SCORELCA

STUDY N° 2012-01

CONSEQUENTIAL LIFE CYCLE ASSESSMENT: STATE OF THE ART, OPERATIONALIZATION AND GOOD PRACTICES

SYNTHESIS EN

May 2013

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SCORE LCA is an association that has been created to financially support collaborative research on LCA and related topics. It aims to promote and organize cooperation between companies, institutional and scientists in order to support the evolution of LCA methods and its practical implementation at European and international level.

- ✓ This work has been supported by ADEME (Agence de l'Environnement et de la Maîtrise de l'Energie) www.ademe.fr

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1 Summary

1.1 Goal and objectives of the study

The present research was carried out by the CRP Henri Tudor for SCORE LCA targeting three main objectives:

1) To perform a comprehensive and independent state of the art of consequential LCA (C-LCA) and its use in the daily LCA practice, highlighting its methodological foundations and its differences with respect to the attributional approach;
2) To build a decision tree aiming at supporting and steering the LCA practitioner in the choice of the right LCA modelling perspective for a given application context, and especially identifying when a C-LCA approach is absolutely necessary;
3) To recommend future research orientations and needs to improve the methodology and operationability of C-LCA

These objectives are extensively addressed in the full report. The aim of this extended abstract is to highlight the main results and conclusion for the sake of maximum transparency and to explain the concept of C-LCA to practitioners without any previous knowledge in the matter.

1.2 Consequential Life Cycle Assessment (C-LCA): its history and conceptual foundations

Despite the term "consequential LCA" was used the first time at a workshop in 2001 (Curran et al, 2002), the term comes from the early 90s, i.e. from the very initial foundation of the LCA framework at the SETAC (Society for Environmental Toxicology and Chemistry).
The discussions which followed recently led to a generic definition of the term: "the assessment of the environmental consequences of one or more action(s) affecting the studied technological system". However, the exact **meaning** of the term**,** and its **practical implications** (when carrying out a LCA), remain unclear and inaccurate until the release of two reports from Weidema et al., in 2003 and 2009 [12] and [13].
The first one showed why it is important to consider the market in which the product studied in the LCA is sold and used, i.e. to account for the socio-economic environment surrounding the mere technological system studied in the LCA. Starting from this work, the notion of "consequential" has always be related to the consideration of market information, but the exact meaning and practical implications of that remained dramatically unclear.
The second report aims at filling this gap by proposing an operational approach to C-LCA, which is claimed to be generally applicable. The approach has, however, two important shortcomings: 1) the specific terminology (jargon) used hampers its intelligibility and makes it suitable only for LCA practitioners already cognizant of the notion of C-LCA; 2) the proposed methodological approach is indeed a specific case of C-LCA; as a matter of fact, there is now evidence that the notion of "consequential" is larger than the one explained in [13], and could be operationalized considering different tools and approaches.

As a conclusion, there is **currently no reference handbook or report** on C-LCA broadly speaking. There is no common agreement on the C-LCA concept and its operationalization, which are still debated in the LCA scientific community. Therefore, the approach is still not ready to be routinely applied in the daily (industrial and policy support) LCA practice. We even doubt that this will be the case in the future and that it is even desirable because, as it is shown in the report, the C-LCA cannot address all the types of decision contexts and industrial problems.

Based on the feedback from the experts interviewed, the literature state of the art and our methodological developments, a **simple introduction to C-LCA starts with the definition of the functional unit (FU)**. The FU is usually not a reference unit of product, service or process operation (for example the transport of one person over 1 km using a conventional vehicle). Instead, the FU quantifies a change **relative to a technological system, which has occurred (or will occur) in a given socio-economic context** (for example the change of transportation mode for 500.000 persons.km, from conventional to electric vehicles).

Because of the relationship between the notion of "consequential" and the assessment of a change, **the results from a C-LCA are not linearly dependent on the FU**. The consideration of actual scale of implementation of the change(in a specific socio-economic environment) is therefore primordial and is the first key distinctive element of **C-LCA as compared to A-LCA**.
The latter allows as well to better explain the notion of "consideration of market information", which is historically related to C-LCA. Indeed, in the aim of defining the actual magnitude of the changes, it is necessary to gather all the information related to the socio-economic environment surrounding the system being analysed and submitted to change, which is basically the market information.

