Engineering of circular economy and good management of industrial material resources

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Abstract. The paper proposes a presentation of the mechanisms of institutionalization by which materials engineering becomes an action instrument for the circular economy. In the proposed variant, the designed actions are grouped under the following steps: analysis of the current situation and of the assimilation potential at the level of socio-economical mechanisms from the perspective of eco-responsibility; constructive establishment and functioning of the regulation framework; innovative technological ideas and the entrepreneurial way of promoting of technical solutions; designing and ensuring finance systems, especially financial instruments. The introduction of specific elements from materials engineering stems from the fact that products and services, no matter how complex, use materials in order to ensure some functionality.

1. Evolution of global politics regarding eco-responsability
Mankind continues its approach of choosing optimal solutions determined by two fundamental existential elements, one linked to the belief in the exhaustion of limited resources and the other determined by the belief of the infinite existence of life. Against this background, global policies have evolved from defined elements related to ensuring the health of population, environmental protection - ecosystem preservation, sustainable development, green economy promotion, and, over the last few years, actions of compliance with a new concept, that of ensuring the principles of "circular economy". This paper is a continuation of some presentations related to market economy conditions at the manufacturing stage of molded parts [1] or the issue of the institutionalization of the circular economy [2].

2. Institutional debate regarding circular economy
At the same time, a professional debate is required at European and national level due to the institutional existence of European documents that emerged in 2014 [3], withdrawn in 2015 and presented in a new formula in the same year [4]. This paper is intended to show gratitude to Nicholas Georgescu-Roegen, born in Constanța, who, through his fundamental work [5], laid the foundations for the actions that are currently grouped within the circular economy. I would note, in this context, an important work by the academician N.N. Constantinescu who prefigures the elements of action of the circular economy [6]. Another element is related to the “state of the environment in Romania”, which requires, according to the latest EU report [7], the transition to the circular economy. According to him, the “productivity of resource” in our country was the lowest in the EU, being of 0.31 EUR/kg, compared to the European average of 2.0 EUR/kg.
The institutionalization of the circular economy, as well as the functioning of other economic and social mechanisms, requires the synergistic cumulation of actions designed at five levels: the level of the existing situation (the analysis of the existing situation and the assimilation potential at the level of economic and social mechanisms from the perspective of eco-responsibility conditions); the level of public policies; the regulatory framework (constructive setting up and functioning of the regulatory framework); the level of technical solutions (developing innovative technological concepts and promoting entrepreneurial solutions); the level of financial solutions, which also includes the means of operation for the financial instruments (designing and securing financing systems, especially financial instruments).

3. Reporting products and services to the requirements of circular economy

Products and services, with various uses determined by market economy requirements, relate to the following values from the perspective of the circular economy objectives: functional value, material value; energy value and environmental value.

At the level of many areas of engineering, especially in the material-quantified engineering – as compared to the engineering of non-material products and services, the constitutive processes are carried out by materializing a concept of putting the materials into operation by using a certain technological infrastructure and some kinds of energy resources. Through this action usually carried out in an industrial manner, besides the useful part, there are also some useless results that affect the environment and the sustainable development.

4. Rationales of materials engineering

The rationales of materials engineering in relation to the institutionalization of the circular economy starts from the fact that most productive activities manage, within a certain framework of ensuring functionality, two participant structures: material and energy. Basically, referring to engineering activities, even if there is only one specialization in “materials engineering”, there is a need for all specializations to have a profile related to the selection, obtaining, processing, exploitation and disposal of materials specific to each particular field. Starting from the desire expressed in the title of the paper, from the perspective of the functioning of the circular economy, I consider that a new area of action appears in materials engineering, related to the use of the functional value, the material value, the energy value and the environmental value of the products and services at the end of use. The correct assessment of these values, from the perspective of integrative engineering, must take into account the considerations envisaged in the design of a wrought material, in the manufacturing of a product, or in the realization of a service: conditionings of functionality; safety; processing; environmental protection requirements; sustainability; end-of-life disposal conditionings.

