmental Circular Index), MCI (Material Circular Index), EcCI (Economic Circular Index) and SoCI (Social Circularity Index).

The Environmental domain can generally be divided into at least two sub-areas: energy and effluents. It can be further broken down if considering emissions, water usage and compressed air usage. The energy part of the environmental KPIs explores into more detail the usage and origin of the energy, may it be in the form of electricity or heat, for the manufacturing process or the company itself. Finding ways of saving energy or reducing it should be compensated, as well as correcting as many inefficiencies as possible. As for the effluents part, it focuses more on the impact that the target leaves on the environment. Its impact can take the form of waste generated, emissions of pollutant gases, water usage and lack of reutilization, anything that brings forth a negative impact on the environment.

The Material domain focuses mostly on the recyclability and reutilization capability of the product and/or the consumables involved in the manufacturing process, the reduction of virgin material quantity introduced and the valorization of sub-products. The attribution of a second life to a product is the core of CE and this domain reflects that.

The Economic domain evaluates the circularity of the target in a more financial way, with special focus on environmentally friendly approaches and circular practices, rewarding the efforts towards a more CE. It also assesses the economic sustainability of the target, measuring its resilience.

The Social domain brings awareness of the impact the target has on society. Even though social impact indicators are not something everyone can agree as to what exactly they should measure [22], for this methodology it was decided that it assesses the target on four main areas: workers involved (safety and satisfaction); clients; corporate governance; local community impact.

Given the importance and general idea of each domain, the KPIs must then be adapted for each different target, depending on its reality and main goal. After the KPIs are defined and the data are collected, the calculation of each sub-index follows so that finally the OCI can be obtained.

For straightforwardness, equal weights were assigned to each KPI within each domain, as well as to each of the four domains themselves. To build each sub-index, the indicators must go through a normalization process since they are expressed in different units. For the normalization process, it is essential to separate the normalized indicators $i$ from the dimension with a positive impact from those with a negative impact on sustainability, each of which has its own generic formula that follow the Minimum-Maximum method [10] being $I^{+}_{Ni,j}$ and $I^{-}_{Ni,j}$ the normalized indicator with a positive and negative impact, expressed in (1) and (2), respectively. The values of the normalized indicators will fall within the range of 0 and 1.

$$I^{+}_{Ni,j} = \frac{I^{+}_{i,j} - I^{+MIN}_{i,j}}{I^{+MAX}_{i,j} - I^{+MIN}_{i.j}} \quad (1)$$

$I^{+}_{i,j}$ represents the indicator $i$ from the dimension of sustainability $j$ with positive impact on sustainability; $I^{+MIN}_{i.j} = minI^{+}_{i,j} \cdot I^{+MAX}_{i,j}$ is the lowest value of indicator $i$ from the dimension of sustainability $j$ with positive impact on sustainability. $I^{+MAX}_{i,j} = maxI^{+}_{i,j}$ represents the highest value of indicator $i$ from the dimension of sustainability $j$ with positive impact on sustainability.

$$I^{-}_{Ni,j} = \frac{I^{-}_{i,j} - I^{-MIN}_{i,j}}{I^{-MAX}_{i,j} - I^{-MIN}_{i,j}} \quad (2)$$

$I^{-}_{i,j}$ is the indicator $i$ from the dimension of sustainability $j$ with negative impact on sustainability; $I^{-MIN}_{i,j}$ expresses the lowest value of indicator $i$ from the dimension of sustainability $j$ with negative impact on sustainability, while $I^{-MAX}_{i,j}$ represents the highest value of indicator $i$ from the dimension of sustainability $j$ with negative impact on sustainability.

Another way of normalizing positive and negative impact indicators is the Multiple Attribute Weighting Method (MADM) [27] in which $r_{ij}$ is the normalization of the indicator that will fall within 0 and 1; $V_j$ is the indicator variable; $x_{ij}$ is the value of the system.

$$r_{ij} = \begin{cases} \dfrac{x_{ij}}{\mathrm{MAX}\, i}\{x_{ij}\} \text{ if } V_j \text{ satisfies "the larger the better"} \\ \dfrac{\mathrm{MIN}\, i}{x_{ij}}\{x_{ij}\} \text{ if } V_j \text{ satisfies "the smaller the better"} \\ \dfrac{\mathrm{MIN}\{x_{ij}, X_j^0\}}{\mathrm{MAX}\{x_{ij}, x_j^0\}} \text{ if } x_j^0 \text{ is the ideal value with respect to } \mathrm{V_j} \end{cases} \quad (3)$$

For example, if $V_j$ fulfills the category "the larger the better", the system must improve its performance by $100(1 - r_{ij})\%$ to reach the current best level with respect to $V_j$.

The Minimum-Maximum method is used when the complexity of the indicators has defined reference values or limits and is recommended for the regularization of all indicators, all of which are calculated in the same way. However, extreme values/or outliers could distort the transformed indicator [28]. The MADM is recommended for its ease of interpretation and its arithmetic form, which values ratio-scale variables.

### *C. Goals Definition*

With the information provided by the OCI, one can conclude which areas have lower indexes and which ones are aligned with the EU circularity goals. The goal under this approach is to increase the lower sub-indexes by tackling the indicators that most bring it down. This step should be about analyzing the resulting OCI and determine which domains the company must work on more closely and urgently to become more circular. A clear objective such as increasing one sub-index by 50%, for example, is one way to do it.

### *D. Strategy Formulation*

With the goal previously defined in mind, it follows the formulation of some strategies to increase specific indexes related to each KPI. A different strategy must be applied depending on the domain, the specific goal and the target. Since the methodology tries to be as generic as possible, it is challenging to suggest concrete ideas but there are some actions that will adapt to different situations.

