

LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency

Rolf Frischknecht

Received: 2 September 2009 / Accepted: 1 June 2010
© Springer-Verlag 2010

Abstract

Purpose and scope Two ISO-compliant approaches on modelling the recycling of plastics and metals are frequently applied in life cycle assessment case studies and intensively debated: the recycled content or cutoff approach and the end of life recycling or avoided burden approach. This paper discusses the two approaches from three different perspectives: (1) the kind of sustainability concept served, (2) the risk perception involved and (3) the eco-efficiency indicators resulting from the two approaches.

Results and discussion The analysis shows that the *recycled content* approach serves the strong sustainability concept. It is based on a risk-averse attitude and results in higher eco-efficiency of metal scrap recycling as compared to primary metal manufacture. The *end of life recycling* approach serves the weak sustainability concept (losses in natural capital can be compensated by man-made capital). It corresponds to a risk-seeking attitude and results in higher eco-efficiency of primary metal manufacture as compared to secondary metal production.

Conclusions It is concluded that a harmonisation of the approaches is hardly possible due to the value choices involved. It is the task of (private and public) life cycle assessment commissioners to decide on the appropriate modelling approach. National authorities may have a rather long-term and risk-averse perspective, whilst industries may prefer a short-term perspective leading them to select the recycled content and end of life recycling approach, respectively. Life cycle inventory databases need to be flexible to serve such opposing perspectives and to enable

practitioners to adapt the modelling approaches according to the needs of the commissioner.

Keywords Avoided burdens · Cutoff · Eco-efficiency · Life cycle inventory · Risk perception · Sustainability concepts

1 Introduction and theses

The life cycle inventory modelling of recycling of materials and in particular of metals is currently very much debated. Recent publications on this issue comprise for instance SETAC (1993), Frischknecht (1994), Klöpffer (1996), Ekvall and Tillmann (1997), Kim et al. (1997), Frischknecht (2000), Weidema (2001), Werner (2002), Ekvall and Weidema (2004), Yamada et al. (2006), Anonymous (2006), Curran (2006), Frischknecht (2006) and Curran (2008). The proposed methodologies can roughly be classified into two distinctly different approaches that are currently used in daily life cycle assessment (LCA) practice:

- Recycled content approach (also known as the cutoff approach) and
- End of life recycling approach (also known as the avoided burden approach).

Their usefulness and appropriateness have been discussed with regard to several aspects such as the promotion of the use of recycled materials, the support of design for recycling, the operationalisation of the precautionary principle or the feasibility from the point of view of the practitioners.

The paper starts from the thesis that the goal of an LCA study does not automatically determine the appropriate modelling approach. The modelling approaches involve value choices, and thus other criteria to choose the

Responsible editor: Hans-Jürgen Garvens

R. Frischknecht (✉)
ESU-services Ltd—fair consulting in sustainability,
Kanzleistr. 4,
8610 Uster, Switzerland
e-mail: frischknecht@esu-services.ch

appropriate modelling approach are required. This paper explores the relation of the approaches to three criteria, namely sustainability concept (see also Box 1), risk perception and eco-efficiency, which should be included in the goal and scope definition according to the ISO standards 14040 and 14044 (ISO 2006a, b).

A description of the two modelling approaches and an assessment regarding their ISO compliance is given in

Section 2, Section 3 highlights the current situation of climate change impacts related to the production of primary and secondary aluminium. Section 4 discusses the two approaches with regard to three different perspectives. It describes what the two approaches tell us with regard to sustainability concepts (Section 4.2), risk perception (Section 4.3) and eco-efficiency concepts (Section 4.4). Conclusions are drawn in Section 5.

Box 1 Weak and strong sustainability

The sustainability concept has been refined since its general definition by Gro Harlem Brundtland in the late eighties ("Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"). Currently, two distinct degrees of sustainability are used and under debate, namely the weak and the strong sustainability (see e.g. Neumayer 2003):

- *weak sustainability*: total capital shall remain constant; natural capital stocks can be diminished as long as it is compensated by gains in the man-made stock ("substitutability concept").
- *strong sustainability*: natural capital shall be kept constant, independent of man-made capital ("non-substitutability concept").

