Coordination : Isabelle Blanc, *EcoSD Annual Workshop Consequential LCA*, Paris, Presses des Mines, 2015



presses@mines-paristech.fr www.pressesdesmines.com

ISBN : 978-2-35671-149-6

Dépôt légal : 2015

Achevé d'imprimer en 2015 (Paris)

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# EcoSD
# Annual Workshop
# Consequential LCA

Coordination :

Isabelle Blanc

MINES ParisTech

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# Introduction

Isabelle BLANC, Maitre de Recherche, MINES ParisTech,
coordinator of the EcoSD Consequential Workshop

## WHAT IS CONSEQUENTIAL LIFE CYCLE ASSESSMENT?

Consequential LCA is becoming widely used in the scientific community as an advanced modelling technique which describes and somehow assesses the consequences of a decision. It is currently referred as C-LCA.

## WHEN HAS IT BEEN IDENTIFIED AS A KEY ISSUE AND WHY?

Although it was introduced already in the 1990s, the topic has been elaborated mainly in the last years, thanks to the debate on the sustainability of biofuels. In fact, in that context, the debate on the competition between food and fuel pointed out the inability of present life cycle-based methods to account for indirect effects.

## WHAT IS THE UNDERLYING CONCEPT? HOW DIFFERENT FROM LCA?

The topic of C-LCA was at the top of the research agenda of many researchers worldwide, and this resulted in the publication of several case studies on a wide range of products/systems. In parallel, initiatives were undertaken, aimed at discussing the role of C-LCA and its modelling principles. New modes or types of LCA have been defined, which represent attempts to capture this new notion of C-LCA. Several underlying concepts related to the perspective adopted (prospective/retrospective), the direction in time (future/past), the temporal behaviour (static/dynamic), the typology of consequences analysed, marginal vs average, etc. are identified in the attempt to cover the multiple dimensions of C-LCA. It reveals the complexity of this new concept and the need for clarification. Methodology to perform consequential LCA is still open as there is yet no standard like for attributionnal LCA.

## IS IT A MODELLING TECHNIQUE OR A CONCEPT?

What emerges is that it is still necessary first to spend efforts on identifying the original questions C-LCA should address and second to enquire on how to properly implement them from the modelling point of view. Clarifying these two issues are the necessary steps to further strengthen the robustness of this approach.

All these questions are shared by a significant number of decisions makers within industry not necessarily belonging to the LCA community. They are very challenging and deserve time and effort.

Under the initiative of the EcoSD network, a full day workshop dedicated to this important and emerging topic has therefore been organized in March 2013 to address these issues and to share the current knowledge from recognized experts.

The workshop was organized around three main topics/sessions:

- What is at stake with consequential LCAs?
- Key methodological issues through the analysis of the state of the art
- Paving the way towards a common terminology, frames and methodology: illustrations through case studies.

The third and last session of the workshop included a few case studies illustrating how consequential LCA has been and can be implemented in the daily practice. The aim of this session was to highlight similarities and differences between the case studies, in order to identifies the key issues (related to terminology, methodology and frames) which should be further investigated and fostered to reach a global consensus and assure the comparability between the studies.

Around 50 researchers both from industry, academics and governmental institutions joined the workshop and had an opportunity to exchange with the experts which ended with a final discussion panel.

EcoSD Annual Workshop

# Consequential LCA

March 21st, 2013

VINCI headquarters, Rueil Malmaison

## AGENDA

| | |
|---|---|
| **Rapporteur :<br>A. Ventura** | 1. **What is at stake with consequential LCAs?**<br>– A review through significant examples<br>– Transport, buildings, *Speaker : S. Le Pochat (EVEA)*<br>– An overview of current initiatives and approach *Speaker : A. Zamagni (ENEA)* |
| **Rapporteur :<br>B. Peuportier** | 2. **Key methodological issues through the analysis of the state of the art**<br>– Defining consequential LCA « a modelling technique which describes the consequence of a decision »: what are the issues ? *Speaker : E. Benetto (TUDOR)*<br>– Identification of the affected processes: challenges and open questions *Speaker : A. Zamagni (ENEA)*<br>– Prospective tool? predictive tool ? to which time horizon ? *Assessing emerging technologies that only take into account short-term effects could be misleading. Speaker : B. Sanden (Chalmers)*<br>– The use of scenarios for LCSA and backcasting LCA *Speaker : R. Heijungs (Leiden University)* |
| | **Discussion and Conclusions** |

| | |
|---|---|
| **Rapporteur : E. Benetto** | **3. Paving the way towards a common terminology, tools and methodology : illustrations through cases studies**<br><br>– The need to consider background processes through a systemic approach.<br>Case study (1): Moving towards consequential electricity production<br>*Speaker : Charlotte Roux Chaire Eco-design of buildings and infrastructure MINES ParisTech*<br><br>– How to account for the equivalence of functionalities?<br>Case study (2) Recycling of slag (co-product of steel manufacturing) into road pavements,<br>*Speaker : Anne Ventura, Chaire of civil engineering and eco-construction, University of Nantes*<br><br>– Which tools?<br>Case study (3) : Economic modeling approaches for consequential LCI of biogas production from energy crops<br>*Speaker: E. Benetto. TUDOR*<br><br>Case study (4) : Using a long-term energy model for the consequential LCA of a future biofuel technology<br>*Speaker: F. Menten. IFPEN* |
| | **Discussion and Conclusions** |
| | **Final Discussion animated by C. Gobin (VINCI Construction France)**<br>What are the perspectives for cLCA? Who are the users? Which key industrial sectors are to be involved? |

# I - What is at stake with consequential LCA?

# A review though significant examples

Stéphane Le Pochat
EVEA (France)

## INTRODUCTION

The topic of consequential LCA (CLCA) emerged around twenty years ago (see for instance [Wei. 1993]), and the number of CLCA studies and publications dramatically increased from 2008 [Zam. 2012]. We can consider the assumption that this inflexion correlates with the high-media controversy about biofuels policies in Europe and USA. Anyway, the emergence of CLCA coincides with an urgent need of public authorities to solve complex questions, for instance: are biofuels really better than conventional fuels if considering the consequences on land use and competition with land for food crops?

Since ALCA and CLCA are frequently opposed (as pointed out by [Zam. 2012]), the stakes of CLCA need to be clearly stated. In fact we support the idea that this debate is not relevant as each of the two approaches addresses different objectives (the aim of CLCA being to assess the environmental consequences of a change within, or induced by, the system under study). We support that what is at stake with consequential LCA is twofold: reliability and cost. First the reliability of the results of the environmental assessment to engage sound sustainable decisions, and second the feasibility for practitioners and in order to engage final costs for decision-makers.

## TWO MAJOR STAKES

The suggestion defended in this short article, is that stakes of CLCA should be considered from the stakeholders' point of view, which are: (i) the "users" of results (i.e. the decision-maker), and (ii) the user of the tool (i.e. the LCA practitioner). Note that decision-makers and practitioners can eventually be the same. The decision-maker addresses the reliability of the LCA information for aiding the decision process, while the practitioner addresses the efficiency (ie. the costs induced by the performance of the LCA to obtain sufficiently reliable results to support sound decisions). Each of these two stakes (reliability and efficiency) are specified here below, and they are illustrated in the next paragraph through the case of rebound effect.

The reliability of information to support decision processes

Figure 1 below illustrates the different ways LCA studies can be used by decision-makers from various types of organizations. Four types of actions can be identified relying on a LCA study and its results:

- To engage strategic decisions (public policies or companies' corporate strategy).
- To support decisions during the design process (continuous improvement or radical innovation).
- To create knowledge
- To support environmental communication.

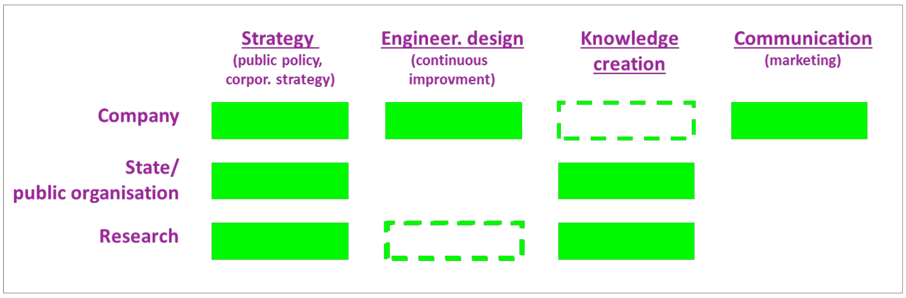


*Figure 1. Different uses of LCA results by organizations. From [LeP. 2011a].*

Of course, stakes of consequential LCA address all these situations but from environmental stakes point of view, the real stake concerns the strategic decision for public policies or orientations defined by companies.

For instance, Maestre Andrés et al. show that a biodiversity policy can be ineffective when not considering rebound effects [Mae. 2012], and a way to address rebound effect into LCA is to perform a CLCA.

The efficiency of obtaining reliable information from CLCA

From the LCA practitioner's point of view, an important stake relates to the efficiency of the method. Efficiency can be defined as the ratio of the performance versus cost:

$$Efficiency = \frac{Performance}{Cost}$$

Where:

- Performance is a measure of the relevance and reliability of the assessment,
- Cost is a measure of the required means (time and competences) to carry out the assessment

Indeed, the challenge of CLCA is that the method relies on prospective scenarios and data. Thus carrying out a CLCA can be highly time-consuming because of the inexistence of some required data. Furthermore the lack of robustness of existing or retrieved data directly questions the reliability of the results.

It should be noted that the stake of aid-decision process partly depends of the stake of efficiency. Indeed, if the study is too expensive (too complex or lacking of knowledge inducing too much time and money to acquire it), it will not be carried out and precious information will be missing for the aid-decision process. On the contrary, if the study is too light (less expensive because less available means), results will probably have a high degree of uncertainty and unreliability and thus will not can be used for the aid-decision process.

## ILLUSTRATION THROUGH THE EXAMPLE OF REBOUND EFFECT

A good example illustrating the stakes of CLCA is provided by the case of biofuels from crops. ALCA of biofuels only considers the environmental impacts of the system of producing 1 MJ of energy for motor-vehicles, while CLCA will also considers the impacts of the land-use change that is a consequence of cultivating large surfaces of crops to produce biofuels inducing deforestation to produce food-crops : first, if public policy does not consider the land-use change the decision will drive to an unsustainable policy, and second, the problem to carry out such a CLCA is to qualify and quantify the land-use change worldwide.

However, to go further, an illustration of these stakes is given here with the issue of rebound effect. Rebound effect can be described by "the consumption feedback loops of product modification. Rebound effect results in market-demand changes induced by introduction of modified products *[or services]*." [Gir. 2010]. Rebound effect is a relevant example because it is a high sensitive issue for environmental assessment but that is not considered with ALCA. Integration of rebound effect into LCA is a good example of implementation of CLCA.

Table 1 below gives some examples of rebound effects for different systems, and their respective retrospective measurement. Table 2 further describes some examples from table 1 and specifies for each what the stakes of reliability and efficiency are.

These examples show that for the considered systems, decision should integrate rebound effects. Indeed, if decision (for instance a public policy relative to energy consumption) is only based on the forecast of energy efficiency improvement, experience shows that this decision will probably support a non-desired result (here increasing of the energy consumption). To engage the right decision (stake of reliability) requires considering behavioral aspects underlying the rebound effect. Thus the decision should rely on a CLCA to integrate this rebound effect issue.

| Sector/ product or service | Figures | Rebound effect related to these figures | Sources / authors |
|---|---|---|---|
| Energy consumptio18n due to rebound effect from public policies in GB | Energy consumption | +30% (1975-2008) | From [Gossart 2010] |
| Energy consumption for heating in France (1973-2005) | Efficiency (kWh/m$^2$) = +41% | Energy consumption = +20% | From [Gossart 2010] |
| Road transport | Road transport<br>Road traffic | [+30; +50%]<br>[+50; +90%] | [Walker 1993]<br>[Hofstetter 2006] |
| Technological transition | Manufacturing energy use in industry | [0; +24%] | [Greening 2000] |
| Mobility | Time-rebound effect<br>Expenditure-rebound effect | kg $CO_2$ eq./h = 5.0<br>kg $CO_2$ eq./€ = 1.2 | [Girod 2010] |
| Electricity use | Time-rebound effect<br>Expenditure-rebound effect | kg $CO_2$ eq./h = 0.1<br>kg $CO_2$ eq./€ = 3.6 | [Girod 2010] |

*Table 1. Examples of quantified rebound effect for different topics. From [LeP. 2011b].*

| Topic | Explanation of rebound effect for this case | Stake of reliability for decision-making | Stake of efficiency |
|---|---|---|---|
| Energy consumption for heating in France | Figures of heating energy (households) in France show that energy efficiency for heating increased by 41%, but during the same period rebound effect induced a global overconsumption of 20%. | ALCA for energy heating will calculate an impact related to 1 kWh while CLCA will calculate an impact for 1.4 kWh. Figures for decision-making are really different. | Difficulties of data retrieval to qualify and quantify the rebound effect parameters (temporal, local and social specificities), inducing added time and means for the CLCA. |
| Road traffic | According to [Hof. 2006], the rebound effect induced by the construction of new infrastructures can reach 90%. That means the real traffic is measured at 190 when the foresight (before construction) was 100 (a new capacity generates an automatic increase of road traffic). | Foresight for the new capacity will estimate a traffic of 100 when a consequential approach will calculated a potential traffic of 190. Figures for decision-making are highly different. | Difficulties of data retrieval to qualify and quantify the rebound effect parameters (temporal, local and social specificities), inducing added time and means for CLCA. |
| Mobility | The time-rebound effect for mobility in Switzerland was estimated to be equivalent to 5 kg of $CO_2$ eq. per hour gained. Based on the example of high-speed train, this means that 1 hour gained thanks to high-speed train will be spent in another activity (more transport or expenditure) which respective GWP impact is 5 kg $CO_2$ eq/h and 1.2 kg $CO_2$ eq/€. | Foresight for the GWP of a mobility service (1 person.km) is estimated to be equal to Xa kg $CO_2$ eq. with ALCA when the same service will be calculated at Xc = Xa + 5 kg $CO_2$ eq./h with CLCA (where a trip of 400 km with TGV in France is assessed to be in a range of [1; 5] kg $CO_2$ eq). | Difficulties of data retrieval to qualify and quantify the rebound effect parameters (temporal, local and social specificities: rebound effect is given here for Switzerland and cannot be straightly extrapolated to other countries). |

*Table 2. Illustration of stakes of reliability and efficiency for CLCA.*

The problem is to succeed in quantifying the rebound effect for the system under study with a limited budget (stake of efficiency). Literature about rebound effect underlines the difficulties to quantify the rebound effect related to a particular system, and even the ability to prove it, as assessment of rebound effect can only be done retrospectively. Furthermore, rebound effect is highly sensitive to local and cultural conditions (see for instance in table 2 the time-rebound effect for Switzerland), potentially leading to high uncertainties.

