Relative Contribution of a Subsystem to the Environmental Impact of a Complex System: Application to Aluminium Electrolysis Conversion Substations

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Abstract: We focus in this paper on the contribution of a subsystem to the environmental impact of a system. In this way we propose to explore some limits related to Life Cycle Assessment (LCA), in particular the consideration of the use phase specificities (for example lifetime, technology or energy mix). Two cases studies concerning AREVA T&D's aluminium electrolysis conversion substations are proposed to illustrate these problems. The first one considers the environmental contribution of a transformer to the electrical substation, whereas the second one studies the contribution of the substation to primary aluminium production. We show that the context specificities of a product should be taken into account in order to assess its real environmental impacts. To ignore them can lead to false conclusions, what is essential to avoid when a company wants to define its eco-design strategy.

Keywords: Environmental evaluation; Life cycle assessment; Complex system; Subsystem; Aluminium electrolysis conversion substation.

1- Introduction

Environmental issues have become a major concern in companies. The environment is now often integrated into product design and completes the economic or technical aspects. It clearly appears like a key-driver to innovation.

Tools like Life Cycle Assessment (LCA) allow evaluating the environmental impacts of a product or service to identify improvement ways. Although LCA has been standardized in the 90s [I1], numerous limits have appeared [RR1, RR2], in particular when considering complex systems. They concern all the four phases (Goal and scope, Life Cycle Inventory, Life Cycle Impact Assessment and Interpretation) and are responsible for potential mistakes, uncertainties or inaccuracies. As Reap *et al.* says, LCA is still *"a tool in need of improvement"* [RR1].

Moreover, from an industrial point of view, knowing the exact contribution of a product to its environment or location site becomes essential. Some works have already highlighted the need to include a specific usage (consumer habits) or exploitation parameters (location, energy, transports…) into LCA [C1], because a generic approach can lead to false results.

We propose in this paper to focus on the relations between a system and its subsystems in terms of environmental impacts in a specific context. It means that great uncertainties can exist on the lifetime

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of a subsystem because of economic aspects at the system level for example. It means also that the same product can be implemented in different location with different specificities.

An application has been made on AREVA T&D conversion substations in two case studies. The first one assesses the contribution of one element of the substation to the substation, so it deals with AREVA T&D internal design considerations. The second one studies the contribution of the substation to primary aluminium production, so it includes more shareholders, in particular AREVA T&D's customers.

We expose in Section 2 the different problems that will be considered. Section 3 is dedicated to the methodology and it presents the two case studies that will be detailed in Section 4 and 5. We conclude on some remarks and perspectives in Section 6.

2- Problem setting

2.1 – LCA, complexity and specific context

Life Cycle Assessment (LCA) becomes really heavy to implement with limited resources face to complex systems. Reap *et al.* summarize in [RR1] and [RR2] the main current problems in LCA (see Table 1.). These topics become particularly problematic when the complexity of the studied system increases.

Table 1. LCA problems by phase (from [RR1])

Phase	Problem
Goal and scope definition	• Functional unit definition • Boundary selection • Social and economic impacts • Alternative scenario considerations
Life cycle inventory analysis	• Allocation • Negligible contribution ('cutoff') criteria • Local technical uniqueness
Life cycle impact assessment	• Impact category and methodology selection • Spatial variation • Local environmental uniqueness • Dynamics of the environment • Time horizons
Life cycle interpretation	• Weighting and valuation • Uncertainty in the decision process
All	• Data availability and quality

Some aspects of these problems concern specific environmental contexts: functional unit definition, alternative scenario consideration, local technical or environmental uniqueness, spatial variation, and dynamics of the environment or time horizons.

2.2 – Problem definition

Actually in a specific context the environmental impact of a system can be extremely different from the theoretical one. We focus in this paper on several reasons:

- For a same subsystem the technology used at the system level can be different from an application to another, or can be changed during the subsystem use phase. This could have great repercussions on the environmental impact of the system, and so on the environmental contribution of the subsystems. As said in [RR1], it is hard to *"predict with confidence the future"*.

