Management of material and product circularity potential as an approach to operationalise circular economy

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Abstract: To make the general action plan more specific, a circular economy must introduce obligations for producers to use recycled materials. The present study suggests not only to restrict manufacturers' access to use primary resources for certain products, but also to establish the only possible access to the material of a particular turnover, thereby creating demand for these or other outputs and maximising the number of uses of the same material. This article focuses on the development of a new approach for the operationalisation of a circular economy based on the management of material and product circularity potential by the following phases: 1) allocation of the explicit available potential; 2) fullest use of materials; 3) building-up of new circularity potential for specific material and product in combination. In particular, the allocation of the explicit available potential reflects the aspect of restricting access to primary resources for manufacturers of certain products. The findings presented and discussed in this article provide a theoretical basis for the development of new metrics for measuring progress towards zero-waste and circular economy.

Keywords: circular economy; operationalisation; circularity potential; measuring circularity; material cycle; resource cycle; closing loop; slowing loop; electrical and electronic products.

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1 Introduction

The introduction of life cycle thinking into waste policy is one of the actions prescribed by the thematic strategy on the prevention and recycling of waste (European Commission, 2005). The thematic strategy on the prevention and recycling of waste and the strategy on the sustainable use of natural resources represent a couple of the seven thematic strategies provided by the Sixth Environmental Action Plan (Decision, 2002); the first concluded in July 2012, but many measures launched under this program continue to be implemented. The Seventh Environmental Action Programme, – the new general Union Environment Action Programme to 2020, 'living well, within the limits of our planet', was approved in 2013 (Decision, 2013), where a new broader meaning appeared in the formulation of tasks concerning the management of resources and waste – "to move towards a lifecycle-driven 'circular' economy, with a cascading use of resources and residual waste that is close to zero." This strategic task was reflected after several years in the 'Closing the loop – an EU action plan for the circular economy' (European Commission, 2015). In order to close the loop of product life cycles, the document outlined an action plan to create a circular economy at each stage of the value creation chain (European Commission, 2017).

To date, the concept of a circular economy, despite there being differences in scientists' opinions regarding 'Rs' activities (reduce, reuse, recycle and recovery), reflection of sustainability's dimensions and business models, is in need of operationalisation (Kirchherr et al., 2017; Murray et al., 2015; Bruel et al., 2019). A limited number of publications have dealt with the operationalisation of circular economy in terms of:

1. a holistic coverage of all possible forms in which circularity potential can manifest in space and time
2. measurement of material and product circularity.

Meanwhile, majority of studies have focused on issues related to circularity such as circular product design (Hollander et al., 2017), circular business model design (Bakker et al., 2014; Hofmann et al., 2017) and circular business strategies (Bocken et al., 2016). These studies definitely contribute to the operationalisation of circular economy, in particular, to the clear indication of specific procedures, techniques, methods or actions to monitor a circular economy. However, from the perspective of the potential of circularity of specific material and product, the whole spectrum of the interdependent processes such as:

1 allocation of the explicit available potential

2 fullest use of materials

3 building-up of new potential of specific material and product circularity should be holistically embraced by management for preserving the value of materials and products in the economy as long as possible due to an increase in the number of turnovers as well as an increase in the time of each turnover – this is the gap this study aims to bridge.

Operationalisation techniques should take into consideration the fact that the extent to which the realisation of opportunities takes place (in the present), the value of available circularity potential will change (in the future). Although the mentioned developments, to a certain extent, are intended to increase new circularity potential, there is a need for continuous build-up of this potential for material and product in conjunction. Furthermore, the available circularity potential should be periodically re-allocated in accordance to the changes in the value of the potential as a result of its increase with time as well as its fullest utilisation according to the current allocation of available potential. Hence, these interdependent processes require management, and such system management can be exploited as the basis for the operationalisation of a circular economy, specifically, to monitor circularity. With regard to material and product circularity's measurement, the current practice of circularity metrics through indicators of reuse and recycling does not correlate with the basic concepts of a circular economy such as the lifetime of a material and product/parts measured in terms of cycles. This challenge has been taken into account by the scientific community and remains underdeveloped; many recent academic papers (Linder et al., 2017; Blomsma and Brennan, 2017) have dealt with the issue of methods of measuring materials' and products' circularity.

The novelty of this study is comprised by the development of the new methodological approach to circular economy operationalisation based on the management of material and product circularity potential. Thus, the 'management of material circularity potential' could be interpreted as the process of creating and supporting the system's ability to preserve the value of materials and product within the national economy or economies through rational allocation of explicit available potential, continuous building-up and the fullest utilisation of the circularity potential of materials and products. In essence, the designated three phases of the management of circularity potential form a conceptual framework for the operationalisation of circularity of materials and products.

2 Background

2.1 Circular economy: from conceptualisation to operationalisation

The circular economic model is gaining popularity in the world, such as in relevant legislative acts adopted prominently in Germany, 'The Waste Avoidance and Management Act' (Federal Law Gazette I, 1994), Japan, 'The Basic Law for Establishing a Sound Material-cycle Society' (Law of Environment Agency Japan, 2000) and China, 'Circular Economy Promotion Law of the People's Republic of China' (Order of the President of the People's Republic of China, 2008). One of the leading global organisations in this area, the Ellen MacArthur Foundation (EMF), makes substantial contributions to the dissemination and clarification of ideas pertaining to circular economy. More specifically, experts and professionals from the Foundation generate new ideas and patterns of accelerating transition to a circular economy model. In particular, the primary provisions and principles related to the transformation of the economic model from a linear to circular one, have been determined in reports prepared by the EMF (2013a, 2013b, 2014). According to one of these reports (EMF, 2013a), the linear ‘take – make – dispose’ economic model depends on large quantities of cheap, easily accessible materials and energy; it is a model that reaches these resources’ physical limits. By the definition given in this resource, a circular economy is an industrial system that is restorative or regenerative by intention and design. It shifts towards the exploitation of renewable energy, eliminates the use of toxic chemicals, which impairs reuse, and aims for the elimination of waste through superior materials, products, systems, and business model design (EMF, 2013a). According to ‘Closing the loop – an EU action plan for the circular economy’ (European Commission, 2015), the more circular economy is one in which the value of materials and resources is maintained in the economic system for the longest possible duration and waste generation is minimised. In this communication, emphasis is placed on the time horizon of material remaining in the economy and assuming different forms.

It is worth observing that the cornerstone of the circular economy is the idea of regenerative design. It was developed by American J.T. Lyle, who first proposed the application of the concept of regenerative design to any system (Official Site of the John T. Lyle Center for Regenerative Studies, 2018). Thus, Lyle can be considered as one of the founders of the new design philosophy of systems – regenerative design. This idea is reflected and further developed in the ‘cradle-to-cradle design’ concept given by Braungart et al. (2007). According to the cradle-to-cradle concept, any materials used in the production system are considered as biological or technogenic nutrients. As referred by these scientists, it is necessary to develop products and materials with life cycles that are safe for human health and the environment and that can be multiplied through biological or industrial metabolism. Industrial metabolism (Ayres, 1994; Chertow, 2000) is one of the forms of industrial ecology that takes place at different scales and is aimed at the optimisation of material and energy flows. At the global level, industrial metabolism is also referred to as the metabolism of anthroposphere (Baccini and Brunner, 2012).

The issues of a circular economy, with regard to product longevity, extension, reconstruction, among others, were analysed by Stahel (2010). The author distinguished two ways of preventing waste generation within technogenic cycles: material processing or recycling and product reuse. Focusing on the environmental and economic advantages of products’ multiple utilisation, he described the economy in terms of loops and emphasised the existence of the axiom of the smallest loop as the most profitable. Primarily, this principle concerns the importance of product restoration (involving the processes of repair, modernisation, reconstruction, reuse of parts and modules of complex products) in comparison to the recycling of used products.