Looking at environmental KPIs, methodologies that rate inefficiencies of processes can be applied. The Multi-Layer Stream Mapping (MSM) [29], [30] is a possible approach. Through MSM, one can split a process into various phases and evaluate each one with a set of KPIs that assess the efficiency of said process phase.

For social KPIs, a way to measure satisfaction of the people involved is to implement satisfaction questionnaires to either stakeholders, clients, workers and/or local community. Following this approach, it is also possible to know from the people involved what specific matters need to be improved and how.

Economic KPIs are the most volatile, given that all the investments made into the other KPIs from other domains, are reflected on economic KPIs. Their improvement is slower than the other KPIs because the return of investments or the gain of profits is dependable of how the other KPIs improve. Therefore, economic KPIs can decrease, from one evaluation to another, without meaning that the investments were not worth it. They can also go up with the increase of sales or productivity, without needing a large sum of investment for it.

For Material KPIs, these are usually tied to the manufacturing process or the product itself. If the target is a product, some specific design strategies could be implemented to either introduce recycled materials on it, optimize manufacturing processes, make it more easily recyclable or allow a second life after use. Allowing refurbishment or easy maintenance are other relevant design strategies to promote circularity. If the target concerns a manufacturing process, then the optimization of the consumables, making the process as efficient as possible is an imperative measure. The reuse of waste material is also essential for raising circularity.

### *E. Strategy Implementation*

Finally, the strategies planned and defined in the previous step should be implemented. At this stage, the specific changes are implemented on the target based on the strategy formulated in the previous step. Product goes through alterations or a machine gets updated in the factory or new policies are made in the company. Whatever the target, it must undergo some alterations in order to improve its circularity according to the goals previously defined.

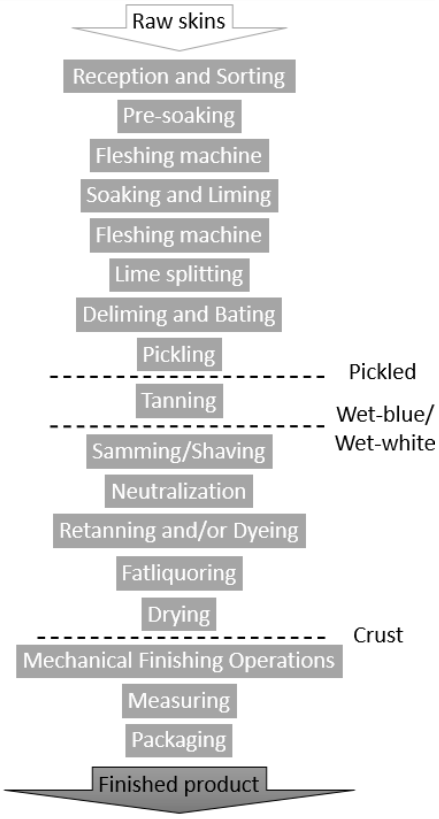


Fig. 2 Manufacturing process flowchart

After completing the Strategy implementation phase, the Circularity level assessment must be repeated, as suggested in Fig. 1. By going back to the first step, the circularity level is reevaluated using the same group of KPIs, to check if the changes made were efficient and the goals were achieved. This continuous assessment highlights that, while the circularity index may have new inefficiencies, it may have emerged requiring improvement. So, the process repeats until a high (close to one) circularity index is achieved, meeting the pre-established goals of the company. This way, the methodology works as continuous improvement for the established target, revealing in each assessment which areas are hindering the circularity level and consequently should be improved. The addition of KPIs is also permitted, if the use case intends to evaluate new parameters.

## III. Methodology Implementation

### A. Use-Case Description

As previously stated, the tannery industry must follow a more circular approach. Therefore, the use case selected to apply and test the proposed methodology is a tannery SME whose manufacturing processes range from tanning the leather into hair to the final product, specializing mainly in varnishes, suedes, x-tan and wet-white items. The company employs approximately 50 workers and its main sectors are the footwear, clothing and leather works.

The company's concept already revolves around circularity as it benefits from the wastes of slaughterhouses, by upcycling the animal skins into valuable products [31]. Specifically, the target chosen is the factory and the manufacturing processes their products involve.

From the arrival of the skins to the departure of the finalized products, they go through a manufacturing process full of chemical and mechanical operations. The use case provided a production flowchart as depicted in Fig. 2.

Depending on the type of leather produced and the kind of feedstock received, some steps of the process can be ignored or skipped. Some products are sold in the Wet-Blue phase, others in Crust, and finally some are sold finished. Besides, not all products are manufactured from raw skins as some are produced from skins at later phases as a service.