- The lifetime is not always clearly known, particularly for industrial systems with a long use phase (>20 years). This is extremely important in order to quantify the environmental impact of electrical and electronic products, where the use phase is often predominant. This problem is in particular highlighted by Cooper [C1] and Günther and Langowski [GL1]. Furthermore the lifetime notion is sometimes hard to define (is the system at its end of life when changing a key subsystem?).
- The energy mix that supplies the system could be really different from an implementation of the system to another. In the primary aluminium industry for example, this could radically change the environmental impact of the system [L1], and the relative contributions of the subsystem to the system.

The fact is that these elements can be extremely important to orient the eco-design strategy of a company towards its customers and shareholders (towards the macro system) and suppliers (towards subsystems).

So our research question is formulated as: how to measure the contribution of a subsystem to the environmental impact of a complex system in a specific context?

We propose to study the relationship between the environmental impact of a subsystem and its system in a changing context. This will be performed thanks to two case studies with AREVA T&D.

3- Methodology

3.1 – Overview of the methodology

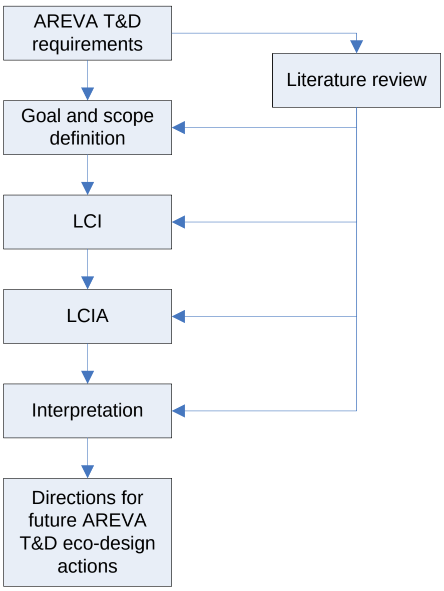

Figure 1. Articulation of the second case study

We have measured the contribution of a subsystem to the environmental impact of a complex system through a classical LCA approach described in ISO 14040 [I1] and two related case studies.

In the first case, all the data were available in the company, so the LCA study has been focused on the subsystem and its contribution to the impact of the system.

In the second case, the data concerning the subsystem (which is the system of the first case study) were available in the company, but not the data concerning the system. A study from the literature that offers us a complete set of eco-indicators results was identified. Thus the LCA is performed by referring at each step to this previous paper, as shown on Figure 1.

We propose a short screening of this approach with two industrial case studies about AREVA T&D's conversion substations.

3.2 – Application

AREVA T&D PEM (Power Electronics Massy) designs, assembles and sells in the whole world conversion substations for the electrolysis of aluminium (see Figure 2). As part of the aluminium smelter, AREVA T&D wishes to identify:

- the contribution of an electrolysis substation to the environmental impact of primary aluminium production to orient its future eco-design actions with customers. Even if environmental assessments have already been performed on primary aluminium production, the detail level is never sufficient to distinguish the substation from the smelter.
- the contribution of the substation subsystems to the environmental performance of the substation to orient internal eco-design actions.

These studies will permit to progress towards more eco-friendly products in accordance with the AREVA T&D environmental policy and previous works [B1, D1].

The next sections present in more details the two case studies.

Figure 2. Example of AREVA T&D conversion substation (ALUAR smelter, Argentina)

4- Application – Scope of the study

4.1 – Systems description

Primary aluminium production is based on the Hall-Héroult process discovered in 1886, using aluminium electrolysis. This process follows different steps identified on Figure 3. We focus in this section on the aluminium electrolysis stage.

An aluminium smelter includes the aluminium electrolysis and casting steps of the primary aluminium production. It is particularly energy-intensive – the amount of energy consumed by a recent primary aluminium plant is comparable to the amount of energy delivered by a nuclear plant unit (about 1 GW) – and it is then located where energy is relatively inexpensive and always available. That is why electricity is generally produced from hydropower, gas or coal. The smelter is moreover often located near consequent transportation ways to import alumina and export aluminium (harbors, roads or rail tracks).