2 Description of the concepts: recycled content and end of life recycling

2.1 Recycled content or cutoff approach

The recycled content approach considers the share of recycled material (metal) in the manufacture of a product. The environmental impacts of extraction, beneficiation and refining of primary metal are attributed to the first use of that metal product (see Fig. 1). The second use of the metal bears the environmental impacts of collection, beneficiation and refining of scrap. In some cases, collection is attributed to the first use and the collection and recycling steps need to be clearly separated. Secondary metals do not bear any environmental load from the primary metal production activities.

A variation of this approach is proposed by Guinée et al. (2004). They consider the recycling of aluminium being a co-production process and use the economic value to determine the shares of impacts and expenses of the recycling process to be attributed to the waste treatment service provided and the secondary material generated.

2.2 End of life recycling or avoided burden approach

The end of life recycling approach considers the end of life fate of the metal. The share of metal recycled after the use phase of a product determines the amount of primary metal that is not required to be replaced by primary metal feedstock. In short, post-consumer recycling avoids primary metal production, and the environmental impacts of the avoided primary metal production are credited to the product that sends the metal to recycling (Fig. 1). The metal input to the product under analysis always bears the environmental impacts of primary metal production; irrespective of the fact whether or not recycled, secondary feedstock is used in the product.

2.3 ISO compliance

Advocates of the two approaches claim that they are compliant with the current ISO standards 14040 and 14044 (ISO 2006a, b). This does not astonish as the standard is not clear with regard to allocation in general and

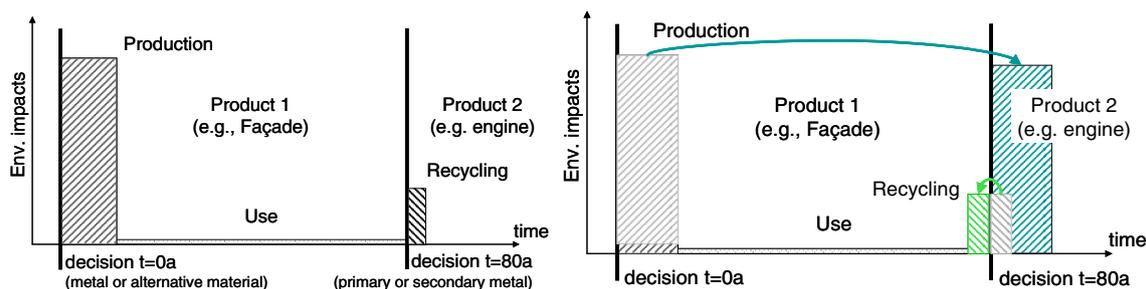


Fig. 1 Environmental impacts in the course of time during production, use and end of life (recycling) of a long-living metal product. *Left* recycled content approach; *Right* end of life recycling approach

its application on reuse and recycling in particular. The end of life recycling approach claims to be ISO-compliant because ISO 14044 prefers system expansion to allocation. The clauses on allocation procedures for reuse and recycling, however, do not mention system expansion explicitly. It does not specify how an open loop allocation procedure looks like. The recycled content approach claims ISO compliance as well. The standard does not specify in a

binding way which basis for allocation to apply nor the way how market values should be determined (i.e. applying discount rates on the economic value of far future scrap). There is a strong aversion against any “subjective” decision or “values” in general since the ISO standards (ISO 2006a, b) as well as the SETAC guideline (SETAC 1993) are based on the fear of misuse. Thus, ISO compliance cannot be denied for any of the two approaches (Box 2).

Box 2 ISO 14044 and allocation procedures for reuse and recycling

4.3.4.3.3 Several allocation procedures are applicable for reuse and recycling. The application of some procedures is outlined conceptually in Figure 2 and is distinguished in the following to illustrate how the above constraints can be addressed.

- a) A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials. However, the first use of virgin materials in applicable open-loop product systems may follow an open-loop allocation procedure outlined in b).
- b) An open-loop procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.

