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Allocation strategies in comparative life cycle assessment for recycling: Considerations from case studies

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ABSTRACT

The objective of this research is to verify whether an end-of-life allocation strategy can affect the choice between two products or two processes. This study evaluates whether a comparison between two products/processes that is obtained by applying the cut-off (CO) approach and substitution method (Sub) can cause a sign reversal for products/processes with different recyclability features. The main intent is to provide a clear picture for Life Cycle Assessment practitioners, who analyze recycling systems and would benefit by knowing whether an end-of-life allocation strategy can affect the preference ranking between products or processes. Two comparative case studies were developed using primary data. The case studies were very different because they referred to different sectors. In the first case study, the analyzed subjects were two plastic products; in the second case study, the analyzed subjects were an incineration line under design and an incineration line under operative conditions. For the first case study, the allocation strategies were implemented in the modeling of the burdens of input waste and end-of-life disposal. For the second case study, the allocation strategies were implemented in the modeling of input waste; in the burdens of end-of-life disposal of slag, ashes and dust; in the recovery of construction materials; and in energy recovery. To confirm the main findings of the first and second cases, an additional case was simulated by combining the first and second cases. The results obtained in the two case studies and in the combined case indicate that comparisons between the analyzed products/processes are only marginally affected by the applied end-of-life allocation strategies and are consistent with both the allocation strategies for almost all of the analyzed impact categories.

1. Introduction

In life cycle assessments (LCAs), when materials of products are combined with materials of other products, allocation problems can arise (Vogtländer et al., 2001; Klöpffer 1996; Ekvall and Tillman 1997; Chen et al., 2010). In addition to the case that occurs when simultaneous products are manufactured and thus different inputs and outputs should be allocated to different products, allocation is also important when subsequent products are realized in recycling or reuse systems (Frischknecht et al., 2005, 2007; Frischknecht, 2010), which increase multi-functionality (Heijungs and Guinée, 2007). Recycling has been considered as a distinct allocation problem that requires a specific strategy since the early 1990s, as previously debated by Huppes and Schneider (1994) and reported by Weidema et al. (2000). Because man-made materials are valuable resources, some authors considered the environmental burden from the virgin material production in proportion to the material quality loss (Karlsson, 1994), suggested the use of socio-economic value or physical properties (Lindejier, 1994) or highlighted that in expanding market there is a general incentive for supplying scraps, whereas in a decreasing market without "virgin" inflow there is a general incentive for using scraps (Weidema et al., 2000).

Several studies appeal to the LCA methodology to quantify the environmental advantage of recovery in many sectors, such as Giani et al. (2015), Hossain et al. (2016), Intini and Kuehtz (2011), Rossi et al. (2015), Sprecher et al. (2014), Stewart and Haszeldine (2015), Yang et al. (2015); and reveal that adequate modelling of scraps recycling and reuse is needed, as discussed by An et al. (2015), Diyamandoglu and Fortuna (2015), Gu et al. (2016), Pauliuk et al. (2017), Tian et al. (2016), Vera et al. (2015). Recycling metrics can influence the behaviors of decision makers (Atlee and Kirchain, 2006; Plevin et al., 2014), and end-of-life recycling is considered to be a complex life cycle stage that is difficult to manage (Berzi et al., 2016; Diener and Tillmann, 2015; Huysman et al., 2015; Vogtländer et al., 2001).

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ISO 14040 and 14044 present the problem of allocation from a general perspective (ISO, 2006a,b), and ISO TR 14049 (ISO, 2012) and the International reference Life Cycle Data (ILCD) system handbook (EC-JRC, 2010) provide some examples and considerations. Other documents that focus on allocation formulas for recycling, which are not specific to LCA applications, are PAS 2050:2011 (BSI, 2011), the Product Environmental Footprint (PEF) Guide (European Commission, 2013) and ISO TS 14067:2013 (ISO, 2013).

However, it is still difficult to find uniform and well shared procedures to address end-of-life allocations for real situations. A number of studies investigate this issue by applying at least two allocation strategies (Nicholson et al., 2009; Shen et al., 2010; Huang et al., 2013; Johnson et al., 2013; Zampori and Dotelli, 2014; Pegoretti et al., 2014; Sandin et al., 2014; Dhaliwal et al., 2014; Reale et al., 2015; van der Harst et al., 2016). They reveal a lack of uniformity in the definition of the formulas. For example, substitution, system expansion, end-of-life recycling and 0/100 are sometimes interchangeably used, which confirms a concern that was previously highlighted by Heijungs (2014); cut-off, recycled content and 100/0 are also interchangeably used. As highlighted in previous research (Ekvall and Tillman, 1997), the main allocation strategies remain cut-off and substitution-equivalent approaches, such as substitution and system expansion (Heijungs, 2014), which are employed in several studies. Cut-off and substitution methods were also compared for recycling aluminum by Atherton (2007) and Dubreuil et al. (2010) who highlighted that the use of cut-off entails that the use of recycled material is a suitable indicator of environmental benefits. Dubreuil et al. (2010) suggested that this method also promotes a market for recycled material that otherwise would be limited, uneconomic and immature. However, as happens for the allocation in case of co-products, no consensus has been reached regarding the best strategy to use. In many cases, allocation can have a significant effect that it is possible to "game" the obtained impacts, as stated by Hanes et al. (2015), or influence the outcomes of an LCA (Wardenaar et al., 2012). Shen et al. (2010) suggested that cut-off fits the business boundary and that substitution can encourage product design for recyclability. Huang et al. (2013) noted that substitution approaches can be supported by material manufacturers because there is an immediate benefit, which is an important concern discussed by Bala Gala et al. (2015).