## CONCLUSION

The aim of this article is to show that stakes related to CLCA mainly focus on two points:

– The first stake is the ability for the decision-maker to engage the right decision with a relevant and reliable information in an aid-decision context.

– The second stake is from the practitioner's point of view and is relative to the efficiency of CLCA as an assessment method. This second stake is partly correlated to the first one.

In term of aid-decision process, both for public policy or corporate strategy, critical issue is about the relevance, the reliability, and the completeness of the available information. Because aiming to address different objectives and analysing different systems, ALCA and CLCA provide different information. From this point of view, ALCA and CLCA are complementary rather than antagonistic.

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# An overview of current initiatives and approaches

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## INTRODUCTION

Consequential LCA (CLCA) is becoming widely used in the scientific community as an advanced modelling technique which describes the consequences of a decision. Although it was introduced already in the 1990s, the topic has been elaborated mainly in the last years, thanks also to the contribution given by the debate on the sustainability of biofuels. In fact, in that context, the debate on the competition between food and fuel pointed out the inability of present life cycle-based methods to account for indirect effects. The topic of CLCA was then at the top of the research agenda of many researchers worldwide, and this resulted in the publication of several case studies on a wide range of products/systems. In parallel, initiatives were undertaken, aimed at discussing the role of CLCA and its modelling principles, and new modes or types of LCA have been defined, which represent attempts to capture the notion that (C)LCA can be conducted in a variety of ways. Concepts related to the perspective adopted (prospective/retrospective), the direction in time (future/past), the typology of consequences analysed, marginal vs average, etc. are sometimes mixed up, in the attempt to better define the application of CLCA. What emerges is that it is still necessary to spend efforts on addressing the original questions about CLCA, i.e. what kind of questions can be answered by CLCA and how to properly implement it from the modelling point of view, so as to further strengthen the robustness of this approach.

## EVOLUTION OF CONSEQUENTIAL LCA

Introduced already in the 1990s, the topic of CLCA has been elaborated mainly in the last decade, with an increasing number of publications addressing both methodological aspects and applications. An important reference in this field is the work by Ekvall [2002], according to which CLCA was defined as aiming "at describing the effects of changes within the life cycle", where "changes" to some parts of the life cycle inventory system led to a series of consequences through chains of cause–effect relationships. Subsequently, more complete definitions were formulated, according to which "the consequential approach to life cycle inventory attempts to estimate how flows to and from the environment will change as a result of different potential decisions". Many other definitions were given, enriched over the years to highlight the market-oriented nature of the model. Thus, the terms "marginal and market-oriented" were used to denote an approach in which environmental profiles are compiled by addressing changes induced by a change in demand for the company's products [Zamagni et al, 2012]. In parallel, initiatives have been undertaken, aimed at clarifying the role of this methodology as a decision-supporting tool and its modelling implications. In the framework of CALCAS project (6 FP), in 2009 guidelines for CLCA have been developed, which describe in detail how to build up a consequential model in terms of: how unit processes are linked into product systems via intermediate product flows; how to deal with unit processes (or product systems) with multiple products; how the functional unit and reference flows should be defined. Recently in 2011 the UNEP/SETAC life Cycle Initiatives published the "Global Guidance Principles for Life Cycle Assessment Databases", i.e. a guidance that supports consistent practices for data collection, dataset development, and all aspects of database management. In the guidance, a definition of what a CLCA is has been provided and CLCA has been also characterised from the modelling point of view (data needed and management of the multi-functionality). In that context CLCA is defined as a "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". Moreover, it is specified that CLCA uses: i) data on actual supplier as long as this supplier is not constrained, otherwise uses data representing marginal technology; ii) system expansion approach to deal with multifunctional processes to expand the analysed system with additional processes.

Recent approach relate to the use of economic models for supporting the CLCA modelling. Although their use has been theorised since the beginning [see Ekvall and Andrae, 2006], only recently their use is becoming prominent. In fact, given that CLCA provides a way for addressing economic mechanisms into LCA, many researchers are proposing approaches in which partial equilibrium models (PEM) and computable general equilibrium models (CGE) are coupled with/integrated into LCA, as a way for detecting the consequences to be modelled in the system. A recent evolution of this approach is the development of macro-LCA (MLCA) [Dandres et al, 2012], which can be described as a prospective CLCA that takes into account non-marginal variations by means of a combined analysis involving LCA, GTAP model and scenario analysis. In many of these approaches the role of economic models is so predominant that it can discussed whether such studies still belong to the LCA domain.

Together with MLCA, different modes or types of (C)LCA have been identified, which represent attempts to capture the notion that CLCA can be conducted in a variety of ways. Frischknecht and Stucki [2010] introduced decisional LCA

(DLCA), based on future actual or anticipated economic and/or contractual relation. Moreover, the authors also propose the (economic) size of the object of investigation as a criterion for choosing among the different modes of LCA. More recently Guinée and Heijungs [2011] suggested that another mode of LCA might be relevant to explore: back-casting LCA (BLCA), a scenario-based way to model specific product systems to normative future targets.

## FRAMING THE QUESTION FOR CLCA

Overall, despite the initiatives in place, the case studies published show that it is still necessary to clarify the role of CLCA and its application in practice. Also in a recent workshop organised by JRC-IES on "Life cycle modelling approaches for environmental assessment of future-oriented scenarios: towards recommendations for policy making and business strategies", the role of CLCA and other approaches in the assessment of future-oriented scenarios was discussed, fuelling the well-known and still-not-solved debate on attributional vs a consequential LCA. Confusion arises in understanding CLCA because practitioners do not formulate the questions the study is aimed to answer in a clear way. Moreover, the concept of consequences is seldom mentioned in the purpose of the study and the authors do not always explain why a consequential modelling has been selected. An explanation for that could be that since CLCA is a "new" modelling approach, most applications have focused on testing the method in order to understand how it works and whether it gives different results compared to other modes of LCA.

In the literature often the authors outline the purpose of the study, which is not enough to decide which modelling approach to use. Simply stating that the purpose of the study is to evaluate the environmental impacts potentials associated with the production of X, or to quantify the change of environmental interventions after the adoption of several development scenarios, or to investigate whether a technology is a more environmentally sound alternative than a conventional way of producing a particular product, still leave rooms for interpretation. An example of how consequential questions have been framed is provided in the table below.

Stating the purpose of the assessment is perfectly in line with what required by the ISO standard in the goal and scope phase (ISO 2006). However, this proved not to be sufficient to properly address and model the problem. In fact, it is necessary to state what exactly the problem is that we are trying to tackle, what the derived question are, what the technological options are, what the scale of the expected changes is, what the time frame of the question is, if a ceteris paribus assumption may hold or not, if the system analysed is replacing another system at a small scale or if it is expected that the technology used in the new system will probably expand to many more applications on a larger scale [Guinée et al, 2009].

| Subject | Questions addressed | Target audience |
|---|---|---|
| Furniture (chair) | To compare the life cycle impacts of two chairs and identify the hot spots | Producers and designers working in the furniture sector |
| Enzyme products | To address the environmental impact potential associated with enzyme production in a cradle to gate perspective | The company that produces the product investigated in the study |
| Cassava | To assess the direct and indirect environmental impacts to be expected if Switzerland should replace 1% of its current diesel consumption with imports of soybean methyl ester from Brazil | Not specified |
| Palm oil biofuel | To determine the env. Consequences of the inclusion of second-generation biofuels towards current palm oil biodiesel production | Not specified |

## FROM CLCA TO LIFE CYCLE-BASED SUSTAINABILITY EVALUATIONS

The initiatives in place and the several approaches developed in the last years, show that CLCA is continuously evolving. Its novelty is represented by the possibility to introduce (micro) economic mechanisms into the analysis, in addition to environmental mechanisms and technological relations already taken into account in LCA. From this point of view, the modelling specifications in terms of which market mechanisms are included in the analysis can provide better indications than the term “consequential” itself, and this could also support a better definition of the questions.

Moreover, the logic of mechanisms could be the reading guide for further developing CLCA, considering it as an approach (and not a modelling principle with defined rules) to include mechanisms in the analysis. The more mechanisms are added, the more the ceteris paribus assumption related to both temporal and causal aspects are relaxed, evolving ultimately towards a dynamic modelling outside the realm of ISO-LCA. Specifying which constraints to impose, why, which we relax (for example change in functional unit, change in technology, constrained capacity, etc), which (market) mechanisms to include and how to report them, would support the introduction of more mechanisms into the analysis and contribute to making the assessment more consistent and robust. This developments go into the direction of life cycle-based sustainability evaluations: in fact, such an extended analysis would make it possible to address the several dimensions involved in a sustainability assessment, like time, the size of change, and the size of the consequences, considering the broad domain of the analysis.

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# II - Key methodological issues through the analysis of the state of the art

# Consequential LCA: what are the issues?

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## INTRODUCTION

Consequential LCA (hereafter C-LCA) has been defined as a life cycle modelling approach which pursues a quantification of the environmental consequences of a specific decision and of the related actions (Ekvall 2002; Zamagni, 2012). C-LCA is increasingly used to link micro-economic actions to macro-economic consequences, by identifying the (marginal) suppliers and technologies prone to be affected by large scale fluctuations in demand of commodities (e.g. Dalgaard, 2008; Schmidt, 2008b; Hertel, 2010). Despite the term "consequential" has been (and still is) often related to specific approaches and methodologies, like the ones developed by Weidema (2009) and Schmidt (2008a), one could argue that the term could refer more generically to the assessment of (direct and indirect) consequences originated by a change in the functional unit (FU) of the system under study, regardless of the methodology and approach chosen. This standpoint is supported by the *Shonan* report, which states that C-LCA can be defined as "a 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" (UNEP, 2011). This approach contrasts with the (conventional) attributional LCA (hereafter A-LCA) perspective, which aims at attributing to the selected FU a part of the overall environmental burden generated by a larger system (e.g. a supply chain or the entire economy) in which the FU is nested. While the fundamental characteristics of A-LCA have been formalized for years (e.g. A-LCA does not consider any mechanism of revenue maximization or price equilibrium under external constraints; it assumes that all the processes involved in the lifecycle are operated under steady-state conditions; it uses average inventory data under the *ceteris paribus* assumption; fully elastic market for all time horizons; ...), the key elements which characterize C-LCA and its related modelling approaches are still a source of discrepancy between LCA practitioners (Marvuglia, 2013a). In practice, the type of questions which can be answered by C-LCA, as well as its operational approach, data needs, limitations, uncertainties and practicability remain dramatically unclear to policymakers and most LCA practitioners in the industrial sector..

Based on the outcomes from a comprehensive and independent review on C-LCA as compared to the other LCA perspectives, drawn in the framework of a research project led by CRP Henri Tudor for SCORE LCA, this paper aims at pointing out what we consider to be the main methodological issues and related questions which characterize C-LCA, to set a common framework for the Workshop discussion.

## MATERILS AND METHODS

Firstly, a comprehensive literature review was carried out. A selection of 44 key published articles and reports was analysed against a number of criteria, depending on whether 1) a change in production and/or in demand or 2) an addition on the market of an innovative technology or product is of concern. In case 1), the criteria, based on Weidema (2009) were: determination of the nature of change (market delimitation, scale, time, multi-output processes); quantification of the change (trend volume in the affected market, changes in supply and demand); consequences (change induced by change in demand of raw materials and energy, due to an increased production of a commodity which requires these raw materials and energy to be produced, avoided production of similar commodities); and, type of question to be answered in the identified decision context. In case 2), the criteria selected were: increased/decreased consumption of raw materials and energy; and, change of end-of-life routes. In both cases, the main methodological issues which are unique to C-LCA as well as the limitations highlighted by the authors and the final outcomes of the study were analysed.

In parallel to the literature review, a comprehensive questionnaire was filled in by C-LCA experts, from academia, industry, public policy and consulting companies. The questionnaire included ca. 40 questions pertaining to the distinctive features of C-LCA as compared to other approaches, the decision context and goals targeted, the way multi-functionality is addressed, the combination of C-LCI and LCIA and so forth. The literature review and the experts' opinions were then consolidated and integrated at the sectorial level (energy, building and construction, mobility, waste and water treatment, manufacturing industry and primary sector). A final executive synthesis transversal to all the sectors was then issued (Benetto, 2013).

Based on the results, we discuss hereafter the main methodological questions and issues which characterize the C-LCA approach.

## RESULTS AND DISCUSSION

A correct definition of the decision context (i.e. the decision question and the related actions that have to be evaluated by the LCA, stakeholders involved, or are assessed using the LCA results as support information) is crucial for an adequate definition of the most appropriate C-LCA approach and for the subsequent correct use and dissemination of the results. A clear distinction between the study of consequences generated by political changes (e.g. a target ratio of biofuels at a given time horizon and spatial scale) and those generated by unavoidable changes (e.g. the increase of cereal production or political change) is observed. How shall the decision question be framed to streamline the scope of C-LCI? The following methodological elements are crucial to this aim.

