TOWARDS MEASURING CIRCULARITY AT PRODUCT LEVEL - METHODOLOGY AND APPLICATION OF MATERIAL CIRCULARITY INDICATOR

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Abstract

Implementation of the circular economy concept involves the need to close the loop of the product life cycles and requires extensive activities related to reverse logistics. Correct execution and efficiency evaluation of these actions require application of appropriate indicators and measures. This paper presents considerations concerning measuring circularity at the product level. Basic circularity metrics at the product level are identified and characterized. In particular, the theoretical and methodological background to determination of the Material Circularity Indicator of a product (MCI_P) is described. An analysis is conducted of example MCI_P calculations that take account of the product various parameters, such as diverse feedstock from recycled sources, different fractions of the product collected for recycling at the end of its use phase, as well as changes in the recycling process efficiency and in the product utility. The analysis results indicate the key parameters for obtaining the best circularity and environmental performance of the product.

Keywords: Circular economy, circularity measuring, material circularity indicator

1. INTRODUCTION

In recent years, the circular economy concept has received increasing attention worldwide due to the recognition of the fact that security of the supply of resources and resource efficiency are crucial for the prosperity of economies and companies. For this reason, it has become necessary to change the linear model of the material flow to a closed loop to capture an additional value from products and materials, to decrease the amount of waste going to landfills and to reduce the risk presented by the material price volatility and changing costs of the material supply.

Introduction of the circular economy principles is not an easy task and necessitates transformation of the current production and consumption patterns. It also requires continuous monitoring of how effective a company is in making the transition from the linear to the circular model, and verifying whether the actions undertaken by the company bring about the intended economic, environmental and social effects. There are several different methods, tools and indicators measuring circularity at the micro, mezzo and macro level. The most commonly used is the Material Circularity Indicator (MCI), which makes it possible to measure circularity at the product and the company levels. The Material Circularity Indicator of a product (MCI_P) is based on a combination of three product characteristics: the mass of virgin raw material used in manufacturing, the mass of unrecoverable waste that is attributed to the product, and the utility factor that accounts for the length and intensity of the product use. This article presents an analysis of diverse changes in individual parameters of the product and their impact on the MCI_P score. The analysis results are to indicate the key parameters for obtaining the best circularity and environmental performance of the product.

2. CIRCULAR ECONOMY AND ITS RELATION TO REVERSE LOGISTICS

The circular economy is seen as an economic and industrial model where resources are used as long as possible and where the maximum value is extracted from products and materials as they are used, then recovered and reused. This model points to the relationship between the economy and the environment emphasizing the need to reduce the consumption of virgin resources and limit the amount of waste and the waste harmful environmental impacts.

The aim of the circular economy is to change the linear loop of material flows ("Take - Make - Dispose") to a circular loop ("Take - Make - Re-use"), keeping the value of products for as long as possible and increasing the amount of products directed for recycling and re-use when they have reached the end of their life [1]. Achieving this goal requires implementation of eight main circular economy processes classified into three categories [2]:

- processes making it possible to use less primary resources: (1) recycling, (2) efficient use of resources, (3) utilization of renewable energy sources,
- processes making it possible to maintain the highest value of materials and products: (4) product life extension and (5) remanufacturing, refurbishment and re-use of products and components,
- processes changing the product utilization patterns and making it possible to reduce the amount of products disposed of in landfills after their use: (6) product as service, (7) sharing models and (8) shift in consumption patterns.

Implementation of the processes mentioned above requires activities such as the collection of goods after their use, transportation and sorting according to ultimate destination, e.g., remanufacturing, refurbishing, reusing or recycling. Therefore, it requires organizing reverse flows of used products, or their parts, from consumers or users and from the supply chain. These activities are undertaken in reverse logistics, which is the process of moving goods from their final destination for the purpose of capturing their value (by re-using, recycling, remanufacturing or refurbishing) or proper disposal [3]. It seems that, by capturing the value of end-of-life goods through closing the loop of the product lifecycles, reverse logistics plays an important role in transitioning to a circular economy.

