In-built Triggered Enzymes to Recycle Multi-layers: an Innovation for Uses in plastic-packaging

D7.3: Initial report on Circular Economy Assessment

WP7: Environmental and economic sustainability assessment of the developed products and food safety assessment

Project Information

Grant Agreement n°	814400
Dates	1st January 2019 – 31st July 2023

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Document status

Document information

Deliverable name	D7.3: Initial report on LCA & LCCA of products
Responsible beneficiary	SIGMA
Contributing beneficiaries	
Contractual delivery date	30/06/2022
Actual delivery date	28/06/2022
Dissemination level	CO

Document approval

Name	Position in project	Organisation	Date	Visa
Vincent VERNEY	Coordinator	SIGMA		

Document history

Version	Date	Modifications	Authors
V0	21/06/2022	Document created	K.Vadoudi
V1	26/06/2022	Document validated	V. Verney
Vf	28/06/2022	Style and typo	T.Langon

Table of content

Abbreviations

C_R	Fraction being collected for recycling at the end of its use
C_E	Circular Economy
E_C	Efficiency of the recycling process
E_F	Efficiency of the recycling process used to produce the recycled feedstock
E_S	Efficiency of collection and sorting
F_R	Fraction from recycled sources
LCA	Life Cycle Assessment
LCI	Life cycle Inventory
LDPE	Low Density Polyethylene
LFI	Linear Flow Index
M	Mass of the finished product
MCI	Material Circularity Indicator
MRS	Material Reutilization Score
PET	Polyethylene terephthalate
PUR	Polyurethane
HDPE	High Density Polyethylene
W	Overall amount of unrecoverable waste
W_C	Waste generated in the recycling process
W_F	Waste generated to produce any recycled content
W_0	Overall waste going into landfilling or incineration
W_S	Collection and sorting waste
V	Fraction from Virgin Feedstock
X	Utility

Executive summary

This report is a description of a circularity indicator in the TERMINUS project with the aim of developing a sector specific indicator for the multi-layer plastic packaging industry. This proposed indicator is an adapted from the Material Circularity Indicator (MCI) as proposed by the Ellen MacArthur Foundation and Granta Design (Ellen MacArthur Foundation, 2015).

To illustrate the use of proposed indicator, a case study on three-layer plastic packaging is applied to three end of life scenarios (Incineration, landfilling and closed-loop mechanical recycling). The results show that 100% increase in recycling efficiency, cause a 20% increase in material circularity, a 17% increase in utility of recycled materials and 19% decrease in linear flow index.

Deliverable report

Introduction

This report is a description of a circularity indicator in the TERMINUS project with the aim of developing a sector specific indicator for the multi-layer plastic packaging industry. This proposed indicator is an adapted from the Material Circularity Indicator (MCI) as proposed by the Ellen MacArthur Foundation and Granta Design (Ellen MacArthur Foundation, 2015).

A traditional literature review was conducted in accordance with the principles of systematic reviews to the maximum extent (Pullin et al., 2018). The aim of this review was to contribute with our findings to an increase in methodological transparency and reliability, while seeking to avoid some of the biases that commonly affect literature reviews (Haddaway et al., 2015). The main sources for searching relevant scientific papers were the databases of the Web of Science and SCOPUS platforms. The searches were performed in March 2021 with English search terms, which included the following keywords: Circular economy, circularity indicator, metrics, LCA, LCI, packaging, multi-layers, plastic, bio-based polymers. We also used combinations of these key words and different Boolean operators only on papers published from 2015 with cradle-to-gate and cradle-to-grave lifecycle design.

Literature reviews identified up to 100 circularity indicators at three or four spatial levels (de Oliveira et al., 2021; De Pascale et al., 2021; Kristensen and Mosgaard, 2020), which could be categorized and presented in different groups. Corona et al., 2019, categorized circularity metrics into two groups; (1) circularity measurement indicators that calculate how circular a system is, by providing a value that ranges from 0 to 1, and (2) circularity assessment tools that present the impacts of circular strategy to the principles of sustainability (Social, economy and environment).

Among the first category indicators, the **Material Circularity Indicator** (MCI) and **Material Reutilization Score** (MRS), seems the most eligible product-level circularity metrics available in literature that incorporates most of the desired CE requirements.

Regarding the second category of indicators, life cycle assessment (LCA) is the most commonly used circularity assessment indicator that evaluates the environmental impact of a product throughout its life cycle (Rebitzer et al., 2004) standardized by two ISO standards (ISO 14040/44, International Organisation for Standardization, 2006).

Material Reutilization Score

This indicator was developed to assess the material reutilization score of a product and to eliminate the concept of waste promoted by the Cradle to Cradle design project (Lawrence, 2013). It is defined accordingly to:

$$\text{MRS (\%)} = [\ (\%\ recyclable\ content * 2) + (\%\ recycled\ content * 1)\ 3\ ] * 100 \qquad (1)$$

It is the ratio of secondary material content and recyclable or biodegradable content in a product. Calculations at the case company showed that there is a small difference between on-site and off-site production waste recycling scenarios due to the low defect rate of the production line. But when considering the closed-loop EOL recycling, the MRS value drastically increases since recycled material input are used to make the product. However, due to the client's requirements, MRS was not able to identify opportunities which can be applied in the case company's manufacturing line as only virgin material is currently allowed (Syu et al., 2022).

