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# Life cycle costing and externalities to analyze circular economy strategy: Comparison between aluminum packaging and tinplate

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ABSTRACT

In the circular economy (CE), the importance of the evaluation of costs, benefits, and externalities capturing the variables involved in a product's life cycle are gaining attention both in the literature and with practitioners. In many cases, costs are isolated across the various life cycle stages and addressed in fragmented ways. The literature indicates the importance of developing and implementing life cycle costing methods from the perspective of the product/material flow life cycle. Numerical application of the product structure-based integrated life cycle analysis (PSILA) with the externalities demonstrates how this method can assist in the management of circular businesses. Therefore, this paper aims to analyze the benefits of using aluminum packaging in the food sector by combining the life cycle costing (LCC) model and externalities in the CE. The results obtained through the LCC concept and externalities indicate an economic benefit and $CO_2$ reduction. This paper seeks to fill the research gap regarding expenditures and benefits for the analysis of production costs, environmental impacts, and externalities in an integrated manner.



## 1. Introduction

From the mid-twentieth century, the circular economy (CE) concept has gained importance for academics, industry, and governments. The CE includes “closing material loops,” which aims at a more conscious use of natural resources and reusing and recycling biological nutrients to extract their maximum value with minimum expenditure (Ellen MacArthur Foundation, 2016; Naustdalslid, 2014; Scheepens et al., 2016; Zink and Geyer, 2017). However, according to Gregson et al. (2014), although the CE concept is gaining increasing prominence in the academic, corporate, and government sectors, its dissemination in practice is still limited. Therefore, it is interesting to discuss the theory and practice to advance knowledge, revisiting existing concepts and approaches in light of the circular models.

Circular business models based on remanufacturing and reuse can generate benefits such as cost reduction and reductions in environmental impacts (Linder and Williander, 2015). However, management tools are needed to assist managers in this analysis. In this context, authors such as Florindo et al. (2017), Almeida et al. (2017), Niero and Hauschild (2017), and Bradley et al. (2018) discuss gaps in the literature related to the need for tools and methods that contribute to better management in the CE.

Florindo et al. (2017) emphasize the importance of adopting methods that allow for the integration of production costs with environmental impacts established throughout the product's life cycle to generate information for an organization's decision-making process, contributing to an efficient management in terms of the creation of a combined environmental and economic value. Thus, studies that find new tools and methods for an evaluation of the costs, benefits, and externalities capturing the variables involved in the entire life cycle of a product are needed. Almeida et al. (2017) reinforce this argument, asserting that decision makers in industry are seeking evaluation methods that address the problem as a whole, and not only as the sum of its parts, to select the most appropriate and reliable option.

Niero and Hauschild (2017) add that, to ensure that manufacturing companies deliver their contributions to society while adopting circular economy strategies, there is a need to translate global or regional environmental impact limits into a set of requirements for measurable industrial parameters. Cites the importance of identifying economic objectives, scopes, and cost allocations consistent with the sustainability parameters. In recent

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publications, Bradley et al. (2018) and Fantozzi et al. (2019) discuss the importance of life cycle costing (LCC) as a guiding concept to analyze the costs involved in a CE context. The authors state that, in the CE, it is necessary to adopt the LCC approach, which will serve as the main model of economic engineering to guide the solutions for sustainable manufacturing and the circular economy vision. This paper seeks to fill the research gap regarding expenditures and benefits for the analysis of production costs, environmental impacts, and externalities in an integrated manner.

The main objective of this manuscript is to analyze the benefits of using aluminum packaging in the food sector by combining the LCC model and externalities, because in the CE, it is also necessary to consider, apart from the cost of a product throughout its life cycle, the product's added value in environmental and social terms. Bringing the discussion and application of these methods to segments such as aluminum packaging, which represents the world's second largest source of aluminum scrap, plays a key role in the transition from a linear economy to a CE (Niero and Olsen, 2016).

## 2. Circular economy

Research on sustainability in business operations has evolved from the perspective of the focal company to beyond organizational boundaries, precisely to include interorganizational links within supply chains (Bourlakis et al., 2014; Walker et al., 2014). The CE aims to transform waste into resources and seeks to work the link between production and consumption activities. Products and processes are redesigned to maximize the value of resources with the aim of disengaging economic growth and the usage of these resources and can be defined as an economic system with loops of returning materials (Ellen MacArthur Foundation, 2010; Lacy and Rutqvist, 2015; Lovins and Braungart, 2014; Mentik, 2014; Webster, 2015).

In the CE context, aspects such as collaboration between value chains and industrial sectors for the establishment of a large-scale circular system are frequently addressed (Ellen MacArthur Foundation, 2010). Over the last decade, companies have systematically implemented circular models that target the life cycle of products, components, and useful waste output, shaping the growth of secondary goods markets supported by circular supply chain models in which organizations from various sectors play more interactive and collaborative roles.

Su et al. (2013) noted that the guiding principles of a CE are termed “3R” (reuse, repair, and remanufacture); they have a local or regional dimension and are able to avoid or reduce packaging, transportation costs, and transaction costs through property maintenance. The 3R principles can be integrated by three additional principles developed by the Ellen MacArthur Foundation (2010). The first of these, appropriate design, stresses the importance of designing products that can be disassembled and reused to avoid waste discharge in landfills. The second presents a reclassification of materials into technical materials and nutrients. Technical materials (such as metals and plastics) are designed to be reused at the end of their life cycles, whereas biological nutrients generally use nontoxic components that can safely return to the biosphere. The third additional principle – being renewable – situates renewable energy as the main source of energy for the CE to reduce the dependence on fossil energy and to improve the adaptive capacity (resilience) of the economic system.