4.3.4.3.4 The allocation procedures for the shared unit processes mentioned in 4.3.4.3 should use, as the basis for allocation, if feasible, the following order:

- physical properties
- economic value (e.g., market value of the scrap material or recycled material in relation to market value of primary material); or
- the number of subsequent uses of the recycled material (see ISO/TR 14049).

3 Case study: current climate change emissions of aluminium manufacture

This section describes the emission situation with regard to climate change of the production of primary and secondary aluminium. In the year 2003, the production of primary aluminium was about 27.4 million tons (Martchek 2006). In the same year, some 23 million tons of new and internal (so-called prompt) scrap and seven million tons of old (post-consumer) scrap was produced and recycled. If we combine these flows with the climate change impact of primary and secondary aluminium from new and old scrap (11,800, 410 and 1,300 kg CO₂-eq per ton of primary, new scrap and old scrap aluminium;ecoinvent Centre 2006, based on EAA 2000), the actual annual climate change impact of primary and secondary aluminium production is 320 million tons of CO₂-eq and 20 million tons of CO₂-eq, respectively.

Each year, society gets a man-made capital of concentrated aluminium of 27.4 million tons at the expense of 320 million tons of CO₂-eq.

Industry experts project that the world aluminium stock will increase by 77% from 520 million tons in 2003 to 920 million tons in 2020 (Martchek 2006). The primary produc-

tion is expected to rise to some 38 million tons of primary aluminium (compared to 27.4 million tons in 2003). At the same time, the global recycled metal supply to industry will rise to some 13 million tons per year as compared to 7 million tons in 2003 (Martchek 2006). The recycling rate (post-consumer recycled aluminium related to primary plus secondary production from post-consumer scrap) rose from some 20% in 2003 to 25% in 2020,¹ which is far from a closed loop reality with 100% recycling feed.

4 Intent of the two approaches

4.1 Introduction

As is shown by, e.g. Werner and Richter (2000) and in Section 4.4, the two modelling approaches described in Section 1 differ in the life cycle inventory (LCI) results and thus in the conclusions drawn from LCA studies applying

¹ Seven million tons relative to 34.4 million tons in 2003 and 13 million tons relative to 51 million tons in 2020.

one or the other approach. The choice of one or the other approach can be the consequence of the particular goal of an LCA study. For instance, the material of a product is chosen (metal) but different product options exist. The end of life recycling approach may then help identify whether or not product options with a high recyclability are environmentally advantageous. When it comes to more general questions such as “which material to use in a product that provides a certain function”, both modelling approaches claim to provide the ideal support. Hence, a goal-dependent selection of the appropriate LCI model does not help.

The following three subsections try to characterise the two concepts from three different perspectives. They are intended to help structure the discussion and to facilitate an informed choice for one or the other approach.

4.2 Which sustainability concept do they serve?

According to the *end of life recycling* (or avoided burden) approach, the metal that will probably be recycled in the future results in avoiding primary metal production. Avoiding primary production avoids substantial emissions and resource consumptions, as is shown in Section 2 with the aluminium example. Attributing these avoided emissions to the product that delivers the scrap for recycling reduces its environmental impacts substantially. The concentrated metal in the product, which is potentially recycled in the future (after its service life ended), is considered equivalent to the natural capital represented by a credit of avoided environmental burdens such as avoided climate change impacts. Thus, the end of life recycling approach is representing the *weak sustainability* concept (see Box 2).

The *recycled content* (or cutoff) approach accounts for the environmental impacts at the time they occur. If a product is made of primary metal, the environmental impacts of primary metal production are attributed to this product. No credits are given in case the metal in the product might be recycled in the future (when its service life ended). This modelling approach is very much in line with the *strong sustainability* concept where natural capital (climate change credits) is not replaceable by man-made capital (concentrated aluminium).

