IS CIRCULAR ECONOMY, CIRCULAR?

Carlos A.V. Costa

FEUP - Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

LEPABE – Laboratory for Process Engineering, Environment, Biotechnology and Energy, FEUP

ALICE – Associate Laboratory in Chemical Engineering, FEUP

Abstract

This paper is an attempt to explain the geometric metaphor, circular economy, and of its range of application. For that, reuse and recycle loops are analyzed in two situations: discrete and continuous systems, both looking for material decay along cycles or time (due to purge) and for the time evolution of its unit price (time value of money and inflation). The case of existing a make-up that compensates the purge is also analyzed. The conclusion is that the geometric metaphor in use, circular economy, corresponds to particular situations. In general, the evolution is spiral rather than circular.

Keywords: *circular economy, reuse, recycle, mass conservation*

INTRODUCTION

After 2nd world war, due to raw materials price increase, heavy industries like oil refining, petrochemicals, chemicals, etc, generally began to recycle unused raw materials and intermediates, instead of letting them go away, also avoiding end of line treatment costs that by the time arrived due to initial pollution concerns. Later, in the last century seventies, the first oil shock also pushed the need for energy conservation. Even later concerns with water conservation led to design for reuse/regenerative water networks. All this gave rise to structuring conceptual design for new, retrofitting or revamping plants, to deal with mass and heat transfer networks (T. M. Mata, et al 2003, P.S. Varbanov and T.G. Walmsley, 2019).

These concepts were not generally applied to consumer products that usually were used and discarded and not designed for easy recycling or reuse, the so-called linear economy.

Circular economy (CE) is a widespread term to classify all the operations where one of the objectives is the conservation of resources, specially abiotic (raw materials) through successive cycles of reusing with or without regeneration (repair) and/or recycling (S. Sikdar, 2019). When doing so pollution and biodiversity loss are also prevented as well as climate change with the wider use of energy from renewable sources.

The origins of the concept of CE are generally attributed to Pearce & Turner (1990) and the term circular is related to the circularity in using materials.

Interesting reviews on circular economy are presented by P. Ghisellini, C. Cialani and S. Ulgiati (2016), V. Rizos, K. Tuokko and A. Behrens (2017), R. Merli, M. Preziosi and A. Acampora (2018) and E. H. Arrudaa et al (2021). Also H. Corvellec. A. F. Stowell and N. Johansson (2022) presented a review on the criticisms that meanwhile appeared on the concept and its applications.

The objective of this article is to understand if the geometrical metaphor “circular economy” represents well the general case of conserving the value of the initial material remaining in the system along successive cycles or time.

When recycling loops are used it is necessary to take-off impurities originated by use and other causes before reprocessing. In this operation it is technically and/or economically impossible to totally separate those impurities from the recyclable material and thus a small part of this material is lost in the necessary purge. The same occurs in reusing loops since some pieces are broken or damaged and thus are purged from that loop although eventually integrated in the exterior recycling loop. Figure 1 is a simplified representation of those loops.

The make-up may be located before pre-processing whenever using the same material as the one being recycled. The position of the make-up in Figure 1 corresponds to the use of new raw materials or of an already pre-processed recycled material. This is also frequently the case.