The circular business model implementation encourages the design of circular or reverse supply chains, allowing products at the end of their life cycles to reenter the supply chain as production inputs through recycling, reusing, or remanufacturing (Nasir et al., 2017; Vorasayan and Ryan, 2006; Ferrer and Swaminathan, 2010). Points such as the effective collaboration between chains and sectors become imperative for establishing a large-scale circular system (Aydin et al., 2015; Genovese et al., 2017; Germani et al., 2015; Zhu et al., 2010).

The literature highlights several challenges associated with the implementation of the CE concept. Among them is the perception of when and in which situations extending the life of a product becomes environmentally beneficial, particularly among products that use energy intensively in their production processes. One method of analyzing the relationship between product durability and environmental impact is to detail the costs involved throughout the entire production process, along the supply chain and up to the end of a product's life (Iraldo et al., 2017; Jawahir et al., 2006). The next section presents the main points of the method of analyzing the costs involved in a productive system and discusses externalities because it is critical to recognize that external effects also contribute to improving the use of the data collected in the LCC.

### 2.1. Life cycle costing (LCC) for the circular economy

The interaction between the CE and the LCC concept derives from the fact that the CE is characterized as an economic system that replaces the ‘end of life’ through a production process that is restorative and regenerative by design and whose objective is to keep the products, components, and materials for creating value. LCC can provide ways to reduce costs throughout the value chain and strengthen the organization's strategic positioning. Thus, the adoption of the circular model together with an appropriate cost tool can guarantee the competitiveness and survival of companies in an increasingly demanding, complex and competitive market (Low and Ng., 2018). Fantozzi et al. (2019) reinforce this assertion in sustainability by mentioning that the LCC is essentially a concept that makes the design process more complete and structured and therefore consciously guides investors in their decisions. Decision makers generally face the challenge of managing and delivering projects that are not only economically viable but also environmentally sustainable (Miah et al., 2015). An integrated analysis can therefore provide decision makers with a balanced set of information to consider the environment and the economy.

Strategic decisions are not entirely cost-based, but this aspect undoubtedly plays an important role in the decision-making process. LCC is an economic method for determining all costs incurred throughout the life cycle of a project or a product from acquisition, installation, operation, and maintenance to the final disposal of the raw material (Hunkeler et al., 2008; Nguyen et al., 2008; Silalertruksa et al., 2012; Weldu and Assefa, 2017). Performing LCC enables the potential cost drivers and cost savings for a product or service to be identified throughout its entire life cycle. When comparing different alternatives, the most profitable option can be identified. Due to the heterogeneity and application scenarios of the analyzed companies, a variety of methods and approaches have been developed under the LCC model (Auer et al., 2017).

Farr et al. (2016) and Bradley et al. (2018) argue that there are many studies combining LCC and life cycle assessment (LCA) as sustainability assessments. Bradley et al. (2018) state that the CE and closed loop are driving new sustainable innovations and an LCC model is needed to achieve a true sustainable future.

Bradley et al. (2018) reinforce the importance of LCC as a guiding concept for analyzing the costs involved in a CE context. The authors state that in the CE, it is necessary to adopt the LCC approach, which will serve as the leading economic engineering model to drive solutions for a sustainable manufacturing and CE vision. An appropriate cost analysis justifies the decision to adopt the CE production model because organizations will have the necessary information on levels of improvement in cost structures.

The study conducted by Iraldo et al. (2017) presents an application of the LCC and the LCA to analyze a product's use from an economic perspective and seek to gather all of the involved costs from project design to the end of the product's operating life, which is often defined by the decision of the consumer and not the producer.

Miah et al. (2017), Hapuwatte et al. (2016), Biernaki (2015) and Hunkeler et al. (2008) discuss environmental life cycle costing (ELCC), which involves all of the costs associated with the life cycle of the product's system (premanufacturing, manufacturing, usage, and postusage), taking into account the effects of externalities during a given study period.

There are several discussions about methods involving LCC concepts and environmental issues combined for application in the CE, but they are methods that do not have a level of detail that allows for the application in practice (Bradley et al., 2018). To address this gap, Low et al. (2014) proposed the product structure-based integrated life cycle analysis (PSILA); that is a cost analysis technique in closed-cycle productive systems based on integrated life cycle analysis. This method of life cycle analysis (PSILA) integrated with externalities was the approach for developing this study.

#### 2.1.1. Product structure-based integrated life cycle analysis (PSILA)

The PSILA is a theoretical model created by Low et al. (2014) that was described as a modeling and cost analysis technique in closed-cycle productive systems. This technique was developed to address the shortcomings that the LCC methods had in integrating the product life cycle into closed-loop systems, but its application is useful in two other factors for the design of this system: (1) in products with high complexity that allow this technique to perform the distribution of the closed-cycle production system in smaller subsystem models; and (2) in the union of the phases of the main production system (MPS) with the end-of-life (EOL) system of the product, allowing for the capture of closed-cycle costs in both phases.

Low et al. (2014) cites that the adoption of closed-loop production strategies assists manufacturers in complying with the manufacturer's extended liability principles of extended producer responsibility (EPR). By adopting closed-loop models, the analysis of cost models becomes the main tool for the introduction of closed-loop strategies by business decision makers, but their modeling in the system is a task that can be highly complex (Low et al., 2016).

### 2.2. Externalities

The ability to recognize external effects also contributes to improving the use of the data collected through LCC and LCA. Externalities occur whenever “an operation between A and B has undesirable consequences, positive or negative, for third parties” (Stiglitz, 2000) or as nonmarketed costs caused an activity paid for by a party who did not choose to incur this cost (or benefit).