The dependence to the market can even be better explained considering the second key distinctive element of C-LCA: the **consideration of the indirect consequences (effects) engendered by the studied change**. The term "indirect" refers to the consequences affecting technologies and production processes which are not essential to the FU, i.e. are not linked to it by technological relationships. These consequences would not have been included in an attributional LCA.

For example, the change of transport mode, because of the introduction of electrical vehicles in the system, may generate an increase of electricity production capacity, i.e. new production infrastructures, replacing older ones or other production activities. In other situations, the increased electricity demand following the introduction of electric vehicles may be answered by a marginal supplier changing its client because of economic reasons. The change would therefore **affect another activity sector** (**not related to the transport sector**), which will have to change electricity supplier because of the introduction of electric vehicles, or to change its production schedule.

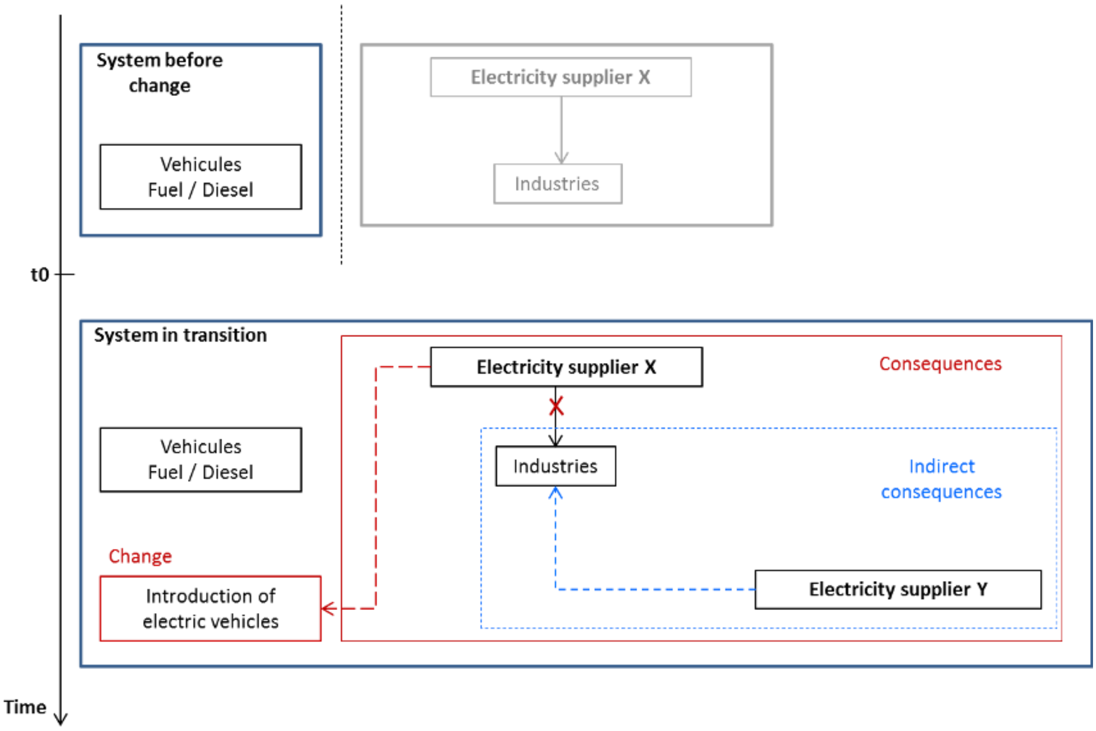

Figure 1 : Consideration of indirect consequences

All these changes affect activities which are not directly required (solicited by) the FU, but whose variations have to be included in the assessment because they **are linked by a cause-effect chain to the studied change in the C-LCA, which is therefore responsible of the chain**.

A second example could be the implementation of bio-fuel production in a region of Brazil. Before the production started, 90% of the cultivated land was used for livestock, while biofuel production was zero. There was no unused land available in the considered area. From the production start on the policy incentive sets a target of increasing production of bio-fuel of 1% per year during 10 years. The system is considered in status quo conditions at the time of production start, i.e. its average technological operation is set in a given political, economic, and social context.
In this situation an example of direct effect would be the land use change, from land originally used to raise livestock, to the land used to produce bio-fuel. An example of indirect effect would be meat imports following the change of land use, from livestock rising to the production of biofuel. The indirect effects basically reflect a substitution mechanism.