Keeping in mind the previous conditions, the expression of the value of the material through the product or service, including the past state - historical, present and future, is made through the following elements: functional value, material value, energy value, environmental value and social value.

5. Elementary values of the product and service from the perspective of circularity

The discussion on mechanisms of ensuring circularity is important in optimizing the analysis methodology proposed in the paper. Starting from material engineering reasoning, circularity, with the significance of circular economy, starts from the fact that the value of a product or service has four elementary components: the functional value \(V_F\), the material value \(V_{MAT}\), the energy value \(V_E\) and the environmental value \(V_{MED}\). Material value refers to the primary material flows used to produce the product or service over its lifetime necessary to achieve the essential stages of manufacture, exploitation and disposal. Energy value \(V_E\) refers to energy consumption over the lifetime of the product or service. Environmental Value \(V_{MED}\) refers to the impact on the environment over the lifetime of the product. The life of the product or service has three phases: manufacture, use of functionalities and disposal. Therefore, each of the elementary values, material,
energetic and environmental values is decomposed into three components according to formulas (1), (2) and (3).

\[
V_M = V_{MAT}^F + V_{MAT}^{UF} + V_{MAT}^{EL} \\
V_E = V_{E}^F + V_{E}^{UF} + V_{E}^{EL} \\
V_{MED} = V_{MED}^F + V_{MED}^{UF} + V_{MED}^{EL}
\]

The schematic presentation of components of consumed values in order to ensure the functionalities of a product or service is done in Figure 1.

The material value \(V_{MAT}\) is expressed by the following components: abiotic raw materials \(\text{MPA}\); biotic raw materials \(\text{MPB}\); consumed water \(\text{AC}\); air used \(\text{AU}\); landslides \(\text{DT}\), all reported at the level of a product - service or even at the level of assurance of a certain functionality. The energy value of a product or service has several components: the energy consumed for the extraction of raw materials, the energy required to carry out the technological processes specific to the product or service, the energy required to provide the intended functionality over time, the energy required to dispose of the product or service at the end of its use, the energy related to the transport of the materials to be processed, the energy related to the transport of the products to be sold, etc.

The environmental value \(V_{MED}\) is expressed by the impact the product or service has on the environment. This indicator can be expressed in two ways, one in which the expression is achieved by the amount of greenhouse gases emitted, expressed in kilograms of \(\text{CO}_2\) equivalent per ton of product.

Figure 1. The dynamics of components of elementary values consumed at the level of ensuring the functionalities of a product or service.
or service, and the other represents a totalization of the environmental effects of the product. In the second expression, the following grouping is possible, following the categories of effects: global effects (increase of greenhouse effect, shrinking of the ozone layer and depletion of non-renewable resources), regional effects (photochemical pollution, acidification and eutrophysis), local scale effects (photochemical pollution, toxicity, ecotoxicity, noise pollution, unpleasant odors and negative landscape impact).

6. The scheme of circularity
Total or partial circularity is ensured if, after processing or other interventions, the functionalities of the resulting materials permit their use in the same process or in similar ones. If the functionalities disappear or their insurance is very expensive, the resulting material becomes unnecessary and its elimination causes massive losses occurring at the level of material, energy and environmental value, corresponding to the fact that raw material quantities of primary energy are lost, and increases the impact on the environment by the fact that the obtaining of the functionalities must start from the primary stage, the extraction and the processing of the raw materials. The scheme of the possible circularity variants is conceived and presented in Figure 2.

![Scheme of circularity](image)

**Figure 2.** Scheme of circularity depending on how the removal of a product or service is managed; $C_L$ – circuit of linear disposal; $C_{C1}$ – circuit of functional circularity; $C_{C2}$ – circuit of material circularity; $C_{C3}$ – circuit of energetic circularity.

The primary circuit ($C_L$) comprises the following phases: the phase of obtaining the material and energy resources; the product processing phase; the use of the product's functionalities and the disposal phase at the end of its use.