These effects can be categorized – particularly the negative external effects – in terms of four economic functions of the environment and the economic concept of sustainability: to negatively impact the value of services; to induce excess extraction of resources, leading to exhaustion; to cause harmful waste output beyond the assimilation capacity of biological systems; and to reduce the regenerative capacity of life support systems. In the case of a company's negative externality, the company transfers adverse harmful effects, as well as the costs of addressing these effects, to another person. The positive externality of a company exists when clients, governments, and/or citizens receive an “unpaid benefit” (Stiglitz, 2000). Both types of externalities lead to deviations in the equilibrium and, therefore, to an inefficient allocation of resources (Stiglitz, 2000). In this context, Carling et al. (2017) discuss the negative externality that emerges from road transport due to $CO_2$-emitting vehicles and note the question of charging a fee to minimize the effects and internalize this externality. The author points out that $CO_2$ accounts for more than 97% of the total greenhouse gas emissions from road transport. In this scenario, the logistics sector needs to change the traditional mode of development and try to achieve sustainable development by equalizing reverse logistics with advanced logistics by balancing the environmental benefits with the economic benefits (Sun, Qiang, 2017).

However, an important factor is that companies effectively begin to integrate this analysis into their economic models, accounting for both positive and negative externalities.

Martinez-Sanchez et al. (2017) discuss the importance of including the costs of externalities in the economic system, and according to these authors, the external costs can have a profound influence on the selection of competitive strategies. The inclusion of ecological externalities in the accounting process is fundamental to understanding their impacts on the company. According to Lima and Viegas (2002), concepts are already being presented by researchers in the field, but additional studies are needed. Additionally, Lima and Vegas (2002) state that one method of neutralizing ecological externalities is their internalization, that is, recognizing their effects in the analysis of the company's results. Li and Yu (2016) also note the importance of internalizing externalities in econometric models for decision making.

Weldu and Assefa (2017) and Sen et al. (2017) present a study addressing the internalized costs of external effects; that is, costs that were formerly externalities are now internalized in monetary units, within the LCC concept. In this study, the authors present the taxation of carbon externalities as a method of accounting for them internally.

The concepts and methods must evolve to help integrate and optimize economic, social, and environmental considerations so that in the future, a more sustainable scenario can be offered. In fact, the principles of sustainability cannot be represented by traditional indicators of economic success and environmental quality but rather by an integrated view of the environment, the economy, and society (Koplin et al., 2007).

The methodology used to evaluate costs and benefits was LCC and PSILA under the approach proposed by Hunkeler et al. (2008), which foresees the internalization of externalities for result analysis. Hunkeler et al. (2008) show that it is possible to define externalities in terms of cost-benefit, or the cost not accounted for in the system or the cost not directly supported by the company.

## 3. Materials and method

The calculation of the closed life cycle cost and the respective externalities of a package take into account the way the package is produced, what raw materials are used, and what type of product is being packed. The transportation from the development of these packages to the arrival in retail has an environmental and economic impact that is fundamental to be analyzed. This section looks at the application of the LCC concepts and externalities.

### 3.1. Stages of the study for calculating LCC and externalities

The study was segmented into four stages: (1) cost of production of cans (comparison between aluminum and tinplate); (2) identification of the economic benefit in its logistic operation; (3) externalities; and (4) comparison of the life cycle cost of aluminum and tinplate. In this case study, the confidentiality of all stakeholders in the chain is maintained. The professionals interviewed to gather information about the plant were business managers, and in the food company, they were the general operations director and the commercial manager; both contacts are decision makers and are responsible for the strategic decisions implemented in their businesses. The food company has a horizontal chain in relation to the supply of its packaging, being responsible for manufacturing the cans. The aluminum plant, responsible for casting and laminating aluminum, has its own recycling operation.

*"Closed-Loop" Supply Chain – Aluminum and Tinplate production*

The supply chain of the model has the following stakeholders and their respective responsibilities within the chain:

1. Recovery Plant (aluminum and tinplate)
   a. Responsible for casting and laminating the aluminum.
   b. Responsible for recycling cans and scrap throughout the chain.
   c. Responsible for collecting (collection points spread throughout the country) and waste management in the chain (collecting industrial scrap in the distribution chain).
2. Food company
   a. Responsible for food processing.
   b. Responsible for manufacturing the cans.
   c. Responsible for food packaging.
   d. Responsible for the logistics operations of its products to food retailers and wholesalers.
3. Retail and wholesale
   a. Responsible for the sale of the product to the end customer.

The structure of the CE adopted by the aluminum plant and the food company follows as is presented, in Fig. 1.

## 4. Results

Based on the chain presented in Fig. 1, costs, benefits, and environmental impacts were calculated for each stage.

### 4.1. Stage 1 - production cost (aluminum and tinplate)

The composition basically consists of two parts (body and "easy open" lid) that are derived from three components (body structure, cover structure, and ring structure). To obtain the three components, the food industry needs to obtain three types of aluminum coil specifications. These variations of specifications are related to alloy and dimensional types (thickness, width, coil size) and defined due to the specifications of machinery (metallurgical production process).

After stamping the body and the lid, the food is bottled in the can and that final product is subjected to a production phase called autoclaving. The set of these productive steps is called the mainstream production phase (Fig. 2).