The global manufacturing process starts from the reception of raw skins and ends at the departure of a finished product. The skins are firstly received, cured in salt and then go through a sorting by size, weight or quality. In the pre-soaking step, the skins are cleaned of their impurities (blood, dirt, fats, etc.) and salt as well as get their fibers rehydrated. Then, they go through fleshing where the skins are subjected to mechanical and chemical processes in a fleshing machine to remove materials from the flesh side. This phase allows a more uniform and easier penetration of chemical products into the skin for future processes, while resulting in the origin of sub-products. In the soaking and liming step, the hair, epidermis and other interfibrillary proteins are eliminated through chemicals while the skin swells enough for the fleshing and splitting processes. The skin goes through the fleshing machine once more to finish eliminating the fats adherent to the flesh side, and afterwards it is submitted to a division of its layers by mechanical action in the lime splitting process, with the purpose of separating the inner layer (flesh side) from the outer layer. The inner layer then becomes a sub-product while the outer layer will continue on the production line. The next phase is the deliming where there is a removal of chemics previously absorbed by the skin while the swell decreases with the increase of temperature and agitation of the bath as well as pH lowering. The bating process continues the clean-up of the skin from all organic matter through proteolysis while providing the desired properties (elasticity, flexibility and softness). Then, the pickling process prepares the skin for the tanning by lowering even further the pH, dehydrating its fibers, ending the bating and sterilizing the skin through tannages resulting in pickled skins. The tanning is a chemically complex process which transforms the pickled skins into tanned ones by stabilizing the collagen fiber through the cross-linking action of tanning agents (e.g., chromium III) without changing the natural structure of its fibers and granting the desired properties (mechanical and heat resistance, dimensional stability, among others specific to each case). Depending on the agents used, the skins are nominated Wet-Blue (WB) or Wet-white (WW), and these can be sold at this point. After the tanning, the WB/WW skins are sorted by their quality and the type of final product expected. Afterwards, the samming and shaving are two mechanical operations aiming to regulate the thickness of the skin. Just before the retanning, the neutralization process fixes the pH by removing the excessive acids originated in the tanning process, readying the WB/WW skins for the following operations. The Retanning allows the production of more uniform physical and aesthetical properties as well as improves the handle of the leathers. The dyeing process grants color to the skins by dyes, mostly acid ones. As for the fatliquoring, it consists in softening the skin for the drying by partially replacing the water existent between the fibers with fats. Then, in the drying, the water and humidity of the skin are removed and its chemical properties are achieved. The drying technique can be by vacuum, chamber, hanging at room temperature, etc. depending on the type of leather. After drying, the leather is referred to as crust and can be sold at this point. The finishing phase involves a few processes to improve the appearance and other extra characteristics. The mechanical finishing processes include a variety of operations like conditioning, staking, polishing, coating, etc. The finished leathers are then sorted by their quality and measured in square feet as per its commercialization habit in a proper machine. Finally, the finished product is packed in plastic ready to be shipped off.

### *B. KPIs Identification and Data Collection*

After the analysis of the processes and steps, it follows the KPI selection. Considering that the factory was the target, the KPIs revolve around what the manufacturing processes involve and the company policy. These are presented in Tables I-IV.

The environmental KPIs focus mostly on energy usage and its origin, quantity of wastes and gaseous emissions, effluents generated and water usage since this is a major issue for this industry. The KPIs were aligned with the use case to accurately reflect its context and meet expectations. This involves the selection of a subset of indicators for which the use case had available data. For the environmental KPIs, nine indicators were collected to ensure that adequate attention was devoted to this domain, given its significant importance, especially in comparison to other industries, owing to the extensive use of chemicals and the generation of wastes.

Regarding the material KPIs, since their product could never incorporate recycled skins, these focus more on the reutilization of process consumables and solid wastes management. Also, the tannery industry originates some sub-products that can be valued, so that issue is also incorporated them in the material KPIs.

TABLE I
ENVIRONMENTAL KPIS

| KPI Identification | KPIs | Units |
|---|---|---|
| $I_{1,1}$ | Renewable energy percentage | % |
| $I_{1,2}$ | Total energy usage in factory | kWh |
| $I_{1,3}$ | Heat recovery rate | % |
| $I_{1,4}$ | Pollutant gases direct emissions | $m^3$ |
| $I_{1,5}$ | Dangerous wastes generated | kg |
| $I_{1,6}$ | Total chemicals usage in process | kg |
| $I_{1,7}$ | Liquid effluents treated in WWTP | $m^3$ |
| $I_{1,8}$ | Water reuse percentage | % |
| $I_{1,9}$ | Water usage per manufacture product | $m^3/kg$ |

As for the economic KPIs, these touch on circular practices and their financial gains, as well as the factory productivity to evaluate its financial sustainability.

Lastly, the social KPIs measure the workers' well-being and work conditions as well as governance of the company. These were the KPIs that the company felt interested in measuring in the long run.

It is important to note that each company can decide the indicators they intend to follow and through time, and evaluate their evolution, always taking into account the European guidelines for the type of industry.

TABLE II
MATERIAL KPIS

| KPI Identification | KPIs | Units |
|---|---|---|
| $I_{2,1}$ | Reutilization of waste material | kg |
| $I_{2,2}$ | Waste generated for landfill | kg |
| $I_{2,3}$ | Reused consumable (salt only) rate | % |
| $I_{2,4}$ | Recovered chromium percentage | % |
| $I_{2,5}$ | Plastic film usage | kg |
| $I_{2,6}$ | Percentage of mineral, vegetal and synthetic agents | % |

TABLE III
ECONOMIC KPIS

| KPI Identification | KPIs | Units |
|---|---|---|
| $I_{3,1}$ | Return Of Investment (ROI) of the solar photovoltaics power plant implementation | € |
| $I_{3,2}$ | Productivity of the production line 1 | € |
| $I_{3,3}$ | Productivity of the production line 2 | € |
| $I_{3,4}$ | Productivity of the production line 3 | € |
| $I_{3,5}$ | Productivity of the production line 4 | € |
| $I_{3,6}$ | Sale of residues | € |
| $I_{3,7}$ | ROI in sustainable solutions | € |
| $I_{3,8}$ | Sale of leftovers | € |

TABLE IV
SOCIAL KPIS

| KPI Identification | KPIs | Units |
|---|---|---|
| $I_{4,1}$ | Number of accidents per year | Quantity |
| $I_{4,2}$ | Absenteeism rate due to casualties | % |
| $I_{4,3}$ | Worker turnover | % |
| $I_{4,4}$ | Annual training hours per worker | hours/year |
| $I_{4,5}$ | Ratio between effective and temporary workers | - |
| $I_{4,6}$ | Ratio between men and women workers | - |
| $I_{4,7}$ | Internal promotion rate | % |
| $I_{4,8}$ | Local slaughterhouse preference | - |
| $I_{4,9}$ | Employment created in the community | % |