3. INDICATORS MEASURING CIRCULAR ECONOMY AT PRODUCT-LEVEL

Introduction of the circular economy principles requires continuous monitoring of how effective a company is in making the transition from the linear to the circular models, and verifying whether the actions undertaken by the company bring about the intended economic, environmental and social effects. Several different methods and tools, including indicators, of measuring performance in the circular economy context have been developed in recent years. Most of them focus on measuring the product circularity [4]. The example indicators which can be used to measure the product circularity are as follows:

- Material Circularity Indicator (MCI) - assesses circularity at the product and the company levels and makes it possible to measure the reduction in the input and use of natural resources, the level of valuable material losses and also the increasing share of renewable and recyclable resources and the product value durability [5],
- Circular Economy Index (CEI) - measures circularity in terms of the ratio between the value of the material recycled from EoL products and the total material value in recycling processes needed to produce new versions of the same product (it focuses only on the recycling process efficiency) [6],
- Cradle to Cradle Certified Product Standard - assesses the product circularity based on five key principles, including material selection, material reutilization, the use of renewable energy in the production system, water stewardship and social fairness [7],
- Product-Level Circularity Metric - is based on the use of the economic value of the product parts as the basis for aggregating recirculated and non-recirculated elements into a combined measure of the product circularity [8].

Each of the indicators mentioned above enables assessment of the product circularity, but each of them has both advantages and disadvantages [9]. It follows from the analysis that the MCI is the most commonly used indicator, and for this reason further considerations of the product circularity measurement are focused on it.

4. MATERIAL CIRCULARITY INDICATOR - THEORETICAL AND METHODOLOGICAL BACKGROUND

The Material Circularity Indicator (MCI), developed by the Ellen MacArthur Foundation and Granta Design, is an indicator which may be applied to assess both the product and the company circularity. The Material Circularity Indicator of a product (MCI_P) measures the extent to which the linear flow has been minimized and the restorative flow - maximized for the product component, and how long and how intensively a product is used compared to a similar industry-average product [5]. In this respect, the product is assigned a score between 0 and 1. The MCI_P is constructed by computing the following variables:

- the total amount of virgin feedstock material (V) used in the product manufacturing, including the product every sub-assembly, part, or material,
- the total amount of unrecoverable waste (W) attributed to the product, which takes account of the amount of unrecoverable waste generated at the time of collection for the product every sub-assembly, part, or material going to the landfill, the amount of unrecoverable waste generated in the process of recycling a relevant sub-assembly, part, or material, and the amount of unrecoverable waste generated to produce any recycled content used as feedstock,
- the Linear Flow Index (LFI), which measures the proportion of materials flowing in a linear fashion, sourced from virgin materials and ending up as unrecoverable waste; the index takes a value between 1 and 0, where 1 is a completely linear flow and 0 a completely restorative flow,
- the utility factor (X), which takes account of the length of the phase of the product use (lifetime) and the intensity of the product use (functional unit).

In order to compute the MCI_P, the following formulae defining relevant variables need to be applied [5]:

- the amount of the virgin feedstock material for each sub-assembly, part or material χ:

$$V_{(\chi)} = M_{(\chi)} * (1 - F_{R(\chi)} - F_{U(\chi)}) \qquad (1)$$

where: $M_{(\chi)}$ is the mass of sub-assembly, part, or material χ, $F_{R(\chi)}$ represents the fraction of sub-assembly, part, or material χ derived from recycled sources and $F_{U(\chi)}$ is the fraction of sub-assembly, part, or material χ from reused sources;

- the total amount of the virgin material:

$$V = \sum_{\chi} V_{(\chi)} \qquad (2)$$

- the amount of unrecoverable waste generated at the time of collection for each sub-assembly, part, or material χ going to the landfill or directed for energy recovery:

$$W_{O(\chi)} = M_{(\chi)} * (1 - C_{R(\chi)} - C_{U(\chi)}) \qquad (3)$$

where $C_{R(\chi)}$ is the fraction of the mass of sub-assembly, part, or material χ being collected for recycling at the end of the product use phase and $C_{U(\chi)}$ is the fraction of the mass of sub-assembly, part, or material χ going into the component reuse;

- the quantity of unrecoverable waste generated in the recycling process of sub-assembly, part, or material χ:

$$W_{C(\chi)} = M_{(\chi)} * (1 - E_{C(\chi)}) * C_{R(\chi)} \qquad (4)$$

where $E_{C(\chi)}$ is the efficiency of the recycling process used for sub-assembly, part, or material χ recycling at the end of the product use phase;

- the amount of unrecoverable waste generated to produce any recycled content used as feedstock:

$$W_{F(\chi)} = M_{(\chi)} * ((1 - E_{F(\chi)}) * F_{R(\chi)} / E_{F(\chi)}) \qquad (5)$$

where $E_{F(\chi)}$ is the efficiency of the recycling process used to produce the recycled feedstock for sub-assembly, part, or material χ;