Setting the temporal scale

Spatial and time scales are interrelated (e.g. long term perspective may engender larger spatial scale). Should LCA be restricted to long term (marginal) consequences, assuming therefore a fully elastic market? Are the transitory periods (short-medium term) of interest? There is no general agreement on the meaning and the setting of the time dimension in C-LCA. Is the use of time series (e.g. on a yearly basis) over the time span of the analysed changes (e.g. 15 years) required for accurate consequential modelling? Are these results easy to communicate to decision makers?

Considering constrains and multi-output processes

Do these elements affect the direct and/or indirect effects engendered by the studied changes? For instance, the consideration of constrained production processes (in relation to the market boundaries and temporal and spatial scales) may lead to the selection of a different supplier and, therefore, to different direct effects. The additional (reduced) availability of co-products from a multi-functional process following a change of production in the FU, may lead to replacements of commodities on the market and thus to indirect effects (ILCD, 2010). Similarly, the consideration of constrained processes and price mechanisms may lead to changes in the suppliers-clients relationships and, therefore, to other replacements. How are these effects included/excluded in consequential modelling? What is the rationale of including them or not with respect to the decision context?

Modelling scenarios and identification of marginal technologies and data

The modelling of scenarios requires considerable insights on the affected markets and (marginally or incrementally) affected technologies, which go beyond the common competence of LCA practitioners, requiring further expertise, e.g. from the macro-economic modelling field. Are data and information available for industrial practitioners? Does the lack of harmonization of field approaches lead to significant uncertainties and subjectivities in C-LCA? For the sake of operability of the C-LCA approach, the main simplifications concern the limitation of the scope (by e.g. neglecting part of the indirect land use impacts and system expansion), the dynamic character of the change (e.g. by aggregating the time series), the price elasticity (most often neglected) and the quality of marginal data and technologies (e.g. by considering average data instead or neglecting undefined processes). How do these simplified approaches cope with more sophisticated modelling approaches, like economic equilibrium models (e.g. Kløverpris, 2007; Rege, 2013; Vázquez-Rowe, 2013) or social models (agent based, e.g. Marvuglia, 2013b and Querini, 2013)? Can these be combined? Are they complementary or alternative options for the same decision context? What is the correct level of sophistication for a given decision context (precision vs. accuracy)?

Positioning C-LCA with respect to other LCA perspectives

Apart from the focus on changes rather than on a normative characterization of (past or future) systems, C-LCA differs from A-LCA (and decisional LCA) in the modelling approach, the system boundaries and the data used. Whereas C-LCA does include all the processes affected by the change, based on market mechanisms (the identification of processes as well as how far they are affected depend on the level of sophistication), the latter perspectives use different rationales. In A-LCA only average processes which are linked by physical exchanges to the FU are included (ILCD, 2010), whereas decisional LCA includes a mix of contractual relationships and average processes (Frischknecht, 2010). Are these complementary or compatible perspectives to answer a large decision context? Or are these incompatible approaches which could jeopardize the conclusions of a LCA and finally weaken the final recommendations? What are the exact boundaries of each approach?

## CONCLUSION

C-LCA is certainly a meaningful approach to address large scale decision processes in a variety of economic sectors (both at industrial and policy level) but, at the present state of development, lacks operability and harmonization. A selection of research questions and challenges has been structured around a number of key methodological steps: the decision context (and its boundaries), the position of the change(s) to be analysed along the time horizon, the availability, transparency and reliability of consequential inventory data and, finally, the correct communication of the results, especially as compared with other LCA modelling perspectives of the same product system.

**Acknowledgement** - The authors gratefully acknowledge the LCA experts who kindly accepted to answer to the questionnaire (a few of them are participating in the Workshop as well). The expert members of SCORE LCA (Hélène Bortoli, Bénédicte Couffignal, Daniel Dunet, Denis Le-Boulch, Stéphane Morel, Philippe Osset, Anne Prieur-Vernat, Olivier Rethoré, Sébastien Soleille, Christèle Wojewodka) are also gratefully thanked for their participation in the survey, as well as for the essential input provided to the project.

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# Identification of the affected processes: challenges and open questions

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## INTRODUCTION

Consequential LCA (CLCA) is indented as a specific modelling technique, which depicts the interactions of the system under study with the market in terms of changes induced by a demand. The modelling consists of including in the analysed system those processes that respond to the change in demand considered (i.e. affected processes), and of solving the multifunctionality problem by means of system expansion. A detailed procedure for supporting the identification of affected processes has been proposed since 1999 [Weidema et al, 1999] and recently revised and updated [Weidema et al, 2009]. However, the case studies published so far show that the methodological choices adopted for their identification are not always clear and transparent and overall, a proper systematization of the approach has not been achieved yet. This paper discusses the main approaches for identifying the affected processes, pointing out challenges and open questions for the research.

## CONSEQUENTIAL LCA AND ECONOMIC MECHANISMS

The inclusion of affected processes is a key element that distinguishes attributional (ALCA) from consequential LCA because – in the system boundaries – processes are included to the extent of their expected change caused by a demand. The identification of the expected changes in turn requires analysing the causal relationships or mechanisms that occur when a decision is taken, and that give rise to several consequences. This process is quite complex as a decision can affect processes through a wide range of mechanisms, which cause different consequences. A change in demand and/or supply may influence prices that determine what is produced (substitution mechanisms) and who can afford to consume it (income effects). Price changes in turn affect income to an extent that depends on how large the cost of the item is relative to the consumer's budget. Rebound effects or ripple effects, might then occur when, for example, the increased real income due to the reduced price of a good causes consumers to increase their demand for other goods [Zamagni et al, 2012]. However, even if the methodology requires that only (but all relevant) affected processes need to be included, not all of these consequences are presently taken into account in CLCA. The analysis is limited to market mechanisms, based on models of equilibrium between supply and demand. Thus, affected processes are identified on the basis of how the market of the system investigated might look like under the hypothesis of the change analysed.

### THE IDENTIFICATION OF THE AFFECTED PROCESSES

Central in modelling market consequences is a quantitative understanding of the markets and how direct and indirect changes in supply and demand of the analysed good or service act in the markets to cause specific changes in demand and supply of other goods and services. A procedure to support the identification of the affected processes has been developed by Weidema et al. (1999), and updated and refined in 2009 (Weidema et al. 2009)[1]. . It is schematised into a decision tree which guides the practitioners throughout the analysis of five steps: i) the time horizon of the study; ii) the analysis of the extent to which the changes in production volume only affect specific processes or a market; iii) the trend in the volume of the affected market; iv) the analysis of the extent to which the technology has the potential to provide the required capacity adjustment; v) the analysis of whether the identified technology is the most/least preferred.

## SIMPLIFICATIONS AND ASSUMPTIONS

Although a procedure exist for the identification of the affected processes, it is not systematically applied and in most of the published case studies the authors identify the affected processes using various arguments not always supported by the evidence of the market information. Moreover, several simplifications are adopted, such as:

- The number of markets dealt with simultaneously

Attempts to links many markets simultaneously have been done, using partial equilibrium models (PEM) or general equilibrium models (CGE), which investigate substitutable goods as they relate to a change in price [see also Earles and Halog, 2011][2]. Criticisms have been raised also about PEM about the following aspects: i) their ability to model only few markets and the uncertainty about which markets to include; ii) their inability to design and analyse different configuration of technology in the energy system than those implicitly assumed in the current business model; iii) difficulties in exploring alternative scenarios in which resources become

[1] Also Schmidt (2008) developed a procedure for system delimitation in agricultural CLCA.

[2] In the last year, the number of publications in which PEM and/or CGE are used together with LCA has increased.

unavailable for satisfying the demand and in which different patterns of consumption arise; iv) the lack of transparency and thus the difficulty in evaluating the degree of uncertainty associated to the data used.

- *The scale of the consequences* (usually marginal changes[3]). Recently, approaches to the investigation of non-marginal changes have been proposed, which gave rise to a new methodological approach called Macro-LCA (MLCA) [Dandres et al, 2012]
- The investigation of a stand-alone increase in demand, assuming that substitution occurs within the same type of products. For example if more carrots are consumed, this is investigated without looking at the simultaneously decrease in the consumption of tomatoes. As a default assumptions, substitution is assumed to occur within the same crops or derived products [Schmidt 2008]. Cross-substitution is thus usually neglected.

One of the major simplification refers to the *substitution mechanisms*. Usually only one market situation is modelled and only one affected process/technology is identified. In this regard, Mathiesen et al [2009] have demonstrated that this assumption about the affected processes is quite strong and it can completely change the results of a study. In fact, especially in the case of electricity, it was discussed that not just one marginal technology should be identified but a mix. In fact, the authors analysed the ability of CLCA to identify marginal electricity technologies by means of an analysis of statistical data on historical developments of the energy system. The results point out that in many situations the actual technologies are not those which could have been foreseen by applying the procedure for their identification. As far as the discrepancies between the actual and the foreseen marginal technologies is concerned, it is not clear – besides the assumptions and simplifications adopted in modelling the market consequences – if they are due to an inappropriate application of the recommended procedure or rather to the individual choices made by practitioners, seldom documented and transparent. Most of the authors state that reference was made to the five-steps procedure developed by Weidema et al. [1999], but this statement is not supported by evidence in the papers. Moreover, staying within the procedure, the techniques applied are different. Static models are used, in which practitioners identify for what technologies the production is constrained by a specific variable (physical, political, etc.). Also dynamic optimising models have been applied, as well as energy system analysis simulation tools.

[3] Typically the scale of the potential changes is small, which means the direction of the trend in market volume and the constraints on and production costs of involved products and technologies are not affected [Weidema et al. 2009].

## CONCLUSION

CLCA stands out as a method that includes (some) market mechanisms into the analysis. They regulate the use and development of a product into the market, by means of price effects, substitution mechanisms and even further with income effects. These mechanisms presently are not endogenised in the model but are derived from economic models/outlooks and then included as input into LCA. The main effects on LCA are related to the way in which the boundaries of the system are set and the processes to be included are selected, namely those affected by the dynamics of the market. The process of identifying affected processes/technologies strongly affect the final results of a CLCA study, as demonstrated by several studies [for an overview see Zamagni et al, 2012]. In fact, there is a high degree of uncertainty and a wide range of possible results, depending on the system enlargements, on the type of indirect effects included and on the assumptions and scenarios made. Moreover, it is worth considering that not only the final state resulting from a decision or action can be important in a CLCA, but information on the "intermediate" consequences, i.e. the transition phase, have been considered valuable for the decision-making context. However, besides the approach proposed by Hondo et al. [2006] this aspect is presently ignored in CLCA.

Considering the important role that CLCA could play in supporting decisions with long-term consequences and at the same time the high uncertainties due to the fact that market conditions may change rapidly, sensitivity analysis and the use of scenarios are unavoidable [Mathiesen et al. 2009].

Scenarios can play an important role in CLCA, contributing to a better understanding of the consequences under several market situations, and thus increasing the robustness of studies by providing an approach to think about plausible future developments in a structured manner. Scenario and sensitivity analysis together can contribute to considering how the consequences might change under several market situations, taking into account relevant parameters to calculate substitution, the possible marginal products on the world market and the feedback mechanisms. In this way they would provide a more scientifically sound basis to model specific product related futures with respect to technology development, market shifts, and so forth.

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# Some fundamentals on ALCA and CLCA

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## INTRODUCTION

There is a continuing debate on the difference between attributional LCA (ALCA) and consequential LCA (CLCA). In the literature, we see goal-oriented contributions, that discuss why ALCA and/or CLCA is important and what they therefore ought to do, and application-oriented contributions, that report case studies, sometimes even in a comparative sense for the same subject. In this short paper, we approach the issue from the foundational side, discussing the epistemological basis (how to obtain the answer to an attributional or consequential question), and we show how to use CLCA for the purpose of back-casting. Note that we do not necessarily build on the current practice of doing ALCA or CLCA; this paper addresses how they ought to operate.

## THE IMPACT FUNCTION AS A STARTING POINT

Suppose we have a mathematical function $\gamma$, that maps a commodity basket of consumed products, **f**, onto an environmental indicator (e.g., $CO_2$, $CO_2$-equivalent) $g$. For simplicity we will assume that there is a single (i.e. one-dimensional) indicator, but the theory may easily be generalized to the case of more than one indicator (e.g., inventory table, characterisation table).

We may refer to $\gamma$ as the impact function, and symbolize its role as

$$g = \gamma(\mathbf{f}) = \gamma\begin{pmatrix} f_1 \\ f_2 \\ \vdots \end{pmatrix}$$

This is all the information we have. Below, we will elaborate how ALCA and CLCA can be derived from this information. Note that **f** and $g$ can apply to the past, the present, or the future. In this way, we detach the discussion on ALCA and CLCA from its use *ex post* versus *ex ante*.

## DERIVATION OF ALCA

In ALCA, we are not interested in a change, but in a status-quo. That is, we wish to attribute a part of the impact to the various elements that make up the consumption basket. For instance, we wish to attribute a part to one unit of product 1, to 1000 units of product 1, or to all $f_1$ units of product 1. The part attributed to an arbitrary amount of $\varphi_1$ units of product 1 is referred to as $g_{\text{ALCA}}(\varphi_1)$.