We can therefore state that the scope of C-LCA does include all the processes **(only these ones)** which are affected by the studied change, even if they are not directly related to the FU. Although the scope of a C-LCA may appear to be larger than the one of an A-LCA, the first one does not include all the processes directly related to the FU, but only the ones which are affected by the change. For this reason, it is not possible to infer that C-LCA systematically implies the collection of more datasets than A-LCA

Indirect effects may be due to **constrained production processes** (for technical, economic, or normative reasons) **in the inventory**, which have to adapt to face the novel demand engendered by the change, for example through a change of the production capacity or novel client-suppliers relationships. According to the feedback provided by experts, constrained production factors are the main sources of indirect effects. Indeed, they are not the most important source according to the literature. For instance, the introduction of electric vehicles on the French market for 10% of the current fleet of household vehicles in 2020 would lead to an increase in electricity demand. If current production capacities are not able to meet this increased demand in 2020, because their operation is already high, the production of electricity is constrained. New technological/infrastructural investments are needed to meet demand (indirect effect).

Other sources of indirect effects are suggested, especially **multi-output processes, i.e. processes producing several products** (main product and secondary co-products). Whenever the studied change (the FU) engender the variation of the available quantity (or of the demand) of the main (determining) product or one of the cop-products, the additional production (or lack of production) has to be absorbed by the market. This effect generates a chain of indirect consequences which has to be internalized by the C-LCA. For instance, the growth of steel (worldwide) market demand generates an increase in steel production in blast furnaces, which induces an increase in production of blast furnace slag, steel co-product. The slag substitutes a larger part of aggregate originally used in concrete mix, because of its wider availability and its advantageous purchase price (probably only applicable for concrete producers present in a limited area of the blast furnaces).
The last source of indirect effects arises whenever a novel product service or process comes into play because of the studied change, contributing to a novel (niche) market which was inexistent beforehand. For instance, the introduction on the market of energy saving light bulbs induces the need to develop their end of life treatment system. The treatment process at the end of life was not existing before the dissemination of saving energy light bulbs.

The notion of indirect effects and the related differences between C–LCA and A-LCA are sketched in the figure below, adapted from [12]. The circles represent the inventory (or the corresponding environmental impacts) of an economic system, for example the mobility needs of a city or region, or the total annual production of vehicles of a car manufacturer.