- the total amount of unrecoverable waste associated with a product:

$$W = \sum_{\chi} (W_{O(\chi)} + (W_{F(\chi)} + W_{C(\chi)}) / 2) \qquad (6)$$

- the Linear Flow Index:

$$LFI = (V + W) / (2M + \sum_{\chi} ((W_{F(\chi)} - W_{C(\chi)}) / 2)) \quad (7)$$

where *M* is the mass of the finished product

- the product utility:

$$X = (L / L_{av}) * (U / U_{av}) \quad (8)$$

where: *L* is the product actual average lifetime, L_{av} is the actual average lifetime of an industry-average product of the same type, *U* is the actual average number of functional units achieved during the product use phase and U_{av} represents the actual average number of functional units achieved during the use phase of an industry-average product of the same type.

- the utility factor built as a function of the product utility X:

$$F(X) = 0.9 / X \quad (9)$$

- the Material Circularity Indicator of a product:

$$MCI^*_P = 1 - LFI * F(X) \quad (10)$$

$$MCI_P = \max(0, MCI^*_P) \quad (11)$$

The MCI_P makes it possible to measure the reduction in the input and use of natural resources, the level of valuable material losses and also the increasing share of renewable and recyclable resources and the product value durability. It should be noted, however, that the model is based on certain assumptions which limit its use. For example, the model does not favour closed loops, which means that material recovered for recycling does not need to return to the original manufacturer. It also assumes that there are no material losses in preparing collected products for reuse, and the product mass does not change from manufacturing to the end of use (no part of the product is 'consumed' during its use). Because of all these limitations, the MCI_P does not evaluate the product circularity to the full extent and it cannot be applied to all products.

5. MATERIAL CIRCULARITY INDICATOR OF A PRODUCT - ILLUSTRATIVE EXAMPLE

In order to indicate the variables that influence the MCI_P score to the greatest extent, the indicator was computed for a hypothetical product. To simplify the calculations and to make them clearer, it was assumed that product was made of one component. In addition, it was decided that the analysis should not take account of the product fraction from reused sources (F_U=0) or the fraction of the product mass going into the component reuse (C_U=0). The recycling efficiency rates E_C and E_F were posited to be the same and equal to E.

The calculations were performed using the formulae presented in section 4. Different variants were taken into account and they included various changes in relevant input parameters, such as the product fraction derived from recycled sources (F_R), the product fraction collected for recycling at the end of the product use phase (C_R), the efficiency of the recycling process (E), and the product utility (X). The results of the MCI_P calculations based on different variants of the input parameters are presented in **Figure 1**.

The results of the calculations reveal, *inter alia*, that:

- the MCIP receives the full score of 1 for a product with a fully restorative flow (FR=1, CR=1, E=1), irrespective of the product utility;
- the product utility (X) seems to be extremely important for the MCIP score. In particular, it concerns a fully linear product. For example, if FR=0 and CR=0, MCIP=0.1 (assuming X=1), MCIP=0.4 (assuming X=1.5), MCIP=0.55 (assuming X=2), and MCIP=0.7 (assuming X=3). In addition, the differences between the MCIP scores for different variants of parameters, with FR=0 compared to FR=1 and CR=0 compared to CR=1, respectively, become much smaller as the product utility increases;
- the product fraction derived from recycled sources (FR) and the product fraction collected for recycling at the end of the product use phase (CR) have a similar effect on the MCIP. If E=1, FR and CR affect

the MCIP to the same extent, irrespective of the product utility. If E<1 and 0<FR<1 and 0<CR<1, the effect of FR on the MCIP is slightly bigger compared to the effect of CR;

- the impact of an increase in the recycling process efficiency on the MCIP score improvement, in particular, is important if FR=1 and/or CR=1.