7. Situations at the level of circularity
Depending on the way the elimination is done, we have to deal with two fundamental variants: the linear elimination variant with the removal of the already processed resources in a certain way and the
reintroduction of the resources in the circuit of the recovered materials at the level of material and energy value, variant which is referred to as circular elimination. This has three possible ways of realization, the first one is done by recovering the processed material possessing a certain functionality, called circular functional elimination - represented by the circuit C₁, the second one in which the material value of the state of the resultant product at disposal is recovered, a variant which is called circular material elimination - represented by circuit C₂, and the third one in which the energy value is recovered, which is called the circular energy elimination - represented by C₃. Overlapping this reasoning with the distribution of a product's value scheme (Figure 2) can determine the conditions for which the circularity, in the sense of circular economy, becomes viable.

Determining the recirculation potential of the value of the products or services starts from the comparison of the value of the recovered material (the material value, the energy value and the environmental value) with the values consumed in the processing operations to which they are subject for disposal.

These situations are grouped in four categories: A - the situation where all the elementary values of the material resulting from the disposal are positive compared to the specific consumption values of the processing; B - the situation where two of the elementary values of the material resulting from the elimination are positive compared to the values of the specific processing consumptions; C - the situation where only one of the elementary values of the material resulting from the disposal is positive compared to the specific processing consumption values; D - the situation where all the elementary values of the material resulting from disposal are negative compared to the specific processing consumption values. Therefore, from the point of view of circularity, we distinguish four situations: A – situation favorable to circularity (circularity of 1st degree); B - a weakly questionable situation in circularity because one of the elementary values does not meet the favorable condition (circularity of the 2nd degree); C - a highly controversial situation in circularity, in that two elementary values do not meet the favorable conditions (circularity of degree 2. b); D - unfavorable circularity (circularity of 3rd degree).

The discussion on the inclusion of functionality over circularity is not included in this paper, it requires a deeper approach because there are two types of degradation, physical degradation and moral degradation. The prefiguration of a discussion on the inclusion of functionality in ensuring circularity we think should start from the quantification of current consumptions. If their value exceeds a critical threshold, you may want to give up on the functionality infrastructure (the product or service that provides a certain functionality). It is appreciated that the analysis should focus on identifying the optimal threshold from the point of view of the circular economy. It is appreciated that in this area it is possible to analyze the system generating certain functionalities. In this process an analogy is made with the “entropy law”, in which functionality is assimilated to the free energy of the system, and the degradation can be assimilated to the system entropy increase.

8. Stages of transition analysis from linear economy to circular economy
Taking into consideration the present preliminaries, the proposed methodology for ensuring a transition analysis to the circular economy, proposes the following steps: addressing the field issue (historical and present state by synthesizing specific data); state of public policies; the regulatory framework; technical and procedural solutions; financial solutions and financial instruments); the institutionalization of processes (defining the actors of institutionally regulated processes, the actions of the actors on the market, institutionalized instruments, institutional actions, taxation and institutionalized funding); the technical solution of the proposed actions; the financial settlement of the proposed actions.

In order to understand correctly the evolution of management activities, we believe that the analysis should be done through the innovative components of the "circular economy", which is a growth strategy without increasing resource consumption: technological innovation; design of materials and processes; product design; resource management (raw materials, water, energy and waste); organizational innovation; integrated solutions and systems; logistics; business models; policy
support tools; social innovation: new patterns of production and consumption; product service models; citizen involvement; skills and knowledge; capacity building and multidisciplinarity; entrepreneurship. The solution to the problem addressed, in order to optimize the actions that ensure the transition to the circular economy, is possible by providing a critical thinking. It starts roughly from a set of questions, which, as they are sorted out, will be in accordance with the established objective.

