ATTRIBUTIONAL VERSUS CONSEQUENTIONAL LIFE CYCLE ASSESSMENT MODELLING IN METALWORKING PRODUCTION SYSTEM

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SUMMARY
Two different system modelling can be distinguished in life cycle assessment: attributional and consequential. Attributional modelling is used to describe the present state of the examined system and is characterised with use of allocation, no substitutions, market average suppliers, and cut-off principle. Consequential modelling is used to describe the consequences of changes in the demand within the system and use of substitutions, marginal suppliers, and system expansion. Although the ISO 14040 standard does not make a clear distinction between attributional and consequential modelling, it does provide basic instructions on how to deal with allocations and supports both types of modelling systems. Therefore, it is important to specify within the goal and scope of life cycle assessment study which modelling is used. This research applies attributional and consequential modelling in life cycle assessment to analyse a case of metalworking production system. The aim of research is to identify if the application of different system models can lead to different conclusions and interpretation of life cycle assessment results. The obtained environmental impacts from life cycle assessment show that two system models provide different results. However the choice which one to use depends on: if investigation has to separate the product from the rest of technosphere and environment, if inputs and outputs need to be attributed to the functional unit, or if there is need for comparative analysis of products and focus on the long-term effect of the changes.

1. INTRODUCTION

Life cycle assessment (LCA) is a comprehensive tool for evaluation of environmental impacts in all product and process life cycle stages [1]. Despite the fact that LCA takes the entire life cycle into account, still many assumptions and methodological choices have to be made throughout a study, which can lead to different outcomes [2]. The ISO 14040 [3] standard does not make a clear distinction between attributional and consequential LCA modelling (ALCA and CLCA), but it provides basic rules how the allocations in LCA should be performed. Therefore, it is important to specify in goal and scope of LCA study if ALCA or CLCA modelling is used. One of the first publicly published documents where ALCA and CLCA are being distinguished is Curran et al., 2005 [4]. ALCA, also called “accounting”, “retrospective”, or “descriptive”, evaluates the system as it is or was. On the other side, CLCA focuses on the consequences of changes in the demand within the system. Table 1 provides description and general differences between the ALCA and CLCA.

The International Reference Life Cycle Data System (ILCD) handbook [5], developed by the European Joint Research Centre, is one of the frequently cited documents in field of LCA. This handbook, which comprises several volumes, provides guidelines on how to perform LCA. ILCD handbook also defines ALCA and CLCA, however, recent research by [6] showed that it needs revision as some guidelines are found to be inconsistent with previous research on ALCA and CLCA. According to research presented in [7], changes to attributional systems have consequences beyond the system boundaries, i.e. in the parts that have been allocated away, or made less important through averaging.

Ecoinvent, one of the most used LCI databases, since version 3.0, contains three model systems that correspond to ALCA and CLCA [8], namely: cut-off, allocation at the point of substitution, and consequential. These system models describe how activity datasets are linked to form product systems. Within these system models ALCA [8] can be divided into:

- value chain (economic or revenue allocation) - where a producer is fully responsible for the disposal of its wastes, and that he does not receive any credit for the provision of any recyclable materials;
- supply chain (mass allocation) attributional approach in which burdens are attributed proportionally to specific processes.

Table 1. Description of the ALCA and CLCA

ALCA	CLCA	Reference
Attributional LCI aims to answer how are environmentally things (pollutants, resources, and exchanges among processes) flowing within the chosen temporal window.	Consequential LCI aims to answer how will flows change in response to decisions.	[4]
System modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule.	System modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit.	[9]
Economic, revenue or mass allocation; Average suppliers; No specific requirements to the functional unit; Market averages - Current relative production volumes of suppliers.	System expansion; Substitution; Functional unit reflects the conditions for substitution; Marginal, unconstrained suppliers - modern, competitive suppliers, when the product demand is generally increasing, old, uncompetitive suppliers, when the product demand is generally decreasing.	[7]
LCI modelling frame that inventories the inputs and output flows of all processes of a system as they occur. Modelling process along an existing supply-chain is of this type.	LCI modelling principle that identifies and models all processes in the background system of a system in consequence of decisions made in the foreground system.	[5]

