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Life Cycle Gaps: Interpreting LCA Results with a Circular Economy Mindset

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Abstract

Circular economies require the closing of material cycles, upcycling rather than downcycling, and increased responsibility of producers for the end of life of their products. This challenges not only the predominant linear business approach but also the way we conduct and interpret LCA studies. The conventional cradle-to-grave approach, even when it includes credits for substituted materials, is not fully suitable for meaningful interpretation within a circular economy setting. We therefore propose the idea of a life cycle gap analysis as an additional means of interpretation and decision support within LCA. It highlights the theoretical circularity gaps with regard to the potential environmental impacts during a product's life cycle in terms of system losses – the so-called life cycle gaps – between an ideal closed system and the status quo. The desired new state of the life cycle gap analysis is the minimization of the gaps to zero while fulfilling the defined restrictions of the approach. Our contribution explains and exemplifies the method.

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Keywords: Life Cycle Thinking; Life Cycle Gap-Analysis; Sustainable Life Cycle Assessment; Design for Circular Economy

1. Introduction

In the context of an ongoing global discussion of sustainable development, irreversible environmental damages such as the additional release of greenhouse gases and the massive exploitation of non-renewable natural resources must be significantly reduced.

In order to meet this challenge, there are various concepts and tools for management and assessment.

The idea of a circular economy (CE) [1], which is deeply rooted within industrial ecology, has gained importance due to recent political agenda-setting by the European Union [2], and been popularized by concepts such as cradle-to-cradle (C2C) [3]. This requires innovations and technologies that close the loop and decouple economic growth from the consumption of natural resources. Hence, C2C can be understood as a qualitative framework for the design and innovation of products to achieve more sustainable development.

The intention of life cycle assessment (LCA) [4] is to quantify the potential environmental impacts of a product system throughout its life cycle. This instrument obliges the practitioner to derive appropriate conclusions and recommendations that reduce the impacts of a product and thus ensure greater sustainability.

However, upon closer examination, it becomes clear that the two approaches do not necessarily work hand-in-hand in order to attain their common goal. For example, C2C is not always favorable from a LCA-practitioner's perspective in terms of the reduction of environmental impacts and the provision of sustainable products. [5, 6] This is especially the case for products with high-energy consumption during use. [7] The reasons for these different viewpoints include the

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varying characteristics and perspectives of both approaches. [8, 9]

The question in this context is therefore: In what way can both approaches benefit from each other in order to ensure more sustainable development on a product level? In other words: How can LCA results be interpreted to take the concerns of C2C and the closing of materials into account without neglecting possible negative trade-offs during the entire product life cycle?

For a better alignment of C2C-/CE-thinking and LCA we propose a life cycle gap analysis (LCG-A). This interpretative approach of LCA results specifically identifies and evaluates the theoretical circularity gaps with regard to the potential environmental impacts during a product's life cycle in terms of system losses – the so called life cycle gaps (LCG) – while taking account of possible negative spin-offs across the entire life cycle. The desired new state of the LCG-A is the minimization of a product's LCG to zero while fulfilling the defined restrictions of the approach. Thus, LCG-A visualizes the distance between the vision of an ideal closed system and the status quo in a simplified way.

This approach can be understood as a complementary interpretation method for LCA-practitioners to incorporate the C2C-/CE-mindset into LCA and serves as a support for decision-making. It is therefore conceivable to combine the LCG-A, which is rooted in the fourth methodological phase of an LCA (the interpretation) with other methods which address the concept of CE within the LCA framework, e.g. the adjustment of the functional unit within the goal and scope definition [10] or the application of different methods to include recycling within the modeling [11].

This study introduces the basic idea of the LCG-A and illustrates its applicability through practical examples.

2. Interpretation of LCA results based on life cycle gap analysis

The identification of potentials for CE within LCA requires closer links between the manufacturing and the end-of-life (EoL) of products. For this purpose, the LCG coefficient was developed and implemented within the LCG-A. This coefficient results from the difference of all environmental effort put into producing the initial product, which includes the materials and the added value of the production process, to the environmental benefit from its second life, which includes the material and the added value of the production process (at the product recycling stage) or only the value of the substituted primary materials (at the material recycling stage).

Chapter 2.1 shows in simplified mathematical terms how LCGs are identified and evaluated. On this basis, chapter 2.2 exemplifies the methodology for a car's electric engine.