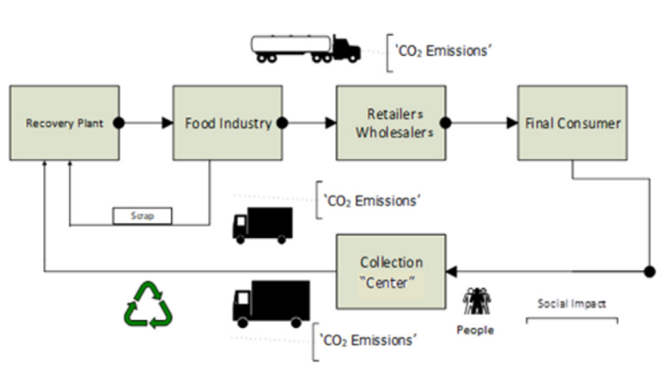


**Fig. 1.** Closed-loop production system (aluminum and tinplate).
**Source**: Authors

After this phase, the can is packed in "master" boxes for protection during transport and distribution of the product. These boxes are placed on wooden pallets and distributed to customers in the food industry as retailers and wholesalers.

According to information from the food industry about the main production cycle of canned food, we summarized the total generation of scrap or the process's inefficiency during the main production phase in Table 1.

These data are important because they will model the cost of the metal raw material of the product, that is, the produced can. Depending on the type of processed food to be canned, the packaging cost may be higher than the food cost itself. That is, the can may cost more than the processed food. This debris can be sent to the aluminum or steel mill to be recycled and used as raw material in the production process, making the product's raw material a component in a closed loop.

For a visualization of the can made in the production process, Table 2 details the production result corresponding to each part of the can for both aluminum and steel (tinplate). For each plate inserted in the press process, there is a number of forming part quantities; for example, for the can body, 30 pieces are generated from a plate that is 0.25 mm thick, 866 mm wide, and 853 mm long. In the production process for each piece, a percentage of scrap is generated; e.g., the body produces approximately 30% of the scrap. We can conclude that for each aluminum sheet (weight of 0.5 kg) that enters the process, it generates 30 bodies of 11.62 g (0.01162 kg) and 0.15 kg of scrap per plate. Based on these results, data are obtained to perform the production orders and cost calculations for each piece, as will be described.

Utilizing the PSILA method, we can apply formulas 1, 2, 3, and 4 to determine the volume of production required to produce the canned food in a closed loop.

$$PV = OV - RV \tag{1}$$

$$OV = OV_{i(t)}.PR\ mp_{\frac{k}{i}(t)},\ i\ \#\ \{root = j\} \tag{2}$$

$$RV = RV_{i(t-1)}.\ PR\ eol_{\frac{k}{i}(t-1)}\ .\ OF\ .\ Bcl,\ i\ \#\ \{root = j\} \tag{3}$$

$$Bcl,\ i\ = \begin{cases} 1, & \forall \in \{closed\ loop\} \\ 0, & \forall \notin \{closed\ loop\} \end{cases} \tag{4}$$

where:

- PV = Purchase volume of material (aluminum) of part i;
- OV = Production volume per can (j), having its component at time t;
- RV = Residual volume of parts (i) for recovery, having its component at time t-1;
- PR mp = Volume of material (k) of part (i) during the main production phase (mp) per can (j) at time t;
- PR eol = Volume of material (k) of part (i) per can (j) generated during the production phase at time t-1;
- OF = Fractional loss of material k; and
- Bcl = Binary variable, where 1 means the part (i) is in a closed loop and 0 means the part is not in a closed loop.

Low et al. (2014) indicate that total variable costs of a closed-loop material are the sum of the variable costs of "procurement" or purchasing materials, manufacturing, distribution, services,

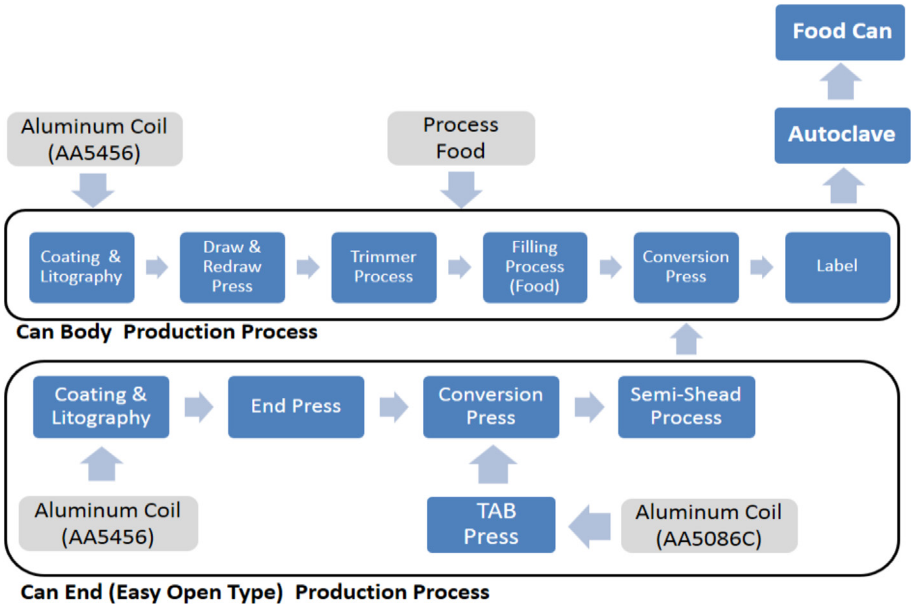


**Fig. 2.** Mainstream production phase.

**Table 1**
Rate of generation of scrap in the production process.

| Scrap Generation | Production Process | Part (i) | | |
|---|---|---|---|---|
| | | Body (Jug) | End (Lid) | Tab (Ring) |
| | % Scrap (Process Inefficiency) | 30% | 30% | 38% |