The function $\gamma$ provides no direct clue to $g_{\text{ALCA}}(\varphi_1)$, because $\gamma$ is an economy-wide model, that is scale- and background-dependent. But there is one consistency requirement that we can pose to $g_{\text{ALCA}}(\varphi_1)$ and to all other similar attributed parts: they should add up to the total $g$ whenever they are scaled in the right proportion [Heijungs, 2001]. Mathematically,

$$g = \frac{f_1}{\varphi_1} g_{\text{ALCA}}(\varphi_1) + \frac{f_2}{\varphi_2} g_{\text{ALCA}}(\varphi_2) + \cdots = \sum_i \frac{f_i}{\varphi_i} g_{\text{ALCA}}(\varphi_i)$$

This still leaves open many possibilities for the calculation of $g_{\text{ALCA}}(\varphi_1)$. One natural option is to make it proportional to the ratio of the functional unit and the amount in the commodity basket that is consumed:

$$g_{\text{ALCA}}(\varphi_i) = C_i \frac{\varphi_i}{f_i} g$$

where $C_i$ is a constant that depends on the product $i$. Obviously, these constants should add to 1:

$$\sum_i C_i = 1$$

The ISO-14040 procedure [ISO, 2006], based on unit processes, is one way to determine these coefficients $C_i$. Other procedures (like EIO-LCA) give different results. And even within the ISO-14040 procedure, different allocation principles, cut-offs, etc. can lead to other values of the coefficients $C_i$. Note that the mathematical analysis presented above does not give any other clue to $C_i$ than the requirement that they add to 1.

## DERIVATION OF CLCA

In contrast to ALCA, CLCA is based on modelling changes. A functional unit represents an extra amount of a certain product on top of the existing commodity basket. For instance, when $\Delta f_1$ extra units of product 1 are consumed, the change of $g$ is

$$g_{\text{CLCA}}\left(\Delta f_1\right) = \Delta g = \gamma\begin{pmatrix} f_1 + \Delta f_1 \\ f_2 \\ \vdots \end{pmatrix} - \gamma\begin{pmatrix} f_1 \\ f_2 \\ \vdots \end{pmatrix}$$

Whenever the change $\Delta f_1$ is small, we may use the derivative of the function $g$ as an approximation:

$$g_{\text{CLCA}}\left(\Delta f_1\right) \approx \Delta f_1 \frac{\partial \gamma}{\partial f_1}$$

Note that the derivative should be taken at the present level, defined by ($f_1$, $f_2$, ...) , i.e.,

$$g_{\text{CLCA}}\left(\Delta f_1\right) \approx \Delta f_1 \left.\frac{\partial \gamma}{\partial f_1}\right|_{f_1, f_2, \ldots}$$

To avoid a cumbersome notation, we will leave out this specification.

More in general, we see that for a functional unit $\Delta f_i$ of product $i$

$$g_{\text{CLCA}}\left(\Delta f_i\right) \approx \Delta f_i \frac{\partial \gamma}{\partial f_i}$$

## THE CASE OF A LINEAR IMPACT FUNCTION

The foundations of ALCA does not give a full recipe for calculating $g_{\text{ALCA}}(\varphi_i)$, but gives only a formula that states a requirement which the recipe should fulfill. The parallel treatment of CLCA does provide a formula for $g_{\text{CLCA}}(\Delta f_i)$, in which the derivative of $\gamma$ with respect to fi shows up. Let us see what happens if we insert the expression for CLCA into the consistency requirement for ALCA, treating the ALCA-based functional unit $\varphi_i$ as a CLCA-based change $\Delta f_i$:

$$g = \sum_i \frac{f_i}{\varphi_i} g_{\text{ALCA}}\left(\varphi_i\right) = \sum_i \frac{f_i}{\varphi_i} g_{\text{CLCA}}\left(\varphi_i\right) = \sum_i \frac{f_i}{\varphi_i} \varphi_i \frac{\partial \gamma}{\partial f_i} = \sum_i f_i \frac{\partial \gamma}{\partial f_i}$$

In the simple case that $\gamma$ is a homogeneous multi-linear function of its arguments, like in

$$g = \sum_i a_i f_i$$

we have a constant derivative throughout:

$$\frac{\partial \gamma}{\partial f_i} = a_i$$

In that case, the previous formula reduces to a simple tautology ($g$=$g$), implying that for a homogeneous multi-linear impact function, there is no difference between ALCA and CLCA on the condition that the CLCA-based functional unit $\Delta f$ is interpreted as being identical to the ALCA-based functional unit $\varphi$. This is conceptually similar to the case of IOA, where the impact function is specified as

$$g = \gamma(\mathbf{f}) = \mathbf{w}^T (\mathbf{I} - \mathbf{A})^{-1} \mathbf{f}$$

with **A** the coefficient input matrix, and $\mathbf{w}^T$ a one row satellite, for a primary factor like labor or environment. With fixed **A** and **w**, marginal data ($d\gamma/df_i$) and average data ($g/f_i$) are just the same, so there is no difference between ALCA and CLCA.

### THE CASE OF A NON-LINEAR IMPACT FUNCTION

The linearity of the impact function is of course not realistic, as there are all sorts of economies of scale and cross-dependencies of sectoral activities. Let us suppose that the impact function is related to the square root of the consumption levels

$$g = \sum_i a_i \sqrt{f_i}$$

implying an economy of scale

$$\frac{\partial \gamma}{\partial f_i} = \frac{1}{2} \frac{a_i}{\sqrt{f}_i}$$

With this assumption, the consistency formula for ALCA will be violated, meaning that in such a case the consequential model may not be used to calculate an answer to an attributional question.

## HOW TO DO CLCA?

Doing CLCA means relying on the empirically established impact function $\gamma$. In classical process-based LCA [Heijungs & Suh, 2002], the impact function is

$$g = \gamma(\mathbf{f}) = \mathbf{b}^T \mathbf{A}^{-1} \mathbf{f}$$

while in IO-based LCA it is

$$g = \gamma(\mathbf{f}) = \mathbf{b}^T (\mathbf{I} - \mathbf{A})^{-1} \mathbf{f}$$

Alternatively, one may use non-linear forms, based on economic equilibrium models. Further, one may add fate, exposure and effect information by including an impact assessment, e.g.

$$g = \gamma(\mathbf{f}) = \mathbf{q}^T \mathbf{B} \mathbf{A}^{-1} \mathbf{f}$$

Such forms are obviously simplified, and only valid for small changes. But they serve a useful approximation, and they are used quite a lot.

## How to do ALCA?

Doing ALCA is in some ways easier than doing CLCA and in other ways more difficult. The easy part is that the impact function γ, a notoriously difficult thing, is not needed. But at the same time, that presents a difficulty. ALCA relies on partitioning the impact *g* over all products $f_i$. The way this partitioning is done does not rely on empirically established cause-effect relations, like in CLCA. Lacking empirical information, the only alternative is a rational point of view. This obviously presents an epistemological challenge, evidence of which is the continuing debate on allocation principles. In CLCA such debates can in principle be settled by doing the experiment. ALCA lacks this validation.

## Broadening into LCSA

Moving to LCSA by adding LCC and SLCA presents no fundamental obstacles; it just adds extra elements to the impact function. Broadening from product LCA to macro LCA (MLCA) is conceptually easy as well, because the impact function $\gamma(\mathbf{f})$ is unlimited in domain (so, it is valid for bigger values than just a small functional unit) and accepts moreover vector-valued arguments (so, it can accommodate a commodity basket). Of course, this poses high requirements on the impact function γ.

## Backcasting with LCSA

LCSA, conceived in consequential terms may be used for backcasting from a planetary boundary to a consumption pattern that fits [Guinée & Heijungs, 2011]. This last section will illustrate the procedure.

We take a simple two-process economy with two products. The production characteristics are

$$g = \begin{pmatrix} 0.1 & 0.12 \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \end{pmatrix}$$

where we concentrate on kg $CO_2$ as environmental indicator, and products 1 and 2 code for kg fuel and kWh electricity. We will introduce a "per year" on the variables, so that the elements of **f** code for kg/yr fuel and kWh/yr electricity, the indicator coding for kg/yr $CO_2$. Specifying the functional unit as a "per year" characteristics enables us to study the sustainability of consumption, in terms of a "safe operating space".

Suppose that environmental experts have determined a safe emission rate h for $CO_2$ as $6\times10^{12}$ kg/yr. Two extreme consumption patterns that fit exactly in this are

$$\mathbf{f}_1 = \begin{pmatrix} 60\times10^{12} \\ 0 \end{pmatrix} \text{ and } \mathbf{f}_2 = \begin{pmatrix} 0 \\ 50\times10^{12} \end{pmatrix}$$

In Figure 1, a solid line indicates all scenarios with a commodity basket that exactly fits.

Moreover, suppose that other experts (psychologists, economists, ...) have found the population's minimum or desirable subsistence levels for fuel ($b_1$) and electricity ($b_2$):

$$\mathbf{b} = \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} 20\times10^{12} \\ 20\times10^{12} \end{pmatrix}$$

These two minimum levels have been indicated by the dashed lines.

We can conclude that there is a feasible region, indicated by the shaded triangle, in which the consumption of fuel is at least equal to the minimum level $b_1$, the consumption of electricity is at least equal to the minimum level $b_2$, and the $CO_2$ emission is not bigger than the maximum level $h$.

Within this feasible range, there is still freedom. Suppose that, in addition, welfare economists specify a utility function

$$U = \begin{pmatrix} 2 & 6 \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \end{pmatrix}$$

meaning that the contribution of 1 kWh to overall welfare is 3 times bigger than the contribution of 1 kg fuel. Clearly, the extreme consumption scenario $\mathbf{f}_1$ has a utility $U=120\times10^{12}$ and extreme consumption scenario $\mathbf{f}_2$ has a utility $U=360\times10^{12}$. The theory of linear programming [Dorfman et al., 1958] teaches us that the optimum solution is in the feasible region with $f_1=b_1$, indicated by the small circle in Figure 1.

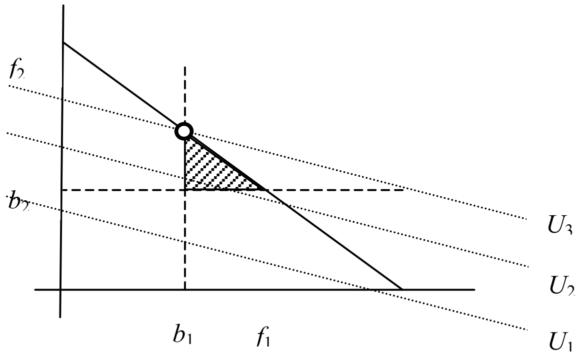


*Figure 1. The horizontal and vertical axis specify consumption levels with the dashed lines at $f_1=b_1$ and $f_2=b_2$ defining minimum or desirable consumption levels (the "good life"). The solid line defines the maximum consumption budget that just fits into the maximum impact level h (the "planetary boundary). The shaded triangle specifies the feasible consumption levels that satisfy all constraints (the "safe operating space"). The dotted lines, finally, indicate consumption patterns of equal utility; line $U_3$ has a higher utility than line $U_2$, which in turn has a higher utility than line $U_1$. The small circle indicates the point in the feasible region which maximizes U.*

## CONCLUSION

We conclude that ALCA and CLCA should build based on an empirically established impact function. For CLCA that suffices, but for ALCA additional attribution rules need to be defined through a rational method. The current homogeneous multi-linear model of LCA yields no differences between ALCA and CLCA; that is indeed observed in IOA.

A backcasting approach can be applied to CLCA, with a macro commodity basket as functional unit. The procedure can be summarized as follows:

- define the (process-based or IO-based) impact function $\gamma(\mathbf{f})$;
- define a planetary boundary or other target or limit on $g$, defined by $h$;
- define minimum subsistence levels $\mathbf{b}$ for each product;
- define a utility function $U(\mathbf{f})$;
- search for the solution $\mathbf{f}$ that maximizes $U$ under the constraints of $g<h$ and $\mathbf{f}>\mathbf{b}$.

A generalisation from inventory to impact level, and from single planetary boundary to the multi-objective is straightforward. A generalisation to the case of non-linear impact or utility function is less trivial.

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# III - Paving the way towards a common terminology, tools and methodology: illustrations through cases studies

# Moving towards CLCA to model electricity consumption in buildings

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## INTRODUCTION

The building and energy sectors have intense connections, especially through electricity consumption and production. Buildings consume in France around 60% of produced electricity; their demand is highly variable (hour of the day, working days, seasons). For these reasons the building sector leads the modulation of the production. For instance, electric heating induces a seasonal peak demand in winter with a high dependency to temperature, which is increasing every year [RTE, 2012].

Buildings can also produce electricity, control or decrease their demand through new technologies which are currently generalizing (heat pumps, photovoltaic modules, cogenerations systems…). They have a long lifespan, usually between 50 to 100 years and the replacement rate is low (less than 1%). This sector thus has both a short term and a long term influence on the electricity system.

Using in life-cycle assessment a static attributional method considering an annual consumption (or production) and an annual average mix disregards these mechanisms. We suggest developing a more integrated framework for electricity evaluation in Life cycle assessment:

- Replacing the use of annual average by an hourly model, using data e.g. from the grid operator (RTE in France),
- Allocating the impacts according to the temporality of each use (e.g. seasonality of space heating whereas the use of electricity for hot water is more constant during the year).
- Given existing capacities, how can buildings influence shares of each technology in the production mix? This requires the identification of the marginal technologies.
- Introducing mid- and long-term scenarios taking into account investments on new generation capacities.

In this paper, we present the research performed on the two first points. The model of use-specific hourly mix that has been implemented in a building LCA tool is explained and applied on a case study. We secondly propose some insights on how to deepen the consequential approach for electricity evaluation in building LCA, starting with determination of marginal technologies.

## BUILDING LCA

The LCA method was first applied in the industry. A first application has been performed in the building sector in the late 80's considering only energy aspects [Kohler, 1986]. The European project REGENER [Peuportier, Kohler, and Boonstra, 1997] sketched out a common methodology for building LCA. Other following projects like PRESCO [Peuportier et al. 2004] and LORE-LCA [Peuportier et al. 2012] have contributed to harmonize the methodology among existing tools and to promote LCA use by building professionals.