We learn from this that we cannot claim one approach being the correct one in scientific terms. This confirms statements in previous papers made for instance by Frischknecht (1994), Heijungs and Frischknecht (1998), Hertwich et al. (2000) and Hofstetter et al. (2000). No “subjective” allocation can claim to be based on science as otherwise this problem would not exist. This paper intends to show that they are both sensible within their respective value system. At the same time, it becomes clear that there is little chance but also no need for a compromise between the two modelling approaches. This is why a sensitivity analysis shall be conducted whenever

several alternative allocation procedures seem applicable (ISO 2006b, clause 4.3.4.1)!

4.3 Which risk perception do they represent?

Metals are not only used in short-living consumer goods such as packaging but also in long-living products such as wall claddings, steel beams, airplanes and railway coaches. The long duration between the manufacture of such products and their potential recycling makes the modelling of their life cycle distinctly different from short-living products such as beverage cans.

The *end of life recycling* approach grants credits to metal recycling that may occur in ten, 20 or more years from now (in the case of metals used in buildings, this can easily be 40 years and more). This approach assumes that the metal will still be in demand by that time in the future. However, this is an assumption and cannot be taken for granted as the future cannot be known. This means that an environmental loan is borrowed from future generations. The risk of not being able or not being ready² to pay back the environmental credit in the future is taken deliberately. Thus, the approach may be classified as risk-tolerant or risk-seeking.

The *recycled content* approach promptly accounts for those environmental impacts that are caused by the consumption of primary metal feedstock, disregarding the fact whether or not the product may be recycled in the future. The time frame within which recycling is likely to happen is considered too long to be able to make sufficiently reliable forecasts. The risk of accepting an environmental credit from future generations is not taken, representing a risk-averse mindset.

With regard to risk perception, the two approaches serve distinctly different views. Similar to the large differences in sustainability concepts supported by the two approaches, a compromise with regard to risk perception seems to be hard to find.

4.4 What is the message of eco-efficiency considerations?

The eco-efficiency concept relates environmental impacts caused by an industrial activity to the economic value added by this activity. The eco-efficiency of an entire supply chain of a material can be characterised with the environmental impacts caused up to a certain point in the value chain related to the price of the material at the same point (see, e.g. Kicherer et al. 2007).

Let us have a look at the current prices and climate change impacts of primary and scrap aluminium (see Table 1). The cumulative climate change emission data are retrieved from

² Future generations may argue with the sunk cost argument that the emissions to manufacture primary aluminium happened in the past and can no more be influenced. Hence, there is no reason to take past emissions into considerations in their decisions.

Table 1 Price, climate change impacts (cradle to gate) and eco-efficiency factors of primary, secondary and scrap aluminium according to the two approaches discussed in this paper

Aluminium	Price (US \$/kg)	Climate change impact (kg CO ₂ -eq/kg)	Eco-efficiency (kg CO ₂ -eq/US \$)
Recycled content approach			
Primary	1.40	11.8	8.43
Scrap	0.76	0.41	0.54
End of life recycling approach			
Primary, avoided burden	0.824	1.55	1.88
Scrap, avoided burden	1.336	10.7	7.98

Prices of primary and secondary aluminium from the London Metals Exchange (average price between November 2002 and March 2003) and of scrap from a Swiss building decommissioning site during the same time period

the ecoinvent database (ecoinvent Centre 2006), the prices of primary aluminium are retrieved from the London stock exchange (period between November 2002 and March 2003), and the prices of Aluminium scrap reflect the actual prices realised on a decommissioning site in the city of Zurich during the same period of time.

The “avoided burden” prices and emissions are calculated on the basis of a 90% recycling efficiency. For the sake of simplicity, the 10% cover the loss in material quality and the material loss is neglected. The following formulae are applied:

$$\begin{aligned}
 CC_{\text{primary, avoided burden}} &= (1 - 0.9) \times CC_{\text{primary}} + 0.9 \times CC_{\text{scrap}}; \\
 P_{\text{primary, avoided burden}} &= (1 - 0.9) \times P_{\text{primary}} + 0.9 \times P_{\text{scrap}}; \\
 CC_{\text{scrap, avoided burden}} &= (0.9) \times CC_{\text{primary}} + (1 - 0.9) \times CC_{\text{scrap}}; \\
 P_{\text{scrap, avoided burden}} &= (0.9) \times P_{\text{primary}} + (1 - 0.9) \times P_{\text{scrap}};
 \end{aligned}$$

with P being price and CC being climate change impact, respectively.