MRS allows a simple classification by scaling the circularity of a product between 0% (non-recyclable and non-recycled) and 100% (fully recyclable, fully recycled). However, the the MRS does not include the influence of % Recycling Rate and the substitution ratio of recycled to virgin materials (Niero and Hauschild, 2017).

Material Circularity Indicator

Material Circularity Indicator (MCI), seems one of the most eligible and complete calculation model for micro-level circularity assessment available in the literature (Elia et al., 2017; Garza-Reyes et al., 2019) as it incorporates not only material flows but also lifetime. Different studies have applied the MCI in their analysis of the trade-off between material circularity and environmental efficiency at micro-level (Lonca et al., 2018; Niero and Kalbar, 2019). Moreover, its interface is simple and easy to use (Elia et al., 2017; Saidani et al., 2017). **MCI is chosen as a starting platform for this study because its general and expandable nature allows it to be adapted to a specific industry or application.** The MCI already includes several aspects of recycling, such as the collection rate, the percentage of recycled material and the efficiency of the recycling process.

Raw materials input

According to circularity indicators introduced by Ellen Mac Arthur Foundation report (Figure 1), the raw materials input needed for the final product's production within the production process is (2):

$$V = M(1-F_r-F_u) \qquad (2)$$

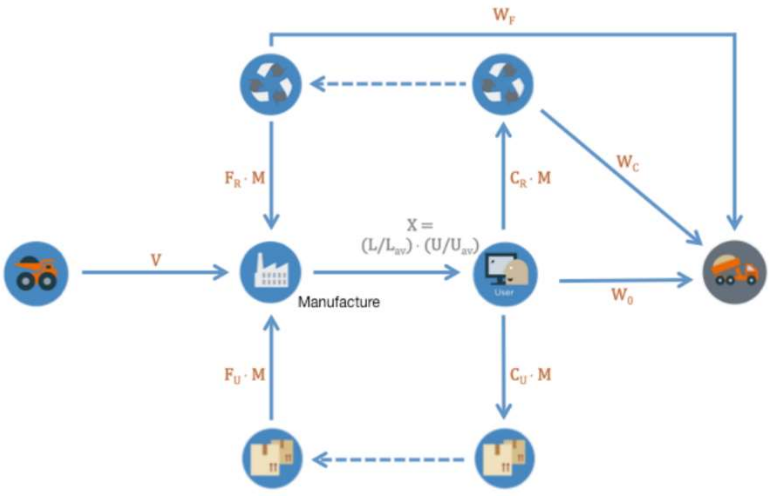

Figure 1. Diagrammatic representation of material flows

Where F_r stands for the fraction of the amount of a product's staple deriving from recycling and F_u stands for the coefficient of the amount of a product's staple coming from input reused.

Unrecoverable waste

If one takes into account the unrecoverable waste, indicator W_0 is depicted below, which shows the relevance between the mass of waste that cannot be recovered from a product, (3):

$$W_0=M(1-C_R-C_u) \qquad (3)$$

C_r stands for the product's mass fraction that is collected as part of the recycling phase, C_u stands for the coefficient related to the product's amount, part of which comes from reuse process.

Unrecoverable waste that is produced whilst recycling a product's parts

W_c indicator stands for the unrecoverable waste that is produced whilst recycling a product's parts (4):

$$W_c=M(1-E_c)C_r \qquad (4)$$

E_c expresses how efficient isthe recycling procedure, C_r is the indicator which presents the amount of product that is used in the recycling procedure.

Unrecoverable waste which derives from recycled input

There are stages in a system studied which produces waste. For instance, during the manufacture phase the cut and multi-layers packaging procedure, the formation phase or the multi-layers packaging process. So this material is deriving from several processes that has the potential to be managed as an input in non linear flows. The amount of unrecoverable waste which derives from recycled input is calculated below (5):

$$W_f = ((1-E_f)F_r)/E_f \qquad (5)$$

W_f is the amount of waste in case recycling mixture is entered to the manufacture process, , E_f shows the potential to use in the production process input from recycling procedure, F_r is the coefficient of the amount of final product derived from recycling input. It is evident that indicators E_f and E_c are depending on the mass of the recycled material.

Linear Flow Index

In order to evaluate the **Linear Flow Index** (LFI), the coefficient introduced V which calculates the amount of product which is produced from the virgin feedstock and ends as discarded quantity. In this occasion the system isn't characterized as closed loop. So, a system is characterized as linear when the entire input material in the manufacture procedure ends up to be waste at the end of life phase without any alternative management such as recycling or reuse. In case there is any kind of management in the product's life cycle and amount of the input material returns to the system's processes then the flow is not linear and closed loops are created. In that case the LFI is calculated based on Equation (6):

$$LFI=(V+W)/(2M+(W_f-W_c)/2) \quad (6)$$

Where LFI is Linear Flow Index, V is the mass of “virgin” input necessary for the product’s production, W is the amount of output not efficiently managed, F_r is the ratio of the amount of a product’s input from recycled mixture, W_f is the amount of output derived when fabricating input from recycled content.