In order to obtain the data necessary for the KPIs, some field work was necessary. Some data were collected through sensors, analyzers or measuring equipment located, for example, in machines. The data could be measured continuously or momentarily according to the needs or obligations of the use case. The indicators $I_{1,1}$, $I_{1,2}$, $I_{1,4}$, $I_{2,5}$ were obtained this way. Other KPIs were measured/calculated either manually or through information saved in the company's ERP (enterprise resource planning), like $I_{1,5}$, $I_{1,6}$, $I_{1,7}$, $I_{1,9}$, $I_{2,1}$, $I_{2,2}$, $I_{2,6}$ and all the economic and social indicators. Some indicators could not be measured due to the lack of available data in the current state of the use case. All the data are relative to the year of 2023.

## IV. Results and Discussion

### *A. Index Calculation - Normalization*

After the data were gathered, it went through a normalization process in order to obtain an index ranging between 0 and 1, since the data obtained come in different units, making direct comparisons impractical. The index serves as a standardized measure, allowing for meaningful comparisons across different indicators. A lower index value suggests a more liner economy, while the goal is to maximize the index value, indicating greater circularity.

For each KPI, it is necessary to establish both minimum and maximum values achievable, which are defined either by the company's objectives or established benchmarks within relevant literature [32]. To normalize KPIs in this user case, the normalization method chosen was MADM, previously presented in Chapter II *A*). In cases where the minimum value cannot reach 0 satisfying the "smaller the better" principle or where the maximum value cannot reach 1 for a KPI following the "larger the better" principle, it is recommended to adjust the targets annually, based on the company's achievement of previous targets.

Each KPI is governed by a unique equation, tailored to its specific variables, applying the data provided by the use case. Depending on the KPI and its standard values, we apply one of two normalization methods, which are duly identified. The equations are represented in the Appendix section.

The indicators $I_{1,1}$, $I_{1,3}$, $I_{1,8}$, $I_{2,1}, I_{2,3}$, $I_{2,4}, I_{2,6}, I_{3,1}, I_{3,2}, I_{3,3}, I_{3,4}, I_{3,5}, I_{3,6}, I_{3,7}, I_{3,8}, I_{4,4}, I_{4,5}, I_{4,7}, I_{4,8}$ and $I_{4,9}$ use the normalization equation (3). The indicators $I_{1,2}$, $I_{1,4}$, $I_{1,5}$, $I_{1,6}$, $I_{1,7}$, $I_{1,9}$, $I_{2,2}$, $I_{2,5}$ and $I_{4,1}$ use the normalization equation (3). The indicators $I_{4,2}$, $I_{4,3}$, and $I_{4,6}$ use the normalization equation (3).

Baseline

Once all the necessary data for index calculation are collected, the baseline is determined by the average of all indexes. The transformed data, converted into indexes, are shown in Table V, along with each corresponding sub-index.

The OCI is then calculated by the average of the four sub-indexes, achieving a value of *0,352*. This number reveals that the use case is more linear than circular and has much room for improvement. Notably, the highest sub-index is the Social one with a value of 0,517 and, even so, it is still half way to a score of 1. The factors that most elevate the SoCI are the lack of worker absenteeism and temporary workers ($I_{4,2}$ and $I_{4,5}$), as well as very little turnover in the company and all employees being from the nearby community ($I_{4,3}$ and $I_{4,9}$). The other indicators affect negatively the SoCI, notably, the lowest KPI index is $I_{4,7}$ registering a value of zero due to the absence of any recorded promotion in 2023. The ECI is the second lowest sub-index of the group. This fact does not come as surprising since the environmental issue is pertained to this industry due to the high usage of water (reflected in $I_{1,8}$ and $I_{1,9}$), chemicals and effluents ( $I_{1,6}$ and $I_{1,7}$) and emissions of pollutant gases ($I_{1,4}$). The heat recovery and water reuse indicators ($I_{1,3}$ and $I_{1,8}$) reveal an index of zero due to the non-existent system to recover neither the heat generated nor the water used within the factory. The $I_{1,1}$ index directly reflects the percentage of energy produced by the company's solar photovoltaics power plant, which is almost a quarter of their full energy demand. Lastly, the $I_{1,5}$ has the maximum value index of the environmental domain, as all wastes generated are forwarded to a waste management facility, resulting in no landfill disposal.