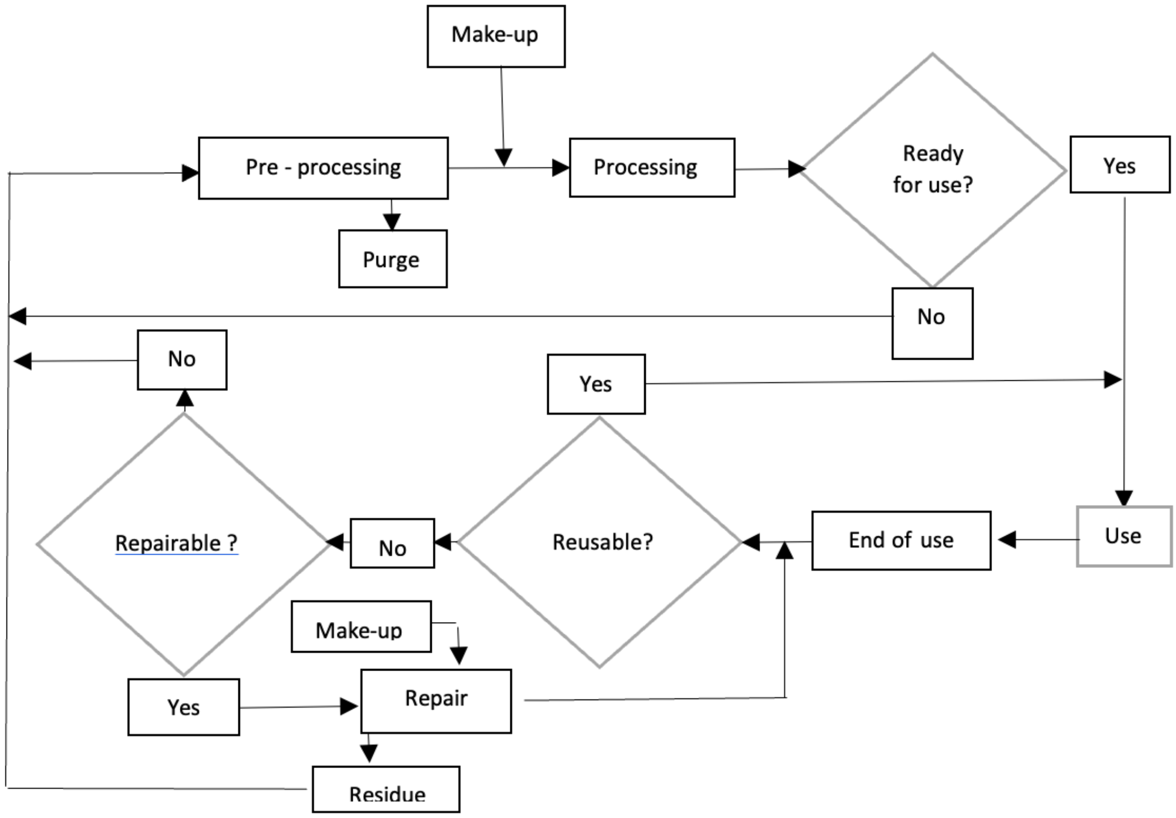

Fig. 1. Simplified scheme of the recycling and reusing loops

CYCLES WITH PURGE BUT WITHOUT MAKE-UP

Due to purge the initial quantity of material in the system, M_0 decreases along cycles or time.

After n cycles the initial quantity still present in the system (that enters pre-processing), M_n, assuming a quasi-exponential decay model, can be calculated by

$$M_{nD} = M_0 * (1-k_D)^n \qquad (1a)$$

where k_D is the cycle decay rate. This will be the case of a discrete system: time constant of the cycle much smaller than the time delay (e.g. storage) between cycles.

On the contrary if the cycle time constant is much larger than the time delay between cycles we approach a continuous system. In this case assuming an exponential decay we can write

$$M_{tC} = M_0 * \exp(-k_C * t) \qquad (1b)$$

where k_C is the continuous decay rate and t is time.

On the other hand the initial unit value, v_0, of the material also evolves along time. This is just the intrinsic value of the material, that enters pre-processing, not the one of the product or products undergoing the reuse/recycle cycle. After n cycles or after time t, its value v, can be calculated by

$$v_{nD} = v_0 * (1+i_D)^n \qquad (2a)$$

$$v_{tC} = v_0 * \exp(i_C * t) \qquad (2b)$$

where i_D and i_C are respectively the cycle and continuous interest rates. In this case we are not considering market effects on the recycled material price.

The evolution of the value, V, of the initial material remaining in the system along cycles or time, can be calculate by

$$V_{nD} = M_{nD} * v_{nD} = M_0 * v_0 * ((1-k_D)*(1+i_D))^n \qquad (3a)$$

$$V_{tC} = M_{tC} * v_{tC} = M_0 * v_0 * \exp((i_C - k_C) * t) \qquad (3b)$$

The idea of circular economy may be interpreted as V = constant along the cycles or time, so

$$V_{nD} / V_0 = 1 = ((1-k_{D*}) * (1+i_{D*}))^n \qquad (4a)$$

$$V_{nC} / V_0 = 1 = \exp((i_{C*} - k_{C*}) * t) \qquad (4b)$$

and thus we have the following conditions:

for the discret case: $i_{hD*} = k_{hD*}/(1-k_{hD*})$ or $k_{hD*} = i_{hD*}/(1+i_{hD*})$ (5a)

for the continuous case: $i_{hC*} = k_{hC*}$ (5b)

showing that for the discrete case k_{D*} is always smaller than i_{D*}, except when $k_{D*} = i_{D*} = 0$. In the continuous case they are equal, $k_{C*} = i_{C*}$.

In the condition of constant value of the material remaining in the system, the three-dimensional geometric metaphor looks like a set of equal diameter circumferences along cycles in the discrete case and of a helix along time in the continuous case, both adjacent to the lateral cylindrical surface where number of cycles or time are in the cylinder axis and the value of the material still remaining in the system is represented by its radius. A cut by a plane containing the cylinder axis is represented in Figure 2.