We observe that the “avoided burden” prices and the “avoided burden” environmental impacts of primary aluminium are substantially reduced. The prices and the climate change impacts of secondary aluminium and scrap are much higher at the same time.

In a next step, the eco-efficiency of the two metals (primary and scrap) is calculated by dividing the climate change impact (CC) by the product price (P). It shows that primary aluminium shows the highest emissions per US dollar, whereas aluminium scrap shows the lowest value, applying the recycled content approach. When applying the end of life recycling approach, the picture turns. Scrap, modelled according to the avoided burden approach, shows the highest emissions per US dollar, whereas primary aluminium credited with scrap aluminium emits the lowest amount per kilogram.

In other words, the manufacture of sorted aluminium scrap shows the highest eco-efficiency applying the recycled content approach, whereas primary aluminium production shows the highest eco-efficiency based on the end of life recycling approach (credits granted for the supply of scrap aluminium; Table 1).

5 Conclusions

The debate on the correct or appropriate approach regarding the modelling of recycling cannot be solved by science only. The way recycling is modelled is influenced by differences in values, views of the world and cultural perspectives. This paper highlights the differences of the approaches with regard to three aspects:

The *end of life recycling* approach is in line with the *weak sustainability* concept where natural capital can be substituted by man-made capital. It supports *risk-seeking* attitude by borrowing environmental loans from future generations for man-made capital potentially being reused or recycled in the future. It results in a distinctly higher eco-efficiency of primary aluminium that is predicted to be recycled in the future as compared to secondary aluminium.

The *recycled content* approach is in line with the *strong sustainability* concept where natural capital must not be substituted by man-made capital and thus environmental impacts are strictly linked to the product (man made capital) that causes them, irrespective of any potential future reuse of it. The approach supports a *risk-averse* attitude in that emissions occurring today are attributed to today’s product and no burden shifting to future generations occurs. Finally, the eco-efficiency of recycling aluminium is substantially higher as compared to the production of aluminium from bauxite.

Further characteristics are listed in Table 2. Depending on the value choices of a commissioner, the LCA of

Table 2 Synopsis of characteristics of the two modelling approaches of recycling

	“End of life recycling” or “avoided burden”	“Recycled content” or “cutoff”
Future utility	Yes	Uncertain
Sustainability concept	Weak	Strong
Environmental grants from future generations	Yes	No
Shift of burdens into future	Yes	No
Risk perception	Risk seeking	Risk averse
Eco-efficiency primary versus secondary metal	Primary > secondary	Secondary > primary

metal-containing products may thus look very different. Whereas the metal industry may well endorse the *end of life recycling* approach and by that follow the weak sustainability concept and adopt a risk-seeking strategy, national authorities may be indebted to long-term welfare and environmental protection and thus may rather follow the strong sustainability concept and act rather risk-averse. National authorities may therefore tend to apply the *recycled content* approach.

Because of the involvement of value judgements and preferences in the modelling of recycling of materials, it is unlikely that a consensus will ever be found. There is even no need to reach consensus with this respect. However, we need clear statements from (public or private) commissioners of LCA study on their preferences with regard to the sustainability concept and risk perceptions to derive the adequate modelling of recycling. Additionally, transparent unit process life cycle inventory data are needed by the practitioner to be able to adjust the modelling to the value choices of the commissioner, if necessary. This freedom of choice is necessary in open, democratic and pluralistic societies.