Utility factor

The calculation of the factor X is presented in (7) and it is related to L and L_{av}. More detailed, L is expresses the lifetime of the unit studied in our case the stone wool or the extruded polystyrene. The L/L_{av} is the ratio which depicts the change in the amount of waste produced in a specific period of time for the flow analysed. L_{av} expresses the lifetime parameter for more than one similar products. U stands for real mean quantity of final products accomplished within the product’s usage stage and Uav is the real mean amount of functional units accomplished in the industry’s use stage. The Uav refers to group of products with common characteristics. So the X parameter expressing the effectiveness of the final unit produced is the factor below (7):

$$X=(L/L_{av})(U/U_{av}) \quad (7)$$

Material Circularity Indicator

The product’s Material Circularity Indicator (MCI) is related with the Linear Flow Index (LFI) and the Utility factor F(X) that affects the product’s X utility coefficient.

$$MCI=1-LFI*F(X) \quad (8)$$

Four main principles drive four sources of value creation

The Ellen MacArthur Foundation report also introduced four main principles that drive four sources of value creation (Sazdovski et al., 2021) in the CE: (i) the power of the inner circle; (ii) the power of circling longer; (iii) the power of cascaded use; and (iv) the power of pure circles (non-toxic, or at least easier-to- separate inputs).

The first principle of value creation, ‘**the power of the inner circle’**, is based on the benefits generated through the higher substitution effects of the virgin material compared to linear value chains. The tightness of the circles is proposed as an efficiency indicator of the value creation potential.

The second principle, ‘**the power of circling longer’**, relates to prolonging the use of virgin material where recycling material provides a substitute during production. From the perspective of LCA methodology, the difference between the two value creation principles lies in the definition of the recycling scenario (i.e. open-loop or closed-loop recycling) and the reuse scenario.

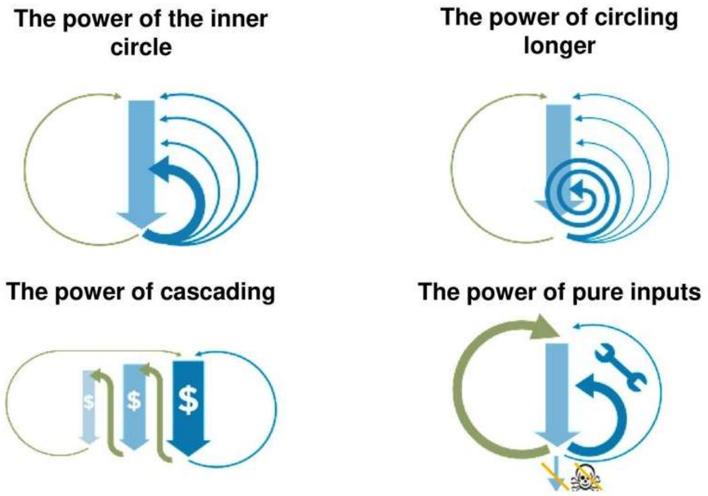

Figure 2. Sources of value creation

The possibility for re-use of components is practically nonexistent in packaging due to the simplicity of design of such packaging.

Multi-layers packaging does not offer the **possibility of cascading** the reuse of materials that can result in the substitution of virgin material.

Regarding the fourth principle, '**the power of pure circles'**, i.e. the use of non-toxic, or at least easily separable inputs and designs, this review assesses the purity of the recycled material and possibility of contamination, together with the ease of separability in the recycling streams.

Therefore, the third and forth principles are not compatible with value creation in the CE in multi-layer packaging.

Three levels of circular hierarchy

Moreoover, three levels of circular hierarchy in the CE are proposed in Ellen MacArthur report : (i) the circularity of the product; (ii) the circularity of the components of the product; and (iii) the circularity of the materials used in the product.

The types of packaging materials studied in this study are of relatively simple design. Film layers are mainly mono material, with differences only in functionality, and thus its impacts can be assessed without separately considering its components; hence we did not need to take into account the second hierarchical level, i.e. the 'circularity of components'.

Although the MCI tries to apply a simple interface to quantify the fraction of material flows that are circular (Elia et al., 2017; Saidani et al., 2017), it is unable to account for some important end-of-life parameters such as the quantity of material cycles that go through recycling processes and the effect of downcycling (Bracquené et al., 2020). In addition, the utility X of a product in MCI is defined in a way that is applicable for products with different parts and components. However, for some single-use product categories like plastics and multi-layer packaging, is not applicable.

Description

System boundary of the adapted Material Circularity Indicator

The closed-loop system boundary of the proposed indicator includes films & multi-layer manufacturing, collection, sorting and recycling processes (see Figure 3). For the first production cycle, 100% virgin material (V) enters the manufacturing process, and part of V leaves the cycle in the overall waste. The overall unrecoverable waste includes materials that leave the system during collection (W_S) and recycling processes (W_C). In the second production cycle, material entering the manufacturing process is a mix of recycled polymer (F_R) from a previous cycle and the remainder is from virgin sources. Two recycling efficiencies are defined in the MCI formula: E_C (for the portion of a product collected for recycling) and E_F (to produce recycled feedstock for a product). In the case of plastics, the cycle is assumed to be a closed loop W_F is considered equal to W_C.