If we consider the projection in a plane perpendicular to the number of cycles or time axis, we get in both cases a circumference: "circular economy".

We can also say that if for a given $i_{D*} = i_D$ or $i_{C*} = i_C$, k_D is larger than k_{D*} or k_C is larger than k_{C*} then the value of the initial material remaining in the system decreases with number of cycles or time; if k_D is smaller than k_{D*} or k_C is smaller than k_{C*} then the value of the initial material remaining in the system increases with number of cycles or time. In practice there will be a minimum quantity of material to make recycling or reusing possible. This means that the quantity of initial material in the system has an economic/technological limit.

In the case of i_D or $i_C \leq 0$ (very low probability) the value of the initial material still in the system will decrease with number of cycles or time.

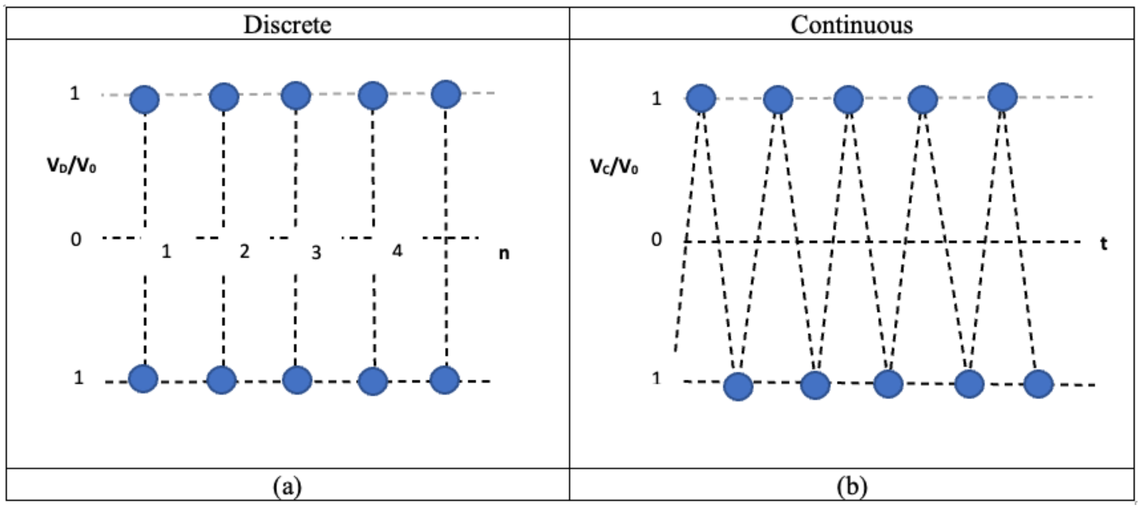

Fig. 2. Cut by a plane containing the number of cycles (a) or time (b) axis of the evolution of the value of the initial material still remaining in the system. Case of constant value of the material remaining in the system.

Using again the geometric metaphor, in the discrete case we have a set of circumferences with decreasing or increasing radius along the number of cycles. In the continuous case we have a conical spiral form with decreasing or increasing radius along time. In both cases they are adjacent to a conical surface with number of cycles or time in the axis and the value of the initial material still in the system in the varying radius.

Figure 3 shows the evolution of the value of the initial material still remaining in the system in a cut by a plane containing the number of cycles or time axis, in the case of decreasing value along number of cycles or time.

If we look for the projection in a plane perpendicular to the number of cycles or time axis we will have:

- discrete case - a series of concentric circumferences with decreasing or increasing radius;
- continuous case - a spiral evolving from the periphery to the center or from the periphery to higher radius.