The results of Bovea et al.’s (2016) research confirmed the significant potential of the reuse of discarded electrical and electronic equipment – in a sample of 87.7 kg (96 units) obtained from a campaign for the selective collection of households, 30.2%, 67.7% and 2.1% of the appliances analysed belonged to the categories of recycling, potential reuse and direct reuse respectively (Bovea et al., 2016). Furthermore, according to Agamuthu et al. (2012), nearly 20–30% of discarded electrical and electronic equipment is suitable for further extended use. Certainly, the potential for reuse is substantial and ought to be exploited. However, it should also be emphasised that product and product parts' restoration focuses on a short-term period of value preservation. In addition, even with the technical possibility of product recovery, in most cases, new products displace old products from the market as new ones become more attractive from the consumer's perspective and more efficient from the manufacturer's. For the long-term, priority should be certainly accorded towards preserving the value of materials that comprise products are made of. Furthermore, the issue of product reuse must be considered in the context of the possibility of *extending the turn of each of these materials*. At the same time, in our opinion, each material passes through a number of products, and the sequence of a particular material's turnover in these or other products requires justification.

Currently, different approaches are applied to achieve circular economy's operationalisation. They are based on circular strategies either for product recycling or product life extension. The optimisation of a product's lifetime can be achieved, which would involve the application of slowing-oriented loop strategies, whereas multiple material use can be achieved through closing-oriented loop strategies (Bakker et al., 2014). The creation, maintenance, repair, reuse, remanufacturing, refurbishing and recycling of long-lasting design underlie these strategies, which can be implemented through business models – different ways of coordinating the provision of goods and services (Hofmann et al., 2017; Wells and Seitz, 2005; Boons and Bocken, 2017).

Depending on closing and slowing loop strategies as central conceptual points of the circular economy (Bocken et al., 2016), the 'value of the material' as well as 'value of the product' become the objects of operationalisation. In our perspective, preserving the value of a material signifies offering a distinct way to effect its multiple transformations in an economy, which can be presented as a material cycle measured in terms of the number of turns and the duration of each turn. The latter, i.e., the duration of the specific material turn, is constituted by the maintenance of the product value. Hence, to preserve the value of a particular material in the economy for the longest duration possible implies providing the maximum possible number of turns and maximising each turn's duration; as mentioned earlier, these two parameters could become the characteristics that need to be monitored, ones that can be used to measure material and product circularity.

To preserve the value of materials and products for the performance of a circular economy, studying the phenomenon of products and materials' 'circularity' in terms of their potential seems reasonable. The circularity potential of both must not only be exploited as extensively as possible, but they should also be rationally allocated and continuously built-up and reallocated. It is assumed that the preservation/minimum loss/increase of the initial value of a material is possible through the allocation of its explicitly available circularity potential, presumably by establishing some sequence of its use for a certain range of products. Consequently, a particular product in the range would inherit the previous product's material. This will facilitate the formation of demand for the recycled material in each j^{th} turn, since this material will not be used arbitrarily by the manufacturers but within the established range of products produced by them. The allocation of material circularity's available potential by establishing such ranges followed by the fullest utilisation of this potential (prioritisation of the processes 'repair – product restoration – product recycling') would allow the product the maximum possible number of turns as well as duration of each turn. Furthermore, the continuous build-up of material circularity potential will extend the material's lifetime in the future (for technogenic material). The mentioned processes, i.e., rational allocation, continuous build-up and optimum utilisation, can be considered as phases of material and product circularity potential's management, in which multi-level strategies serve as tools for implementation, and the new institution can be entrusted with the issue of coordination – compliance organisation for non-renewable material circularity.

Furthermore, it is important to observe that extending the lifecycle of a particular material leads to the transformation of the entire resource cycle in which the material cycle forms a separate segment. The closing and slowing of the material loop will result in the narrowing of the main substance's flow at the previous segment of the resource cycle. Certainly, a particular volume of narrowing of this segment's flow is caused by the dematerialisation processes. However, it is necessary to measure the volume of narrowing caused by circular processes, in spite of the fact that the resource cycles for many countries are territorially separated. Hence, the narrowing in volume at the mentioned segment can be considered an indirect parameter of the circular economy's performance.

2.2 Material's circularity and resource cycle development

The issues of 'cycle' and 'cyclicity' have been already discussed. In the context of the rational use of natural resources, the mentioned definitions are reflected in the works of Commoner (1971) '*The Closing Circle*', Boulding (1966) '*The Economics of the Coming Spaceship Earth*', Komar (1975) '*Rational Use of Natural Resources and Resource Cycles*', Osipov and Sharygin (1988) '*Energy-Substance Cycles*', among that of others. In the context of a circular economy's operationalisation with the application of the cycles tool, the scientists actualised and investigated the issues concerning the creation of the material-cycle society (Yoshida et al., 2007), measurement of the society's metabolism through material cycles (Hashimoto and Moriguchi, 2004; Moriguchi, 2007; Yamashita et al., 2000; Bailey et al., 2008), the relationship between material cycles and economic growth (Dijkema et al., 2000), and the design of the recycling cycle of material regardless of the product to be designed (Candido et al., 2011).

'Everything must go somewhere' – this is one the laws of ecology formulated by Commoner (1971). This is the law concerning the preservation of the substance's mass, from which the postulate regarding the existence of waste follows, that is, waste generation and the side effects of this process are unavoidable in any economic cycle and can only be transferred from one form to another or moved in space. Commoner described the biogenic cycles in nature and observed that for any organic substance produced by organisms, a natural enzyme exists that can decompose this substance. Consequently, no organic substance will be synthesised if there is no means for its decomposition, and this is caused by circularity. Therefore, when a person synthesises a new organic substance whose structure is significantly different from natural substances, it is probable that no decomposing enzyme exists for it and it will be accumulated (Commoner, 1971) or be reused multiple times if an analogue of the decomposer is provided in the economic system. For instance, polymers are resistant to the decomposition processes, as evidenced by their durability, and as a consequence, they are accumulated in nature as soon as they lose their value in the economy. However, if *the* *cascade of decomposers* is provided for this material, then its lifecycle will comprise a set of interconnected closed loops.

Boulding, in contrast to the open economy or the ‘cowboy economy’, described the closed economy and called it the ‘spaceman economy’, in which, Earth has become a single spaceship, without unlimited reservoirs of anything, either for extraction or for pollution. In a closed system, the outputs of all parts of the system are linked to the inputs of other parts (Boulding, 1966). In such a system, *all outputs* of consumption would be *constantly recycled* to become inputs for production.

In the context of the energy-substance cycle concept (Osipov and Sharygin, 1988), the cycle was considered as a sector but a particular sector with a clear territorial selection criterion. Unlike the energy-substance cycles, the resource cycles of Komar (1975) cover all stages of the transformation and movement of a substance (group of substances) of nature. In the concept of ‘resource cycles’, the scientist developed the idea of a social link (unit) in the substance’s cycle on Earth (Komar, 1975). The author divided the resource cycles in terms of the type of the primary substance (the combination of substances) involved in them. With the characteristic of duration, Komar determined two cycles, short-term cycles, which ensure the biological existence of human, and the long-term cycles, which cover the manufacturing and consumption of non-expendable goods. According to Komar, *resource cycles develop over time*, signifying a change in their territorial structure. The emergence of new cycles is caused by scientific and technological progress and involvement in the economic circulation of previously unused raw materials and fuel as well as energy resources. It is also possible to reconstruct already established cycles, since the transition to new types of raw materials and fuel or energy modifies the nature of production processes (Komar, 1975).

By this line of reasoning, it can be concluded that in the context of a circular economy, the development of resource cycles does not only involve change in their established territorial structures but also their qualitative transformation in accordance with three benchmarks:

1 elimination of the use of toxic and harmful substances and materials in the process of product manufacturing

2 maximum possible replacement of non-renewable resources by renewable ones

3 reduction of waste to zero.

With regard to the first benchmark, the replacement of toxic materials by non-toxic ones may lead to the formation of entirely new resource cycles or the reconstruction of existing ones due to change in the mode of transformation of the basic substance or combination of substances at some stage. As for the following two benchmarks, if non-renewable resources cannot be replaced by renewable ones, it would be necessary to develop the resource cycle towards the renewability of the material within the technogenic system and concentrate on a separate segment of the resource cycle. To ensure the material’s renewability by means of the technogenic system’s forces (for a non-renewable resource), the involvement of primary resources will be required only to meet the increasing needs and cover inevitable losses.