Linked to the thermal dynamic simulation tool COMFIE [Peuportier and Sommereux Blanc, 1990], the EQUER tool was developed to model the life-cycle of buildings [Polster et al. 1996]; [Peuportier, Thiers, and Guiavarch, 2013]. It considers twelve indicators, mostly from the CML2000 and Ecoindicator 99 methods to get a comprehensive set of environmental impacts. It also includes an extension to urban district evaluation [Popovici, 2005].

The assumption regarding the electricity mix is an important issue in LCA. Temporal variation and the possibility to use a marginal mix was already discussed by [Dones, Ménard, and Gantner, 1998].

## CONSTRUCTION OF HOURLY AND USE-SPECIFIC ELECTRICITY MIXES

The French electricity grid manager (RTE) provides hourly production values for nuclear, hydro-electricity, gas & coal, and fuel thermal plants. At time of study, data was available from 2007 to 2009. Our model has been based upon 2008 data because this year fits the most with a typical climate.

The electricity production is expressed as a sum of periodic functions corresponding to frequencies identified by Fourier analysis (daily, weekly, seasonal and yearly variations). Due to the importance of the heating use, the production also depends on climatic conditions, and mainly external temperatures. The production P is then expressed as a function of this average temperature $T_{av}$ and of time t:

$$P(t, T_{av}) = \sum(X_i(T_{av})*\cos(w_i*t+Y_i))+Z(T_{av}) \quad (1)$$

Where $w_i$ are the identified frequencies; $X_i$, $Y_i$ and $Z_i$ are parameters evaluated by a least-square method (quasi-Newton algorithm).

The average discrepancy between calculated and measured production is 4%. A part of the consumed electricity is imported (around 6% of production). This has been integrated to the model, so that a complete electricity production mix is derived.

This mix has then been disaggregated on four components, by analogy with co-products and allocation method in LCA: a base load component for yearly homogeneous use (hot water production) satisfied by nuclear energy and run-of-river hydraulic, a seasonal component (heating and cooling) satisfied by nuclear and thermal technologies (coal, gas and fuel), a weekly component for professional appliances, a daily component for domestic appliances, both integrating the three technologies.

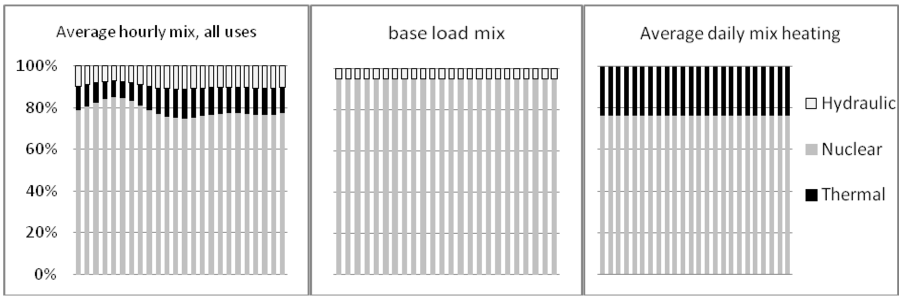


*Figure 1: Results of the model presented as aggregated daily mixes*

## CASE STUDY

This model has been tested on a case study. A single family house has been chosen in this first step (Incas platform, near Chambery). It was built according to the passive house performance level. The heated floor area is 90m². Using the thermal dynamical simulation tool COMFIE, the calculated heating load (19°C temperature set point) is 18 kWh/m2/year and the cooling load (26°C set point) is 4 kWh/m²/year. Electric air heating is used for space heating except for the "Cogeneration" alternative. Hot water is produced by an electric hot water tank. The annual consumption for other uses (lighting, ventilation, domestic appliances) is set to 2700kWh, corresponding to an average consumption per household in France [ENERTECH, 2007]. We have used Ecoinvent 2010 database [Ecoinvent, 2010] for the evaluation of environmental impacts. The considered annual mix is 78% nuclear power, 12% hydraulic power, 5% coal power, 5% gas power.

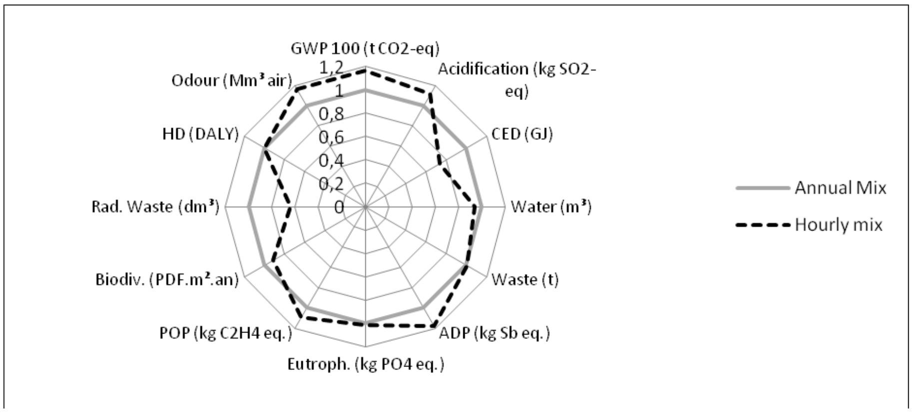


*Figure 2: LCA results of Base Case, Annual and Hourly use-specific mix comparison*

Differences between the two methods are significant (figure 2): 18% discrepancy for abiotic depletion potential, 16% for global warming potential and 36% for radioactive waste production. Using simulation instead of a constant annual average is therefore justified.

Electricity produced by photovoltaic or cogeneration systems and exported to the grid has also been evaluated. Standard technologies have been identified at each hour using the electricity mix model presented above, and the results are compared to the average annual mix. The use of an annual average mix underestimates the avoided impacts from the replacement of thermal and nuclear plant by cogeneration systems and overestimates it for PV systems.

This model could be further refined, using longer time-series for calibration, using more precise temperature reference and introducing parameters such as solar irradiation.

## DEEPENING THE CONSEQUENTIAL APPROACH

Consequential LCA is defined as a modelling technique aiming at evaluating consequences of a decision [Earles and Halog, 2011]; [Ekvall et Weidema, 2004]; [Zamagni et al. 2012]. This method is of great interest when feedback loops of important magnitude occur between the studied system (here a building or urban settlement) and background processes (e.g. electricity production). The study presented here is a first step towards the integration of consequential parameters in life cycle assessment of buildings. Providing an hourly production mix can still be classified as attributional LCA. However, allocating impacts to each use implies to relate a use to a specific technology assuming that the mix is a consequence of the use. It can be seen as an integration of the temporal segmentation of the electricity market [Mathiesen, Münster, and Fruergaard, 2009]; [Lund et al. 2010].

One main practical difference between attributionnal and consequential approaches is the use of marginal instead of average data. The determination of the marginal technology requires the knowledge of the economic merit-order of technologies and technical constraints (saturation). Several methods are developed in the literature to choose a marginal technology or mix (set of technologies), distinguishing: simple marginal technology, dynamic marginal technology or complex marginal technology [Mathiesen, Münster, and Fruergaard, 2009].

Simple and dynamic short-term hourly marginal technologies for electricity consumption have been estimated using [Weidema, Frees, and Nielsen 1999]; [Mathiesen, Münster, and Fruergaard 2007] and Guidance from the GHG Protocol for grid connected projects activities [Broekhoff, 2007]:

- Single hourly marginal: evaluation at each hour of technology on the top of the merit-order
- 5% or 10% of merit-order: set of marginal technologies at each hour covering 5% (or 10%) of total production

Results show a predominance of thermal technologies (coal and gas) in marginal mixes. Marginal mix at 5% compares well with a reference given by RTE resulting from marginal mix simulation.

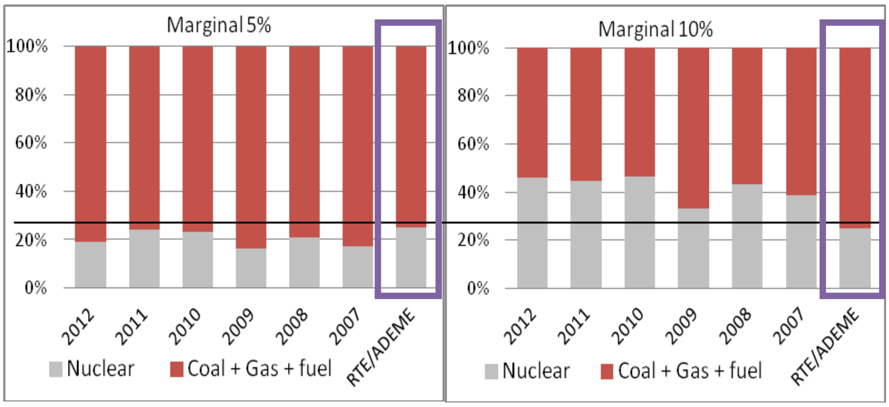


*Figure 3: Marginal mix at 5 and 10 %, from years 2007 to 2012*

Imports are not taken into account here, mostly due to the difficulty to classify them in the merit-order as there are several types of exchange contracts with high price differences. If the main advantage of these methods is the simplicity of the calculation, it does not allow a full understanding of the mechanisms involved. For instance, it does not allow to derive use-specific mixes, which can only be done using a complex model of the electric system taking into account both economic (merit-order) and technologic constraints (capacity saturation, on-off switch cycles, interconnections). On the other hand, modelling the electric system is highly data intensive and time consuming.

Investigating long term marginal technology is even more complex. It brings three questions that require energy system analysis and scenarios development (due to uncertainties related to resources prices, demand, public policies, emissions quotas...):

- How will evolve the installed capacity: which capacity will be installed, which will become obsolete? Under which conditions?
- How will evolve the demand on each technology installed? Under which conditions?
- What trends do the studied building project influences? (e.g reinforcing peak)

Actual prospective studies indicate a development of wind and solar power. However, planned future of fossil power plants and nuclear plants shows large variations between scenarios [Percebois and Mandil, 2012].

## CONCLUSION

Choosing an hourly or annual production mix model to perform building life cycle assessment has a large influence on impact evaluation. Using an annual model is not precise enough, and life-cycle simulation is more adapted.

First results considering marginal technologies show the high influence of thermal electricity production on environmental impacts. This calls for deeper research using energy system analysis and long-term scenarios. Great caution might be taken for long-term analysis due to the high uncertainties related to prospective studies.

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# Raising questions on system expansion and CLCA through examples from the construction sector

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## INTRODUCTION

Consequential LCA (CLCA) has been introduced through the initial allocation problem when considering waste management questions and allocation (Ekvall and Weidema, 2004; Ekvall, 1999; Weidema, 2008; Weidema et al., 1999). Avoiding allocation using system expansion, relies upon the concept that a given waste or co-product can compete with an existing one on the economic market, and that environmental credits can be attributed to the studied waste or co-product, because the production of the competing product is considered avoided (Weidema, 2008). The competing and avoided products are issued from a so-called marginal technology (Weidema et al., 1999). The equivalence between new and substituted products is modeled through supply and demand market equilibrium. That is basic model used in CLCAs. Since the initial question of allocation, CCLA has been the subject of many reflexions on the definition of its methological nature. (Sandén and Karlström, 2007) differenced ALCA and CLCA on static/dynamic concepts: in ALCA, the studied object is responsible for a share of the total environmental impacts of a steady state system, whereas in CLCA, the addition of a unit of the studied object is expected to change the state of the system, and the consequential LCA describes how the environmental impact is affected when the state is changed. The notion of a changing system is now widely adopted for the CLCA concept.

This article is based on examples from the construction sector, and aims at raising methodological questions about the relevance of using system expansion based on CLCA modeling. As written for a workshop, the article's objective is mainly to fill further discussions with the participants. It is organized in two parts around three main questions. The first part describes the use of consequential modeling for system expansion used to avoid allocation problems. The second part is focused on actual models used for CLCAs, on the three following steps: the relationship between competing products, the modeling of market equilibrium, and the environmental credits of substituted marginal technologies.

## SYSTEM EXPANSION, ALCA AND CLCA

If ALCA is a steady-state system LCA, and CLCA a system change oriented LCA provoked by additional units of products, using system expansion to avoid allocation, is indeed a mixing these two approaches. In a steady state system, the contribution of a product's life cycle is investigated at a given moment. In a changing system, the contribution of the change is investigated and there is thus an induced comparison between initial and final states of the system. This simple observation has consequences in term of modeling. For ALCA using system expansion, observed market equilibrium at the moment of the study (generally the present time) should be preferred, whereas for a consequential LCA, modeled market equilibrium should be preferred. Ekvall and Weidema (2004) detail how to expand systems for various allocation situations. For a multi-output processes where a product A is studied, they distinguish two cases where systems are expanded differently: first case (i) if a B co-product depends on the production of A, and second case (ii) or if A depends of the production of co-product B. Thus, studying A as a product or a co-product, leads to different results. If different perspectives can be acceptable when forecasting changing systems, they are contestable for present steady states sytems. Integrating an equilibrium which is representative of the actual situation, as suggested above, would resolve this point.

The reflexion is developed on the example of steel production and slag. To assess environmental impacts of steel as a study objective, steel producers (IISI, 2000) use a system expansion: slag is considered to replace natural aggregates into public works construction and the quarry production system is subtracted from the steel production system. Data observed on the French market of slag and public works have been collected (CTPL, 2006a, 2006b) between 2006 and 2010. Results show that only carbon and inox-alloys slag show confident averages of use in public works, whereas blast furnace and electric arc furnace slag are irregularly recycled in this sector. The recycling trend of carbon and inox-alloys slag is observed stable for 5 years. Substitution ratios of aggregates by slag are calculated to 0.03% instead of 1 as defined by (IISI, 2000).