TABLE V
KPI Indexes

| KPI Identification | KPIs | Index |
|---|---|---|
| $I_{1,1}$ | Renewable energy percentage | 0,231 |
| $I_{1,2}$ | Total energy usage in factory | 0,582 |
| $I_{1,3}$ | Heat recovery rate | 0 |
| $I_{1,4}$ | Pollutant gases direct emissions | 0,089 |
| $I_{1,5}$ | Dangerous wastes generated | 1,000 |
| $I_{1,6}$ | Total chemicals usage in process | 0,332 |
| $I_{1,7}$ | Liquid effluents treated in WWTP | 0,142 |
| $I_{1,8}$ | Water reuse percentage | 0 |
| $I_{1,9}$ | Water usage per manufacture product | 0,120 |
| - | **Environmental Circular Index** | **0,277** |
| $I_{2,1}$ | Reutilization of waste material | 0,315 |
| $I_{2,2}$ | Waste generated for landfill | 0,626 |
| $I_{2,3}$ | Reused consumable (salt only) rate | 0 |
| $I_{2,4}$ | Recovered chromium percentage | 0 |
| $I_{2,5}$ | Plastic film usage | 0,567 |
| $I_{2,6}$ | Percentage of mineral, vegetal and synthetic agents | 0,639 |
| - | **Material Circular Index** | **0,358** |
| $I_{3,1}$ | Return Of Investment (ROI) of the solar photovoltaics power plant implementation | 1,000 |
| $I_{3,2}$ | Productivity of the production line 1 | 0,056 |
| $I_{3,3}$ | Productivity of the production line 2 | 0,093 |
| $I_{3,4}$ | Productivity of the production line 3 | 0,047 |
| $I_{3,5}$ | Productivity of the production line 4 | 0,537 |
| $I_{3,6}$ | Sale of residues/sub-products | 0,315 |
| $I_{3,7}$ | Return Of Investment (ROI) in sustainable solutions | 0 |
| $I_{3,8}$ | Sale of leftovers | 0 |
| - | **Economic Circular Index** | **0,256** |
| $I_{4,1}$ | Number of accidents per year | 0,267 |
| $I_{4,2}$ | Absenteeism rate due to casualties | 0,980 |
| $I_{4,3}$ | Worker turnover | 0,923 |
| $I_{4,4}$ | Annual training hours per worker | 0,038 |
| $I_{4,5}$ | Ratio between effective and temporary workers | 1,000 |
| $I_{4,6}$ | Ratio between women and men workers | 0,197 |
| $I_{4,7}$ | Internal promotion rate | 0 |
| $I_{4,8}$ | Local slaughterhouse preference | 0,250 |
| $I_{4,9}$ | Employment created in the community | 1,000 |
| - | **Social Circular Index** | **0,517** |

In the MCI, the indexes are moderately average except for the indicators $I_{2,3}$ and $I_{2,4}$ which lower significantly the sub-index by having no reutilization/recovery whatsoever, despite in previous years the chromium being fairly recovered on an outside facility. The highest index of this group belongs to indicator $I_{2,6}$ since the use case shows preference to the natural tanning agents rather than synthetic ones, given their significantly lower environmental impact.

As for the Economic domain, its index is also rather low, with the exception of $I_{3,1}$ which reveals that the investment on the solar photovoltaics power plant has already completely paid off. On the other hand, the ROI of sustainable solutions ($I_{3,5}$) is still zero, since those investments were made in the previous year and, as such, have no return so far. The sale of leftovers ($I_{3,6}$) also results in an index of zero since there is no policy in place for the sale of leftovers skins, regardless of availability. There is, however, the sale of sub-products ($I_{3,4}$) that is derived from the manufacturing process that the company takes profit from it. The productivity of the four assessed lines of production reveals a discrepancy between each index. The production line 4 ($I_{3,6}$) shows much more profit of its sales since it represents the final phase of the production process and all sold products are finished ones, with a higher price. The production lines 2 and 3 ($I_{3,3}$ and $I_{3,4}$) represent intermediary phases so the products sold at the end should not bring much profit. Production line 1 ($I_{3,2}$) does not show as much profit, even though it sells finished products from WB skins, due to the high price of the feedstock.

All in all, the OCI of the use case reveals that the factory tends to be more linear than circular, with only a few circular practices, but with plenty of potential to improve.

Strategy Design

The transition from linear to CE is a continuous and gradual path with various ways to achieve it. The Strategy Design phase consists of several approaches to improve the weakest points, whether they involve general ideas or specific lines of action.

Starting with the lowest sub-indexes of the four domains, the ECI has much potential for improvements as most indicators lower its index. When it comes to the energy use, $I_{1,1}$ and $I_{1,2}$ are directly connected to each other and can reach a value closer to 1 by implementing energy controllers in the factory to differentiate the energy consumed by the production and the energy consumed by the rest of the building. As soon as those rates are defined and monitored, the problem can be identified and solved in advance making the index going up, since currently, the data of the energy consumed do not divide the energy consumed by the factory and the one consumed by the rest of the facility. When it comes to water usage, $I_{1,9}$ was calculated assuming that all incoming water to the company was used in production. At the time, it was not possible to determine the shares that corresponded to each different water usage: production; internal consumption; washing water; others. The real indicator index should be, therefore, higher than the determined value. To counteract this issue, the first step is to install flowmeters in strategic places in the company to understand the breakdown of incoming water, which will mean that in the next calculation of the indicator, only the water used in production will be taken into account. It is at this point, when the real value of water consumption by production is known, that measures to reduce water consumption can be implemented. $I_{1,7}$ is directly related to $I_{1,9}$, as the more water is consumed by production, the more water has to be treated by the WWTP. Therefore, when the above measures are taken, this value will also increase and will assume the value closest to reality. Another solution to address excessive water consumption involves implementing a system for water reuse within the production line. This will allow to increase mostly the index of $I_{1,8}$, but also the previous ones, $I_{1,7}$ and $I_{1,9}$. $I_{1,6}$ increases as the amount of chemicals used in production decreases. Given that, there are two ways to increase the indexes value: optimization of the processes that rely on chemicals, so there is no waste or overdo in the use of chemicals, and; the replacement of chemicals by products that are less harmful to the environment and continue to fulfil their function in the treatment of leathers. As for the emissions issue, in order to increase $I_{1,4}$ by lowering the emissions from the finishing phase of the process, the use case can implement the use of water-borne coatings in combination with an efficient application system to limit emissions of volatile organic compounds.