Therefore, the resource cycles in which the main substance is a non-renewable resource can be developed or reconstructed through the materials’ regeneration processes within the anthropogenic *regenerative system*. Such a system is characterised by a set of interrelated circle-oriented processes as well as by adequate inputs and outputs, whereby the previous process's output acts as an input for the subsequent process. While designing the system, it is important to focus on the aggregate resource cycles that have already taken place in a certain territory as well as resource cycles' specific segments.

In the following section, a distinct way of coordinating the circle-oriented transformation of a specific material, which, in our opinion, allows the preservation of the material/product/part's value in the economic system for the longest possible time, will be discussed.

The central idea of the present paper is to consider the materials and products' circularity in terms of the potential that should allow the rational allocation, continuous build-up and optimal use. This notion is based on the cradle-to-cradle design of Braungart et al. (2007), the economy in loops approach to assess the circular economy's performance developed by Stahel (2010), the closing and slowing loop strategies studied by Bakker et al. (2014) and Bocken et al. (2016) and the resource cycle concept developed by Komar (1975).

3 Results

3.1 Material and product circularity through the prism of potential

3.1.1 Interpretations of potential with regard to the circular economy

The central notion in a circular economy is ensuring the circularity of specific materials or substances (multiple turnover) and specific products (multiple use).

From the perspective that an ecosystem decomposer's (reducer) technical analogue should be available in the technogenic system (Commoner, 1971), its design, the term 'circularity' of material can be interpreted as an acquired feature (peculiarity) that is to be used multiple times in order to become a nutrient (Braungart et al., 2007) in the distinct system of providing goods. Followed to the mark, we suggest that material circularity can be studied *from the viewpoint of the potential* of specific materials that need to undergo multiple turns. In a similar manner, product circularity, from the perspective of the potential of specific product, implies one that has to be used multiple times.

We will now proceed to interpretations and definitions.

Different formulas and interpretations of 'potential' with regard to the circular economy have been mentioned in the reports of the EMF (2013a, 2013b, 2014). Most of them focus on single aspects of the circular economy: companies' readiness to execute activities, a set of economic models, the reverse cycle being as short as possible, and a set of opportunities in the context of analysing supply chains, among other aspects.

The phrase 'potential for the circular economy' (EMF, 2013a, 2014) implies a circular design, innovative business models, core competencies along reverse cycles and cascades, and enablers to enhance cross-cycle and cross-sector performance. This interpretation is sufficiently broad as it reveals the essence of appropriate potential as being unused opportunities and available resources.

The term 'circularity potential' (EMF, 2013b) connotes a set of opportunities in the context of analysing the supply chains of circular businesses, and a similar interpretation – 'the full circularity potential' (EMF, 2013b), – suggests that making the reverse circle as short as possible is essential to capturing the complete circularity potential.

Slightly different interpretations are as follows (EMF, 2013a, 2013b): 'the full potential of going circular' signifies all companies' readiness to perform activities in accordance to the tasks of the circular economy; 'the potential for increasing material productivity' is explained in the context of all pre-existing models, among which, the lease model, refurbishing model, pay-per-wash model have illustrated this potential in particular.

According to Braungart et al. (2007), 'circularity potential' is considered directly in the material's context. The authors assert that the material, which is frequently synthetic or a mineral, that has the potential to remain safely in a closed-loop system of manufacturing, recovery and reuse (the technical metabolism), *maintaining its highest value through many product life cycles*, can be defined as a technical nutrient. Whether an output constitutes a technical nutrient or not (desired or undesired), among other things, depends on the economic circumstances that change over time (Kronenberg and Winkler, 2009).

In conclusion, all interpretations and definitions are indisputably broad and reflect a wide range of mechanisms and approaches to ensure a circular economy. However, essentially, the potential for circularity requires optimal allocation and continuous build-up. Based on the fact that the focal points of a circular economy are specific materials and products' values, it may be appropriate to introduce the terms '*material circularity potential*' and '*product circularity potential*'. Together, these two terms reflect the primary benchmarks of the circular economy – the processes of closing and slowing the loop – preserving the value of the material and product in the economic system as long as possible.

We propose determining the '*material and product circularity potential*' as a multilevel, integrated and dynamic complex comprising all kinds of explicit opportunities, unused or partially used reserves and available resources, including the prospects of their increase, which are used or can be used to ensure materials' and products' multiple turnover in the economic system.

The approach to study materials and products' circularity from the perspective of potential is aimed at the identification of all possible forms of potential appearances of a given material or product in space and time. Therefore, opportunities, reserves, available resources, as forms of appearance of the potential, comprise their integrated set, being concentrated within the regenerative system.

To optimise the closing and slowing loop processes, one should understand where the material and product circularity potential appears and the scope of this potential in each case.

3.1.2 The scope of appearance of material circularity potential

Studying resource cycles in terms of their development towards preserving the stage-by-stage created value of materials/products/parts appears promising. By definition, the resource cycle entails a set of transformations and spatial shifts of a specific substance or group of substances that takes place at all stages of its human use (Komar, 1975). In our opinion, the development of resource cycles in the circular economy acquires a new significance, preserving the value of not only the material but also the product/module/detail.

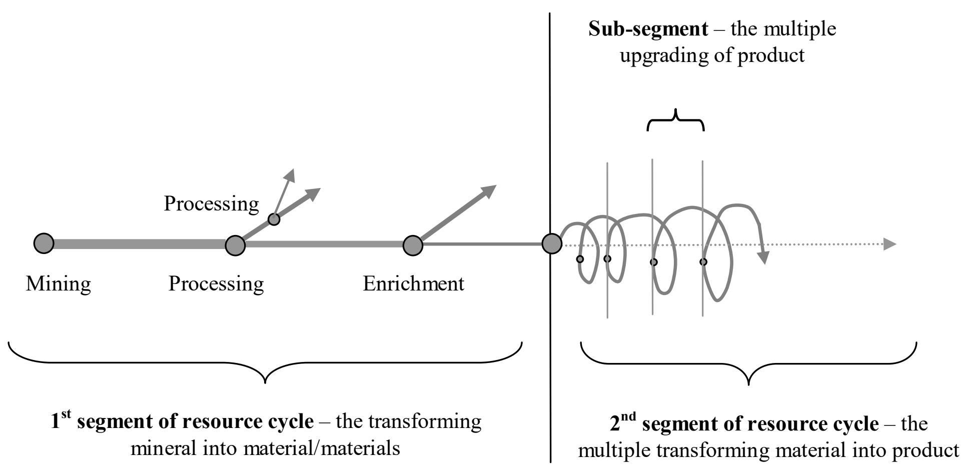
Preserving the value of materials/products/parts implies, first, extending the life cycle of products and their parts through repair, modernisation, regeneration, and second, extending the life cycle of a material through recycling. The provision of the processes of slowing and closing the loop (Bakker et al., 2014) in the economy is associated with the development of specific segments of resource cycles towards the regeneration of materials/products/parts. The segment covers specific phases of an individual resource cycle, completed as if they formed a spiral in some sequence and each turn of the spiral represents the product lifecycle. Therefore, after the raw material in the form of a mineral gradually acquires a material's form, it falls within a regenerative system's scope. In this system, it moves along the chain "material – product – used product – regenerated product – end-of-life product – raw material – regenerated material – new product." Without exiting this system, the material is gradually transformed, changing its form or status, and the cycles' final and initial stages combine these materials' regeneration processes.

To substantiate the tools to ensure the resource cycle's development towards closing, slowing and narrowing of certain segments of this cycle, we assume that *the segmentation of resource cycle approach* can be applied. The resource cycle can be divided into the following two segments:

1 'transforming mineral into material or materials' (mining – processing – enrichment)

2 'transforming material into product' (Figure 1).