The usual direction of questions in system expansion using CLCA is "what is the marginal technology that will be affected by the use of my co-product?" However, the new functionalities of a co-product should be examined in general, between several possible markets, given for actual situations that should be used to system expansion in ALCAs, whereas economic equilibrium models should be reserved for the study of system changes, where there is indeed an induced time dimension

## MODELING SUBSTITUTION BY SYSTEM EXPANSION

According to literature, once the marginal technology has been defined, there are three steps in the system expansion method: first, the relationship between competing products must be characterised, second, the equilibrium between markets must be modelled, and third and last, the environmental credits of the substituted marginal technology must be accounted.

Concerning the first step, the functional equivalency between different materials is not obvious. For example, the slag quantity necessary for a road construction can differ from the natural aggregates, depending on road structure and other materials, as previously shown (Sayagh et al., 2010). In the case of cement, slag can bring particular properties to the binder, and therefore new functionalities. It is dubious to assert that one material does substitute another. The actual equivalence of functionalities of different materials is almost a case by case question. Another important aspect concerning materials is the possible alteration of their functions with time. This point is particularly important in the construction sector (Ventura et al., 2012) where many objects are expected and designed to have a long service life. The functional equivalence between competing products should account for the alteration speed of main functions, in a given environment of use. Using system expansion only considers functional equivalence between competing products at the initial time.

Concerning the second step, the current practise in the literature, based on the neo-classical economic theory of "supply and demand" may not be sufficient to predict future equilibrium, some local quality constraints will influence markets, as well as the time behaviour of materials.

- In France, the production of natural aggregate resource is highly variable according to the region (Albecker et al., 2011). As road transport costs of aggregates becomes the main responsible for economic cost beyond 30 km, aggregates can be considered as a rare or an abundant resource according to the French regions.
- Quality constraints will influence future markets equilibrium: if standards are currently used for "classical" materials, they do not always exist for "alternative" ones. In that context, building and infrastructures owners do not will to engage their legal responsibility for non-standardized technical solutions. Regulation plays thus a major role for the adoption of a new material or new technology. This has been described as a third order consequence by (Sandén and Karlström, 2007).
- Finally, the other aspect of modeling market equilibrium is the influence of time span. As previously discussed, functions of construction material are generally altered with time. The differences of service life durations between different materials will affect the demand of these materials in the future and modify the market equilibrium, and there are lacks of such modeling.

The last step of the method is to calculate environmental credits once the market equilibrium has been defined. This situation can be described from the example of natural aggregate production. These are produced in quarries, using mechanical processes to crush and screen rocks into finer and sorted granular fractions. When competing materials, such as slag, reclaimed asphalt pavement or demolition concrete are produced from other systems, they are, after being sorted, also crushed and screened, just like natural aggregates, in order to suitable for further recycling. As they are themselves composed of initial fractions of natural aggregates, their fraction after recycling is generally finer than those of natural aggregates obtained from gross rocks. In order to obtain similar properties of alternative materials, these are generally not used alone; they are supplemented with natural aggregates of wider granular fractions. However, in the quarry process, producing wider granular fractions cannot be performed without producing finer ones. Finally the quarry activity does not decrease, it remains stable or even increase, and finer granular fractions are accumulated whereas the economic market is tensed on wider granular fractions. Furthermore, according to quarry administrators, the timespan duration of aggregate stockpiles can vary from 1-2 days for tensed fractions, to 10 years for finer fractions. The example on aggregate is a closed loop recycling, however, this problem is not specific to closed loop recycling. Another example in construction materials is the replacement of bitumen as a binder for road pavements, by oil binders, issued from vegetal production. Environmental credits due substitution of bitumen cannot correspond to the whole refining plant and crude oil extraction, knowing that many other products are provided. In a more general ways, this type of configuration is current. The calculation of environmental credits attributed to avoided marginal materials or products does not imply that the impacts of the marginal technology are avoided.

## CONCLUSION

Whereas ALCA are focused on the environmental impacts of steady state systems, CLCAs are focused on environmental impacts of changes in the system. This difference can be translated into methods to model influence of competing products on an economic market. Avoiding allocation and assessing environmental credits using system expansion in ALCA, i.e. steady state systems, should be calculated from observed data, considering all observed uses of the alternative products and not only one chosen as a “suitable” marginal technology. Forecasting market modeling should be dedicated to “real” CLCA, i.e. change oriented LCA. However, new modeling developments are needed, considering that, especially in the construction sector, markets can be very dependent on local conditions that will affect the scarcity of resources. In construction, objects have long life cycles, and forecasting models should also consider the speed of alteration of the functions of materials because they may affect future market demands. Finally, the calculation of environmental credits attributed to avoided materials or products does not imply that the impacts of the marginal technology are avoided. As soon as the marginal technology has multiple outputs; the increase in the demand of one of these outputs will increase the stocks of others but will not decrease the impacts of the technology itself. The method leads to a paradox: avoiding allocation using system expansion will lead to other allocation at the frontier of the expanded system. Should the system be expanded again, or could this paradox be solved by defining partition coefficient between the outputs of the marginal technology?

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# Economic modelling for consequential LCI of biogas production from energy crops

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## INTRODUCTION

Consequential Life Cycle Assessment (C-LCA), which is the life cycle modelling approach that seeks a quantification of environmental consequences of a specific decision (UNEP, 2011; Zamagni, 2012), is an increasingly utilized methodology to bind micro-economic actions to macro-economic consequences, in order to identify the marginal suppliers and technologies that may be affected by large scale fluctuations in demand (Schmidt, 2008b). In fact, C-LCA has proved to be a useful tool to determine the indirect environmental consequences linked to bioenergy production (Reinhard, 2011). This is due to the fact that a consequential approach takes into consideration the current worldwide land use changes (LUCs) that can derive from an expansion in the production of energy crops (Searchinger, 2008).

Detecting which technologies or crops will be most affected by changes in the production system is a critical issue in C-LCA (Brander, 2009), especially in agricultural systems with bioenergy production, linked to the displacement of other crops or other land use classes (e.g forest). Hence, LCA practitioners have started to gradually apply different models to combine with the life cycle consequential perspective to determine the LUCs that may derive from changes in the agricultural production system and, ultimately, the related environmental consequences (Kløverpris, 2007).

Therefore, the main objective of this article is to analyse one single case study linked to the cultivation of maize for bioenergy purposes in Luxembourg. For this, four different consequential modelling approaches were considered with the main aim of determining the degree of convergence or divergence of the results, as well as the appropriateness and validity of their assumptions for the selected case study.

## MATERIALS AND METHODS

### Characteristics of the case study

The case study selected seeks the computation of the environmental consequences in the agricultural sector in Luxembourg linked to an expected increase in maize production to produce bioenergy. This new input, set at 80,000 tonnes of maize, was the amount estimated that would be required to produce a total of 144 GWh of energy by 2020 from biocrops (MECE, 2010).

### Description of modelled consequential approaches

Firstly, a *computable general equilibrium (CGE) model*, named Global Trade Analysis Project – GTAP (Narayanan, 2012), based on the notion of market clearance, was used to provide a complete representation of national economies, as well as the specification of trade relations between different economies. A second approach, using partial equilibrium (PE) models, was developed. PE models treat international markets for a selected set of traded products and are driven by optimization assumptions. Moreover, these models, when applied to agriculture, consider agriculture as a closed system without links to the rest of the economy, but take into consideration a high level of detail of the endogenous assumptions within the assessed sector. For this case study, two different approaches were modelled within PE models. On the one hand, a linear programming PE model was developed to explore the *maximization of revenues by farmers* based on their crop cultivation activities, but also on the livestock sector, which is strongly related to agricultural operations in Luxembourg. On the other hand, the other PE model is inspired on the model developed by Panichelli (2008), which aims at *minimizing a total opportunity cost* to satisfy a specific demand of maize produced in Luxembourg. Opportunity costs are defined as the additional economic effort implied by the choice to grow the second best (i.e. second most remunerative) crop available in terms of crop to plant. Finally, the third modelling perspective consists of a cut-off approach that does not use economic models to support C-LCA. It has been named the *consequential system delimitation for agricultural LCA*, and is widely described in Schmidt (2008a). It considers a wide range of economic variables, forming a coherent set of rules of thumb based on a deep knowledge of the markets that are linked and influenced by the decision and production system under study.

### Function and functional unit and System Boundaries

An initial functional unit (FU) was set as the shock of maize that would be injected into the agricultural system in Luxembourg in the period 2009-2020: 80,000 tonnes of maize. However, this FU was then rescaled to 1 MJ of energy injected into the natural gas grid. The system boundaries were not limited to the domestic agricultural system in Luxembourg, but were extended beyond these limits to account for the new import and export flows that arise as a consequence to the introduction of bioenergy production in domestic arable land. In fact, it was in the foreign fraction of the production system that a higher degree of difference between the approaches was detected, due to the underlying assumptions that were considered. Finally, the entire supply chain of biomethane production from maize was included within the system boundaries.

**Life Cycle Inventory and Life Cycle Impact Assessment**

The Life Cycle Inventory (LCI) stage presented small variations between the different modelling perspectives that were considered. This was mainly linked to the fact that these approaches generated different LUCs, affecting different types of crops within the domestic system in Luxembourg, and different effects on the international import and export flows. ReCiPe Midpoint and Endpoint (H) were the selected assessment methods in the computation of the environmental consequences. The software that was used was SimaPro v.7.2.

## RESULTS AND DISCUSSION

The simulations run with GTAP for Luxembourg were based on the FAO trade data, indicating that trade in the agricultural sector was being performed mainly with neighbouring nations (e.g. Belgium, France or Germany). However, results showed that the impacts on national and foreign production linked to the modelled shock would be very low, needing a shock of at least 100% higher to start to see any changes. Therefore, the results obtained wit GTAP indicate that the changes in the domestic system in Luxembourg would be fully absorbed by other nations without any need for increasing their production. Unfortunately, though, the GTAP simulations show that it is not an appropriate model to compute LUCs at a regional or micro-nation level.

Results for the other three approaches did deliver a series of LUCs patterns with considerable differences not only between the modelling approaches, but also between the scenarios that were predicted within each modelling perspective. On the one hand, the two PE models presented complex shifts in LUCs, which were linked to the endogenous optimization assumptions of the models. Nevertheless, while the differences in LUCs were minor in the scenarios modelled for the opportunity cost PE model, these were more noticeable in the maximization of revenues PE model due to the strong influence of livestock inclusion in the modelling. The latter issue is linked to the fact that despite the maximization of revenues strategy by farmers, they also seek cheap feed sources for their cattle. On the other hand, the decision tree model proposed by Schmidt (2008a) presented limited changes in crop patterns, since the expert opinion approach constitutes a simplification of the potential LUCs occurring in the region.

Once the crop pattern changes were integrated to calculate the environmental consequences linked to the modelled shock, results showed to be limited. The similar environmental impacts associated with the different crops cultivated in Luxembourg implies that the relevant LUCs identified in the different models (excluding GTAP), are not translated into substantial environmental consequences. In fact, all the modelled scenarios show a similar range of environmental consequences (all with a slight increase as compared to the 2009 baseline scenario), except for scenario C1 which considers imports of soybean from South America rather than imports from neighbouring regions (Fig. 1). Hence, the environmental consequences beyond Luxembourg's borders increase substantially in this scenario.

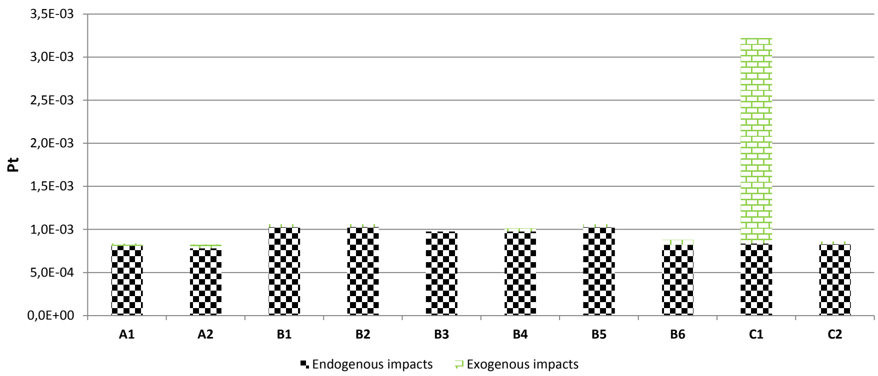


*Figure 1. Environmental impact consequences for the selected scenarios based on their exogenous or endogenous link to the economic models (Results reported per FU). A scenarios= maximization of revenues; B scenarios= opportunity costs; C scenarios= decision tree approach.*

## CONCLUSION

Results prove the importance of methodological assumptions when a C-LCA study is developed. In fact, the selection of the modelling approach to determine the LUCs, as well as the delimitation of the cascade effects through the market showed to constitute important sources of result variability. When analysing the different modelling perspectives, none of them fully managed to cover the entire cascade of relevant consequences identified in the case study. For instance, the GTAP model lacked the level of granularity needed to assess a limited domestic market like the case of Luxembourg. The PE models showed a good level of detail regarding the LUCs within the domestic market, but lacked the mechanisms to assess how these limited LUCs would impact beyond Luxembourg's borders. Finally, the decision tree model suggested by Schmidt (2008a) provided a deep understanding of the market interrelations, but with a limited level of detail regarding the specific consequences.

Based on the obtained results and on the derived discussion, we defend that the use of scenario modelling in C-LCA, which can be considered a common procedure in this type of studies, should also be complemented by the use of several modelling approaches, since the endogenous uncertainties linked to the specific modelling approach may be as important as the assumptions performed directly by the LCA practitioner. Finally, we argue that given the limitations found for all the different approaches, a future development could be the integrated use of two or more modelling approaches in order to cover a wider range of indirect effects throughout the marginal boundaries of the analysed case study.