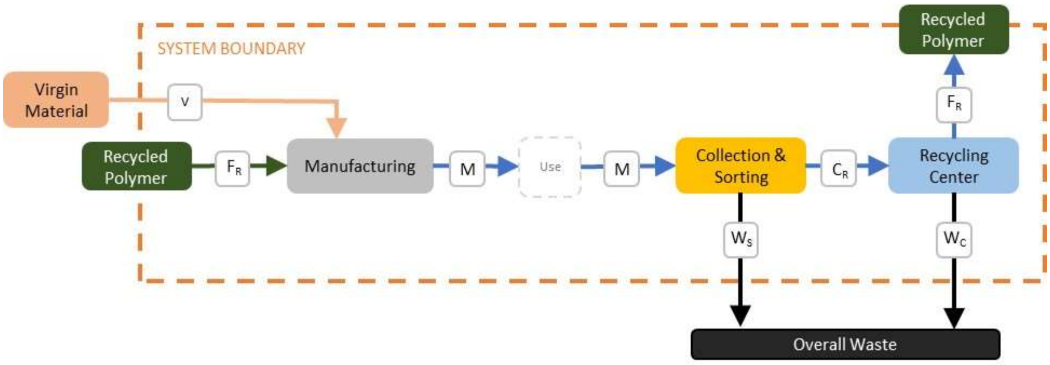

Figure 3. System boundary of the adapted Material Circularity Indicator

Waste collection efficiency

Waste collection efficiency (W_S) is one more factor that affects the circularity and value creation in this industry. W_S is calculated based on Equation 4, where F_R is the fraction from recycled sources, V is the mass of virgin feedstock and E_S represents the efficiency of sorting and collection processes. In this equation, the collected waste from virgin feedstock is separated from recycled waste (F_R (1-E_S)), which helps to differentiate and track the circulated percentage especially in the large quantities.

$$W_S = V\left(1-E_S\right)+F_R\left(1-E_S\right) \quad (9)$$

Fraction of the mass entering the recycling process

In the adapted calculation method, we have distinguished the calculation of C_R for the first cycle of recycling from the later cycles. The amount of C_R for the first cycle is equal to the total mass of finished product, manufactured from 100% virgin material, and the next rounds are based on the amount of recycled fraction that enters at the end of the previous cycle, as shown in the following equations:

$$C_{R\,\text{(First round recycling)}} = M \times E_S \quad (10)$$

$$C_{R\,\text{(Later rounds recycling)}} = F_R \times E_S \quad (11)$$

Quantity of waste during the recycling process

This approach helps to differentiate and track the circulated percentage that enters from the end of first round recycling to the later rounds of manufacturing. After having the fraction of the mass entering the recycling process (C_R), the quantity of waste during the recycling process (W_C) is calculated as:

$$W_C = W_F = E_C \times C_R \quad (12)$$

Overall amount of unrecoverable waste

The overall amount of unrecoverable waste (W), not only covers the amount of the recycled portion from sorting and collection processes (W_S) and the recycling process (W_C), but it also covers the fractions of virgin materials (V) that flows through both processes. Therefore, by taking into account the mass of finished product (M) that enters to the collection and sorting process with an efficiency (E_S) and the recycling process, with an efficiency (E_C), the total amount of waste (W) is obtained:

$$W = M \times (1 - E_S \times E_C) \tag{13}$$

Utility factor

Another important parameter in the MCI methodology is the utility factor (X). In Ellen MacArthur it is defined for the use phase of a product based on two parameters; one considers the length of the use phase of the product (L), and the other the intensity of use (U). However, using these two parameters is not practical for plastic film. Therefore, we decided to define the value based on the utility of recycled material in production systems (Equation 14), where ΣF_{Ri} is the sum of recycled fractions from previous cycles up to the current one. Based on this parameter, when the fraction from virgin feedstock (V) is 100%, there is no fraction from recycled source (F_R = 0) and the utility factor equals the actual industry average (X=1). By increasing the amount of fraction from recycled sources, the value of X rises above 1 and consequently, the value of the MCI is closer to 1, which presents more circularity.

$$X_i = 1 + \frac{\sum (F_{Ri})}{M} \tag{14}$$

Material Circularity Indicator

Except applied modifications in previous equations and parameters, the Linear Flow Index (LFI) and MCI calculations are based on original equations (Equations 1&2). However, each mono-material layer in the multi-layer plastic can have a different degree of circularity due to the different recycling processes and efficiencies. Therefore, a more consistent approach needs to be applied to obtain a generic value for the circularity of the whole product (MCI_{total}). Thus, applying a mass-based weighting methodology that already is used in some studies (Lonca et al., 2018) could lead to a more representative value. This approach represents the weighted sum of the MCI_i of each component (i) of the assessed multi-layer, n_i being the number of components and m_i their respective masses.

$$\mathrm{MCI}_{\mathrm{total}} = \frac{\sum \mathrm{i}(\mathrm{n_i} \times \mathrm{m_i} \times \mathrm{MCI_i})}{\sum \mathrm{i}(\mathrm{n_i} \times \mathrm{m_i})} \tag{15}$$

Case study on three-layer plastic packaging.