The MCI has two obvious indicators to correct - $I_{2,3}$ and $I_{2,4}$. $I_{2,3}$ can only increase if investments are made in the factory that can contribute to the recovery, treatment and reuse of the salt used in the early phases of the process. $I_{2,4}$ can improve if the use case resumes its partnership with SIRECRO, a local recovery system that allows to capture the chromium in the wastewaters. The next worst indicator index is the $I_{2,1}$. This index can be improved by considering other residues that are currently sent to landfill but with capacity to be sold to other companies, promoting upcycling approaches. These wastes, with capacity for a second use, are not considered by the company for now. Only the ones that get sold are accounted for, hence the reason why $I_{2,1}$ has the same value index as $I_{3,6}$. Indicator $I_{2,5}$ is directly linked with the volume of production, i.e., with the increase of product manufactured, the quantity of plastic usage increases as well. Since the plastic is used mainly for packaging, a possible solution is replacing the plastic for another material more environmental-friendly that can also satisfy the packaging parameters such as paper film or corrugated fiberboard. $I_{2,6}$ approaches 1 as more natural (mineral and vegetal) agents are used rather than synthetic ones.

The Economic domain has two indexes with a value of zero. The indicator $I_{3,7}$ already has some investment made, since the company has already invested in an IV drying tunnel for heat recovery, thus the indicator will increase as soon as the system starts to work, being able to calculate the return on investment. The solar photovoltaics power plant is not included in this sustainable solutions investment indicator, as it is considered a separate system with its own investments and profits. $I_{3,8}$ has an index of 0 because it has zero sales, due to the current company policy to not sell leftover production. This index can increase if the leftovers of finished products are reintroduced into the value chain, promoting upcycling approaches, or if the leftovers of intermediary skins are reintroduced in other production lines. With these approaches, the company can achieve zero-waste and provide feedstock for other companies. The sale of sub-products ($I_{3,6}$) can only increase if all residues/ sub-products generated are sold. The productivity of each line, represented by $I_{3,2}$, $I_{3,3}$, $I_{3,4}$ and $I_{3,5}$ can be increased with the traceability of the products of each line, thus analyzing production needs, resulting in sustainable production without excessive storage.

Lastly, in the Social domain, there are only a few concerning indicators. $I_{4,1}$ is associated with the number of accidents per year, so in order to increase the index to 1, the objective is to have no accidents, which can be reduced by implementing some safety measures, in addition to those that already exist. $I_{4,4}$ increases as the use case undertakes more training hours per employee. To reach an index of 1, the use case must fulfill the Portuguese standard 40 hours of training per employee, per year. Indicator $I_{4,7}$ increases with the implementation of internal job promotion policy in the use case, instead of hiring higher positions outside. $I_{4,8}$ increases if more local slaughterhouses are contracted instead of outsourced slaughterhouses, with the objective of reducing the transportation's environmental impact. Another low index, $I_{4,6}$, which represents the equality issue in the use case, reaches a value of 1 when the number of women and men workers is equal. The other social indicators elevate the sub-index and do not have much more to improve. $I_{4,2}$ is already well above average for the circularity index, even though it is difficult to control because it depends exclusively on employees' casualties' leaves. Indicator $I_{4,3}$ suggests that there is little staff turnover over the year assessed, as there are few hirings and dismissals, which implies that the use case is a stable company at the social level.

For the exemplary indicators with an index of 1, $I_{1,5}$, $I_{4,5}$ and $I_{4,9}$ only have to uphold the procedures carried out so far. The indicator $I_{3,1}$, however, will keep its value of 1 only if the company refrains from further investments in this area, as it represents an economic indicator of ROI and the company has already made a full return of this investment. However, as the aim is to invest more in the renewable systems, the index will vary according to the investments made and their associated profits, always considering the previous ones.

## V. Conclusions

The present study consisted of developing a new circularity assessment methodology. This new methodology is expected to fill in some gaps found in previous circularity methodologies, in particular the lack of reformulation of SME's circularity index. Above all, it is hoped this methodology would be applicable to SMEs in order to contribute for the assessment of their current circularity level. This approach allows to obtain an OCI that can be constantly improved over the years, aiming to achieve the highest circularity level of the company. This methodology, as a differentiating factor, focuses on the calculation of the OCI. By allowing the reassessment of the main goals and production strategy over time, while acting on production lines and in company's management, the methodology contributes to a more sustainable and circular SME. The proposed methodology was applied to a use case, a Portuguese SME in the tannery industry, the data were collected and the OCI was calculated based on KPIs of the different domains and respective indexes. Considering the first step of this approach, the target chosen was the factory, resulting in a final index of *0,352* meaning that the company is associated with a more linear economy rather than a circular one. The data gathered to obtain each sub-index (Environmental, Material, Economic and Social) were relative to only the year 2023. The methodology was able to identify in which areas the factory needed considerable changes through the compilation of KPIs for the various domains, tracing the most important aspects of the manufacturing process. It was concluded that this index could easily be improved with small changes, although most of them involve investments, and these changes would not interfere with the quality or design of the products.

The methodology has not been applied in any more use cases so far but as a future work, it should be tested on more targets, preferably with different products and applications to assess the accuracy of the methodology. With additional data and use cases, the methodology can be validated, offering the potential for improvements, to demonstrate a wider applicable across various industries. Another possibility, that will be implemented in future assessments, involves the application of weighting factors on the index's equations of the selected KPI for each sub-index. This approach allows each use case to prioritize specific subjects of concern over others.