2.1. Life cycle gap analysis (LCG-A)

LCG-A could become an important part of LCA interpretation and is explained in mathematical terms in the following paragraphs.

$$E_{total}(X_{old}) = \sum_{i=1}^{n} E_M(x_i) + E_P(X) + E_{Use\,old} + E_{EoL\,old}(X;x_i) - C_{EoL}(X;x_i) \quad (1)$$

Whereby $X = (x_i)_{i=1}^{n}$, i.e. the final product X (distinguishing between the *old* (cradle-to-grave oriented) and *new* (cradle-to-cradle oriented) product version) consists of the mass x of the materials i $x_1, x_2, ..., x_n, n \in \mathrm{N}$

- E_{total} is the total sum of the environmental impacts of the final product X across the entire life cycle.
- E_M is the sum of all environmental impacts of the product's materials (M) related to the mass x and the type of material i.
- E_P is the sum of all environmental impacts of the production processes (P) related to the final product X – including the energy input and all operation and auxiliary materials which were needed to fulfill the function of the product.
- E_{Use} is the sum of all environmental impacts resulting from the operation of the product X (including transportation). Focusing primarily on high-tech products, dissipative losses within the use phase of the product X can be neglected [12].
- E_{EoL} is the sum of all environmental impacts of the end-of-life (EoL) activities of the final product X or the product's materials x_i (distinguishing between product recycling and material recycling) – including the energy input and all operation and auxiliary materials which were needed to run the recycling processes.
- C_{EoL} is the sum of all environmental credits of the EoL activities of the product X or the product's materials x_i (distinguishing between product recycling, which includes credits for the substitution of primary materials and the added value of the production process and material recycling, which includes only credits for the substitution of primary materials)

Following the idea of the LCG-A and the challenge of addressing the potential for CE in terms of system losses within the LCA, the general equation (1) is modified in formula (2) by implementing the *LCG* denominator. Thus, the LCG can be expressed in (3) as the product of three factors:

- E_{LCG} is the life cycle gap of a product X. It results from the difference between E_M, E_P, and C_{EoL}.

$$E_{total}(X_{old}) = \sum_{i=1}^{n} E_{LCG}(X_{old}) + E_{Use\,old} + E_{EoL\,old}(X;x_i) \quad (2)$$

$$E_{LCG}(X_{old}) = \sum_{i=1}^{n} E_M(x_i) + E_P(X) - C_{EoL}(X;x_i) \rightarrow MIN! \rightarrow E_{LCG}(X_{new}) \quad (3)$$

With the survey of the LCG, it is now possible to search for ways to minimize →*MIN*! the system losses with regard to closing circularity gaps − for instance with the help of design for CE. Within (3) it is then possible to calculate the LCG of the new (C2C oriented) product version $E_{LCG}(X_{new})$. This leads in (4) to the total environmental impact of the new product version across the entire life $E_{total}(X_{new})$.

$$E_{total}(X_{new}) = \sum_{i=1}^{n} E_{LCG}(X_{new}) + E_{Use\,new} + E_{EoL\,new}(X; x_i) \quad (4)$$

This indicates the challenge of avoiding negative trade-offs with regard to the product's environmental impacts across the entire life cycle. Hence, the following restriction (5) is introduced as a mandatory element within the LCG-A approach.

$$E_{total}(X_{new}) \leq E_{total}(X_{old}) \quad (5)$$

The defined restriction ensures an effective contribution of the LCG-A within the interpretation of LCA results towards a CE and the sustainable development of products. At this point, it is important to mention that this kind of interpretation of results does not imply that the optimum solution can be found.

In summary, the application of the LCG-A requires the following iterative procedure:

- *Step 1:* Determination of the product's total environmental impact $E_{total}(X_{old})$ according to (1).
- *Step 2:* Determination of the product's LCG $E_{LCG}(X_{old})$ according to (3).
- *Step 3:* Derivation of measures to minimize the product's system losses and therefore the LCG. This can be achieved for instance by comprehensive technology and innovation management, e.g. application of design for CE.
- *Step 4:* Determination once again of the product's LCG $E_{LCG}(X_{new})$ according to (3) by including the derived findings of *Step 3*.
- *Step 5:* Determination of the product's total environmental impact $E_{total}(X_{new})$ according to (4).
- *Step 6:* Comparison of the environmental impact of (4) with (2). Ensuring that restriction (5) is fulfilled.