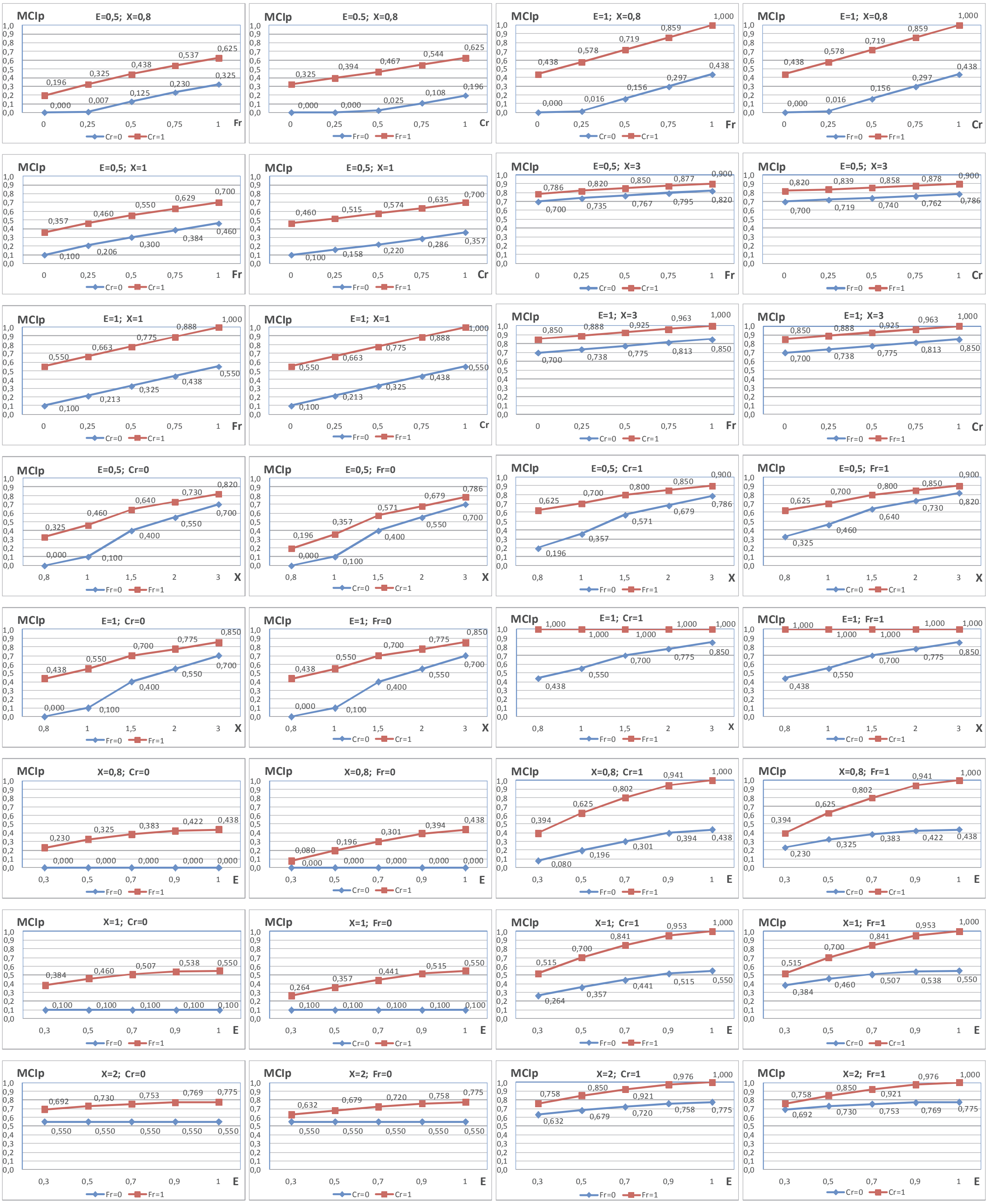

Figure 1 Results of MCIP calculations based on different variants of input parameters [own analysis]

6. CONCLUSION

The need for rational management of natural resources resulting from their depletion should inspire the search for solutions enabling a transition from an economy with the linear flow of materials to the circular economy. One of the indicators that make it possible to define the extent of the transition from the linear to the closed-loop model is the Material Circularity Indicator (MCI), which can be applied both at the product and at the company level. The Material Circularity Indicator of a product (MCI_P) provides valuable information on the product circularity, both at the stage of the product design and improvement.

The considerations presented in this paper indicate that for the product circularity it is absolutely essential that, without compromising its quality, the product should be manufactured using an increasing amount of recycled materials. Efforts should also be made to ensure that, at the end of its life, the biggest possible portion of the product components should be reused or recycled. The product utility, which is affected by the product lifetime and intensity of the product use, is of particular importance. The intensity of use can be increased by dissemination of the idea of the product sharing.

It should be added that the product circularity will most often require taking account of complex supply chains, including reverse logistics, because the product components or the materials recovered due to recycling may become the starting point for another production process. The development of appropriate solutions in this area may require adequate forms of cooperation [10] and utilization of complex tools intended for the support of innovation and eco-innovation implementation [11,12,13].

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