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## APPENDIX

TABLE VI
EQUATIONS OF NORMALIZATION

**Environmental KPIs**

$$I_{1,1} = \frac{Electricity\ from\ Renewable\ Sources}{Total\ Energy\ Consumed} \tag{4}$$

$$I_{1,2} = \frac{Minimal\ Standard\ Energy\ Consumed}{Total\ Energy\ Consumed} \tag{5}$$

$$I_{1,3} = \frac{Heat\ Recovered}{Total\ Heat} \tag{6}$$

$$I_{1,4} = \frac{Minimal\ Standard\ of\ Pollutant\ Emissions}{Pollutant\ Gases\ Direct\ Emissions} \tag{7}$$

$$I_{1,5} = \frac{Minimal\ Standard\ of\ Dangerous\ Wastes}{Dangerous\ Wastes\ Generated} \tag{8}$$

$$I_{1,6} = \frac{Standard\ Chemicals\ Usage}{Total\ Chemicals\ Usage} \tag{9}$$

$$I_{1,7} = \frac{Minimal\ Standard\ of\ Liquid\ Effluents}{Liquid\ effluents\ treated\ in\ WWTP} \tag{10}$$

$$I_{1,8} = \frac{Water\ Reused\ Volume}{Total\ Water\ Volume} \tag{11}$$

$$I_{1,9} = \frac{Minimal\ Standard\ of\ Water\ Usage}{Water\ usage\ per\ manufacture\ product} \tag{12}$$

**Material KPIs**

$$I_{2,1} = \frac{Quantity\ of\ waste\ sold}{Quantity\ of\ total\ waste\ generated} \tag{13}$$

$$I_{2,2} = \frac{\frac{Standard\ Waste\ Generated}{Standard\ Production}}{\frac{Waste\ Generated}{Total\ Production}} \tag{14}$$

$$I_{2,3} = \frac{Reused\ Salt}{Produced\ Salt} \tag{15}$$

$$I_{2,4} = \frac{Quantity\ of\ Chromium\ Recovered}{Quantity\ of\ Chromium\ Generated} \tag{16}$$

$$I_{2,5} = \frac{\frac{Standard\ Plastic\ Film\ Usage}{Standard\ Production}}{\frac{Plastic\ Film\ Usage}{Total\ Production}} \tag{17}$$

$$I_{2,6} = \frac{Quantity\ of\ mineral\ agents}{Total\ quantity\ of\ agents} \tag{18}$$

**Economic KPIs**

$$I_{3,1} = \frac{Investment\ Gain}{Investment\ Cost} = I_{3,7} \tag{19}$$

$$I_{3,2} = \frac{Profit\ Margin}{Product\ Sales\ Value} = I_{3,3} = I_{3,4} = I_{3,5} \tag{20}$$

$$I_{3,6} = \frac{Sale\ of\ Waste}{Total\ Amount\ of\ Waste} \tag{21}$$

$$I_{3,8} = \frac{Sale\ of\ Leftovers}{Total\ Amount\ of\ Leftovers} \tag{22}$$

**Social KPIs**

$$I_{4,1} = \frac{Standard\ Number\ of\ Accidents}{Number\ of\ Accidents} \tag{23}$$

$$I_{4,2} = \frac{Hours\ of\ Absenteeism\ rate\ due\ to\ casualties}{Effective\ hours} \tag{24}$$

$$L_{4,3} = \frac{\frac{Admissions+Demissions}{2}}{Number\ of\ Employees} \tag{25}$$

$$L_{4,4} = \frac{Real\ training\ hours\ per\ employee}{Standard\ training\ hours\ per\ employee} \tag{26}$$

$$L_{4,5} = \frac{Fixed-Time\ Employees}{Number\ of\ Employees} \tag{27}$$

$$L_{4,6} = \frac{Female\ Employees}{Male\ Employees} \tag{28}$$

$$L_{4,7} = \frac{Promoted\ employees}{Number\ of\ Employees} \tag{29}$$

$$L_{4,8} = \frac{National\ Slaughterhouses\ Used}{Total\ of\ Slaughterhouses\ Used} \tag{30}$$

$$L_{4,9} = \frac{Employees\ living\ within\ a\ 50\ km\ radius\ of\ the\ factory}{Total\ number\ of\ Employees} \tag{31}$$

## REFERENCES

[1] P. Morseletto, "Restorative and regenerative: Exploring the concepts in the circular economy," J Ind Ecol, vol. 24, no. 4, pp. 763–773, Aug. 2020, doi: 10.1111/jiec.12987.

[2] European Commission, "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - A new Circular Economy Action," 2020. (Online). Available: https://www.un.org/sustainabledevelopment/sustainable-consumption-production/

[3] J. Pinyol Alberich, M. Pansera, and S. Hartley, "Understanding the EU's circular economy policies through futures of circularity," J Clean Prod, vol. 385, Jan. 2023, doi: 10.1016/j.jclepro.2022.135723.

[4] T. Bauwens, M. Hekkert, and J. Kirchherr, "Circular futures: What Will They Look Like?," Ecological Economics, vol. 175, Sep. 2020, doi: 10.1016/j.ecolecon.2020.106703.

[5] European Commission, "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - EU Strategy for Sustainable and Circular Textiles," 2022. (Online). Available: https://ec.europa.eu/eurostat

[6] J. Goddin et al., "Ellen MacArthur Foundation Project Team (in alphabetical order)," 2019. (Online). Available: http://www.ellenmacarthurfoundation.org/circularity-indicators/.

[7] P. Dräger, P. Letmathe, L. Reinhart, and F. Robineck, "Measuring circularity: evaluation of the circularity of construction products using the ÖKOBAUDAT database," Environ Sci Eur, vol. 34, no. 1, Dec. 2022, doi: 10.1186/s12302-022-00589-0.

[8] J. Widheden and E. Ringstrsm, "Life Cycle Assessment.", 2007, doi: 10.1016/B978-0-444-51664-0.50021-8.

[9] M. Nardo, M. Saisana, A. Saltelli, S. Tarantola, A. Hoffman, and E. Giovannini, "OECD Statistics Working Papers 2005/03 Handbook on Constructing Composite Indicators: Methodology and User Guide," 2005, doi: 10.1787/533411815016.

[10] S. G. Azevedo, R. Godina, and J. C. de O. Matias, "Proposal of a sustainable circular index for manufacturing companies," Resources, vol. 6, no. 4, Dec. 2017, doi: 10.3390/resources6040063.