**Table 2**
Comparison of aluminum and tinplate processing.

| Process (Stamping) | Material | T (mm) | W (mm) | L (mm) | Total Area ($mm^2$) | Yield Rate ($mm^2$) | Scrap Rate (%) | Qty (Food Can Body/foil) | Weight (foil - g) | Scrap (g) | Final Weight (g) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Food Can Body (FBS) | Aluminum | 0.25 | 866.00 | 853.00 | 738,698 | 517,089 | 30% | 30.00 | 490.71 | 147.21 | 11.45 |
| | Tinplate | 0.22 | 866.00 | 853.00 | 738,698 | 517,089 | 30% | 30.00 | 1279.71 | 383.91 | 29.86 |
| **Process (Stamping)** | **Material** | **T (mm)** | **W (mm)** | **L (mm)** | **Total area ($mm^2$)** | **Yield Rate ($mm^2$)** | **Scrap Rate (%)** | **Qty (Food Can Body/foil)** | **Weight (foil)** | **Scrap (ton)** | **Final weight (g)** |
| Food Can End (FES) | Aluminum | 0.22 | 780.00 | 1.034.00 | 806,520 | 564,564 | 30% | 72.00 | 489.20 | 146.76 | 4.76 |
| | Tinplate | 0.21 | 780.00 | 1.034.00 | 806,520 | 564,564 | 30% | 72.00 | 1337.32 | 401.20 | 13.00 |
| **Process (Stamping)** | **Material** | **T (mm)** | **W (mm)** | **L (mm)** | **Total area ($mm^2$)** | **Yield Rate ($mm^2$)** | **Scrap Rate (%)** | **Qty (Food Can Body/foil)** | **Weight (foil)** | **Scrap (ton)** | **Final Weight (g)** |
| TAB-FTS | Aluminum | 0.46 | 96.01 | 37.00 | 3552.37 | 2202.47 | 38% | 4.00 | 4.41 | 1.68 | 0.68 |
| | Tinplate | 0.46 | 96.01 | 37.00 | 3552.37 | 2202.47 | 38% | 4.00 | 12.83 | 4.87 | 1.99 |
| | | | | | | **Scrap Rate Process Generation** | **30%** | | | | |

collection, processing, and disposal/waste. In this case study, only the analysis of the raw material cost, which is the phase of procurement or purchase of raw material and scrap disposal, will be analyzed. For these two phases, the equations can be structured according to the literature review, in equations (5)–(8). Note that the scrap comes from a previous time (t-1) or a current production time (t), and it must be accounted for in the cost of the raw material in current values.

$$CV_{i(t)} = CV_{procurement\ i(t)} + NPV_{sucata\ i(t)} \quad (5)$$

The purchase and scrap costs can be represented in the following equations (6)–(8).

$$CV_{procurement\ i(t)} = PV_{i(t)}.\ PR\ mp_{\frac{k}{i}(t)}.\ P\ metal_{.k(t)} \quad (6)$$

where:

- OV = Production volume per piece (i) at time t;
- PR mp = Volume of material (k) of part (i) during the main production phase (mp) per can (j) at time t; and
- P metal = Purchase price of metal raw material (aluminum plate or tinplate - k) at time i(t).

$$NPV_{scrap,\ i(t)} = \frac{CV_{scrap,\ \ i(t-1)}}{(1-d)^{t}} \quad (7)$$

**Table 3**
OV production i(t) and RV i(t-1) for a PV i(t) (production) of 1000 Cans.

| | Material | |
|---|---|---|
| | Aluminum | Steel (Tinplate) |
| PV i(t) | 1.000 | 1.000 |
| RV | 30% | 30% |
| PV i(t-1) | 1.000 | 1.000 |
| OF | 98% | 98% |
| RV i(t-1) | **294** | **294** |
| OV i(t) | **706** | **706** |

$$CV_{scrap,\ i(t-1)} = RV_{i(t-1)} \cdot PR_{eol\ ,\ \frac{k}{i}(t-1)} \cdot OF \cdot P_{process.,\ \ k(t-1)} \tag{8}$$

where:

- RV = Residual volume of parts (i) for recovery, at time t-1;
- PR eol = Volume of material (k) of part (i) per can (j) generated during the production phase at time t-1;
- OF = Fraction loss (e.g., Al - fusion in the oven of the plant/steel plant) of material k;
- P process = Price of processing scrap into reusable raw material (coil or aluminum plate) at time i (t-1) by the aluminum/steel plant; and d = Financial cost of scrap stock.

The composition of a metal laminate is composed of two variables: the metal cost and its processing cost. For the closed-loop recycling operation, the food manufacturer sends the scrap metal to the factory/steel mill and will only have the cost of processing the scrap metal into coils. However, in the recycling process, there is a fusion loss, called outgoing fraction (OF) in the mathematical model, which will have to be calculated to assess the production amount and the cost of the can, according to Table 3.

It is important to point out that to simplify the calculation, (a) was considered the sum of PRmp k/i and PR eol k/i for the metallic materials (k) of parts (i) as the body, lid, and ring, since both materials k (aluminum and tinplate) have the same OF, Pmetal, and Ptransf.

The next calculation stage is the definition of the metallic raw material costs and the costs of processing scrap or metal for each material (P process k), as mentioned previously and shown in Table 4.

From the analysis of Tables 3 and 4, the values of the variables for the cost calculation are obtained, as shown in the results in Tables 5–7. Two important points are that (1) the variable P process k (t) will be considered equal to its previous period (t-1) since in the period of the research, their costs were identical and (2) the financial cost d is 1.98% per month or at period t (t = month) to update the cost in current values.

Considering this mathematical model together with the assumptions raised above, we can note that the metallic raw material cost of the tinplate packaging is 32% higher (US$ 58.14 > US$ 39.95) when compared to the metallic raw material cost of the aluminum packaging. From the material cost data and process costs, we calculated the total cost of aluminum and tinplate packaging, according to Table 8.