A generic smelter consists in:

- potrooms that contains hundreds of electrolysis pots (commonly between 200 and 400 in a one-kilometer long building),
- a casthouse,
- an electrode plant that produces anodes for the electrolysis process,
- an AC to DC conversion substation that supplies energy to the potlines from the grid (Figure 2),
- some other elements such as storage and auxiliaries buildings, silos or transportation facilities.

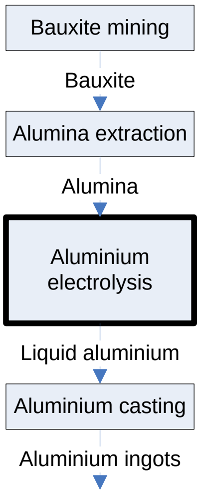

Figure 3. Process flow of primary aluminium production

The conversion substation is a key element of an aluminium smelter, as it permits to convert energy from the high voltage network to energy that can be used for aluminium electrolysis.

A conversion substation is made of several groups (4 on Figure 2) which are composed of a regulating transformer, a rectifier transformer and a rectifier. The groups are connected on one side to the high voltage network through a high voltage substation (air or gas insulated, AC current). On the other side they are connected to a busbar that is directly connected to the electrolysis potline (DC current). Filters are also added to the assembly to protect the network against harmonics and to improve the power factor. All the groups are supervised by control elements which are also connected to the electrolysis pots control system to regulate the process.

4.2 – Data collection

As no internal data were available to model the primary aluminium production process, results from the literature were used.

Aluminium data in LCA databases are often based on reports from EAA (European Aluminium Association) [E1] or IAI (International Aluminium Institute) [I2] which are representative of the aluminium industry. These two organisms regularly update the data dedicated to LCA databases. They include mass, energy and emissions overview related to the different aluminium processes.

Other literature references have also been identified on the subject. Tan and Khoo [TK1] perform an LCA of primary aluminium production on an Australian case study, whereas Koch and Harnisch [KH1] focus on greenhouse gases for the European aluminium industry. Norgate *et al.* [N1] propose as well environmental indicators for different metal production including primary aluminium. Finally, Leroy [L1] offers very useful and complete environmental data for the European aluminium industry.

However, one very interesting study about the environmental assessment of primary aluminium production, based on a real case is the LCA conducted by Schmidt and Thrane commissioned by ALCOA [ST1]. Its goal is to quantify the environmental impact of a project of a new aluminium smelter in Greenland. It takes into account almost all the previous studies and proposes numerous different scenarios with different energy mixes and two types of pot technology ("existing" and "new").

However none of these papers distinguish the substation from the other capital goods (the smelter in particular). Our life cycle inventory data are mainly based on a substation for a 360,000 tons per year smelter (same capacity as the ALCOA Greenland project in [ST1]). For different reasons (time, data availability…) the substation modeling has been simplified. The only following equipments are considered: regulating transformers, rectifier transformers, rectifiers, busbars and civil engineering.

The LCI includes specific data concerning masses, distribution, energy and end of life. The other data (materials extraction and production, energy production and distribution, end of life) are generic data from the Ecoinvent 2007 and IDEMAT 2001 databases.

4.3 – Modeling

We choose to focus on three main scenarios from the Schmidt and Thrane study [ST1]:

- Scenario A: smelter in Greenland, new technology, 100% hydropower.
- Scenario B: smelter in China, new technology, 100% coal.
- Scenario C: equivalent to the recommended alternative scenario (Sc0) in [ST1], corresponding to a new technology in China, Middle East or CIS. The electricity mix is: coal 62%, gas 9% and hydropower 29%. We assume that the smelter is located in central Russia for transport data.

The LCA is performed with Simapro 7.1 and the Stepwise 2006 method [W1], which considers indicators from EDIP 2003 and Impact 2002+.