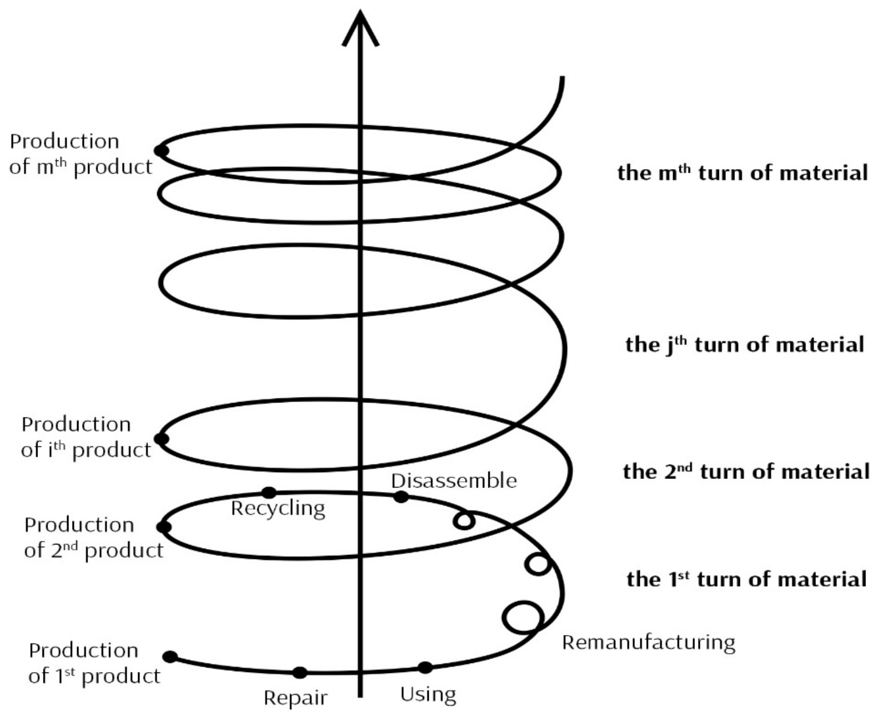
Figure 1 Segmentation of resource cycle



The latter segment can be represented as a cycle comprising multiple material turnovers, in which the specific material is used successively in a certain number of different products – for closing the flow. This segment can definitely be represented in the form of a cycle, since it contains all properties of one (a complete sequence of processes in space and time). For slowing the flow, it is essential to single out a cycle of multiple product use within each turn (sub-segment) of a cycle of multiple material turnover. It is worth emphasising that the actions involved in slowing and closing the flow, developing the second segment of the resource cycle, will inevitably lead to the narrowing of the first segment's flow. In other words, the development of the first segment of the resource cycle takes place through the second segment's development.

Returning to the issue concerning potential, we assume that the potential of material circularity emerges within the whole cycle of multiple material turnover. It is defined as the material life cycle in a part of its multiple use – the second segment of the resource cycle – that involves 'transforming material into product'. The mentioned cycle can be presented in the form of a spiral with a specific number of turns (Figure 2). The life cycle of a specific product is contained within each turn, and a set of stages and processes are involved in each turn, where the potential can assume different forms. In our view, in order to increase the number of turns of a specific material's cycle in the economic system, it is essential to form *an optimal range of products*. This is necessary for the rational allocation of explicit and available circularity potential.

Figure 2 Overview of the cycle of multiple material turnover



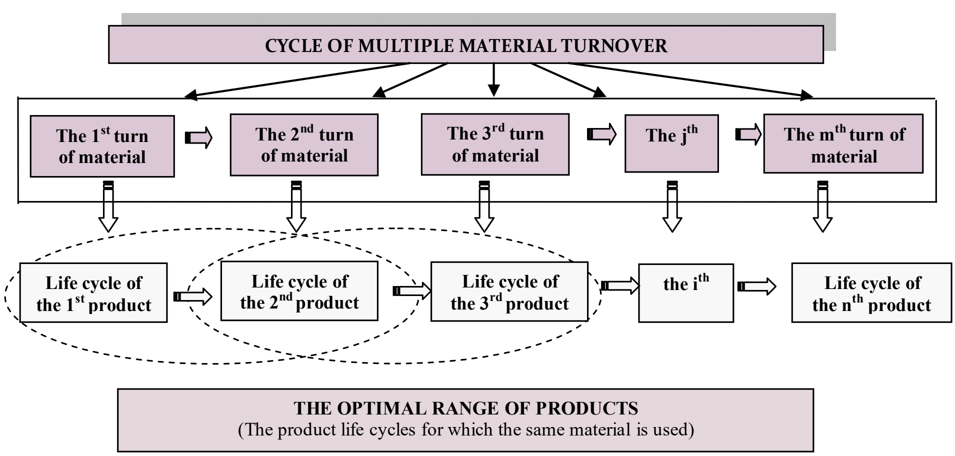
The optimal range of products for multiple material turnover represents a sequence of products for which the same material is successively utilised (Shevchenko et al., 2018). This range is determined on the basis of the analysis of two factors: the technical requirements for the material to produce the product and the quality of the material at the end of the turn (commonly, the quality of recycled material gradually deteriorates – a phenomenon referred to as downcycling). Each subsequent product of the range is selected based on the criterion of the minimal loss of the material's original value in its turnover through this product. In other words, the products' ranking is performed, and priority in the material turnover sequence is accorded to those product/products exhibiting a minimum change in material quality parameters at the end of a turn. In order to determine the most profitable input for the available output, with regard to providing the maximum number of turns, it is also necessary also to depend on the material's technical characteristics in the process of manufacturing a particular product. Therefore, inherently, the optimal range of products forms a cycle of multiple material turnover with a maximum number of turns.

Material employed in production for the first time (primary material) is nominally defined as 'material of the 1st turn', material used in production for the j^{th} time is nominally defined as 'material of the j^{th} turn'. If we consider the structure of the cycle of multiple material turnover formed according to the optimal range of products, then the j^{th} turn of material covers the life cycle of the i^{th} product of this range (Shevchenko and Kronenberg, 2017). Since the material's circular usage implies its turnover in the production along a certain range of products, it is important to analyse the life cycles of *corresponding products* (situated next in the range) rather than the life cycle of a single product only.

3.1.3 Corresponding (correlative) product life cycles

The need for considering the corresponding product lifecycles (Figure 3) is caused by the need to coordinate the allocation and build-up of material circularity potential with the processes involved in the maximum exploitation of this potential.

Figure 3 The corresponding (correlative) product life cycles as side-by-side elements of the cycle of multiple material turnover (see online version for colours)



On the grounds that an optimal range of products should be created, *each product becomes an 'addressee' and a 'sender' of specific material simultaneously*. If the optimal range of products is modelled, the producers of these products will constitute the demand for the material in the specific j^{th} turn. Thus, manufacturers of certain products could be deprived of the right to use the primary material.

The initial allocation of the explicit circularity potential (by modelling the optimal range of products) takes place before the incorporation of a particular material into the 'production – consumption' system. Since the start of the material turnover, new opportunities for its regeneration can appear as the regeneration system is undergoing continuous development. Hence, at the end of each turn of the modelled cycle, an evaluation of the new identified opportunities should be performed, and if necessary, the identified explicit potential should be reallocated.

This scheme significantly expands the scope of accumulation and exploiting the material circularity potential as it represents the entire material lifecycle in terms of multiple use as well as the lifecycles of all corresponding products.

In this manner, a rational allocation of material circularity potential (explicit potential) can be performed, and in the future, it would require the monitoring of material movement and transformation within the modelled optimal range of products.

3.1.4 Description parameters of the cycle of multiple material turnover

The cycle of multiple material turnover can be presented in another manner (Figure 4). This forms the same production spiral (see Figure 2) but seen from the top. In this case, it can be observed that the specific material acquires a new life due to recycling. Based on this scheme, several parameters (indicators) that describe this cycle can be distinguished (Table 1). In fact, these parameters reflect the explicit circularity potential of a specific material. Some parameters of a cycle of multiple material turnover can be determined before the moment of its involvement in a turnover.