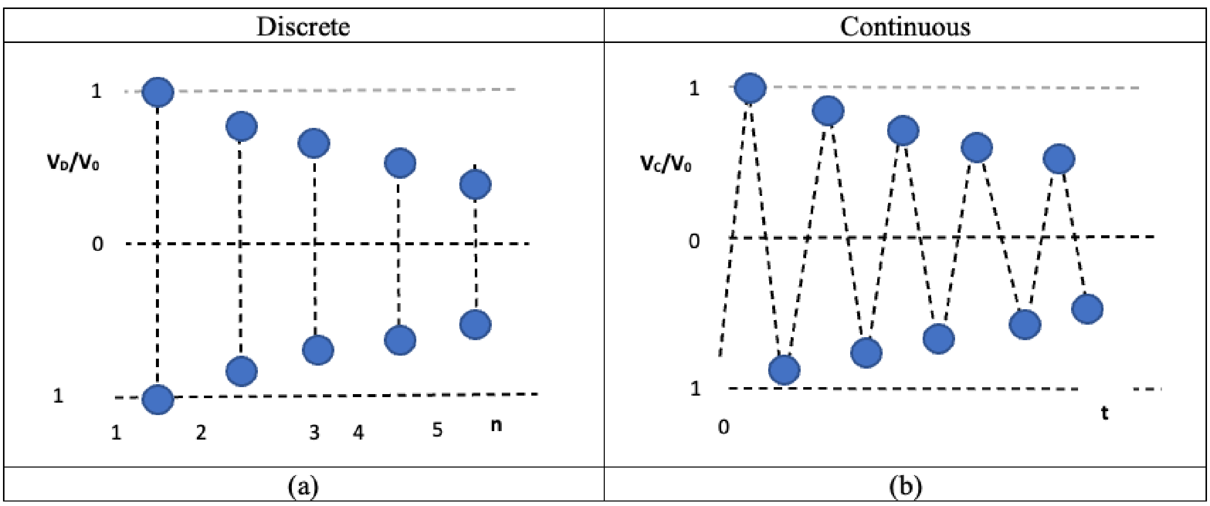

Fig. 3. Cut by a plane containing the number of cycles (a) or time (b) axis of the evolution of the value of the initial material still remaining in the system.

This is shown in Figure 4.

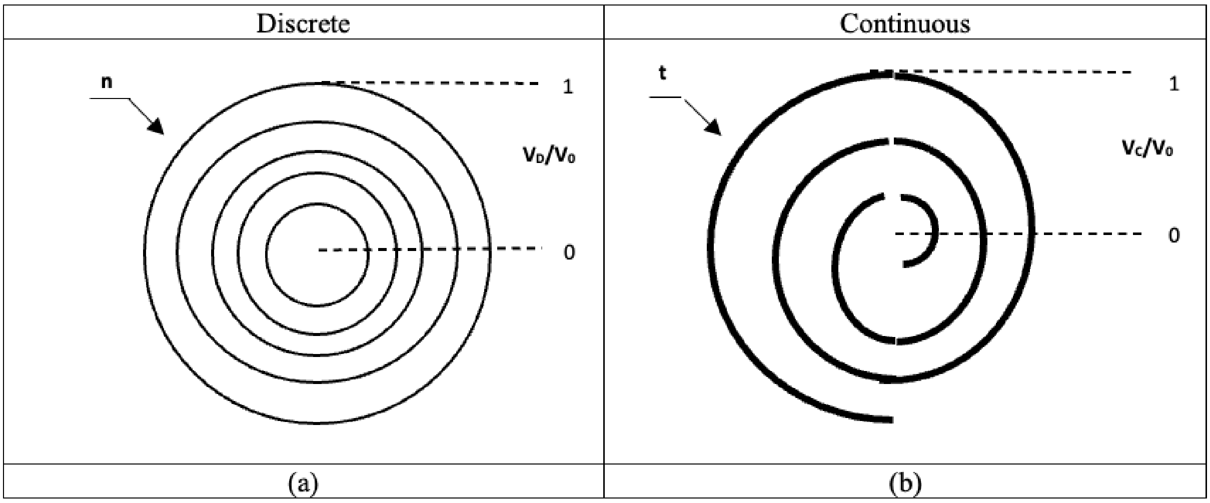

Fig. 4. Projection in a plane perpendicular to the number of cycles (a) or time (b) axis of the value of the material still in the system. Case of decreasing value of the initial material still in the system.

We can also look for the cumulative purge, $P_n = M_0 - M_n$, evolution along cycles or time, $P_t = M_t - M_0$

$$P_{nD}/M_0 = 1 – M_{nD}/M_0 = 1 - (1 – k_D)^n \qquad (6a)$$

$$P_{tC}/M_0 = 1 – M_{tC}/M_0 = 1 - \exp(-k_{C*}t) \qquad (6b)$$

For a given k_D or k_C, if the normalized purge is above its values calculated with k_{D*} or k_{C*} (for constant value of the initial material remaining in the system along cycles or time), then the value of the initial material still in the system decreases. If it is kept below those values then that value of the initial material still in the system increases.

Let's take an example: 12 cycles per year and an annual interest rate of 4%. In this case the monthly interest rate is $i_D = 0.33\%$, which gives a decay rate $k_{D*} = 0.0033$ (for constant value of the initial material still in the system) and $(M_{12}/M_0)_{D*} = 0.961$. In this case the purge represents 3,9% of the initial material after 12 month. The same result is obtained using the continuous formulation.