[11] J. A. Garza-Reyes, A. Salomé Valls, S. Peter Nadeem, A. Anosike, and V. Kumar, "A circularity measurement toolkit for manufacturing SMEs," Int J Prod Res, vol. 57, no. 23, pp. 7319–7343, Dec. 2019, doi: 10.1080/00207543.2018.1559961.

[12] D. Krajnc and P. Glavič, "A model for integrated assessment of sustainable development," Resour Conserv Recycl, vol. 43, no. 2, pp. 189–208, Jan. 2005, doi: 10.1016/j.resconrec.2004.06.002.

[13] A. A. Ahmed, M. A. Nazzal, B. M. Darras, and I. M. Deiab, "A comprehensive multi-level circular economy assessment framework," Sustain Prod Consum, vol. 32, pp. 700–717, Jul. 2022, doi: 10.1016/j.spc.2022.05.025.

[14] Ellen Macarthur Foundation and Granta Design, "Circularity Indicators - An Approach to Measuring Circularity," May 2015.

[15] A. Colloricchio, C. P. Siguenza, F. Sollitto, and Y. Ahmed, "The Circularity GAP Report 2023," 2023.

[16] A. González, C. Sendra, A. Herena, M. Rosquillas, and D. Vaz, "Methodology to assess the circularity in building construction and refurbishment activities," Resources, Conservation and Recycling Advances, vol. 12, Dec. 2021, doi: 10.1016/j.rcradv.2021.200051.

[17] C. M. Angioletti, M. Despeisse, and R. Rocca, "Product circularity assessment methodology," in IFIP Advances in Information and Communication Technology, Springer New York LLC, 2017, pp. 411–418. doi: 10.1007/978-3-319-66926-7_47.

[18] Global Sustainability Standards Board, "Consolidated Set of the GRI Standards," 2024.

[19] E. Giama and A. M. Papadopoulos, "Benchmarking carbon footprint and circularity in production processes: The case of stonewool and extruded polysterene," J Clean Prod, vol. 257, Jun. 2020, doi: 10.1016/j.jclepro.2020.120559.

[20] S. Karayılan, Ö. Yılmaz, Ç. Uysal, and S. Naneci, "Prospective evaluation

of circular economy practices within plastic packaging value chain through optimization of life cycle impacts and circularity," Resour Conserv Recycl, vol. 173, Oct. 2021, doi: 10.1016/j.resconrec.2021.105691.

[21] S. Dominic, Y. A. W. Shardt, S. X. Ding, and H. Luo, "An Adaptive, Advanced Control Strategy for KPI-Based Optimization of Industrial Processes," IEEE Transactions on Industrial Electronics, vol. 63, no. 5, pp. 3252–3260, May 2016, doi: 10.1109/TIE.2015.2504557.

[22] A. Padilla-Rivera, S. Russo-Garrido, and N. Merveille, "Addressing the social aspects of a circular economy: A systematic literature review," Sustainability (Switzerland), vol. 12, no. 19. MDPI, Oct. 01, 2020. doi: 10.3390/SU12197912.

[23] A. Luthin, M. Traverso, and R. H. Crawford, "Assessing the social life cycle impacts of circular economy," J Clean Prod, vol. 386, Feb. 2023, doi: 10.1016/j.jclepro.2022.135725.

[24] A. Padilla-Rivera, B. B. T. do Carmo, G. Arcese, and N. Merveille, "Social circular economy indicators: Selection through fuzzy delphi method," Sustain Prod Consum, vol. 26, pp. 101–110, Apr. 2021, doi: 10.1016/j.spc.2020.09.015.

[25] V. Prieto-Sandoval, L. E. Torres-Guevara, M. Ormazabal, and C. Jaca, "Beyond the circular economy theory: Implementation methodology for industrial smes," Journal of Industrial Engineering and Management, vol. 14, no. 3, pp. 425–438, 2021, doi: 10.3926/jiem.3413.

[26] A. Dwivedi, D. Agrawal, and J. Madaan, "Sustainable manufacturing evaluation model focusing leather industries in India: A TISM approach," Journal of Science and Technology Policy Management, vol. 10, no. 2, pp. 319–359, Jun. 2019, doi: 10.1108/JSTPM-06-2018-0054.

[27] P. Zhou, B. W. Ang, and K. L. Poh, "Comparing aggregating methods for constructing the composite environmental index: An objective measure," 2005, doi: 10.1016/j.ecolecon.2005.

[28] European Commission. Joint Research Centre. and Organisation for Economic Co-operation and Development., Handbook on constructing composite indicators: methodology and user guide. OECD, 2008.

[29] E. J. Lourenço, J. P. Pereira, R. Barbosa, and A. J. Baptista, "Using Multi-layer Stream Mapping to Assess the Overall Efficiency and Waste of a Production System: A Case Study from the Plywood Industry," in Procedia CIRP, Elsevier B.V., 2016, pp. 128–133. doi: 10.1016/j.procir.2016.04.086.

[30] J. Aguiar, "Application and Development of Multi-Layer Stream Mapping methodology-an extension of MSM 1.0 For resource efficiency and productivity management-applied to a heating device production system in a metalworking industry," 2019.

[31] Michael. Black et al., Best available techniques (BAT) reference document for the tanning of hides and skins: Industrial Emissions Directive 2010/75/EU (integrated pollution prevention and control). Publications Office, 2013.

[32] F. Chiampo, S. Shanthakumar, R. Ricky, and G. Pattukandan Ganapathy, "Tannery: Environmental impacts and sustainable technologies," Mater Today Proc, 2023, doi: 10.1016/j.matpr.2023.02.025.