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# Using a long-term energy model for CLCA of a future biofuel technology

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## INTRODUCTION

It has been recognized that often, well-intentioned policies are ineffective due to the narrow, event oriented, reductionist models that were used in their definition (Sterman, 2002). An example is the use of attributional LCA to determine greenhouse gas (GHG) emission reduction thresholds for biofuels in the European Renewable Energy Directive (RED). By assessing only the emissions associated to the steps physically linked in the products' life-cycle chain, it fails to capture underlying feedback on other elements that might be affected by the decision to promote biofuels. Therefore, numerous researchers are currently working in the development of broader tools (e.g. Acquaye et al., 2012; DeCicco, 2011; Delucchi, 2010), such as consequential LCA (CLCA), that would help us to better understand the global warming consequences of biofuel production. By doing so, better operating policies could be designed.

Following this trend, our work contributes to the development of methodologies for the prospective environmental evaluation of actions in the energy sector. These actions, such as the introduction of a new biofuel technology, may induce non-marginal changes in the system, which are characterized by nonlinearities that can only be observed with the use of models. The goal of this paper is to show how a TIMES-type long-term energy model can be adapted for use in an LCA framework (i.e. following the ISO 14044 guidelines).

## METHODS

**Goal and scope definition.** Our approach is applied in a case study about the production of synthetic hydrocarbons (diesel, naphtha and kerosene) from biomass, a second-generation biofuel known as BTL (biomass to liquids). In order to illustrate our methodology, we seek to answer the following question: *What are the global warming impacts in the French energetic and transportation systems occurring as a consequence of the decision to produce BTL (introduction of a 100kt/year autothermic BTL plant in the system by 2020)?* The nature of this question leads us to use MIRET, a TIMES generated prospective model developed at *IFP Energies nouvelles*, as an assessment tool. Since it has a rich representation of technologies available to meet energy needs exogenously defined (bottom-up model) within a relatively large time-horizon (2007-2030), it can be used for the identification of changes occurring as a consequence of a previous decision regarding the investment in a new biofuel technology.

The functional unit (FU) adopted in this LCA study corresponds to the quantities associated to the function of the system represented in the model: *to satisfy the energy and energy services demand (heat / electricity household and industry demands, population mobility demand) in France from 2007 to 2030.* With respect to the system's boundaries, MIRET is able to capture a significant part of primary consequences induced by BTL production: processes operated as a direct market consequence of an additional demand for lignocellulosic biomass, processes substituted as a consequence of a supplementary availability of diesel, kerosene and electricity (coproduct of the autothermic BTL plant). Consequences on the petrochemical industry induced by the production of naphtha cannot be directly assessed since this sector is not described in the model. The inability to estimate indirect land use changes can also be cited as an important limit of the model. These limits, can be treated using classical CLCA techniques (step-wise approach – see Reinhard & Zah (2011)) or even broader models (e.g. general equilibrium).

**Life cycle inventory (LCI) modeling.** Originally, the MIRET model contained information concerning GHG emissions only in the technology descriptions. In order to build a proper LCI, however, upstream emissions associated to the commodities consumed in the energetic system had to be introduced in the model. Two different kinds of commodities were distinguished and treated differently:

**A.** Commodities produced in France: mainly agricultural products (rapeseed, sunflower, sugar beets, etc.), but also some intermediary products such as oxygen and hydrogen. Life-cycle heat, electricity and diesel consumptions were associated to the production of these commodities. Agricultural products were associated with aggregated energy consumptions related to machinery operation (tractors, irrigation, etc.) and to the production of fertilizers, pesticides, etc. It was essential also to incorporate the field $N_2O$ emissions to the model.

**B.** Imported commodities: mainly primary energy resources (coal, uranium, crude oil, natural gas, etc.), but also some manufactured products such as vegetable oils are possibly imported to France in the model. Life-cycle emission factors for $CO_2$, $CH_4$ and $N_2O$ were associated to these commodities. In the case of natural gas, for example, these emission factors correspond to its extraction from nature, treatment and transportation to the French borders.

*Hardlinking* the economic model with the LCI is important to maintain consistency within the calculations. For example, the electricity consumed in the production of French products is provided by the mix of technologies resulting from the model's simulation and we do not need to use an electricity mix from a generic LCA database. The relevant aggregate emission factors, such as the ones associated to electricity production, are built endogenously within the model.

**Life cycle impact assessment (LCIA).** The model computes emissions between 2007 and 2030. In other words, the LCI of GHG is built for this period. Traditionally, in LCIA the mass values for each pollutant accounted for in the inventory are associated to the potential impacts they may cause through linear characterization factors. However, questions have been raised about the accuracy of these linear characterization factors when emissions occur over a long period of time, as an instantaneous release of a pollutant does not have the same impact as releasing the same amount of this pollutant at a small rate over several years (Levasseur et al., 2010). In order to treat this matter (to sum the impacts of emissions happening over a long period of time) more rigorously, we used time-dependent characterization factors from IPCC (IPCC, 2007) for each GHG to calculate the Global Warming Potential (GWP).

**Results interpretation.** It is well known that long-term prospective models have large uncertainty. Most of the epistemological uncertainties of this study come from not knowing what are the market constraints in the future. In CLCA, it is important to have information on market constraints in order to accurately quantify changes in supply and demand of affected technologies (Weidema et al., 2009). Constraints of different nature can be included in MIRET: physical constraints (biomass availability, production capacities, etc.) and political constraints (minimum or maximum activity for a given technology, emission quotas, etc.). Uncertainties about political constraints in the long-term are very high so the results of our case study were analyzed under different political environments. Two contrasting scenarios were built: a REFERENCE scenario where the model is run under no political constraints; and a POLICY scenario including the European Union's RED with the National Renewable Energy Action Plans (NREAP), and the Fuel Quality Directive (FQD).

## RESULTS

In Figure 1 we can observe how each sector in MIRET is affected by the production of BTL in France. The values represented are obtained by subtracting the GWP result for a scenario in which BTL is produced from the GWP result of a scenario where no BTL is produced. Figure 2 represents the detail of the changes occurring in the electricity sector due to BTL production. It works as an example of how our numerical results can be fully explained by the technology substitutions occurring as a consequence of a decision. The "green" electricity coproduced in the BTL plant replaces electricity produced from fossil resources in both, REFERENCE and POLICY. The marginal technologies in POLICY have better yields and emit less GHG than in REFERENCE, which explains the lower GWP reduction observed for POLICY in comparison to REFERENCE in the electricity sector (Figure 1).

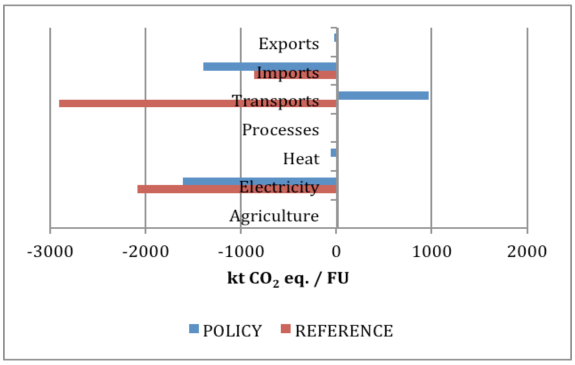


*Figure 1 - Contribution to the GWP of each sector of the modeled system*

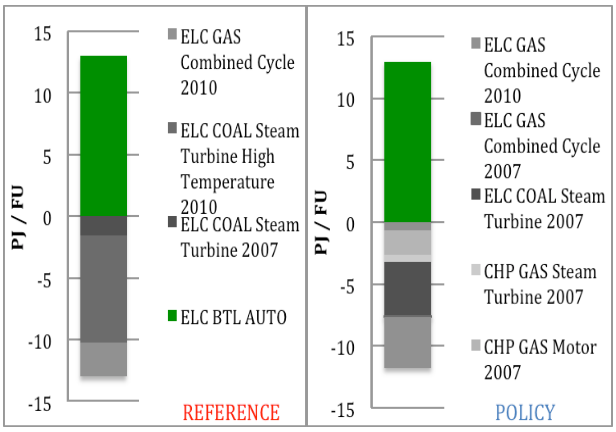


*Figure 2 - Substitution effects in the electricity sector for REFERENCE and POLICY*

## CONCLUSION

Bottom-up energy models can be adapted to perform the environmental evaluation of future technologies. In our work, different actions were taken so that the model could be used consistently with the ISO 14040 guidelines in each LCA phase (goal and scope definition, LCI, LCIA, Interpretation). The results show a high sensitivity to the policy and economic context (whether or not renewable energy production is favored). Under the specific conditions of this study, the consequences of introducing BTL are not clear-cut. Therefore, we focus on the lessons from the detailed analysis of the results more than in the precise-looking projections, illustrating how this type of models can be used for strategic planning (industry and policy makers).

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# The Consequential LCA program of Efficacity research institute

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## INTRODUCTION: MOVING TOWARDS SUSTAINABLE CITIES

European and French national commitments plan a reduction of 20% of the energy consumptions and the greenhouse gases emissions of the cities by 2020. To achieve this goal, it becomes urgent to take strong measures encouraging urban renovation, in order to improve the energy efficiency and decrease the carbon footprint of the cities, while ensuring quality of live and comfort for the citizens.

A city is a complex system in perpetual evolution, but these changes occur at different speeds depending on the scale (building, neighbourhood, district), the land use (housing, tertiary activities, public equipment) or the network type (energy, water, transport). Therefore, the urban issue has to be addressed with a **systemic approach**, that allows to optimize both the technological matters and the governance standards, so as to meet the demands of energy efficiency at a urban scale. Developing such a systemic tool, shared by all the urban stakeholders, is precisely the target of **Efficacity** research institute.

The organism includes partners from various sectors involved in urban design: 6 industrials (VINCI Construction France, Veolia, EDF, GDF Suez, IBM, RATP), and various engineering companies, universities and academic laboratories. Efficacity has the ambition to become a research platform recognized at an international level in the field of **energy efficiency at the urban scale**.

## THE CHALLENGE: APPLY THE CLCA TO THE URBAN DESIGN

Attributional LCA consists in assessing the environmental impacts of a system all over its operating cycle, assuming that this system corresponds to a definite functional unit. If LCA is well understood at the building scale, upgrading the methodology at the **neighbourhood scale** is still a topic of research. Moreover, when dealing with a problem at a city scale, the complexity of the system required more comprehensive tools. In fact, *classic* LCA, limited to the environmental aspects, does not deal with all the aspects of the urban issue, which **are environmental, economic and social**, and which often involve **dynamic processes**, such as the energy mix variations, the evolutions related to the use of the buildings, or the equipment aging. The ambition of the project "Life Cycle Analysis at urban scale" of Efficacity is to **extend the LCA approach** to all this features, and to apply at least this practice at the neighbourhood scale. If a focus is made on energy savings and greenhouse gases reduction targets, addressing the multi-dimensional features of the urban system in a relevant way makes compulsory a **systemic approach**, integrating environmental, economic and social issues. Three main fields of scientific challenges are at stake:

**The multicriteria aspects of the urban system**

The city management implies decisions taken different administrative scales (district, town, region…), by several actors (mayors, engineers, architects, citizens…). Moreover, a multicriteria modelling is compulsory when specific technologies (such as district heating or waste water treatment), physical phenomena (such as climatic aspects), or specific issues (such as transport) are addressed. Therefore, making a decision at a given scale, the neighbourhood for example, requires to know the boundary conditions of the system.

**The background system.**

One purpose of the developed method is to account for the influence of the studied system, i.e. a urban area, on the background system, i.e. the energy, the water or the transports networks, but also on other characteristics of the surrounding system: the quality of water, the economic situation of the region or the social life.

**The integration of inter-sectorial approaches.**

Dealing with all the previously mentioned questions necessitates the creation of an applicable platform making possible to couple building, energy and transport issues, with economic, environmental and social models.

The purpose is to develop a sustainability assessment tool based on CLCA, with an original approach.

## THE OUTLOOK: CLCA AS A MULTICRITERIA ASSESSMENT

Without a definite ISO standard, such as ISO 14040 and ISO 14044 [ISO, 2006] for attributional LCA applied to the building, there is still a discussion about the modelling principles of consequential LCA. Actually, the locution C*onsequential Life Cycle Analysis* can convey a variety of notions, depending of the background and the scope of the study. A general definition, given by Ekval, considers CLCA as a method "describing the effects of changes within the life cycle" ; the term *changes* refers to the fact some modifications in the LCA hypotheses lead to a chain of consequences, through a causal relationship [Ekval, 2002].

The Efficacity approach of consequential LCA stresses on the quantification the **environmental, economic and social impacts** of a project on the overall urban system with a progressive time scale [Efficacity, 2012]. This application of CLCA also intends to tackle **dynamic issues**, for instance the technologies, energy mix or demographic evolutions. The objective is to develop an assessment method to promote **energy efficiency as a driver for the ecological transition** towards a carbon-free city. In this way, the scientific program of Efficacity includes the **development of a multicriteria decision support methodology based on CLCA**. To reach this target, measuring tools will be developed, thanks to simulations of several technological and organizational scenarios and their effects on the general city performance. The Efficacity evaluation method will thus allow to compare various city planning operations, from new construction to refurbishment projects, and to analyse their impacts at a greater scale.