Schmidt & Thrane's functional unit is *"1kg of virgin aluminium (ingots) supplied at a plant (100% aluminium, 0% alloying metals)"* [ST1]. This functional unit is kept to obtain comparable results. As the substation is designed for a 360,000 tons per year smelter and is assumed to have a life time of *n* years, 1/(360,000,000**n*) of the substation is allocated to 1kg of virgin aluminium. Three values are considered for *n*: 30, 40 and 50 years.

5- Application – Case studies

5.1 – Case study 1: Regulating transformers/Substation

We study in this first case study the environmental contribution of the regulating transformers to the electrolysis substation. A simplified mass balance is given for the modeled substation in Table 2. Figures are voluntary rounded off for confidentiality reasons.

Table 2. Simplified mass balance for the substation

Regulating transformers	5*217 tons
Rectifier transformers	5*245 tons
Rectifiers	5*18 tons
Busbars	600 tons
Total mass (without civil engineering)	**3000 tons**
Civil engineering	6240 tons
Total mass	**9240 tons**

These figures show that the five regulating transformers account for 12% of the total substation mass. On energetic aspects, they are responsible of about 31% of the electrical losses of the substation.

The LCA simulations give us the results presented in Table 3. In this table the contribution of the regulating transformers materials to the transformer is first evaluated, and then we assess the whole life cycle (including materials, fabrication, distribution, use and end of life) for each of the three scenarios described in Section 4.3. The LCIA of the substation is also given in Figure 4. It shows in particular that the distribution phase is negligible.

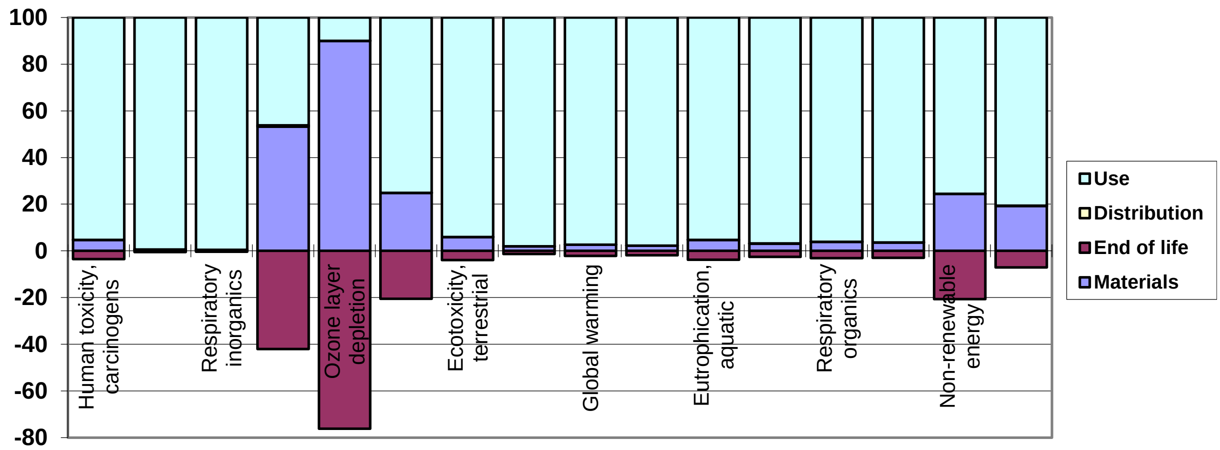

Figure 4. Example of life cycle impact assessment for Scenario C with a lifetime of 30 years

The regulating transformers are a major environmental contributor to the impact of the substation for all the Stepwise indicators. In terms of materials (including civil engineering), except for the mineral extraction criteria, they contribute to more than 50% to the substation impact. It could seem strange because the rectifier transformers are heavier than the regulating transformers. In fact this result is due to the mass of insulating oil which is more important for the regulating transformers than the rectifier transformers.

When including the other life cycle phases (in particular the electrical losses during 40 years), the contribution of the regulating transformers is lower. Scenario B (100% coal in China) and C (coal 62%, gas 9% and hydropower 29%, in Russia) are quite identical. The contribution in Scenario A (100% hydropower in Greenland) is about half the contribution in Scenarios B and C.