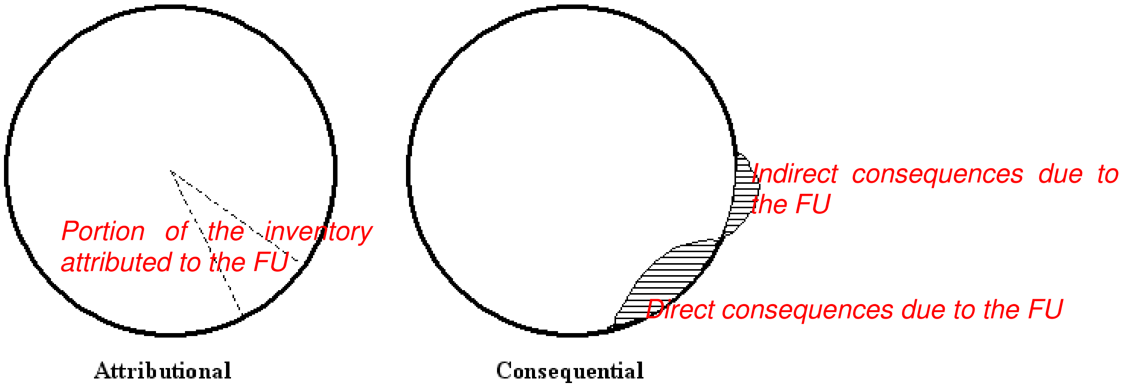

Figure 2 : Boundaries of an attributional and a consequential LCA

The goal of an **attributional LCA** is to **attribute a portion of the whole inventory to the specific FU**, which is in most of the cases a sheer reference unit, for example the transport of one person over 1 km with a conventional vehicle (specifying the brand, engine, etc.). Such a portion is highlighted by the dashed line, and is calculated in the specific inventory by separating the different components of the whole system (for example by isolating the inventory data per production line) and by applying the allocation rules (for example to attribute a part of the total electricity consumption of the production line to the different products produced by the line, as a function of their number, mass, or economic value).
It should be noted that when the system is very large (for example when it represents an entire economic sector, like e.g. the European production of car vehicles), it is very important to attribute consistently the inventory parts to the different products, in order to guarantee that the sum of the individual portions equals the total at the end of the repartition. In the case the partitioning is done by different actors (e.g. in the case of environmental labelling of car vehicles, done independently by each manufacturer), the risk of inconsistency is very high, because of the possibly different methodological approaches used.

The goal of **consequential LCA** is instead to assess **the consequences of the studied change** (for example the change of transport mode for 500.000 personnes.km from conventional to electric vehicles) affecting the system (representing for example the regional mobility needs). One can observe direct effects, which represent the consequences affecting foreground technologies and processes which are essential to the functional unit. For example processes which are no longer part of the system (for example conventional vehicles). Indirect effects are also arising because of the system expansion (for example the additional electricity production and any other activity whose variation is indirectly imputable to the introduction of electric vehicles, even without any direct link to them.
It is important to note that, historically, the notions of "replacement" and "avoided impact" have been considered as an alternative approach to the allocation, also by the ISO 14040-44 standards. However, there is a **major conceptual difference between the notions of "substitution/system expansion" and "replacement/avoided impacts"**. The latter aims at virtually eliminating the co-products by approximating their part of environmental impacts (formally unknown because of the related multi-functional processes which cannot be partitioned) by the environmental impact of an alternative system fulfilling the same function. There is actually no substitution or replacement in the market, just a value statement. On the contrary, "substitution/system expansion" formally adopts a

consequential perspective, by assessing the avoided (or additional) impacts by means of the **product replacement that could actually occur in the market**. These are indeed the indirect effects previously described. In some special cases, the two approaches could lead to the same results, but the conceptual differences still hold. Interestingly enough, the need to clarify these two interpretations has probably boosted the development of C-LCA, as an alternative to A-LCA.

The **identification and quantification** of the direct and especially **indirect effects play a primordial role in the practical implementation of C-LCA**, especially regarding the scope definition and the datasets collection. As it will be shown afterwards, currently there is no universally agreed procedure to this aim: different approaches are equally possible but none of them is ready to be used in the industrial practice. Based on the results, we can however highlight a few points that would deserve to be further explored for a better understanding of C-LCA and the related stakes:
i) a **problem** of **comparability** can be set between two C-LCA studies done on the same FU, i.e. studying the same change. The rational and ultimate consistency of the comparison is however unclear. Is there a need to compare two C-LCA studies? As it was shown, each study is strictly related to a specific socio-economic context and shall not be used for benchmarking purposes. The comparison of different modelling approaches for C-LCA is certainly interesting from a scientific perspective **Erreur ! Source du renvoi introuvable.**.
ii) the chain of consequences related to the change can be very large and articulated. **How could one be sure to have included all the relevant and significant changes**? In an A-LCA, cut-off rules are defined and the question is less important thanks to the (technological) cause-effect relationship between the inventoried processes and the FU. In a C-LCA, there is currently no solution to this problem.

1.3 How to practically carry out a consequential LCA?

As already mentioned, there is currently no operational guideline for the practical implementation of C-CLA. The report operationalizing at best the methodology [13] provides a specific approach without accounting for the diversity of modelling approaches available.
In the present research, the main methodological and practical questions to be solved to operationalize the C-LCA have been identified and an operational framework has been proposed by means of a decision tree.

First, the **question** of **when C-LCA is necessary** (or mandatory) to address a specific decision has to be tackled. We can argue that C-LCA is potentially needed to assess the environmental consequences of the changes affecting a system at meso or macro scale, especially the ones related to socio—economic developments, strategic industrial decisions and policy making.