2.2. Illustration of the LCG-A approach with an example

For better understanding of the idea behind the LCG-A, we shall now consider the introduction of a simple example. We will examine the fictitious environmental impacts of a car's electric engine during one life cycle. For reasons of clarity and simplicity we implicitly assumed a life cycle impact assessment [13] that produces a single-score result, expressed in Eco-Points (*EP*) [14]. The method can be applied to midpoint- and multiscore-assessments, though. In such cases, the user needs to choose appropriate methods to consider potentially conflicting results in different impact categories (normalisation, weighing methods etc.). Table 1 includes the selected numerical example.

Table 1. Fictitious LCA results of a car's electric engine.

Life Cycle Phases	Environmental Impacts [*EP*]	Credits [*EP*]
Materials	75	
Production	25	
Usage	150	
EoL	5	-20

Considering equation (1) and *Step 1*, the environmental impact of the electric engine is then:

$$E_{total}(X_{old}) = 75EP + 25EP + 150EP + 5EP - 20EP = 235EP \quad (6)$$

Fig. 1 visualizes the LCA results according to the different life cycle phases, using a common bar chart.

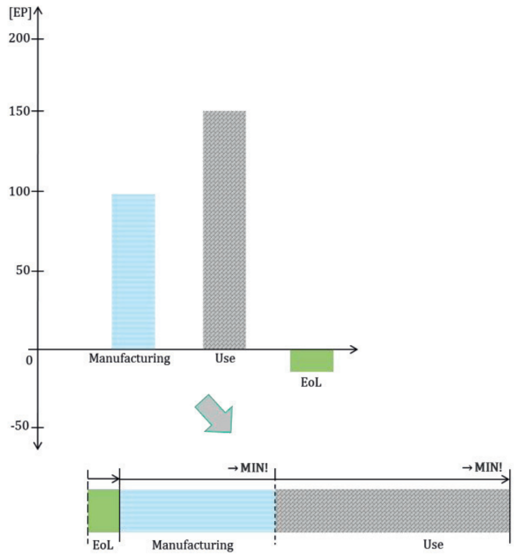

Fig. 1. Interpretation of LCA results from a conventional perspective.

The diagram shows in a simplified way that the major environmental impacts of the electric engine fall in the use phase, followed by manufacturing. The extension of credits in the EoL phase suggests a positive environmental spin-off with a limited effect on the total environmental footprint of the product.

In the case of high-tech products this is not surprising, given that these products are very cost-intensive in terms of energy and materials, in both, the use and the manufacturing phase. Due to the associated economic pressures, the manufacturers of high-tech products have often reached high standards of energy and resource efficiency during the production and operation of the products. In production, this can be achieved for example by implementing material flow analysis (MFA) [15] to ensure minimal material losses. In operation, it can be achieved for instance by implementing energy management systems like ISO 50001 [16].

With regard to the challenges of a sustainable development and the massive exploitation of non-renewable resources, this raises the question of whether a conventional and straightforward interpretation of LCA results (as in Fig. 1) takes the concerns of C2C and the closing of material cycles fully into account.

Following the LCG-A approach according to *Step 2*, the interpretation of the LCA is extended as follows:

$$E_{LCG}(X_{old}) = 75EP + 25EP - 20EP = 80EP \rightarrow MIN! \rightarrow E_{LCG}(X_{new}) \quad (7)$$

$$E_{total}(X_{old}) = 80EP + 150EP + 5EP = 235EP \quad (8)$$

Fig. 2 illustrates the interpretation of LCA results with the implementation of a *LCG* denominator. Environmental credits in the EoL phase are considered separately from the environmental impacts for recycling within the EoL phase, and shifted to the manufacturing of the product, as they include the materials and the added value of the manufacturing process.

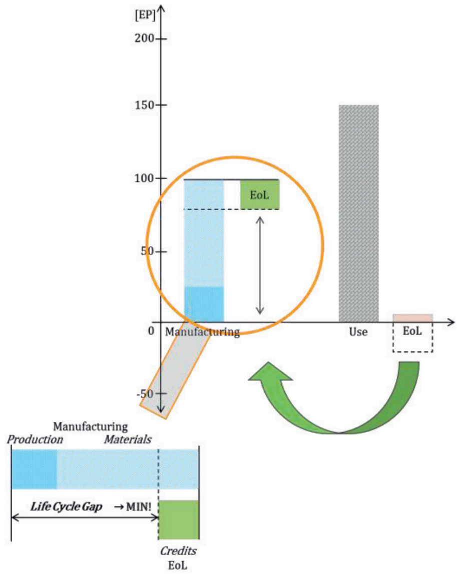

Fig. 2. Interpretation of LCA results from a LCG-A perspective.