There is a increased number of researches that involve comparison of ALCA and CLCA. Buyle et al. [2] performed a screening LCA of an apartment with ALCA and CLCA approach in order to identify and compare possible differences in results between the two approaches when applied on the same case. Their results showed that there is a shift of proportion between the environmental impacts per life cycle phases. Kua et al. [10] used ALCA and CLCA to evaluate and compare substitution of concrete with bricks on Singapore case study. Their results showed that for ALCA approach, the environmental impacts of replacing concrete with bricks may be increased, while using a CLCA approach, replacing concrete with bricks may result in small reduction of GWP. Parajuli et al. [11] evaluated environmental impacts of producing bioethanol and bio based lactic acid from standalone and integrated biorefineries using ALCA and CLCA. They concluded that for producing bio based products from an integrated system ALCA and CLCA approaches had similar impact pattern for most of the impact categories. In general, ALCA is more used than CLCA modelling, but one of the problems that occurs in some studies is that it is not defined if ALCA or CLCA is used.

Previously discussed show that LCA community has increased interest in distinguishing the ALCA and CLCA modelling choices. Following this trend, this investigation applies ALCA and CLCA modelling in order to analyse a case of metalworking production system. The aim of the research is to identify if two system models can lead to different conclusions and interpretation of LCA results.

2. MATERIALS AND METHODS

Differences between ALCA and CLCA modelling will be shown on simple example with production of aluminium parts by milling. In this example joint production of A and B products is investigated. The functional unit is defined as production of one kilogram of product A that is made from aluminium alloy. System boundaries for ALCA and CLCA are different and shown in figures 1 and 2. The use of workshop building, milling machine, cooling fluid, and other consumables is not considered in system boundaries because of the negligible environmental impact.

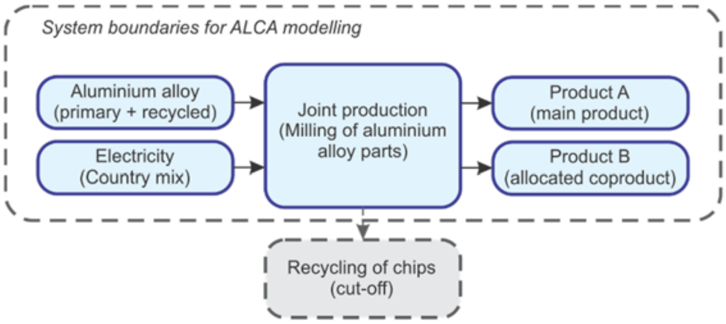

Figure 1. *System boundaries for ALCA modelling*

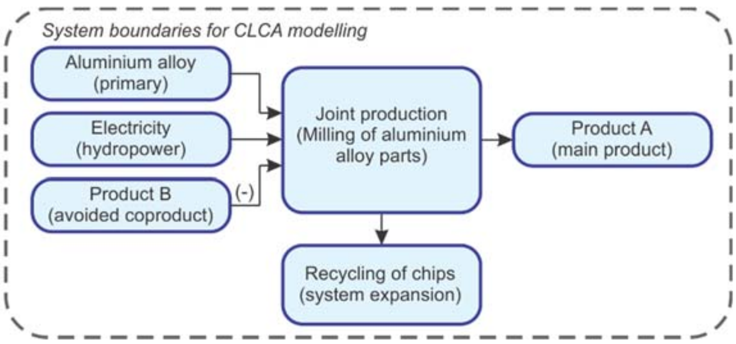

Figure 2. *System boundaries for CLCA modelling*

In ALCA modelling aluminium alloy is produced from primary (virgin) aluminium, and recycled aluminium. Electricity needed for production is from country mix that consists of electricity mainly from burning of lignite in power plants (66%) and hydropower (32%). Mass allocation was used for allocating the environmental impact between the products A and B. Recycling of waste chips is not included in ALCA modelling because of cut-off criteria.

Situation with increase in demand for product A where average supplier cannot satisfy the increase in demand is considered in CLCA modelling. Therefore, increase in demand for product A is compensated with marginal suppliers of aluminium alloy and electricity. In consequence of increased demand, only primary aluminium is used for production of aluminium alloy and hydropower is used instead of country mix. System expansion was used for allocation of environmental impacts between the products A and B. Recycling of waste chips is included in CLCA modelling because of system expansion.