If an annual inflation rate f = 4% is present and considering an annual compound interest plus inflation rates i + f = 8%, then $k_{D*} = 0.0064$ and $(M_{12}/M_0)_{D*} = 0.926$. Maximum purge after 12 months will represent 7.4% of the initial material. The presence of inflation can accommodate a larger purge keeping "circular" economy conditions.

CYCLES WITH PURGE AND MAKE-UP

As we saw, the existence of a purge implies a decay of the initial material in the cycle. In order to compensate this lost the same quantity is introduced in the system through a make-up. This compensation is normally made with raw or pre-processed recycled materials /new products with an initial unit price, vMU_0, usually larger than the unit value of the recycled/reused material and introduced in the system before the processing step. If the make-up is made with the same recycled material, it will be introduced before pre-processing and its unit value will be v_0.

So, in this case the amount of material remains constant in the system.

$$M_{nD} = M_0 \text{ or } M_{tC} = M_0 \qquad (7)$$

The purge and the make-up are also constant cycle after cycle and equal to k_D in the discrete case.

The unit value of the remaining material in the system and of the purge are the same but if the unit value of the make-up is different, thus the material value in the system, VMU, is

$$VMU_{Dn}/M_0{*}v_0 = (1+i_D)^n * (1 + k_D * (vMU_0/v_0 - 1)) \quad (8a)$$

$$VMU_{Ct}/M_0{*}v_0 = \exp(i_C{*}t) * (1 + (1- \exp(-k_C t)) * (vMU_0/v_0 - 1)) \quad (8b)$$

The conditions for constant value along the cycles imply $VMU_{Dn}/M_0{*}v_0 = VMU_{Ct}/M_0{*}v_0 = 1$, only possible if $i_D = i_C = 0$ which will be quite unusual. Even if this condition occurs then we still need $k_D = k_C = 0$ or $vMU_0 = v_0$ that are also not interesting since they represent trivial cases: no purge or equal initial unit values for make-up and material in the system.

In this more general case, the material value on the system keeps growing for i_D or $i_C \geq 0$ and $vMU_0 \geq v_0$.

If we take the same example: a year with 12 cycles and annual interest rate i = 4% (monthly: $i_D = 0.33\%$), $k_D = 0.019$ (approximately 4 years to purge almost all the initial material in the system, $k_C = 0.25$) and $vMU_0/v_0 = 1.5$ we obtain after 12 monthly cycles $VMU_{D12}/M_0{*}v_0 = 1.139$ and after one year $VMU_{Ct=1y}/M_0{*}v_0 = 1.156$.

CONCLUSIONS

Including not only the circularity of materials but also time value of money it was possible to verify the applicability of the geometric metaphor "circular economy".

If we consider recycling or reusing loops with purge but no make-up and the time value of money, the geometric metaphor for the general case would be:

- discrete case - a series of concentric circumferences with decreasing or increasing radius along number of cycles;
- continuous case - a conical spiral evolving from the periphery to the center or from the periphery to increasing radius along time.

If we look for the projection in a plane perpendicular to the number of cycles or time axis the geometric metaphor is:

- discrete case – a series of concentric circumferences;
- continuous case – a spiral.

For the particular case of constant value of the material remaining in the system we have:

- discrete case – a series of equal radius circumferences along number of cycles;
- continuous case – a helix along time.

The projection in a plane perpendicular to the number of cycles or time axis is, in both discrete and continuous cases a circumference: "circular economy".

If we also consider make-up then the geometric metaphor would be:

- discrete case - a series of concentric circumferences with increasing radius;
- continuous case - a conical spiral evolving from the periphery to increasing radius.

Thus, the general conclusion is that, circular economy as a geometric metaphor, represents well the case of discrete or continuous systems with purge and no make-up with constant value of the initial material still remaining in the system. In the general case, both for discrete or continuous systems without or with make-up, "circular economy" geometric metaphor is not so close to the behavior of the systems.

NOMENCLATURE

k_D – cycle decay constant

k_C – time decay constant

i_D – cycle interest rate

i_C – continuous interest rate

M – quantity of initial material still in the system

P – cumulative purge

p – purge in each cycle or time, t

t – time

v – unit value of the initial material still in the system

vMU – unit value of the make-up material

V – value of the initial material still in the system

VMU – value of the material when make-up is present

Superscripts

n – number of cycles

t - time

Subscripts

C – continuous

D – discrete

0 – initial

* – conditions of constant value of the material still in the system

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