The application of this proposed indicator is presented through a case study on three-layer plastic packaging.

This case study evaluates and compares the material circularity and the environmental impacts of three end of life scenarios (Table 1) for 1 kg of three-layer plastic packaging consisting of 730g HDPE (high-density polyethylene) and 247g PET (polyethylene terephthalate) films as outer layers and 23g film as an inner adhesive PUR-layer. The first and second scenarios are assumed to be linear production systems and the third scenario is circular. As the circularity is highly dependent on the quality of the recycled material (Eriksen et al., 2019), possible quality reductions represent a limitation in the use of recycled materials. Based on available literature (Shen et al., 2020), it might be possible for virgin PET and HDPE to be cycle a maximum of three times.

Table 1. End of life Scenarios for three-layer packaging (PET/PUR/HDPE).

Scenarios	End of life Strategy	Lifecycle	Material Source	Recyclability
S 1	Incineration	1 Time	Virgin	0%
S 2	Landfilling	1 Time	Virgin	0%
S 3	**S 3-1**	1st Production	Virgin	PET=20% HDPE=80%
	Recycling - Incineration	2nd Production	Recycled + Virgin	
		3rd Production	Recycled + Virgin	
	S 3-2	1st Production	Virgin	PET=20% HDPE=80%
	Recycling - Landfilling	2nd Production	Recycled + Virgin	
		3rd Production	Recycled + Virgin	

Figure 4 shows the system boundary for MCI calculation. Production of virgin PET, PUR and HDPE are supposed to be outside of the boundary and these polymers enter the manufacturing process, whenever the recycled polymers can not fill out the mass of finished product (1kg). After manufacturing and use stages, 40% of the three-layer multi-layer plastic packaging leaves the system boundary as waste (W_S) and the reminder (C_R) feeds the recycling process. 80% of HDPE, 20% of PET and 0% of PUR are recycling in this stage and the rest joining to the overall waste (W) as recycled waste (E_C).

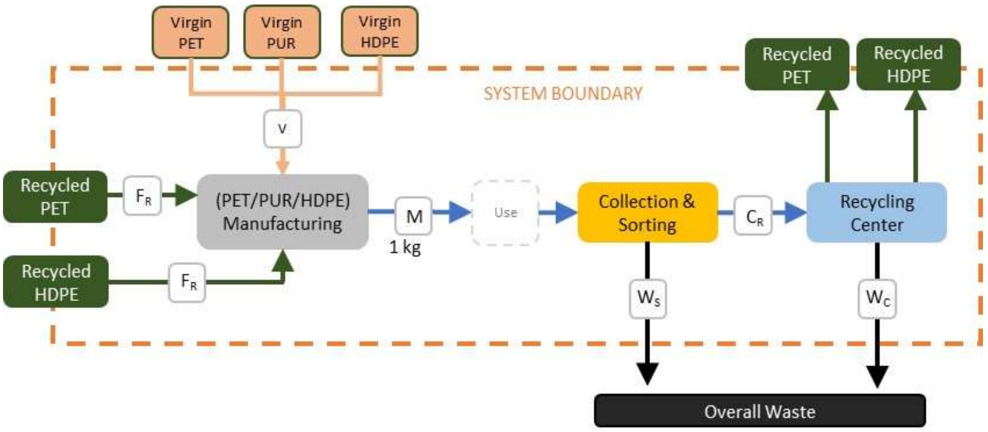

Figure 4. System boundary of material circularity, three-layer packaging (PET/PUR/HDPE)

Table 4 provides the parameters used for the computation and MCI results for each scenario. In the 1st Production cycle, 247 g PET and 730 g HDPE films are manufactured 100% from virgin feedstock. At the end of the first recycling process, 29.64 g recycled PET (Equation 16) and 350.4 g recycled HDPE enter the 2nd Production cycle (F_R) and the rest of the needed materials are provided from virgin feedstock (217.36 g for PET and 379.60 g for HDPE) to reach the mass of finished product (M). The linear flow index (LFI) for the first lifecycle results in high percentages: 0.94 for PET and 0.76 for HDPE. These values are relatively high due to the high percentage of input materials from virgin sources. However, in the second lifecycle this value decreases to 0.88 for PET and 0.52 for HDPE as the share of recycled PET and HDPE increases. At the end of 2nd lifecycle, 3.56 g PET and 168.19 g HDPE enter the 3rd Production cycle as the recycled portion. These quantities are the remainders of the virgin polymers that entered the 1st Production cycle and through the two recycling processes at the end of first and second production cycles. The materials lacking in the 3rd Production cycle are provided from virgin sources (242.26 g for PET and 561.81 g for HDPE). As at every recycling round a percentage is lost, more and more virgin material is needed to replenish with exception of the first cycle. Therefore value of LFI increases consequently to 0.64 for HDPE and 0.93 for PET.

$$F_{R2^{st}\ Production(PET)} = (M \times E_S - E_C \times C_R)_{1^{st}\ Production(PET)} = (C_R - W_C)_{1^{st}\ Production(PET)} \tag{16}$$

$$F_{R2^{st}\ Production(PET)} == (247 \times 0.6 - 148.2 \times 0.2) = (148.2 - 118.56) = 29.64g$$

Table 2. Circularity Calculation for the three-layer plastic (PET/PUR/HDPE).