Inventory for ALCA and CLCA modelling of aluminium parts production is shown in tables 2 and 3.

Table 2. Inventory for ALCA modelling of aluminium parts production

Activity	Name of the activity in Ecoinvent database	Amount	Note
Input flows			
Aluminium	Aluminium, cast alloy {GLO}| market for | Alloc Def, S	1.62 kg	1 kg (A product) + 0.5 kg (B product) + 0.12 (metal chips from milling 8%)
Electricity	Electricity, medium voltage {RS}| market for | Alloc Def, S	0.036 kWh	0.3 kWh is consumed for removal of 1 kg of metal chips
Output flows			
Product A	-	1.0 kg	Main product
Product B	-	0.5 kg	Environmental impact of coproduct is allocated with mass allocation

Table 3. Inventory for CLCA modelling of aluminium parts production

Activity	Name of the activity in Ecoinvent database	Amount	Note
Input flows			
Aluminium	Aluminium, cast alloy {GLO}| market for | Conseq, U	1.62 kg	1 kg (A product) + 0.5 kg (B product) + 0.12 (metal chips from milling 8%)
Electricity	Electricity, high voltage {RS}| electricity production, hydro, reservoir, alpine region | Conseq, S	0.036 kWh	0.3 kWh is consumed for removal of 1 kg of metal chips
Output flows			
Product A	-	1.0 kg	Main product
Product B	Product A (Avoided)	0.5 kg	Coproduct is avoided product with positive impact on the environment
Aluminium recycling	Aluminium, primary, ingot {GLO}| market for | Conseq, S	0.12 kg	Avoided product with positive impact on the environment

For life cycle impact assessment (LCIA) ReCiPe midpoint method was used [12]. ReCiPe expresses environmental impacts through the following 18 midpoint impact categories: climate change, terrestrial acidification, freshwater eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, freshwater ecotoxicity, marine ecotoxicity, natural land transformation, metal depletion, fossil depletion, ozone depletion, marine eutrophication, terrestrial ecotoxicity, ionising radiation, agricultural land occupation, urban land occupation, and water depletion. For purpose of investigation of differences between the ALCA and CLCA, and simplification of interpretation, only the results from climate change midpoint impact category will be analysed as climate change is most used as a single environmental indicator on midpoint level.

3. RESULTS

The results from ReCiPe midpoint method for climate change midpoint impact category are shown in figures 3 and 4 for ALCA and CLCA modelling.

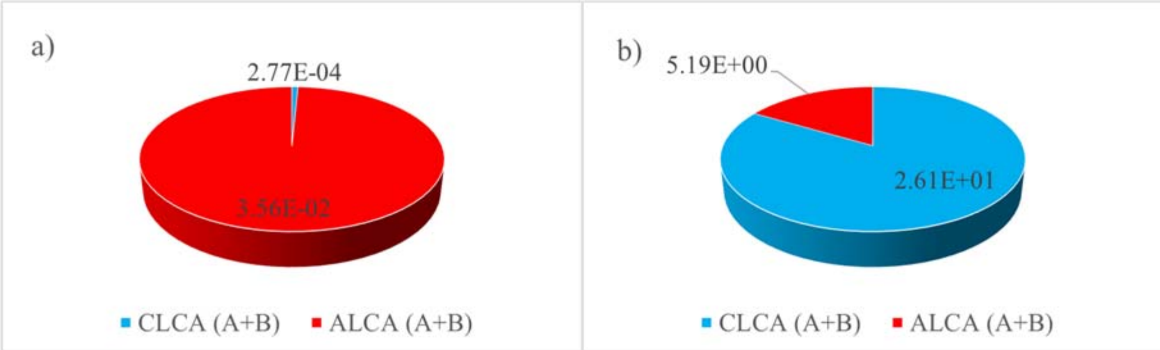

Figure 3. *Impact on climate change in kg of CO_2 eq. for: a) consumption of electricity for joint production of products A and B, b) consumption of aluminium alloy for joint production of products A and B*