Figure 4 The cycle of multiple material turnovers (conditional example)

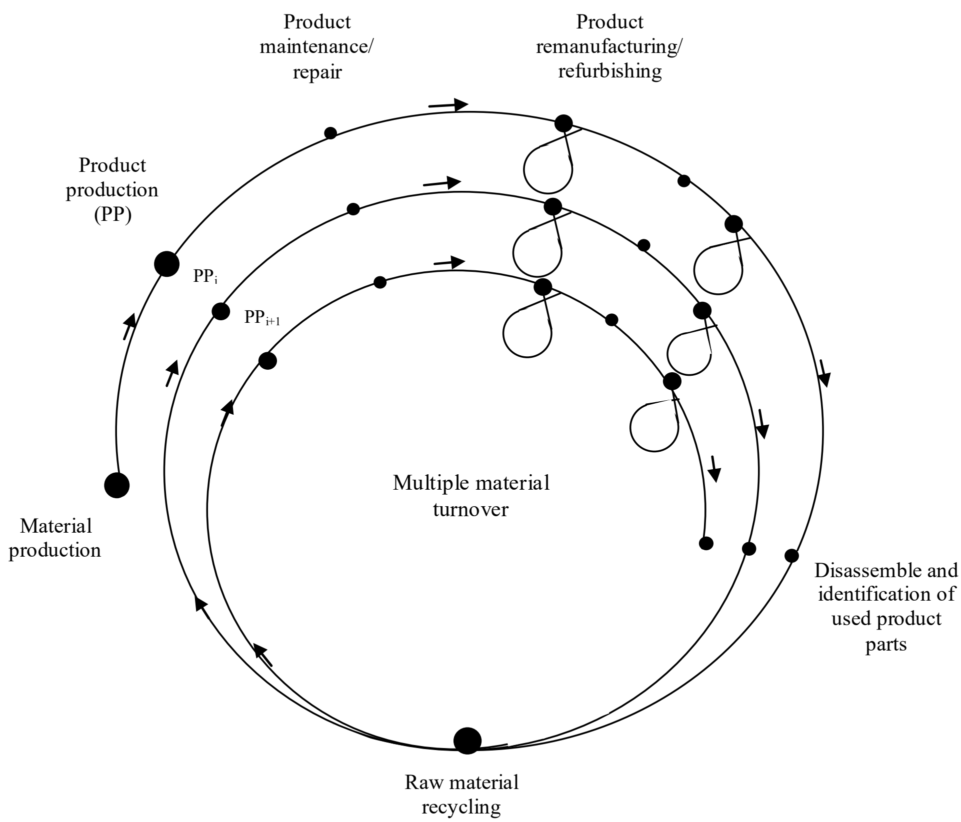


Table 1 Description parameters (indicators) of the cycle of multiple material turnover

	Name of parameter	*Ability to determine a parameter*	
		Difficult to determine	*Possible to determine*
1	Number of material's turns		X
2	Number of turns of the product within each material's turn	X	
3	Duration of the i^{th} turn of the material	X	
4	Duration of the cycle	X	
5	Number of product types to ensure the circularity of material (length of range)		X
6	Type of cycle (infinite spiral, limited spiral)		X

The number of a material's turns depends on the product design as well as the design of the material embodied in the product; another important factor in this regard is the mentioned rational allocation of explicit circularity potential. The number of product turns within the material's j^{th} turn depends on the product's technical characteristics laid down in the design stage, the availability of modules, unified parts, among other things.

The duration of each material's turn is presented in segments, from 'PP_i' to '$PP_{(i+1)}$' (see Figure 4). The categorisation depends on the production cycle's duration, the product useful time, its obsolescence, repairability, the possibility of product lifecycle extension by upgrading or modernisation. Additionally, the duration of the material's turn depends on the time required for the processes of regeneration of the material's quality characteristics (the segment from 'disassembling and identification of used product' to 'PP_i'). This time is not useful from the perspective of maintaining the value of the material within the 'production – consumption' system. This time should be minimised, and there is a need to locate for reserves to effect this reduction.

The duration of the entire cycle of multiple material turnovers is determined as the sum of the material's turns' durations.

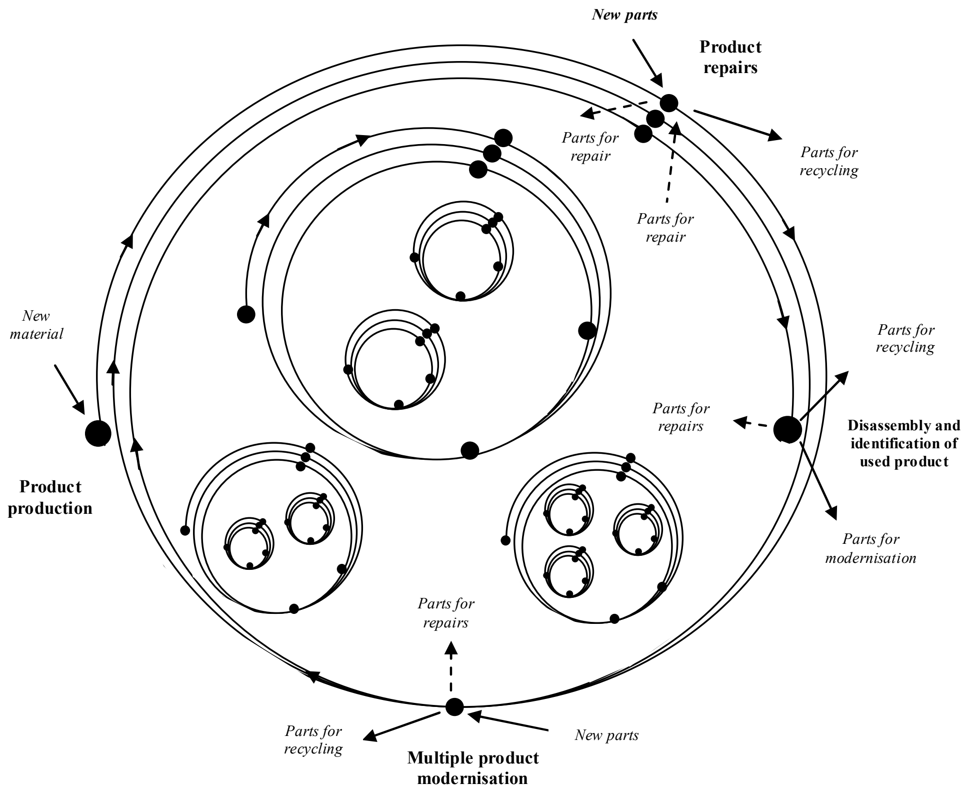
Separate parts of the cycle, from 'product production' to 'disassembling and identification of used product', represent *the cycles of multiple product turnover*. These will be described in the following section.

3.1.5 The scope of appearance of the product's circularity potential

The cycle of multiple product turnover constitutes a part of a cycle of multiple material turnover. However, it cannot be said that the material's cycle consists of the product's cycles as the latter only forms a part of a separate turn of the former. The cycle of multiple product turnovers has been presented in Figure 5.

This cycle forms the same length from the stage of 'product production' to 'disassembly of used product and identification of parts' (see Figure 4). As depicted in Figure 5, the product acquires a new life as a result of modernisation or upgrading, with the product life becoming longer with repair. In the inner section, other products that ensure the extension of specific products' lifecycles can be observed.

Figure 5 The cycle of multiple product turnover (conditional example)



3.1.6 Parameters to describe the cycle of multiple product turnover

Any cycle of multiple product turnover can be described with the help of a set of parameters (indicators) as well (Table 2). The number of product turns depends on the factors mentioned above. The duration of the 1st product's turn is formed by the time period from 'product production' to 'product modernisation' (see Figure 5). At the end of the product's service life, it can be modernised or upgraded. The duration of the cycle of multiple product turnover is constituted by the sum of the product's turns (see Figure 5). The last three parameters constitute prerequisites to increase the number of product turns.

Among the parameters that describe the product cycle, the list of materials employed in this product should be included. Each material in this list should be connected with another product that will inherit this material (if for the material, the cycle is modelled). The modelled cycle of multiple material turnover reflects this interconnection (the product 'addressee' and the product 'sender'). Thus, each type of material will have its own cycle with *m* number of turns.