We can also notice that the variation of the indicators values is never higher than 1% by changing the lifetime to 30 or 50 years instead of 40 years, as it impact at once the transformers and the substation in the same magnitude.

5.2 – Case study 2: Substation/Primary aluminium production

This second case study considered the contribution of the substation to the environmental impact of primary aluminium production. So it includes the aluminium electrolysis stage, but also bauxite mining, alumina production as well as transports.

Concerning the smelter itself, Schmidt and Thrane [ST1] consider in 2009 that the electrolysis process needs 13.3 kWh (respectively 15.3 kWh) to produce 1 kg of liquid aluminium with a new pot technology (respectively an existing pot technology). In our study we consider that the substation is the same for the two types of technology. A calculation indicates that the substation electrical losses account to 1.5% (respectively 1.3%) of the energy necessary to electrolysis.

The results of the LCA simulations presented in Table 4 show the contribution of the whole substation life cycle to the primary aluminium production as described in [ST1]. The three scenarios are taking into account as well as two alternatives with existing technology instead of new technology (Scenarios A1 and C1).

Almost all the indicators are under 1% (or even 0,1%) except one (*ecotoxicity, aquatic*) for Scenario A and Scenario A1. For scenarios B, C and C1, most of the indicators are between 1 and 4% (which is not negligible), except *ionizing radiation* and *ozone layer depletion* which are lower, *respiratory organics* that accounts between 12 and 16% of the aluminium production, and *ecotoxicity, aquatic*, which shows problematic values (much more than 100%). These last values are mainly due to the transformer oil. One possible explanation is that oil is not taken into account in [ST1] when evaluating the capital goods impact from the USA IO-LCA database. It shows that those results have to be processed with attention. Further work will focus on this point.

Finally, changing the substation lifetime has a great impact for Scenario A. A lifetime of 30 years (respectively 50 years) instead 40 years causes a increasing (respectively decreasing) of all indicators of about 35% (respectively 20%). For Scenarios B and C, it concerns only some indicators, with equal or lower differences than Scenario A. As the smelter lifetime is *a priori* not correlated with the substation lifetime, it means that the relative contribution of the substation can be clearly modified.

5.3 – Discussion

Table 3. Relative contribution of the regulating transformers to the substation for the characterized Stepwise indicators

		Substation life cycle (lifetime of 40 years)		
Impact category	**Materials**	**Scenario A**	**Scenario B**	**Scenario C**
Human toxicity, carcinogens	52.18%	10,37%	30,80%	30,71%
Human toxicity, non-carc.	52.24%	10,18%	30,99%	30,98%
Respiratory inorganics	55.61%	13,62%	31,01%	31,00%
Ionizing radiation	52.95%	14,13%	27,06%	25,94%
Ozone layer depletion	56.82%	11,65%	19,52%	18,75%
Ecotoxicity, aquatic	56.10%	10,74%	30,16%	29,68%
Ecotoxicity, terrestrial	52.62%	11,87%	30,63%	30,41%
Nature occupation	51.29%	14,57%	30,92%	30,86%
Global warming	54.91%	14,30%	30,93%	30,89%
Acidification	56.04%	11,94%	30,96%	30,93%
Eutrophication, aquatic	55.95%	13,33%	30,88%	30,80%
Eutrophication, terrestrial	55.77%	14,61%	30,93%	30,88%
Respiratory organics	54.80%	13,24%	30,90%	30,83%
Photochemical ozone, vegetat.	55.07%	13,61%	30,91%	30,85%
Non-renewable energy	56.70%	11,71%	30,29%	29,89%
Mineral extraction	26.34%	12,14%	28,03%	26,60%

Those two case studies show that great dependences can appear when key parameters like lifetime or energy mix are changed, even if it is not always true. It is then useful to study in details these aspects in order to obtain valid conclusions.