Circularity Calculation Adapted MCI		**Scenario 1&2**		**Scenario 3 (Recycling)**					
		Incineration & Landfill		1st Production		2nd Production		3rd Production	
	Parameter	PET	HDPE	PET	HDPE	PET	HDPE	PET	HDPE
V	Virgin Feedstock (g)	247	730	247	730	217	379	242	561
F_R	Recycled quantity (g)	0	0	0	0	29.64	350	3.56	168.19
M	Finished product (g)	247	730	247	730	247	730	247	730
E_S	Collection efficiency	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
W_S	Collection waste	98.8	292	98	292	98	292	98	292
C_R	Collected for recycling	0	0	148	438	17.78	210	2.13	100
E_C	Recycling efficiency	0	0	0.2	0.8	0.20	0.8	0.20	0.8
W_C	Recycling waste	0	0	118	87.6	14.23	42.05	1.71	20
W	Total waste (g)	247	730	217	379	217	379	217	379
LFI	Linear flow index	1	1	0.94	0.76	0.88	0.52	0.93	0.64
X	Utility	0	0	1	1	1.12	1.48	1.13	1.71
F(X)	Utility factor	0	0	0.9	0.9	0.80	0.61	0.79	0.53
MCI	Circularity of materials	0	0	0.15	0.32	0.29	0.68	0.26	0.66
MCI_{Phases}	Circularity of each phase	**0**	**0**	**0.27**		**0.57**		**0.55**	
MCI_{Total}	Circularity of product	**0**		**0.46**					

After the LFI calculations for each polymer in the different lifecycles, the amount of the utility factor (X) must be applied to calculate the MCI. The amount of X in the first round of recycling is calculated as 1 (the industry average), where the fraction from virgin feedstock (V) is 100%. By increasing the amount of fraction from recycled sources, the value of X rises above 1 and consequently, the value of the MCI is closer to 1.This amount increases to 1.12 for PET as it is illustrated in Equation 17, and, 1.48 for HDPE based on same calculation approach. By increasing the percentage of virgin material and decreasing the recycled portion, the value X has to decrease. However, existence of the small percentage of polymers that are recycled for a second time has significantly increased the utility factor to 1.13 for PET (equation 18) and 1.71 for HDPE.

$$X_{2^{st}\,Production(PET)} = 1 + \frac{F_{R1^{st}\,Production} + F_{R2^{st}\,Production}}{M} = 1 + \frac{0 + 29.64}{247} = 1.12 \tag{17}$$

$$X_{3^{st}\,Production(PET)} = 1 + \frac{F_{R1^{st}\,Production} + F_{R2^{st}\,Production} + F_{R3^{st}\,Production}}{M} = 1 + \frac{0 + 29.64 + 3.56}{247} = 1.13 \tag{18}$$

Based on the values of the utility factor and LFI, the MCI_{phases} are calculated using equation 1 for each lifecycle with the minimum amount of 0.27 for the first cycle (equation 19) and (0.57) for the second. Except for the significant decrease in the quantity of recycled polymers in the third cycle the MCI remained the same (0.55) due to the percentage of polymers that are recycled twice. The MCI_{total} result of three-layer packaging is 0.46 at the end of third lifecycle (Equation 20).

$$\begin{aligned} MCI_{1^{st}\,Production} &= \frac{MCI_{PET} \times M_{PET} + MCI_{PUR} \times M_{PUR} + MCI_{HDPE} \times M_{HDPE}}{M_{PET} + M_{PUR} + M_{HDPE}} \\ MCI_{1^{st}\,Production} &= \frac{0.15 \times 247 + 0 \times 23 + 0.32 \times 730}{247 + 23 + 730} = 0.27 \end{aligned} \tag{19}$$

$$MCI_{Total} = \frac{0.27 + 0.57 + 0.55}{3} = 0.46 \tag{20}$$

Results and Discussion

As recycling plays a crucial role in the circularity of polymers, a sensitivity analysis is performed to obtain a more comprehensive view on the impact of recycling efficiency on the variations of the linear flow index, utility of recycled material and material circularity. As scenario 4, we assume the same mass for both PET and HDPE, but considered 100% efficiency for the collection and sorting processes. Moreover, the utility of the recycled material is normalized, in order to be comparable with other parameters. The recycling efficiency is not changed as compared to scenario 3 (80% for HDPE and 20% for PET). Table 7 presents the assumptions and results of calculations for parameters compared.