At first sight, focusing on the parameters of the cycle of multiple product turnover does not reduce specific material's circularity potential. However, if specific material circularity potential is allocated, i.e., the optimal range of products is established, the product cycle would form the structural element of the modelled material cycle. Furthermore, if the build-up of a new circularity potential is considered, for instance, the design of new material, the closing and slowing loop goals can conflict – not always designing to increase the product's longevity reflects the purpose of the circularity of material, which, in fact, renders the product durable. It should be indicted that preserving the material's value embodied in a specific product is no less important, it is in fact crucial for the circular economy, and this is the primary point in the subject of the closing loop. Thus, studying the product cycle as a structural element of the modelled cycle of material will allow reconciling the purposes of maintaining product and material value to increase the circularity potential for both.

Table 2 Description parameters (indicators) of the cycle of multiple product turnover

	Name of parameter	*Ability to determine a parameter*	
		Difficult to determine	*Possible to determine*
1	Number of product turns	X	
2	Duration of each product's turn		X
3	Duration of the cycle of multiple product turnover	X	
4	Number of unified parts in the product and availability of modules		X
5	Number of product's types ensuring specific product's durability		X
6	Number of the specific product's parts covered by other products' parts		X
7	List of materials		X

The parameters mentioned to describe the material cycle and product cycle (Tables 1 and 2) can serve as the background for the measurement of the circular economy's performance.

Returning to material and product circularity potential, now we will consider the processes of its allocation, build-up and optimum utilisation.

3.2 Management of material and product circularity potential

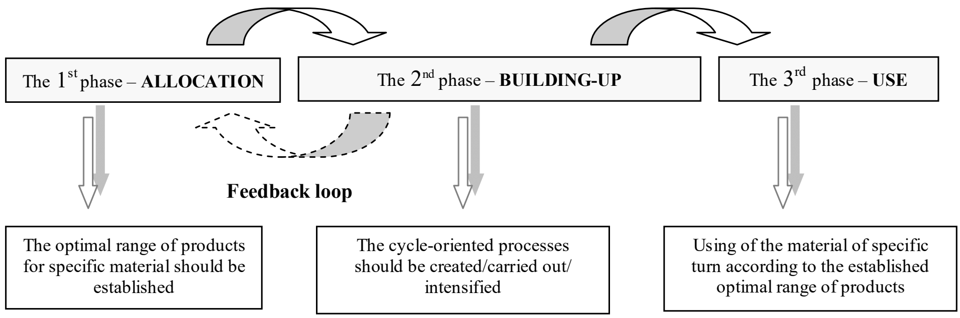
3.2.1 Definition and phase identification

The system's ability to provide multiple turnovers of specific materials and products is created as a result of the management of circularity potential. Based on the essence of the terms 'potential' and 'management of potential' (Bovea et al., 2016; Parajuly and Wenzel, 2017; EMF, 2016; Park and Chertow, 2014; Stahel and Reday-Mulvey, 1981), we define 'the management of material circularity potential' as the formation and support of the system's ability to preserve the value of materials in the economic system for the longest possible duration.

Reasoning based on the conceptualisation of material circularity with regard to potential, we identified the following phases of its management: rational allocation, continuous building-up and fullest use (Figure 6).

The first phase – '*rational allocation of the material circularity potential*' – implies a process of allocation of available potential by modelling the optimal range of products based on a minimum loss of the original value of the specific material. The material that is to be allocated makes the j^{th} turn and proceeds to the following (j + 1) turn in accordance with the modelled distinct way of material movement.

Figure 6 Phases of material circularity potential management



The second phase – '*continues building-up of the material circularity potential*' – can be interpreted as a process of identifying and creating opportunities or preconditions and necessary resources to provide the circularity of specific material within the system as well as structuring and arranging opportunities and available resources across all participants' actions within a system, and finally, identifying the implicit opportunities for their potential growth in the future. In a broader sense, it implies that the circle-oriented processes should be stipulated, executed and intensified within the lifecycles of corresponding products as elements of the modelled material cycle.

The last phase, *the fullest use of material circularity potential*, implies that the material of the specific turn should be involved in the production of the specific product in accordance to the modelled optimal range of product. Furthermore, the fullest utilisation of circularity potential is comprised by respecting the priorities of the three cycles: product repair, product upgrading or modernisation, material recycling.

The process of feedback between two consecutive phases of management – allocation and building-up – have been highlighted in the scheme. This concerns the fact that explicit potential requires reallocation over time.

As mentioned above, material circularity is correlated with product circularity to a certain extent. In order to slow the loop, product circularity potential should be managed too. Making an analogy with material circularity, there will be allocation, build-up and fullest use phases of product circularity potential management; however, some specificity is involved.

The cycle of multiple product turnover is difficult to model since the basic parameters of this cycle are difficult to determine in advance (see Table 2), although obsolescence can be predicted. Therefore, the allocation of explicit product circularity potential means the creation of pre-conditions to satisfy the following priorities in processes' fulfilment: repair, regeneration, and modernisation. Furthermore, we think that it is important to emphasise the fact that the product itself has a lifetime, but when we consider the processes of product regeneration, the replacement of a specific part that has lost its useful function is being referred to. Hence, the life cycles of the remaining details and modules would be considerably longer than the product itself, and in this case, the main task would be exploiting their resource potential to the greatest extent possible based on the priorities of the mentioned processes.

In this regard, enterprises' activity that dismantles the product and identifies the parts becomes important for the allocation of product circularity potential. To rationally allocate the product's parts' circularity potential, it is necessary to establish interrelations between enterprises that differ in terms of the field of activity or service provision in order to ensure the maximum possible utilisation of unified details and product modules, regeneration of broken products and modernisation and upgrading of used products.

The phase of building up the product circularity potential, as an analogy to material circularity, is a process of identifying and creating pre-conditions and necessary resources for providing the circularity of specific product/its parts and identifying the implicit opportunities for potential growth in the future. For instance, the design of a new product that, in comparison, comprises better parameters of a cycle (longer, more useful life, greater coverage through unified parts, among other things) (see Table 2).

There are many circle-oriented processes that relate to one or another phase of material and product circularity potential management that will be determined in the following sub-section.

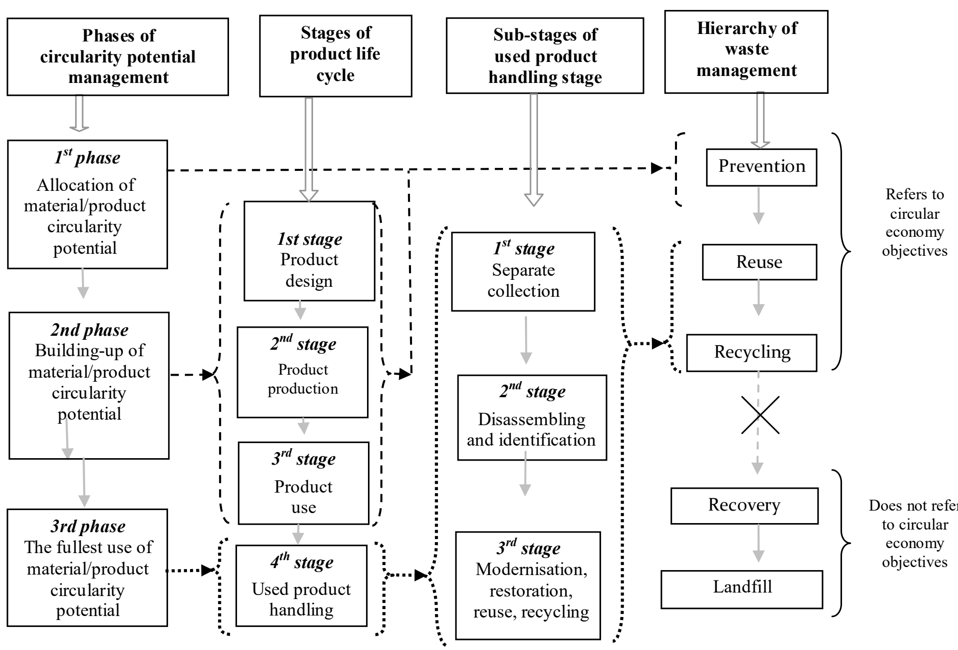
Table 3 The circle-oriented processes within each phase of circularity potential's management