**Table 4**
Cost or price of metallic materials (k).

| AA5xxx Aluminum Coil for the Can | |
|---|---|
| LME ($/kg) | 1.65 |
| MWP ($/kg) | 0.11 |
| P proces k (t) ($/kg) | 1.10 |
| P metal k (t) ($/kg) | 2.86 |
| **Steel coil (Tinplate) for the Can** | |
| Metal Cost ($/kg) | 0.778 |
| P proces k (t) ($/kg) | 1.241 |
| P metal k (t) ($/kg) | 1.306 |

**Table 5**
Material Acquisition Cost - CV procurement i(t).

| | Material | |
|---|---|---|
| | Aluminum | Steel (Tinplate) |
| OV i(t) | 706 | 706 |
| PR mp k/i (t) (kg) | 0.01696 | 0.04480 |
| P metal | $ 2.86 | $ 1.31 |
| **CV procurement i(t)** | **$ 34.24** | **$ 41.30** |

**Table 6**
Material Acquisition Cost - CV scrap i(t).

| | Material | |
|---|---|---|
| | Aluminum | Steel (Tinplate) |
| RV i(t-1) | 294 | 294 |
| PR eol k/i (t-1)kg | 0.01696 | 0.04480 |
| P process | $ 1.10 | $ 1.23 |
| C scrap i(t-1) | **$ 5.48** | **$ 16.18** |
| C scrap i(t-1) | 5.48 | 16.18 |
| D | 1.98% | 1.98% |
| T | 2.00 | 2.00 |
| NPV scrap i(t) | **$ 5.71** | **$ 16.84** |

## 4.2. Stage 2 - identification of the economic benefit in logistics operations

Aluminum has one of the lowest densities among metallic materials. Due to this characteristic, the use of aluminum as a raw material can bring ergonomic and economic benefits to the operation. Based on research and simulations of packaging process costs by the aluminum plant, the comparative model presented in Table 9 can be used to analyze the weight differences in food packaging used in this case study and for calculating freight expenses.

**Table 7**
Variable Cost of Material - CV can (j(t)).

| | Material (1.000 cans) | |
|---|---|---|
| | Aluminum | Steel (Tinplate) |
| CV procurement i(t) | $ 34.24 | $ 41.30 |
| NPV scrap i(t) | $ 5.71 | $ 16.84 |
| CV can ($/000) | **$ 39.95** | **$ 58.14** |

**Table 8**
Comparative Production of can (j) costs.

| Costs | Aluminum | Steel (Tinplate) |
|---|---|---|
| Metal | | |
| CV procurement i(t) | $ 34.24 | $ 41.30 |
| NPV scrap i(t) | $ 5.71 | $ 16.84 |
| **Net cost** | **$ 39.95** | **$ 58.14** |
| Washing & Pretreatment | $ 0.30 | $ 0.10 |
| Painting | $ 0.80 | $ 0.99 |
| Reprocessing Cost | $ 0.15 | $ 0.35 |
| Workmanship | $ 5.00 | $ 5.11 |
| Overhead Costs | $ 2.33 | $ 2.41 |
| Depreciation | $ 3.58 | $ 4.20 |
| **Subtotal** | **$ 12.16** | **$ 13.16** |
| Total Cost | **$ 52.11** | **$ 71.30** |

**Table 9**
Difference in Weight of Aluminum and Tinplate Packaging (weight per 1000 cans).

| Packing | Package Weight (kg) | | Weight Savings (kg) |
|---|---|---|---|
| | Aluminum Package | Tinplate Package | |
| Food Can Body (FBS) | 11.45 | 29.86 | 18.41 |
| Food Can End (FES) | 5.44 | 14.99 | 9.55 |
| Total Weight | **16.89** | **44.85** | **27.96** |

In the research conducted at the food company, the cargo capacity of a truck, when used to its maximum extent, is 50,000 cans. If this capacity were multiplied by each type of packaging in Table 10 and compared, then we would have a reduction of 1398 kg in transportation of the aluminum packaging, increasing transport efficiency by 16%.

Based on a study conducted by the Brazilian Aluminum Association (ABAL, 2015) about the fundamentals of aluminum and its applications, for weight reduction in transportation, each 100 kg reduces fuel consumption by 0.4 l per 100 km. Technical data for Volkswagen trucks shows that the average lifetime of a truck is 500,000 km. Considering the cost of diesel fuel (US$ 1.04/l) consumed during the period of the case study, it is possible to establish the fuel cost savings during the truck's lifetime (Table 11).

These savings can be used as a catalyst for the payback of investments made by the food industry. This method allows comparisons between cost elements during the product's lifetime stages. Thus, the user can, for example, opt for a higher initial cost to have lower maintenance costs in the future. LCC is also required when decisions are made about the operation and maintenance costs over the product's lifetime. Using this concept, it is possible to model the life cycle cost of the logistics asset. Based on the model presented by Sherif and Kolarik (1981) and relating this model to an elaboration of heuristic basis, the life cycle cost of the logistic asset is dimensioned.

$$Total\ Cycle\ Cost = Caq + Cop + Cm + C\ deprec - V.sale(asset), \quad (9)$$

where:

- *Caq = Truck acquisition cost*
- *Cop = Truck operational cost (fuel)*
- *Cm = Truck maintenance cost*
- *C deprec = Truck cost (depreciation)*
- *V.sale(asset) = Value of the residual sale of the truck or its parts at the end of its life cycle.*

According to ABAL (2015), the reduction in the operating weight in the system leads not only to cargo efficiency but also to improved maintenance costs of the parts. This savings was not quantified and is a variable to be added in future studies with the LCC model.