References

- Anonymous (2006) Declaration by the metals industry on recycling principles. *Int J Life Cycle Assess* 12:59–60
- Curran M-A (2006) Co-product and input allocation approaches for creating life cycle inventory data: a literature review. *Int J Life Cycle Assess* 12:65–78
- Curran MA (2008) Development of life cycle assessment methodology: a focus on co-product allocation. Erasmus University Rotterdam, Rotterdam
- EAA (2000) Environmental profile report for the European aluminium industry, April 2000. European Aluminium Association, Brussels
- ecoinvent Centre (2006) ecoinvent data v1.3. Final ecoinvent reports no. 1-16. Swiss Centre for Life Cycle Inventories, Duebendorf. ISBN 3-905594-38-2
- Ekvall T, Tillmann A-M (1997) Open-loop recycling: criteria for allocation procedures. *Int J Life Cycle Assess* 2:155–162
- Ekvall T, Weidema B (2004) System boundaries and input data in consequential life cycle inventory analysis. *Int J Life Cycle Assess* 9:161–171
- Frischknecht R (1994): Allocation—an issue of valuation? In: Huppes G, Schneider F (eds) European Workshop on Allocation in LCA. Society of Environmental Toxicology and Chemistry, SETAC, 24–25 February 1994, Leiden, The Netherlands, pp 122–131
- Frischknecht R (2000) Allocation in life cycle inventory analysis for joint production. *Int J Life Cycle Assess* 5:85–95
- Frischknecht R (2006) Notions on the design and use of an ideal regional or global LCA database. *Int J Life Cycle Assess* 11:40–48
- Guinée JB, Heijungs R, Huppes G (2004) Economic allocation: examples and derived decision tree. *Int J LCA* 9:23–33
- Heijungs R, Frischknecht R (1998) On the nature of the allocation problem. *Int J Life Cycle Assess* 3:321–332
- Hertwich E, Hammit JK, Pease WS (2000) A theoretical foundation for life-cycle assessment: recognizing the role of values in environmental decision making. *J Ind Ecol* 4:13–28
- Hofstetter P, Baumgartner W, Scholz R (2000) Modelling the value-sphere and the ecosphere: integrating the decision makers' perspectives into LCA. *Int J LCA* 5:161–175
- ISO (International Organization for Standardization) (2006a) Environmental management—Life cycle assessment—Principles and framework. ISO 14040:2006; Second Edition 2006-06, Geneva
- International Organization for Standardization (ISO) (2006b) Environmental management—Life cycle assessment—Requirements and guidelines. ISO 14044:2006; First edition 2006-07-01, Geneva
- Kicherer A, Schaltegger S, Tschokohei H, Ferreira Pozo B (2007) Eco-efficiency. Combining life cycle assessment and life cycle costing via normalization. *Int J Life Cycle Assess* 12:537–543
- Kim S, Hwang T, Lee K-M (1997) Allocation for cascade recycling system. *Int J LCA* 4:217–222
- Klöppfer W (1996) Allocation rule for open-loop recycling in life cycle assessment—a review. *Int J Life Cycle Assess* 1:27–31
- Martchek K (2006) Modelling more sustainable aluminium. *Int J Life Cycle Assess* 11:34–37
- Neumayer E (2003) Weak versus strong sustainability: exploring the limits of two opposing paradigms. Edward Elgar, Cheltenham
- SETAC (1993): Guidelines for life-cycle assessment: a “Code of Practice”. SETAC Workshop. Society of Environmental Toxicology and Chemistry (SETAC), Brussels, Belgium and Pensacola (Florida, USA). Sesimbra, Portugal, 31 March–3 April 1993
- Weidema B (2001) Avoiding co-product allocation in life-cycle assessment. *J Ind Ecol* 4:11–33
- Werner F (2002) Interdependencies between LC-modelling and the use of LCA in product design-related decision situations. PhD thesis, ETHZ, Zürich
- Werner F, Richter K (2000) Economic allocation in LCA: a case study about aluminium window frames. *Int J LCA* 5:79–83
- Yamada H, Daigo I, Matsuno Y, Adachi Y, Kondo Y (2006) Application of Markov chain model to calculate the average number of times of use of a material in society. An allocation methodology for open-loop recycling. Part 1: methodology development. *Int J Life Cycle Assess* 11:354–360