Table 3. Circularity calculation in scenario 4 for three-layer (PET/PUR/HDPE)

Circularity Calculation (PET/PUR/HDPE)		**Scenario 4 (Recycling)**					
		1st Production		2nd Production		3rd Production	
	Parameter	PET	HDPE	PET	HDPE	PET	HDPE
V	Virgin Feedstock (g)	730	730	584	146	700.8	262.8
F_R	Recycled quantity (g)	0	0	146	584	29.20	467.20
M	Finished product (g)	730	730	730	730	730	730
E_S	Collection efficiency	1.00	1.00	1.00	1.00	1.00	1.00
W_S	Collection waste	0.00	0.00	0.00	0.00	0.00	0.00
E_C	Recycling efficiency	0.20	0.80	0.20	0.80	0.20	0.80
LFI	Linear flow index	0.90	0.60	0.80	0.20	0.88	0.28
X	Utility of recycled material	1.00	1.00	1.20	1.80	1.24	2.44
F(X)	Utility factor	0.90	0.90	0.75	0.50	0.73	0.37
MCI	Circularity of materials	0.19	0.46	0.40	0.90	0.36	0.90

The relations are depicted in Figure.5, where a 100% increase in recycling efficiency, cause a 20% increase in material circularity, a 17% increase in utility of recycled materials and 19% decrease in linear flow index. These parameters show variant sensitivity due to the differences in their calculations approach. The utility of recycled material depends to the total amount of recycled quantity that enter from previous production that enters the current actual one, and the value of linear flow index is dependent on other production cycles, i.e. the portion of virgin materials to the total mass in each production cycle. Changes in both parameters have an impact on material circularity.

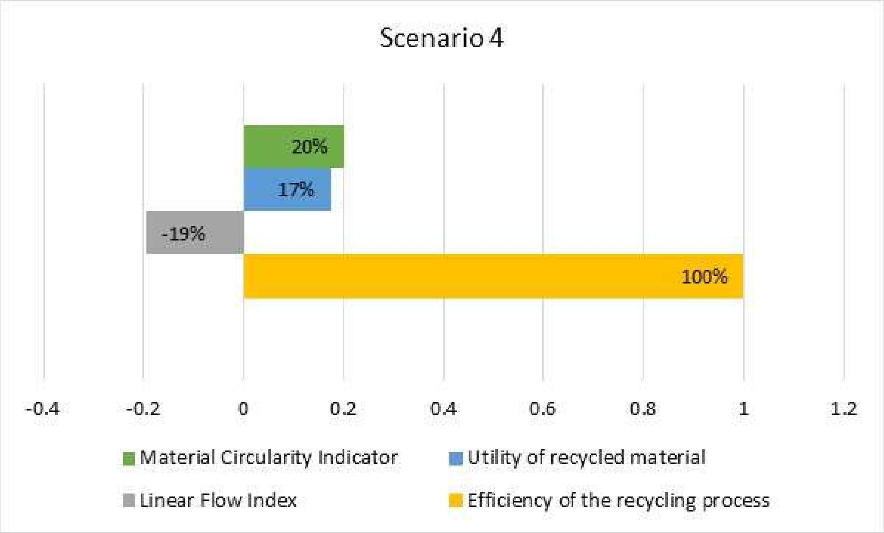

Figure 5. Impact of increasing 100% recycling efficiency on the variations in the linear flow index, utility of recycled materials and material circularity (Scenario 4).

Conclusion and next steps

In our adapted indicator, some parameters are calculated in the way as in the MCI. However, some modifications are implemented in terms of defining new parameters, such as "collection efficiency". We also adapted the utility factor and calculation of the quantity collected for recycling. Moreover, as a multi-layer plastic consists of different components, we proposed the weighted sum of the circularity of components as a circularity degree for the final product. We believe this indicator could be applied to all types of plastics and other recyclable materials in different industries.

To determine whether the proposed indicator is functional, and also could lead to environmental benefits, a case study on three-layer plastic packaging was done. In this case, the material circularity is calculated for three end-of-life scenarios of incineration, landfilling and closed-loop recycling with different recycling efficiencies for any mono-material in three production cycles. In addition, a sensitivity analysis is performed as forth scenario about the impact of recycling efficiency on the variations of other parameters. Results show that a 100% increase in recycling efficiency, causes a 20% increase in material circularity.

Nevertheless, there are some limitations in the proposed indicators which need to be considered, and would be the subject of future works. At present, the efficiency of manufacturing is not taken into account because there are different manufacturing technologies. As waste in the manufacturing process could represent up to 50% of the input, considering this parameter in calculations would improve the functionality of the proposed indicator.

In addition, the impact of the duration and quantity of recycling is not studied, to determine whether the sequences and quantity of recycling could change the results in terms of circularity and environmental impact. As the circularity is highly dependent on the quality of the recycled material, the recyclability of different polymers is also an important factor that should be considered in recycling efficiency.