Secondly, it is mandatory to **define (in an interrelated way) the spatial context, the time horizon as well as the magnitude of the change and the substitution mechanisms** associated. This is needed to **define the scope of the study** and to identify the processes affected by the change, to be included in the inventory. As the market in which the studied system is placed is the first one to be affected, it has to be characterized concerning its size, nature (open or restricted), trend (increasing, decreasing, stable), expansion capacities, trends of imports and exports and price fluctuations, which can affect significantly the reliability of the inventory modelling.
The definition of the time horizon depends on the nature of the questions posed by the study, on the type and magnitude of the change as well as on the spatial context. The latter is a function of the affected market characteristics, of the type of changes, its magnitude and substitution mechanisms and time horizon.

The magnitude of the change and of the related direct and indirect consequences is determined by the spatial context and the time horizon. The **magnitude** is considered to be **low** whenever the

consequences are at the **margin**: the affected processes were already part of the system before the change occurred and their demand changes over the time period of the change. The function of the system may also evolve over the time period depending on the demand, but always at the margin. Average technologies can still be considered, whose evolution will not be significant enough to reach the point of constraint. The **magnitude** is considered to be **high** whenever the change is so important that the processes, in order to be able to respond, have to increase their capacity through "breakthrough investments". Novel technologies could potentially come into play, and average technologies (already considered before the change) can evolve significantly. For instance, an action implemented to reduce the number of diesel vehicles in favor of LPG vehicles corresponds to a shift of the use of existing technologies. Regardless of the size of the transport market considered in the study, the system therefore moves towards a change characterized by a low magnitude. At the opposite, an action set up to introduce electric vehicles in the market corresponds to the introduction of a new technology. Depending on the size of the transport market considered in the study, the system is probably moving towards a large change since the introduction of a new technology requires (for example) the development of related technologies and infrastructure(e..g charging stations).
The affected technologies can then be identified through the application of **simplified market mechanisms or by economic and social modelling of interactions between processes, in a specific spatial and temporal context**. The use of economic equilibrium models and social models is pertinent to this aim. The inventory of processes has to reflect as closely as possible the state of the technologies over the studied period. The adoption of a **dynamic approach** is highly **recommended** to monitor the evolution of the system over the time period of the change. Also, the use of different **prospective scenarios** to simulate future socio-economic situation is **suggested** to **reduce** the **uncertainty** of C-LCA.

The **decision tree** (mindmap) developed within the present research supports and steers the LCA practitioner through the different methodological "nodes" mentioned above. Through each step, the practitioner can identify the correct LCA approach for a specific question and decision context, which is also better defined and operationalized thanks to the tree. The final aims is to support the preparatory phase of a LCA study, in order to better define and carry out the LCA and to finally gather results which are consistent with the initial aim and goal of the study, and therefore could have a more important impact in the practice.

1.4 Comparison between attributional and consequential LCA

The table below lists the main **differences between the attributional and consequential approaches** relative to the main LCA phases and to the methodological "nodes" highlighted by the experts interviewed.

Table 1 : Comparaison between consequential and attributional LCA

	Consequential ACV	**Attributional ACV**
Objectives	Assess the environmental consequences of a **change** implemented in a system (product, service, socio-economic system) over a time period and at a given time horizon	Assessment of the environmental performances of a system (product, service, socio-economic system) at a given time horizon under **status-quo** conditions (no changes considered)
Goal	Support decision making, environmental communication (not yet fully operational), benchmarking	Reporting, benchmarking, environmental communication (labelling)
Functional Unit (FU)	Actual magnitude of the change (ex. additional 500'000 electric vehicles),	Virtual reference unit (e.g. 1 electric vehicle) at a given time horizon (e.g.