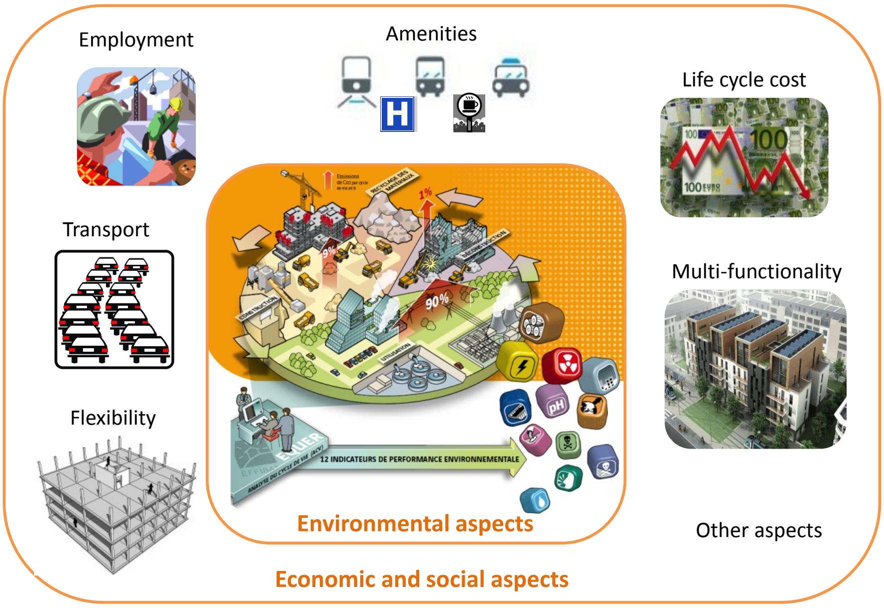


Figure 1: Principles of the consequential LCA approach in Efficacity

The field of application for this assessment tool is broad. Accordingly, major works of **urban design**, such as ring road construction, tramway network creation or a factory implantation can be investigated; these actions have indisputably great repercussions on the transport, land use, activities localization, and households settlement in the urban area. Besides, the studies will emphasize on the central question of **urban renovation**, not only at the building scale but **at the city scale**. Especially, the change of use of the buildings will be studied, with its impacts on the surrounding amenities in the area, as well as the use of recycled materials.

## THE METHOD: AN HYBRID APPROACH

To perform an efficient methodology based on multicriteria CLCA at a urban scale, an **hybrid approach** is implemented, combining **modular and systemic processes**.

The **modular approach** is based on the **system discretization into components** specific to a sector (energy, construction, waste treatment, etc.). Thus, each component of the city (buildings, stations, etc.) can be accurately studied and modelled, so as to feed the CLCA based assessment tool.

In parallel, the **systemic approach** consists in visualizing the territory as a huge **unitary system with its own metabolism**. Consequently, interactions between various factors can be taken into account with a distinction between strong interactions (inside a module) and weak interactions (between two modules). At this stage, optimization of the global system consists in finding a suitable compromise between those coupled phenomena, and potential technological couplings in the urban context will be studied (i.e. recovery of energy byproducts, local energy production, etc.).

The researches will eventually lead to the **definition of a comprehensive set of sustainability indicators**. The purpose is to develop a **label, *Efficacity Insight***, which aims to certify the energy efficiency at all the scales involved in the urban environment, from technologies to the whole city scale. In the end, this assessment tool will help beforehand the decision-makers to set their technical and managerial choices, and afterwards to measure the impacts of these choices on **the sustainability of a urban area**.

After three years of research and development, **the commercialization phase** of the *Efficacity Insight* will be launched. This phase will consist in selling measuring protocols and methodologies based on the sustainability indicators of the city, via engineering services provision.

## CONCLUSION

Aware that the sustainable city building is a key issue of the 21th century, contributors from various sectors, energy, construction, informatics or transport, decided to join their efforts into a common research institute, Efficacity. The purpose is to develop a comprehensive method to assess the sustainability of a urban project, whether it is a building, a neighbourhood, a network construction, or a larger operation.

The assessment method developed within the Efficacity framework is a step forward a complete life cycle based sustainability assessment. The challenge is to deal with all the dimensions of sustainable development (environmental, economic, and social) while taking into account the time dimension and the effect of the change characteristics in the system. The hybrid approach of Efficacity takes advantage of two complementary aspects, a modular and a systemic approach, both allowing to analyse individually all the city sub-components and the metabolism operating of the whole city system. Eventually, this *Efficacity Insight* label has the ambition to become an international reference for all the city stakeholders: conception, simulation, evaluation and management actors.

## REFERENCES

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# Conclusions

During this workshop on Consequential LCA (C-LCA), discussions between the experts and the audience were lively and we will report them through the following summuray articulated around three points: what are the questions to be adressed by C-LCA, what are the methodological issues of C-LCA and what are the research needs?

## WHAT ARE THE QUESTIONS TO BE ADDRESSED BY C-LCA?

According to Reinout Heijungs, there is no difference between A-LCA and C-LCA when impacts are evaluated using constant multi-linear functions. Both types of LCA have thus a common mathematical basis. However, there was a strong agreement that their objectives are different, on importance to identify which question(s) to adress for the system under study and on the identification of the frame to use, namely Attributionnal LCA, Decision LCA, Consequential LCA, Macro LCA and Backcasting LCA. Matching the issue and the proper frame has been illustrated by Alessandra Zamagni by relating a serie of issues within the electricity production to each type of frame:

- Which environmental impact can be attributed to the consumption of an average kWh of electricity at low voltage level purchased in Italy in 2008? Such question is clearly to be handle by attributionnal LCA (A-LCA).
- Which environmental impact can be attributed to the consumption of an extra kWh of electricity at low voltage level purchased in Italy in 2008? This one is related to Decision LCA (DLCA).
- Which effect the decision to purchase an additional kWh of electricity has on the electricity market and/or on the environmental impacts? This issue requires to be treated with a consequential approach (C-LCA).
- What would be the global indirect environmental impacts of a new energy policy in Europe? To be able to answer such question needs economic models (sectoral IO models coupled to LCA models) named Macro LCAs.
- What technologies are appropriate for fulfilling society-wide demands that fit within sustainability constraints? Backcasting LCA is the frame to consider for this issue (BLCA).

Discussions mainly turned around the comparison between A-LCA and C-LCA. Jeroen Guinée pointed that “there is no A-LCA against C-LCA, the question is how can we work together?” There should be a smart combination of approaches. Reinout Heijungs pointed out that the aim of A-LCA was to identify responsibilities of products in a given system whereas the aim of C-LCA was to assess the consequences of a change in a system. He used a simple example of a consumer basket to clarify the differences between A-LCA, aiming at attributing a part of the impact to the various elements of the basket, and C-LCA, aiming at evaluating the impact corresponding to an extra amount of a certain product.

Anne Ventura raised questions concerning the system expansion method used to avoid allocation as a valuable question to address in the frame of C-LCA. The term “system expansion” was qualified as misleading, because in that case, the change of functional unit drives the extension of system boundaries while the purpose is not to study the expansion of the system itself. Following this discussion we ended asking ourselves whether the system boundaries of C-LCA were identical to A-LCA or whether the definition of the functional unit was different as suggested by Jeroen Guinee.

As recalled by Enrico Benetto, consequential LCA has been identified as a relevant frame to study consequences at macro-level (ILCD decision context B) when changes in demand or supply of the market are foreseen.

The relevance of C-LCA for eco-design has been confirmed in the discussion: even if each decision is made at micro level, the sum of all decisions may have large consequences at macro level.This aspect was mainly highlighted through Björn Sandén’s presentation: he showed that with the aim of managing a system towards an advisable change, who showed that social mechanisms, initially considered as marginal causes, could induce drastic changes.

## WHAT ARE THE METHODOLOGICAL ISSUES OF C-LCA?

### How to set system boundaries?

As previously mentioned, discussions on the main difference between C-LCA and A-LCA have identified the shifting in system boundaries. In general you start A-LCA and then you enlarge the scale. However setting boundaries of a system for C-LCA is a very delicate issue: which system to account for?

Because C-LCA accounts for the interaction between the studied system and the background system, it requires identification of affected processes. Some methods are proposed like a procedure developed by Weidema and based upon a decision tree. But several simplifications reduce the reliability of practical applications, particularly regarding substitution mechanisms. Uncertainties remain high due to the fact that the market may change rapidly, so that sensitivity studies and use of scenarios are unavoidable. Varying scenarios is proposed to improve the robustness of the results.

System boundaries are set by the choice of scenarios and Jeroen Guinée raised was on how to build valuable scenarios. Isabelle Blanc stressed that the definition of interesting scenarios highly depends on the question C-LCA is in fact addressing.

A few participants highlighted that consequential LCA is still too much imprecise and inaccurate to be defended as a decision support frame towards top management in industry. In some cases, outcomes are more sensitive to uncertainties and these can be larger than marginal effect themselves. The question of assessing uncertainties related to prospective scenarios is raised and should not be overlooked to avoid discrediting C-LCA results.

## How to model the link between foreground and background systems?

Alessandra Zamagni showed the complexity of this question due to the **complex chain of consequences involving many indirect effects and market mechanisms**. The chain of consequence is complex: from substitution effects to rebound effects. While substitution refers to the introduction of new products on a market that may (or should), after a certain amount of time, replace current products, rebound effect (or take-back effect) refers to the behavioral or other systemic responses of the market to the introduction of new technologies that increase the efficiency of resource use. The type of modeling the time evolution can be continuously dynamics, discrete, and some studies do not really model but use comparison between various states of systems with a static approach using average values. Choosing between static and dynamic models should be justified for both the foreground and background systems. Setting the temporal scale is still under debate and is indeed a part of the scenario definition.

Two presentations focused on biofuels were presented based on Economic models.

Enrico Benetto underlined the necessity to use economic equilibrium models and presented a Partial Equilibrium model (PEM) approach to investigate the consequential effects of the implementation of a biogas policy in Luxembourg, aiming at producing bio methane from energy crops (maize). Two different PEM models, one rooted in opportunity costs minimization and the other on revenue maximization, specifically developed for the consequential inventory, were discussed and the results compared to the classical consequential approach based on expert opinions. The main conclusion was that the two PEM models lead to similar results and could be effectively complemented by the expert opinion approach, especially for the mechanisms which cannot be included in the PEM due to lack of data or information.

Fabio Menten presented the results of the application of a TIMES model (MIRET) for the consequential LCA of a future biofuel technology. Demands for energy and energy services were treated exogenously and technology innovation was included (through performance improvements). The life cycle impact assessment characterization factors (mainly Global Warming Potentials) were directly included in the economic model, differently from the previous study, were the LCA calculations were done separately from the PEM. It was found, as expected, that the consequences (to be included in the consequential inventory) do not scale linearly with the magnitude of the change and that the running of LCA calculation within an economic model is perfectly feasible.

To build up, Björn Sandén described a chain of effects from direct physical effect to linear response, negative feedback (mainly economic) and positive feedback (related e.g. to learning processes) which are more related to social mechanisms rather than purely economic ones. The influence of the last aspect on environmental impacts may be very large, but also very uncertain. If this effect is not taken into account there is a risk that society invests too little in advanced technologies with short-term drawbacks but potential huge long-term advantages.

Anne Ventura highlighted the issues of functional equivalence between products in the case of substitution mechanisms, in the civil engineering sector, treating the case of recycling of slag (as a co-product of steel manufacturing) into road pavements. If this question may be negligible for energy, it appears as a central one when studying construction materials. Equivalence of functions will not only depend on economic mechanisms, but on regulations (standards and responsibilities of decision-makers). Furthermore, economic aspects are very local, and related to availability and forecasting of stocks.

## SYNTHESIS FROM DISCUSSIONS AND RECOMMENDATIONS

### About questions to be addressed by C-LCA …

This part is not a direct transcription of the discussions from the workshop but it reflects our current conclusions on the consequential LCA with the aim of extracting synthetic knowledge from the workshop, considering discussions and presentations with a year of distance.

Through discussions, we can propose common points that seem to have the agreement of the participants to the workshop, about questions to be addressed by C-LCA:

- C-LCA accounts for the interactions between the studied system and the background system
- C-LCA is relevant to enquire consequences of these interactions at the macro-level of the background system
- C-LCA has been identified as a relevant frame to address marginal change decision as well as large scale decision process.
- The questions addressed by C-LCA frame aim at forecasting consequences of these changes within a given period of time by modelling market mechanisms.

From these collective observations, we deduct that in all cases (marginal change or large scale decisions) questions addressed by C-LCA are related to the **changes induced by the perturbation of the background system,** and that considering changes (i.e. comparison between different states of a system) **induces a time-dimension problem**.

## About allocation…

As a direct consequence of the above assertions, the use of "system expansion" to avoid allocation is not always synonymous of C-LCA, depending on how the time dimension is integrated. The importance of a proper disntinction between "system expansion" and "substitution" was highlighted by the auditors, the former being an artificial (virtual) weighting of the value of the co-function whereas the latter being an actual consequential approach, where the substitution actually occurs in the market. We thus give the following recommendations:

- In system expansion approaches, where the aim is only to avoid allocation and not to study system changes, C-LCA is not a suitable frame and substitution should be treated using the current state of market.
- If long term consequences are forecasted, the C-LCA becomes a suitable frame, requiring defining scenarios and/or models of substitution mechanisms, as well as sensitivity analysis.
- In addition, because "system expansion" was considered as a misleading terminology by the audience, we recommend that it should be replaced by "functional expansion".

## What are the research needs?

The introduction of the workshop by Stéphane Lepochat highlighted the stakes of C-LCA for companies, public organizations and researchers, by a necessary balance between reliability of LCA results in a strategic decision context and efficiency of the method.

Several issues and perspectives have been addressed in the final discussion between participants:

(1) It is essential to link LCA to other field of expertise and in particular we suggest fostering cooperation between LCA and macro-economic modelers.

(2) The social dimension should not be left out. The example of mobility was given where consumer's choices are found out not to be market based.

(3) The definition of the decision context and question to be asked by consequential LCA is mandatory for a consistent study. To design realistic and comprehensive scenarios for consequential LCA is key and require defining probabilistic scenarios accounting for uncertainties. There is no such thing as a correct scenario.

(4) The elaboration of a code of practice for C-LCA is needed to reach enough transparency and accuracy within an acceptable timeframe.

(5) Consequential LCAs are of high interest for decision makers for political decisions such as the ones related to the energy debate worldwide or to urban design as reported through the *Efficacity* research program. International journals should significantly increase the publications of such studies.

We closed the workshop recognizing that C-LCA is currently facing several challenges but should go ahead because “*It is better to be roughly right than precisely wrong”* (John Maynard Keynes).

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