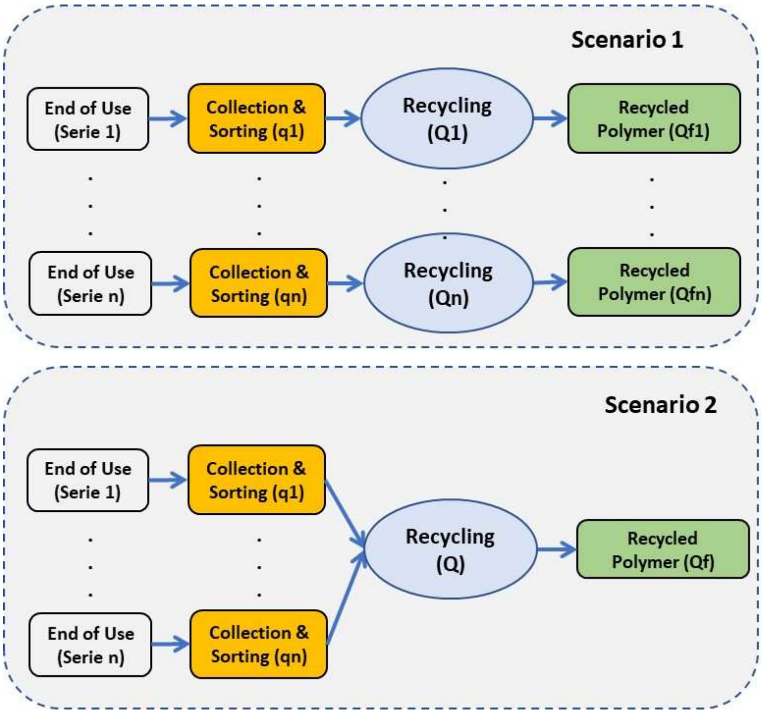

Figure 6. Scenario1: Collection and recycyling in small quantities, Scenario2: Collection in difference sequences (small quantities), but recycyling in one process (big quantity)

As illustrated in figure 6, two scenarios can be used to study the impacts of recycling quantity and recycling sequences. In scenario 1, recycyling is not in one cycle and after each collection process, the collected quantity is going to be recycled. In scenario 2, the recycling is applying after collecting and reaching to a certain quantity in a longer period compare to scenario 1.

References

Bracquené, E., Dewulf, W., Duflou, J.R., 2020. Measuring the performance of more circular complex product supply chains. Resour. Conserv. Recycl. 154, 104608. https://doi.org/10.1016/j.resconrec.2019.104608

Corona, B., Shen, L., Reike, D., Rosales Carreón, J., Worrell, E., 2019. Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. Resour. Conserv. Recycl. 151, 104498. https://doi.org/10.1016/j.resconrec.2019.104498

de Oliveira, C.T., Dantas, T.E.T., Soares, S.R., 2021. Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments. Sustain. Prod. Consum. 26, 455–468. https://doi.org/10.1016/j.spc.2020.11.024

De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., Ioppolo, G., 2021. A systematic review for measuring circular economy: The 61 indicators. J. Clean. Prod. 281. https://doi.org/10.1016/j.jclepro.2020.124942

Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: A critical analysis. J. Clean. Prod. 142, 2741–2751.

Garza-Reyes, J.A., Salomé Valls, A., Peter Nadeem, S., Anosike, A., Kumar, V., 2019. A circularity measurement toolkit for manufacturing SMEs. Int. J. Prod. Res. 57, 7319–7343.

Kristensen, H.S., Mosgaard, M.A., 2020. A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? J. Clean. Prod. 243, 118531. https://doi.org/10.1016/j.jclepro.2019.118531

Lawrence, J., 2013. Cradle to cradle, TCE The Chemical Engineer. McGraw-Hill Education. https://doi.org/10.51202/0043-7131-2021-12-700

Lonca, G., Muggéo, R., Imbeault-Tétreault, H., Bernard, S., Margni, M., 2018. Does material circularity rhyme with environmental efficiency? Case studies on used tires. J. Clean. Prod. 183, 424–435. https://doi.org/10.1016/j.jclepro.2018.02.108

Niero, M., Hauschild, M.Z., 2017. Which role for Life Cycle Thinking in the definition of meaningful indicators for the circular economy?, in: Proceedings of Italian LCA Network Conference XI. pp. 11–19.

Niero, M., Kalbar, P.P., 2019. Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. Resour. Conserv. Recycl. 140, 305–312. https://doi.org/10.1016/j.resconrec.2018.10.002

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environ. Int. 30, 701–720.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., 2017. How to assess product performance in the circular economy? Proposed requirements for the design of a circularity measurement framework. Recycling 2. https://doi.org/10.3390/recycling2010006

Sazdovski, I., Bala, A., Fullana-i-Palmer, P., 2021. Linking LCA literature with circular economy value creation: A review on beverage packaging. Sci. Total Environ. 771, 145322. https://doi.org/10.1016/j.scitotenv.2021.145322

Shen, M., Song, B., Zeng, G., Zhang, Y., Huang, W., Wen, X., Tang, W., 2020. Are biodegradable plastics a promising solution to solve the global plastic pollution? Environ. Pollut. 263, 114469.

Standardization, I.O. for, 2006a. Environmental management: life cycle assessment; requirements and guidelines. ISO Geneva, Switzerland.

Standardization, I.O. for, 2006b. Environmental management: life cycle assessment; Principles and Framework. ISO.

Syu, F.S., Vasudevan, A., Despeisse, M., Chari, A., Bekar, E.T., Gonçalves, M.M., Estrela, M.A., 2022. Usability and Usefulness of Circularity Indicators for Manufacturing Performance Management. Procedia CIRP 105, 835–840. https://doi.org/10.1016/j.procir.2022.02.138