Phase of circularity potential management	*Object of circularity*	*The cycle-oriented process*	*The process's place in the hierarchy*	*Type of process*
Allocation	Material	Modelling of the cycle of multiple material turnover	Prevention	Closing
	Product	Modelling of the cycle of multiple product turnover		Slowing
Building-up (accumulation)	Product and material	Design of product, material, technology, system for multiple turnover of specific products within the cycle of multiple turnover of specific material	Prevention	Closing and slowing
		Production of the product from the material/materials taking into account the sequence of its/their turnover within the modelled optimal range of products		
		Purchase of cycle-oriented products		
		Monitoring of the material and product or parts movement within regenerative system		
Use	Product	Product repair	Reuse	Slowing
		Product refurbishment		
		Product remanufacturing		
Use	Material	End-of-life product recycling	Recycling	Closing
		Involvement of the j^{th} turn material into the production of the i^{th} product according to the modelled optimal range of products		

3.2.2 Circle-oriented processes within the phases

The main circle-oriented processes have been presented in Table 3. They are divided by the phases of management of material and product circularity potential. In particular, the allocation phase includes the processes of modelling the cycles of multiple material turnover and multiple product turnover. The cumulative phase covers a number of processes related to the stages of design, production and consumption of product, namely, the design of product, material, technology, system for multiple use of specific material and specific product, the creation of the product from the material considering the sequence of its turnover and the purchase of such a product. Additionally, this phase should include the processes associated with the identification of specific material and products to further monitor the movement of both within the regenerative system. The phase of the optimum utilisation of circularity potential includes the processes of closing and slowing the loop (see Table 3).

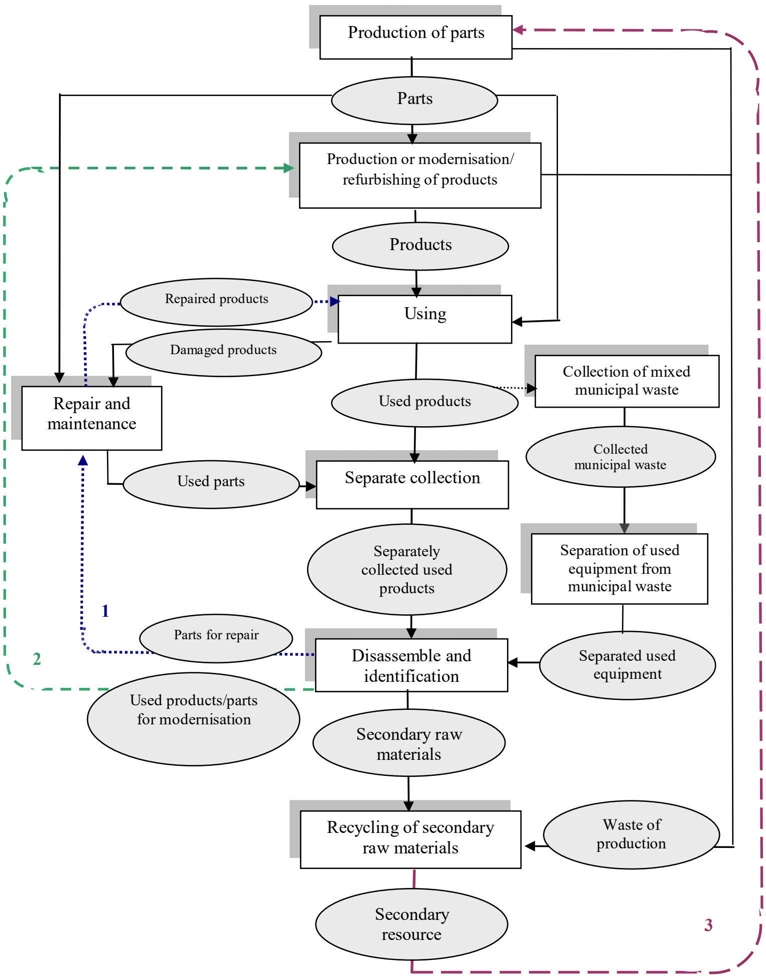
Figure 7 Prevention for repair, reuse and recycling



Together, the allocation and building-up phases cover the processes that belong to the highest level in the waste management hierarchy – prevention of waste generation (Figure 7); they refer to waste prevention measures to a certain extent. Inherently, these processes create the prerequisites for slowing and closing the loop and hence for reuse and recycling respectively.

The optimal utilisation of circularity potential consists in respecting the priorities of the three circles: product repair, product upgrading or modernisation, material recycling (Figure 8). Recycling is the central cycle that is relevant to closing the loop (multiple material turnover), despite the fact that recycling has lesser priority. Two more circles (small and medium) are relevant to slowing the loop through repair and modernisation (multiple product and part utilisation). In this scheme, each cycle-oriented process is characterised by appropriate input and output; moreover, an output of an earlier process would become an input for the following process for circularity performance.

Figure 8 Three circles within the fullest use phase (see online version for colours)



Notes: – Specific process characterised by appropriate input and output.
– Output of the previous process and an input for the next process.
1 – Multiple product turnover through repair and maintenance.
2 – Multiple product turnover through modernisation (reuse).
3 – Multiple material turnover (recycling).

3.3 *The multi-level strategies of circularity potential management for the creation of a regenerative system*

With circularity potential management, the system's ability to provide multiple turnover of specific materials/products/parts is highlighted. In the presence of this ability, the system can be termed as a regenerative one: the system that can provide a special way to transform a material in a chain ‘material, product, used product, regenerated product, end-of-life product, raw material, regenerated material, new product’ for a circular economy’s performance.

The initial stage in the creation of a regenerative system is regenerative design and modelling. Based on the study of segments of resource cycles at the regional level from the viewpoint of specific segments’ development, the system and regeneration processes should be modelled for materials/products/parts’ circulation. When modelling of a regenerative system, the available potential for closing and slowing the loops at the region is subject to assessment. If a region does not have sufficient potential to complete a certain chain, it is important to analyse the potential of other regions. It should meet sufficient preconditions for the implementation of vertical relations (integrated product policy) and horizontal inter-branch relations. These relations arise, first of all, between relevant stakeholders, and they form one of the key conditions for ensuring the preservation of materials/products/parts’ value in the economy to the longest possible duration.

Furthermore, a regenerative system cannot function without the implementation of a smart identification system for materials and products’ circulation. This step is based on the application of identification standards designed to identify materials/products/parts circulating in an economic system. The need of a smart identification system is created by the necessity to monitor and perform logistic coordination of material and product flows. The implementation of the mentioned standards will allow using the tool the ‘internet of things’ (EMF, 2016) to offer information support for the materials and products’ movement. This tool contains significant implicit potential for the closing and slowing of loops.

The presence of a set of interdependent processes of allocation, building-up and use of material and product circularity potential gives rise to the need for management’s diversification. It is proposed that management’s diversification should be considered as multi-levelness and the objects’ diversity of management as well as the multi-version of forms and methods of impact on the objects (primary actors). The possibility of allocating the tasks among the actors within the chain, ‘material – product – used product – regenerated product – end-of-life product – raw material – regenerated material – new product’, is an objective precondition for achieving the management diversification of material and product circularity potential. The multi-levelness of management comprises offering the mentioned processes at the national, regional and organisation levels. To effect the rational behaviour of all actors in the chain, we think it is essential to develop a multi-level strategy for the management of material and product circularity potential simultaneously.

At the national level, such a strategy should include a national action plan differentiated by the processes of rational allocation, continuous build-up and the optimum utilisation of circularity potential of specific materials and products to preserve the value of each. Regional action plans are commonly developed based on the national plan, taking into account the peculiarities of regions (the regional aggregated resource cycles) and the best practices. Obviously, the management of material and product circularity potential for the operationalisation of the circular economy demands institutional support. For the implementation of the multi-level strategies, a compliance organisation for non-renewable materials’ circularity can be created, which will be responsible for the design and management of a regenerative system.