	over a time period (e.g. 10 years) and at a given time horizon (e.g. 2010-2020).	2020).
Relationship between the UF and the inventory results	Not linearly dependent: if the FU is multiplied by 10, the inventory results are not necessarily tenfold.	Linear dependence: if the FU is multiplied by 10, the inventory results are always tenfold.
Scope	Include all the processes affected by the change, even if they are not directly or indirectly required (solicited) by the FU, i.e. are linked to the studied system (product, service, socio-economic system) by a technological cause-effect chain. The processes not affected by the change, even if they are solicited by the FU, are not included	Include all the processes linked to the studied system (product, service, socio-economic system) by a technological cause-effect chain.
Identification of the inventory processes to be considered	Simplified approach [13], economic equilibrium models, complex systems models (e.g. agent-based)	Based on the product composition, the process flow-sheeting and the chain of suppliers, users, and end-of-life processes.
Type of inventory data (datasets)	The datasets reflect **technological and market interactions** between the inventory processes **following the change**, i.e. are marginal data (eventually average marginal data)	The datasets reflect the **average technological interactions** between the inventory processes. These are **average** data at a given time horizon
Inventory data sources (datasets)	Datasets to be built *ad hoc* depending on the market information. Ecoinvent 3.0 for the marginal data of background processes	Average data specifically for the studied product, process, service. LCI databases for the average background data
Management of multifunctional processes (which cannot be solve by partitioning)	System expansion / substitution (Allocation methods **not to be used**)	Allocation methods Avoided impact approach
Type of Life Cycle Impact Assessment methods to be used	All	All
Comparability between LCA studies	Not strictly mandatory as the C-LCA study is dependent on the socio-economic context and modelling approach adopted. Prospective scenarios for a same study should be comparable as they are considering the same socio-economic context. However, two independent studies carried out to address the same question are probably not comparable.	Mandatory
Reliability of	Uncertainty and sensitivity analyses	Uncertainty and sensitivity analyses

results (uncertainty, sensitivity)	are mandatory (also through prospective scenarios). The reliability depends on the modelling approach chosen.	are mandatory. The reliability mainly depends on the inventory data quality (see decision tree).

A third LCA approach, named **Decisional LCA**, has been recently proposed [35], but the scope of application and the number of case studies are very much reduced as compared to the other two approaches analysed in the table above.
Decisional LCA considers a system (product, service, socio-economic system) under status-quo conditions as well, at a past, present of future time horizon. As compared to the attributional approach, the decisional one reflects the interactions between the inventoried processes based on **contractual relationships**. The corresponding inventory datasets are also constituted by average data but relative to the processes (and their operation) based on the contractual relationships. As a result, the scope of the study reflects the sphere of influence of the decision makers who are concerned by the contractual relationships. The latter imply decisions which have already been taken, i.e. whose **consequences are not being assessed through the LCA**. The latter is the realm of C-LCA. **Neither market mechanisms nor constrains are therefore included in the decisional approach**: only contractual relationships drive the inventory modelling. For this reason, **no indirect effects are evaluated** in the decisional approach.

Let us consider here a practical application example of the three approaches: in Luxembourg, the subsidies for electric vehicles are subject to the supply of green electricity, i.e. an individual who does not subscribe to green electricity supply does not benefit of the subsidy.

Attributional: LCA of an electric vehicle (FU= 1 p.km) in 2020, average electricity mix (Lux) in 2020.
The LCA provides an average ecoprofile of the vehicle (corresponds to situation C of the ILCD handbook [8])

Decisional: LCA of an electric vehicle (FU= 1 p.km) in 2020, green electricity mix according to the contractual requirements in 2020.
The LCA assesses the influence of the contractual decision in the framework of the promotion (or environmental communication) of the environmental profile of the vehicle (situation A of the ILCD handbook [8])

Consequential: LCA of additional 40.000 electric vehicles; the FU is a number of p.km, calculated based on the detailed use of each vehicle type and transportation distance (coming, for example, from multi-agents simulation of mobility scenarios) entering the market between 2012 and 2020. Electricity mixes are considered according to market simulations (e.g. economic equilibrium between 2012 and 2020). Indirect effects engendered by the additional increase of electricity demand are evaluated using economic models as well.
The LCA provides the consequences engendered by the e-mobility policy or by a strategic industrial decision determining the studied change (situation B or A of the ILCD handbook, depending on the socio-economic environment affected by the change)

The decision tree provides the detailed conditions under which the three approaches are used, can be combined or are actually equivalent.

1.5 Future developments of consequential LCA: from standardisation to best practices

The present research confirmed that **C-LCA** is **primarily aimed to support strategic decision making** at meso-macro scale, irrespective of the targeted economic sector, both in public and private domain. In some cases, for example for policy questions related to mobility and biofuels, C-LCA is the

only LCA approach which can correctly evaluate the consequences of the policy implementation. Regarding environmental communication and labelling, C-LCA is by far less pertinent than the attributional approach.

However, at the current state of development, C-LCA lacks of operability and harmonisation of the different approaches, hampering its implementation in the daily LCA practice and thus limiting its use and development essentially to the scientific community.