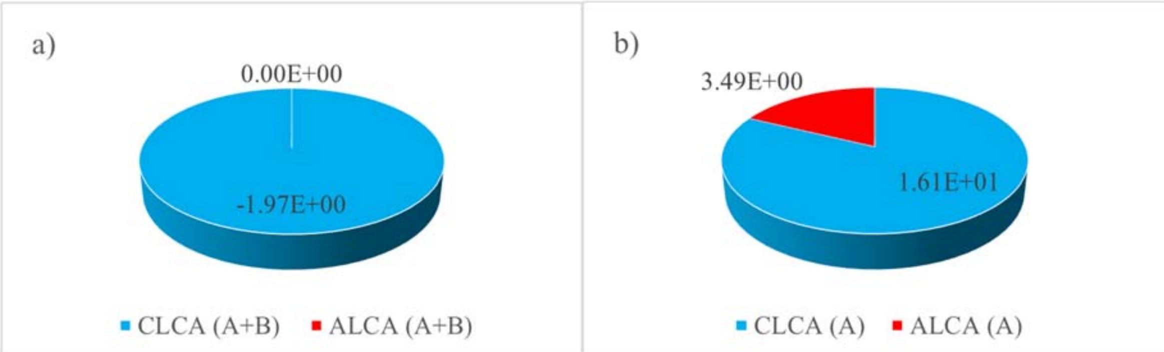

Figure 4. *Impact on climate change in kg of CO_2 eq. for: a) Recycling of aluminium for joint production of products A and B, b) product A*

4. DISCUSSION

As can be expected, ALCA and CLCA modelling provide different results (figure 4b). Although the environmental impact of electricity consumption for joint production of A and B products is much lower than the impact of aluminium consumption, the difference between results from ALCA and CLCA (figure 3a) is more than 100 times (2.77E-04 versus 3.56E-02). Reason for such results lies in the different source of electricity. The electricity in ALCA is from Serbian electricity mix, while the electricity used in CLCA is only from hydropower which is the cleaner energy source. The main differences in results of two modelling approaches are related to consumption of aluminium alloy (figure 3b). Considering the fact that use of virgin material has larger impact on the environment, aluminium alloy in CLCA modelling had larger environmental impact (5.19E+00 kg CO_2 eq.). Here one can easily see the difference between the two modelling approaches in Ecoinvent 3 LCI database where activity “Aluminium, cast alloy {GLO}| market for | Conseq, U” uses primary aluminium (marginal supplier) while activity “Aluminium, cast alloy {GLO}| market for | Alloc Def, S” uses primary and recycled aluminium (average supplier) for production of aluminium alloy. In ALCA modelling mass allocation was applied and result is same as in CLCA modelling where system expansion was applied with use of negative flows of product B (figure 2). If economic (revenue) allocation was applied instead of mass allocation, different results could occur. Including the recycling of aluminium chips in CLCA modelling provides environmental benefit (figure 4a). On the other side, recycling is excluded in the system boundaries of ALCA and therefore in CLCA benefits from recycling of aluminium for joint production of products A and B are -1.97E+00 kg CO_2 eq. Finally, when environmental impacts of product B are allocated, the product A generates impact on climate change of 3.49E+00 kg CO_2 eq. for CLCA, and 1.61E+01 kg CO_2 eq. for ALCA (figure 4b). Another point of interest would be different modelling of coproduct B flow. In general, for this example, results from CLCA produce larger environmental loading then ALCA.

5. CONCLUSIONS

This research represents an attempt to draw attention to differences between the ALCA and CLCA modelling where significantly different results can occur. Therefore, it is very important to address the modelling choice in goal and scope of LCA because it will impact the choice of activities in LCI, allocation rules, and finally, obtained LCA results. The main differences between the ALCA and CLCA can be identified as following: differences in activities included in within the system boundaries, differences in activities from Ecoinvent LCI database, differences in linking the activities within the system boundaries. It can be concluded that the choice which one to use depends on following: if investigation has to separate the product from the rest of technosphere and environment, if inputs and outputs need to be attributed to the functional unit, or if there is need for comparative analysis of products and focus on the long-term effect of the changes. Direction for future research is that experts in field of LCA should focus their efforts towards development of international guide for ALCA and CLCA. The new guide for ALCA and CLCA should be compatible with present ISO 14040 standard, gather proven findings of previous research, include all possible situations of ALCA and CLCA modelling, and it has to define how practitioners should select whether ALCA or CLCA is the right choice.

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