This changed perspective allows the LCA practitioners to identify the theoretical potential for CE within the interpretation of results. With the example of the electric engine, the identified life cycle gap $E_{LCG}(X_{old})$ is *80EP*. In accordance with *Step 3* it is now possible to consider potentials for improvement which lead to a reduction of the life cycle gap. Such improvement includes the provision of new innovations. Here, design for CE and C2C come into play. At the same time, it is important to ensure that possible adjustments with regard to life cycle engineering do not result in negative side effects of the environmental impacts during the product life cycle. In our example, the product designer might change the material system of the motor housing to ensure better material recycling and thus the generation of higher environmental credits for substitution of the primary materials. This subsequently leads to a minimization of the LCG, e.g. *from 80EP to 40EP* (compare *Step 4*). Trade-offs cannot be excluded, however. For instance, the innovation might affect the total weight of the electric engine and in turn the environmental impacts of the car's use phase, by increasing the energy demand (the higher the overall vehicle weight, the higher the fuel consumption). In our example, we assume that the environmental impact of the use phase for the new electric engine $E_{Use\ new}$ increases from *150EP* to *160EP*. Hence, the total environmental impact of the new product in relation to *Step 5* is:

$$E_{total}(X_{new}) = 40EP + 160EP + 5EP = 205EP \tag{9}$$

Finally, within *Step 6* the defined restriction (5) is applied (10).

$$205EP \leq 235EP \tag{10}$$

The results show that the environmental impact of the new product version across the entire life cycle is reduced by *30EP* (from *235EP* to *205EP).* The requirement for lower impact is therefore fulfilled.

In summary, the iterative procedure of the LCG-A within the interpretation of LCA results and the adherence to the defined six steps ensures (in our example) an effective contribution to the more sustainable life cycle engineering of a car's electric engine by the minimization of the LCG.

3. Discussion & Conclusion

The above discussion in the context of LCA and CE, especially in terms of the applicability of LCA for C2C purposes, concludes that the two approaches do not necessarily work hand-in-hand to attain their common goal of sustainable development, due to different characteristics and perspectives.

Based on this challenge, the introduction of the LCG-A was identified as an effective approach to ensure a better alignment of C2C-/CE-thinking and LCA. The determination of LCG allows the quantitative results of the LCA to be interpreted in a way that supports new innovations within the qualitative framework of a CE.

LCG-A highlights CE potentials and environmental impacts in terms of LCGs without ignoring trade-offs across the entire product life cycle. In this, LCG-A differs from other approaches such as material flow cost accounting (MFCA) [17]. The focus is therefore not on minimal use of materials and zero waste in a production system, with a view to increasing efficiency, but on minimal downcycling losses and closing the loop across the entire product life cycle, with a view to improving consistency. In other words: an increased use of materials (decreasing efficiency) within the manufacturing of a product could be acceptable within the LCG-A, if the challenges of high-quality recycling routes (increasing consistency) and the avoidance of negative trade-offs during the product's life cycle are tackled. After application of the LCG-A in the interpretation of LCA results, it is quite conceivable to use methodologies like MFCA in order to identify advantageous solutions which lead to a reduction of the LCGs – closing the theoretical gap by reducing the environmental impacts for the manufacturing or by achieving higher environmental credits within the EoL phase. Thus, the LCG-A can be understood as a complementary interpretation method to incorporate C2C-/CE-thinking into LCA.

LCG-A thereby supports innovation and technology managers, product designers and engineers by analyzing the consequences of their ideas and decisions with regard to both, the vision of circular economies and the actual consequences for current life cycle systems.

This paper explained and exemplified the idea of the LCG-A as an additional means of interpretation and decision support within LCA. Challenges for future research include the validation of the method with real case studies and the identification of effective measures to close the gaps. Furthermore, it is conceivable to adopt the LCG-A to address economic issues and potentials concerning the product's life cycle costs (LCC) [18] and the implementation of new business models (e.g. functional service models [1] – manufacturers retain the ownership of their products and act as service providers).

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