With reference to this context, even if there are several fictional examples in the literature, the objective of this research is to verify whether the choice of the end-of-life allocation strategy in the case of recycling can affect the comparison between different products or processes in real cases. This study evaluates whether a comparison between two products/processes that apply the cut-off (CO) approach and the substitution method (Sub) can cause a sign reversal for products/processes with different recyclability features. This study attempts to give an answer to LCA practitioners who perform LCAs of recycling systems and need to determine if an allocation strategy can affect the choice between two products or two processes. As stated by van der Harst et al. (2016), the multitude of methods and guidelines do not facilitate the selection an appropriate strategy by LCA practitioners.

The selected method of investigation was a multiple case study application of comparative LCA with reference to real products and processes using primary data. An additional case was also simulated to confirm the main findings of the real cases.

We note that the term recycling is used in accordance with the definition of the Directive 2008/98/EC, namely, "operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes". The term "recycled" is used to identify materials with a content of reprocessed waste, and the term "recyclable" is utilized for materials that can be reprocessed after use (European Parliament, 2008).

2. Materials and methods

2.1. Computational scheme

CO and Sub strategies were selected for this study; they are presented in Formula (1) and formula (2), respectively, where E represents the life cycle impact (BSI, 2011).

$$E = (1 - R_1)E_V + R_1 E_R + (1 - R_2)E_D \tag{1}$$

$$E = E_V + (E_r - E_V)R_2 + (1 - R_2)E_D \tag{2}$$

The main parameters in Formulas (1) and (2) are R_1 and R_2, which represent the recycled content of materials and the recycling rate, respectively. E_V represents the impacts that are associated with the utilization of virgin materials, E_R and E_r address the impact that arise from the recycling processes of R_1 fractions and R_2 fractions, respectively, and E_D considers the environmental burdens from the disposal of waste materials.

However, the management of waste includes not only recycling and landfill disposal but also incineration with energy recovery. Formula (2), which considers the recycling rate and related avoided impacts, does not address possible energy recovery and related avoided energy utilization. Thus, it was modified based on the European Commission (2013) and Formula (3) was elaborated

$$E = E_V + (E_r - E_V)R_2 + (1 - R_2)E_D - R_3 LHV X_{ER} E_{SE} \tag{3}$$

where R_3 is the proportion of material that is incinerated with energy recovery; LHV is the lower heating value of the material in the product that is used for energy recovery; X_{ER} is the efficiency of the energy recovery process and E_{SE} considers the environmental impacts from the specific substituted energy source.

Table 1 presents the components of Formulas (1)–(3) and adopts the thematic blocks proposed by Allacker et al. (2014) and previously identified by Ekvall and Tillman (1997) : Block A considers the production of virgin materials; Block B considers the recycled content of the materials; Block C considers recycling at end-of-life minus credits from avoided primary production; Block D regards energy recovery and avoided energy production and Block E regards final disposal. The computation scheme for the application of CO and Sub is presented in Fig. 1 using the blocks proposed by Allacker et al. (2014). These formulas were applied to the three cases.

2.2. Conducting the LCA

The conduction of LCA was developed in the following steps:

1. The goal and scope for each case study was defined. The main items of the goal and scope phase were independently selected from the end-of-life allocation strategies, such as the function, functional unit and system boundaries. The system boundaries, including the following stages, were established in accordance with ISO (2006a): acquisition of raw materials; inputs and outputs in the main manufacturing/processing sequence; production and use of fuels, electricity and heat; disposal of process wastes and products; recovery of used products (including reuse, recycling and energy recovery); and manufacture of ancillary materials. Successively, the life cycle stages affected by the end-of-life allocation formulas were identified by highlighting the related components of the formulas in the scheme of the system boundaries.
2. The inventory analysis was developed for each case study using three points: data collection, data calculation and allocation of flows. Data collection was performed to determine the energy inputs, raw material inputs, ancillary inputs, other physical inputs, waste, emissions to air, discharges to water and soil to