**Table 10**
Weight Saving in Transportation using Aluminum Material.

| Packaging by truck | Total weight reduction – truckload – kg |
|---|---|
| 50,000 | 1398 kg |

**Table 11**
Fuel saving.

| Fuel saving (l) - 100 km | Vehicle-life savings (l) |
|---|---|
| 5.592 ([a]) | 27,960 |
| Average price of diesel (US$) | Vehicle-life savings (US$) |
| 1.04 | $ 20,420.00 |

[a] 56 ml/km (0.005592 l/km).

### 4.3. Stage 3 – externalities – impact on $CO_2$ emissions (carbon dioxide)

Weight reduction in both commercial and utility vehicles is one of the main strategies for reducing pollutant emissions. The lower the weight is the lower the need for the mechanical system to perform combustion for vehicular movement. According to ABAL (2015), for every 100 kg of weight reduction, there is a reduction of approximately 10 g of $CO_2$ in a 100-km route (0.001 g $CO_2$/km). Using this assumption, it is possible to estimate the $CO_2$ emissions reduction in the logistic chain, according to Table 12.

In addition to the economic benefit, $CO_2$ reduction adds value to the company's sustainability strategy, which benefits the environment by reducing $CO_2$ emissions, adding value to its operations and products. Just as it is in society's interest to internalize pollution, it is also socially beneficial to internalize the social benefits of activities that generate positive externalities, as presented in Table 7.

Fig. 3 shows the externalities associated with the $CO_2$ emissions that are impacting the entire product life cycle along with the RV (scrap volume sent to processing - 30% - RV) and in the distribution/redistribution operation of retailers/distribution centers for their stores.

Using the data assessed from the research, the average distances during the company's operations were collected with the purpose of calculating the $CO_2$ emissions generated during the life cycle of a can, per 1000 cans (Table 13).

### 4.4. Stage 4 – comparison of the life cycle cost of aluminum and tinplate

The next step is to internalize the $CO_2$ externality for the ELCC calculation. In Europe, according to Market Research & CRU (2018), using the data assessed from the research, the average distances during the company's operations were collected with the purpose of calculating the $CO_2$ emissions generated during the life cycle of a can, per 1000 cans (Table 13).

The $CO_2$ emissions per ton are, on average, € 8.90 (January 2018 - dollar rate - R$ 3.20).

To account for $CO_2$ in the ELCC, these values were used as a reference for the application of equation (10), as elaborated by Miah et al. (2017). Table 14 shows the internalization and calculation of the ELCC.

**Table 12**
$CO_2$ reduction as vehicle load reduction.

| $CO_2$ reduction (g/km) | Truck life (km) |
|---|---|
| 1.398([a])<br>$CO_2$ reduction in life span (kg)<br>699 | 500,000 km |

[a] 0.001 g $CO_2$/km.

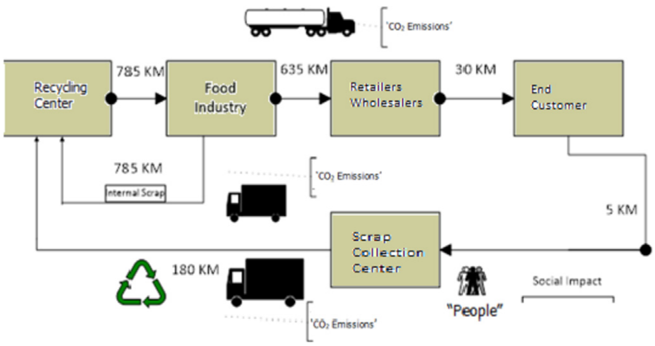


**Fig. 3.** Closed-Loop Production System ($CO_2$ emissions).

$$T_{ELCC} = \sum_{Raw-materials} C_n X_n + \sum_{Manufacturing} C_n X_n + \sum_{Freight\ LCC} C_n X_n + \sum_{Disposal} C_n X_n + \sum_{Externality} C_n X_n \quad (10)$$

This study demonstrates the use of aluminum as a solution that can provide benefits to the stakeholders in terms of production cost, logistics, and environmental impact of the business model analyzed in this study. The benefits were quantified as a reduction in direct costs, sustainability benefits (recycling and $CO_2$ emissions reduction), and savings in the logistics costs of the food company, demonstrating the obtained results in a holistic manner. Moreover, recycling aluminum, in addition to saving natural resources, allows a reduction in electric energy consumption in the process, given that recycling aluminum consumes only 5% of the energy required for the production of primary aluminum (ABAL, 2015).

When comparing different alternatives, the most profitable option is identified as presented in Table 14.

### 4.5. Validation of method selection

The practical application of the proposed model to calculate the closed life cycle cost and the respective externalities, by a combination of the methods, was of paramount importance for the model's validation. First, the study was directed at the packaging chain for the food industry, where possible, to map the respective actors in the chain. The first step consists of analyzing the circular business model, raising the role of all the stakeholders involved and their CE operations. The second step was the LCC analysis, supported by the PSILA tool. The third step consisted of the survey of externalities during the product life cycle and their internalization and integration with the LCC. The cost factor is critical because it represents a significant share of the total cost of the food product (ABAL, 2015). Performing externalities and PSILA makes it possible to identify the potential cost factors and cost savings of a product or service throughout its entire life cycle, as discussed by Auer et al. (2017), showing a consistent combination.