Concerning the lifetime, which directly influences the environmental impacts of the use phase, the study shows that it does not influence the relative contribution of the substation elements to the substation, as their lifetime is correlated. But it clearly affects the substation contribution to the macro system (primary aluminium production).

Table 4. Relative contribution of the substation to the primary aluminium production for the characterized Stepwise indicators with a lifetime of 40 years

Impact category	Scenario A (new technology)	Scenario A1 (existing technology)	Scenario B (new technology)	Scenario C (new technology)	Scenario C1 (existing technology)
Human toxicity, carcinogens	0,04%	0,02%	2,10%	1,56%	1,00%
Human toxicity, non-carc.	0,01%	0,01%	2,92%	1,96%	1,96%
Respiratory inorganics	0,07%	0,06%	**15,89%**	**14,99%**	**12,79%**
Ionizing radiation	0,23%	0,23%	0,88%	0,71%	0,69%
Ozone layer depletion	0,07%	0,07%	0,13%	0,11%	0,11%
Ecotoxicity, aquatic	**16,31%**	**16,18%**	**371,40%**	**240,05%**	**237,36%**
Ecotoxicity, terrestrial	0,14%	0,14%	2,54%	2,11%	1,94%
Nature occupation	0,03%	0,03%	2,11%	1,68%	1,57%
Global warming	0,07%	0,06%	2,80%	2,66%	2,31%
Acidification	0,07%	0,06%	3,89%	3,64%	3,17%
Eutrophication, aquatic	0,03%	0,03%	1,91%	1,55%	1,44%
Eutrophication, terrestrial	0,08%	0,07%	2,76%	2,57%	2,28%
Respiratory organics	0,03%	0,03%	2,09%	1,76%	1,59%
Photochemical ozone, vegetat.	0,04%	0,04%	2,29%	1,92%	1,77%
Non-renewable energy	0,35%	0,33%	2,82%	2,39%	2,16%
Mineral extraction	0,84%	0,79%	4,29%	3,20%	3,04%

The technology choice (new or existing) has only minor effects on the results regarding the contribution of the substation on primary aluminium production.

The energy mix appears as extremely important in the two case studies. In the first one, the materials highly supplant the use phase for Scenario A (100% hydropower), whereas the contrary is observed in Scenarios B and C (dominated by coal). It means that environmental improvement ways could not be the same from a substation to another. This system is highly context-dependent.

As an illustration, some improvement actions (see Table 5.) can be proposed to minimize the environmental contribution of the subsystem to the system, depending of the energy mix.

Table 5. Example of eco-design actions according to the energy mix

System	Configuration	Improvement actions
Regulating transformers	100% hydropower	• Vegetal oil instead of mineral oil • Mass decreasing • End of life improvement
Regulating transformers	100% coal	• Electrical losses decreasing • End of life improvement
Substation	100% hydropower	Eco-design actions to improve the intrinsic substation performance
Substation	100% coal	Collaboration with customer on eco-design

6- Conclusions and perspectives

The two case studies exposed in this paper have shown that the environmental impact of a subsystem can be extremely dependent of the context of the macro system. It can clearly influence the LCA results, and thus the conclusions of the studies. We have in particular highlighted the great influence of the lifetime and the energy mix to the contribution of AREVA T&D's conversion substations to primary aluminium production. According to the context, LCAs will lead to different actions, which would not be identified in a generic assessment.

Concerning the lifetime, the problem is that the functional unit, described in ISO 14040 [I1], does not permit to include a more sophisticated model into LCA. Maintenance, which has not been taken into account in our study, and lifetime are key-elements to model the real life cycle of a product. They are necessary to assess the real environmental impact of a product in a usage context. When considering industrial systems, the lifetime is sometimes linked to political and economic choices (including ROI). Then it appears necessary to build a model that consider life cycle costs, technological choices, performances, obsolescence and maintenance together. For example, a subsystem like the substation will be updated after some years, when the technology pot will be changed to increase the smelter capacity. Such a model would permit to optimize choices in a system perspective and a changing context. Further works will exploit those aspects.

7- Acknowledgment

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