4 Discussion

Some scientists consider the concept of circular economy as a tool for the operationalisation of the concept of sustainable development (Murray et al., 2015; Skene, 2017). At the moment, to some extent, the implementation of this concept has involved repeating the same mistakes, i.e., it does not limit the consumption, in this case, of the primary resource and attempts instead to minimise the undesirable outputs within the system that generate these outputs. To become a program comprising concrete actions, this concept must, first of all, accommodate some restrictions in the utilisation of primary materials. Otherwise, this concept, similar to the concept of sustainable development (WCED, 1987), will attempt to impossibly reconcile aspects and will end up appearing like 'old wine in new bottle', according to the metaphor used by Potting and Kroeze (2010). The research suggests not only to restrict manufacturers' access to certain products for use as primary resource but to establish the only possible access to the material of a particular j^{th} turnover, thereby creating demand for these or other outputs and allowing the maximum number of turns of the same material. To model the sequence of using the material in a number of products, i.e., a cycle of multiple material turnover, the range of products is modelled, wherein the available output finds the most optimal input. Certainly, this range should be constantly updated as the new circularity potential of specific materials and products is building up, so the loop of re-allocation of circularity potential must take place in the regenerative system. The mechanism for implementing this loop requires further investigation.

The graphical representation and interpretation of Figure 2 – the cycle of multiple material turnover seems logical, however there are challenges to dealing with the materials' circularity in the urban system (Broto et al., 2012; Miller and Mukherji, 2010; Daddi et al., 2015). Theoretically, all recyclable materials should complete the m^{th} turn, and in the meantime, it may not be the case because there are inherent factors in the system (Nieuwenhuis and Lammgard, 2013; Park and Chertow, 2014), such as recycling efficiency, efficiency of the technology and characteristics of materials, etc. The study conducted by the EEA (2016) showed that, even in a highly-circular system with aluminium collection and pre-processing rates of 97%, only 16% of aluminium remains in the cycle after ten years. In that respect, Zaman et al. (2018) argued that resource recovery connected to direct reuse potentially offers a higher efficiency and less associated pollution and energy use that is indeed important in each stage of resource consumption and waste management. In any case, the re-allocation loop in circularity potential management can take place only with appropriate government regulation at the national and regional levels.

Currently, many of the recent academic papers refer to the issue of circularity metrics to monitor the progress towards circular economy (Linder et al., 2017; Blomsma and Brennan, 2017). It is worth noting that the essence of the methodological approaches to the assessment of circularity such as EMF and Granta Material Intelligence (2015), Franklin-Johnson et al. (2016), Haas et al. (2015), Linder et al. (2017), Elia et al. (2016), Figge et al. (2018) and Bailey et al. (2008) is measurement of the result our decisions in the past. These approaches should be identified as the assessment of available circularity potential in the form of available resources – the 'potential' in terms of the past. For continuous build-up of this potential, new metrics should be aimed at identifying and monitoring all the possible forms of the potential appearance (resources/unused reserves/possibilities) and the findings presented in this article provide the theoretical basis for the development of such metrics. It is essential to measure material and product circularity in terms of the available circularity potential of a given territory that will allow answering the question: how fully is the available circularity potential used? Furthermore, it is important to track the progress towards the creation of a new circularity potential that does not yet have the form of resources – the explicit unavailable circularity potential, but will, in the future, reduce the amount of the uncovered undesirable outputs of the processes.

As for the limitations of this article, at the moment the proposed approach is grounded in a number of hypotheses and we have not provided a hypothetical scenario or example outlining the system boundary to conceptualise the operationalisation of material circularity. To present a hypothetical scenario, the preliminary studies should be conducted regarding the justification of basic properties of circularity potential, such as integrity, dynamism, territorial appearance and coordination of different strategies as well as underlying categories of circularity potential by various features. We propose a future study that includes a hypothetical scenario. Furthermore, a number of questions arise and require further investigation. What are the territorial boundaries of the potential distribution? The industry structure of the countries differs and the technologies for processing of used products differ not only in the context of the same product but also in terms of specialisation. How is it possible to concentrate the accumulated potential within one country and should this be done? Circularity potential also represents the product itself, and it can be imported or exported.

5 Conclusions

For significant upward advancement in the waste management hierarchy in future, new requirements will inevitably arise for the EU member states based on 'Closing the loop – an EU action plan for the circular economy'. Probably, these requirements will be differentiated according to two benchmarks for a circular economy, closing the resource loop and slowing it.

Foremost, depending on closing and slowing the loop strategies as a central conceptual point of the circular economy, we argue that the objects of operationalisation are the 'value of the material' as well as the 'value of the product'. To maintain the value of a material implies providing a unique way for its multiple transformations in an economy that can be presented as a material cycle measured in terms of the number and duration of turns. The duration of the specific material's turn is caused by the maintenance of the product value. Hence, to preserve the value of a particular material in the economy for the longest possible duration implies offering the maximum possible number of turns and maximising the time (duration) of each turn. It's worth noting that these two parameters could become the characteristics that require monitoring, the characteristics that measure the material and product's circularity.

Furthermore, this study supposes that the mentioned processes:

1 multiple material turnover

2 multiple product use – should be reflected in the category 'circularity' of specific materials and specific products respectively.

In fact, the categories ‘recycling’ and ‘reuse’, which deal with the priority of waste management actions, focus primarily on the product, and more precisely, its end-of-life form. In view of this the existing approaches to circular economy operationalisation do not allow the holistic embrace of the issues of rational allocation of the explicit available circularity potential of the specific material and product as well as continuous build-up and fullest utilisation of the potential. However, these issues are crucial for increasing the number of turns and the time of each turn.

Moreover, this study proposes interpreting the phenomenon ‘circularity’ of materials and products from the perspective of potential as well as introduces the new terms ‘material circularity potential’ and ‘product circularity potential’. Thus, the ‘material and product circularity potential’ as a multilevel, integrated and dynamic complex comprising all kinds of explicit opportunities, unused or partially used reserves and available resources, including their prospective increase, which are used or can be used to ensure materials and products’ multiple turnover in the economic system. Examining material and product circularity in terms of the potential is aimed at the identification of all possible forms of potential appearances of a given material in space and time. In fact, opportunities, reserves, available resources are integrated set of the circularity potential as they are concentrated within one regenerative system. Additionally, the circularity potential of both the material and product appears in various mentioned forms along the entire cycle of multiple material turnover and corresponding cycles of multiple product utilisation.

Interpreting the theoretical implications of this study, the interdependent processes:

1 of allocation of the explicit available potential

2 fullest use of materials

3 build-up of new potential of specific material and product circularity could be holistically embraced by management that will allow for preserving the value of materials and products in the economy as long as possible due to an increase in turnover number as well as an increase in the time of each turnover.

To coordinate these interdependent processes, we justify the new methodological approach to circular economy operationalisation based on the management of material and product circularity potential. Thus, the ‘management of material circularity potential’ could be interpreted as the process of creating and supporting the system’s ability to preserve the value of materials and product within the national economy or economies through rational allocation of explicit available potential, continuous building up and the fullest utilisation of the circularity potential of materials and products. In essence, the designated three phases of the management of circularity potential form a conceptual framework for operationalisation circularity materials and products.

Interpreting the practical implications of this study, this approach could be implemented through a multi-level strategy based on the differentiation of actions in phases of management of circularity potential of specific material and product – allocation, build-up and fullest use. For institutional support to realise such strategies, the new compliance organisation for non-renewable materials circularity can be created that will be responsible for designing and managing regenerative systems at different levels. Given the current urban challenges, the findings of the study would be vital to develop future urban policies.

Finally, in order to justifying the proposed approach, for continuous build-up circularity potential, new metrics for measuring progress towards zero-waste and circular economy should be aimed at identifying and monitoring all the possible forms of the potential appearance – opportunities, reserves, available resources, rather than available resources only (a result of our decisions in the past) and the findings presented and discussed in this article provide a theoretical basis for the development of such metrics. At the moment, it is important to track the progress also towards the creation of a new circularity potential that does not yet have the form of resources – the explicit unavailable circularity potential, but will, in the future, reduce the amount of the uncovered undesirable outputs of the processes.

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