9. Analysis of the material circularity potential at the manufacturing stage of the cast parts

From the balance of the production of one tonne of castings in cast iron, considering the annual production of 14,505 tons at the level of a casting manufacturing facility, it is noted the use of a significant amount of resources, of which a significant share is recycled, as follows:

- old cast iron: 593 kg/to cast parts (GMR);
- cast iron sponge: 49 kg/to cast parts (GMR);
- scrap: 394 kg/to cast parts (GMR);
- sand: 325 kg/to cast parts (GMPMP);
- furanic resin: 49 kg/to cast parts (GMPMP);
- hardener: 17 kg/to cast parts (GMPMP);
- chrome sand: 9 kg/to cast parts (GMPMP);
- refractory paint: 19 kg/tons cast parts (GMPMP);
- grit blasting: 11 kg/to cast parts and so on (GMMP);

When referring to the production of a casting plant - expressed in tonnes over a year - to the amount of waste generated within it - expressed in kg, the following situation is observed:

- used sand: 325 kg/to cast parts (GMGR);
- slag: 34 kg/to cast parts (GMPR);
- cast iron sponge: 49 kg/to cast parts (GMPR);
- sawdust: 5 kg/to cast parts (GMPR);
- used oil: 0.19 kg/to cast parts mate (GMGR);
- plastic packaging: 0.724 kg/to cast parts (GMPR);
- metal packaging: 1.25 kg/to cast parts (GMPR);
- wooden packaging: 0.23 kg/to cast parts (GMPR);
- PCB containing capacitors: 0.333 kg/to cast parts (GMGR).

It can be noticed, from the enumeration made, that reporting the production of castings (with a positive value at the level of the balance sheet) is accompanied by a significant non-useful part (with negative value at the level of the balance sheet), which in most cases turns into waste. From the perspective of the analysis of the circular economy, at the level of the material balance, the following material groups are proposed: the group of recycled materials (GMR); the group of materials starting from raw material processes (GMPMP); the group of materials with recycling potential (GMPR); the group of materials which are difficult to recycle (GMGR).

Taking into account the actual level of the resultant trajectory of the materials entering the casting process and the traces followed by the resulting materials, the following distribution is found at the input level: “Recycled materials group” (GMR): 1036 kg / cast parts and “the group of materials starting from raw material processes” (GMPMP): 430 kg / to cast parts. It is noted that from the total of the main materials entering the process, the materials with a recycling capacity have a weight of 70.7%, and the materials resulting from processes starting from the raw materials are 29.3 of the total entered.

Regarding the outputs of the technological process, using the mentioned groups, we have the following distribution: the group of materials which are difficult to recycle (GMGR): 325.52 kg / to cast parts, with a weight of 78.30% and the group of materials with recycling potential (GMPR): 90.20 kg / to cast pieces with a weight of 21.70%.
The analysis shows that the production of molded parts includes the entry of recycled materials, which is favorable to the circular economy, and from the point of view of the outflows it is found that the weight of the recyclable materials is high, which is unfavorable to the development of the circular economy.

10. Conclusions
According to the assessments made, there are several steps in the circular economy, the first in which it is possible to achieve good results, the second one in which the circularity is conditioned from the perspective of the system management through the financial instruments, and the third in which circularity, at least at the level of existing possibilities, is not possible. Therefore, the proposed method can serve to correctly identify situations where the application of circular economy is possible, as well as to identify the measures that can be taken for its proper functioning. At the same time, we recognize the state in which "our possibilities are limited to space, time, matter, and energy" [8] and fundamentally disturbs "the man (who is inclined to believe that there must be a form of energy capable of self-perpetuation" [8], with the observation that today, even in the name of institutional documents, evoking the wish of the “zero waste” situation, a situation arises to doubt the proven situation that the entropy of the universe is constantly growing. Starting from this finding, there is a need to set up a “circular economy” between “growth” and “decrease” in relation to the available resources and the need for individual and community development. The analysis of the material circularity at the manufacturing stage of castings highlights the fact that, from the entry point, it is favorable to the circular economy. Instead, from the point of view of material outputs, at least for the process under consideration, the process is not favorable to circularity, which must lead to the undertaking of significant efforts to diminish this state.

11. References
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