**Table 14**
LCC and externalities (aluminum and tinplate).

| Costs | Aluminum (US$) | Steel (Tinplate) |
|---|---|---|
| Metal | | |
| CV Procurement i(t) | 31.75 | 41.30 |
| NPV Scrap i(t) | 5.01 | 16.84 |
| **Metal Value** | **39.95** | **58.14** |
| Washing & Pretreatment | 0.30 | 0.10 |
| Painting | 0.80 | 0.99 |
| Reprocessing Cost | 0.15 | 0.35 |
| Workmanship | 5.00 | 5.11 |
| Overhead Costs | 2.33 | 2.41 |
| Depreciation | 3.58 | 4.20 |
| **Subtotal** | **12.16** | **13.16** |
| **Total Cost** | **52.11** | **71.30** |
| **Externality** | | |
| $CO_2$ emissions (g) | 22.13 | 58.46 |
| US$ 0.0890/kg | **$ 0.10020** | **$ 0.0052** |
| **Freight (Life Cycle)** | | |
| Freight - LCC (km) 2366 | **$ 71.88** | **$ 71.88** |
| Total **ELCC** | **$ 123.98** | **$ 143.18** |

*Currently, the disclosure of the price paid for carbon credits is based on the international market.

## 5. Discussion of the results

A variety of methods and approaches has been developed from the perspective of LCC due to the heterogeneity and diverse application scenarios of the businesses under analysis. In the CE context, combining LCC with externalities makes it possible to extend the discussion of costs and benefits for value creation. This study allowed for the quantification of costs and benefits from the aluminum plant to the end customer, integrating the externalities analysis through the calculation of $CO_2$ emissions. With LCC and externalities, the entire life span of a product can be evaluated: the production, use, and disposal at the end of life. Impacts related to economic, environmental, and social aspects occur along the entire supply chain: at the production site itself, in the extraction of raw materials and their transport, and at power plants supplying the energy to the production site. Capturing both direct and indirect impacts can help avoid shifting the environmental burden from one life cycle stage to another.

The gap noted in the literature indicates the importance of

**Table 13**
$CO_2$ emissions.

| Life Cycle | | Distance (km) | $CO_2$ emissions (g) (per 1000 cans) | |
|---|---|---|---|---|
| | | | Aluminum | Steel (Tinplate) |
| 30% RV | Plant<br>Recycler | 1516 | 7.71 | 20.38 |
| Distribution | Manufacturer<br>Retailer | 635 | 10.77 | 28.45 |
| Redistribution | Retailer<br>Store (Hypermarket) | 30 | 0.51 | 1.34 |
| Use & Disposal | Use | 5 | 0.08 | 0.22 |
| | Disposal<br>Collection | 180 | 3.05 | 8.06 |
| | | | **22.13** | **58.46** |

developing and implementing LCC methods from the perspective of the product/material flow life cycle. Numerical application of the integrated PSILA with the externalities demonstrates how this method can assist in the management of circular businesses, according to the gaps discussed by authors such as Florindo et al. (2017), Almeida et al. (2017), Niero and Hauschild (2017), and Bradley et al. (2018).

The theoretical contribution of this paper is related to the combined method for analyzing the costs, benefits, and environmental impact from the perspective of the closed-loop supply chain aligned with the CE concept (Su et al., 2013; Nasir et al., 2017) and complements the PSILA method, with the variables related to logistics costs (life cycle) and $CO_2$ impact. The PSILA method addresses the shortcomings that LCC methods have in integrating the product life cycle into a circular system, and the application is useful in the design of production systems. However, the PSILA method does not capture the cost of logistics freight and the impact on $CO_2$ emissions. Thus, by mapping the business model to identify the variables for the freight (life cycle) calculation and the emissions resulting from reverse logistics, we obtain an advance in terms of theoretical methods for a better management of the circular models. The second contribution of this research is related to the perspective of understanding how companies are managing their ecosystems under conditions of low margin profitability, contributing to the development of a framework for implementing circular business models.

In terms of managerial implications, the supply chain managers can make decisions by incorporating environmental emissions into their costs. In addition, a follow-up can be performed to calculate the reduction in maintenance due to vehicle weight reduction, thus allowing a more robust analysis for the decision-making process. Methods are increasingly needed to stimulate the effectiveness of the system by revealing and excluding negative externalities from the beginning, in addition to demonstrating positive externalities. Life cycle thinking must become a fundamental requirement for all production decisions, ensuring that the most appropriate material is chosen for a specific application, taking into account all aspects of a product's life.

However, using LCC for cost evaluation presents some challenges. First, the cost factors for elementary flows across the product supply chain are volatile, thus challenging the application of LCC. There are different actors involved in the supply chain of products with different organizational management structures; thus, the procedure for defraying the environmental life cycle faces the technical challenge of allocating the exact fraction of the cost factors among the multiple actors in the production, transportation, and plant life cycle phases. Regarding the environmental performance evaluation of the use of recycled aluminum, it is also necessary to continue the study to define standardization and weighting schemes to support the decision-making process.

## 6. Conclusion

The growing scale of packaging waste generation and disposal in global supply chains is attracting the attention of both academics and practitioners because of their environmental, social, and economic impacts. Selecting the most viable packaging option is a key approach to reducing resource depletion and packaging elimination. This search for sustainable solutions involves the evaluation process, which, in turn, requires a comprehensive analysis.

In a CE context, one should consider not only the cost of a product during its life cycle but also the economic benefit and added value for society and the environment. This study contributes to theory by indicating the combination of the LCC tool with the impact of externalities and by offering recommendations to managers that can assist in the evaluation of benefits for the packaging segment in the CE context. By applying LCC combined with environmental externalities, drivers for saving and cost impacts (for example, investment or operating costs, emissions related to energy or resource consumption) can be identified. Thus, the obtained results allow LCC, in conjunction with externalities, to provide useful information about the process of value creation related to the use of aluminum packaging for the food industry.

Future research may complement this study, such as the quantification of the variables in the LCC model regarding the impact of truck maintenance costs during the truck's lifetime in the system, the benefits of brand values to the consumer and the market, and the sustainability strategy of companies within their business models. In this context, new business models and innovative collaborations may be required to develop more integrated systems to effectively capture the potential benefits identified in an LCC study.

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