SCORE LCA

STUDY N° 2017-04

MULTIPLE APPLICATIONS IN LCA: METHODOLOGICAL ASPECTS AND CASE STUDY ON THE CALCULATION OF SECOND-LIFE BATTERIES ENVIRONMENTAL IMPACTS

Summary

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Scientific managers

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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.

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- ✓ The views and recommendations expressed in this publication are those of the authors and do not necessarily reflect, unless otherwise stated, the views of all members of SCORE LCA.

- ✓ The information and conclusions presented in this document were established on the basis of scientific and technical data and regulatory and normative framework in force at the date of the drafting of documents.

1 Context, goals and content of the study

1.1. Context of the study

❖ *The combined emergence of circular economy and the energy transition*

The concept of **circular economy** namely appeared to answer the challenges of efficient resources use and of the related environmental impacts. The shift from a linear model to one that operates in closed loops is gaining ground. A distinction is drawn between material loops (recycling) in which materials are collected and reinjected into the economy, and the product loops in which the products (either as a whole or as a part) are reinjected into the economy, after a potential repair or reconditioning for instance.

Simultaneously, public policies, namely in Europe and in France, have set ambitious targets for the years to come, towards a more responsible energy consumption and production. In particular, specific measures[1] were taken in the transportation sector, such as the withdrawal of conventional motor vehicles (internal combustion) in cities in 2050. To achieve this, an acceleration of the renewal of the car fleet towards new vehicle technologies (electric vehicles) is essential.

Several projects or initiatives, such as the reuse of electrical vehicle batteries for a stationary second-life, are at the crossroads between circular economy and the energy transition. Indeed, they seek both to optimize the use of goods and services, and to serve the production and consumption of a more sustainable energy.

❖ *In response, are the evaluation methods, including the environmental evaluation, adapted ?*

The development of projects said “of circular economy”, to meet the energy transition goals, raise the question of their environmental and economic performance. The methods for environmental impact quantification, and especially LCA, must adapt themselves for a better characterisation of the material and product loops, and the specific characteristics of energy transition projects, which raise new issues. The life cycle analysis has been for long describing linear systems, in spite of the use of the word “cycle”. It has mostly focused on material loops without paying close attention to product loops. The current emergence and development of a truly circular economy call for a revision of the LCA methodology, in particular regarding the treatment of multiple lives.

1.2. Goals and content of the study

Given these issues, the goals of the project initiated by SCORE LCA and its content are the following:

A. Reporting on the **State of the Art of LCA methodologies that deal with the reuse of a product** (having several lives during its life cycle, with possibly multiple applications), and drawing **recommendation for the LCA practitioner**, under an operational format. The State of the Art was analysed 1/ through a comprehensive listing of the LCA publications considering several successive lives and 2/ by conducting a detailed analysis of five publications considered the most relevant, to highlight the most judicious methodological cases. This summary focuses on the recommendations for the LCA practitioner and does not go over the State of the Art (which served as a reference for the definition of the recommendations) presented in the study report.

B. Illustration of these methods on a specific case, through the conduction of an **LCA on batteries with a second life**. The data and the methodological framework of the LCA are based on a literature review of LCAs of batteries (according to the use case, whether it is mobile or stationary, etc..) in complement to the methodological literature review realized in the frame of the State of the Art. This summary

[1] SWD(2016) 226 final – Commission Staff Working Document : The implementation of the 2011 White Paper on Transport "Roadmap to a Single European Transport Area – towards a competitive and resource-efficient transport system" five years after its publication: achievements and challenges

focuses on the LCA and does not go over the literature review of the batteries LCAs (presented in the study report). The LCA is an illustration of the methodological challenges and is not enough complete to provide accurate environmental impacts.

C. From the literature review of LCAs of batteries, creation of a structured database, useable for a future meta-analysis. This last part, presented in the study report, is not covered in this summary.

2 Recommendations for the consideration of multiple lives in LCAs

2.1. Preamble and reading guide of the recommendations

The purpose of this section is to support the LCA practitioner in the realisation of environmental evaluations or LCAs, including the consideration of multiple lives and/or multiple applications, the reuse or the refurbishment of a product. Before addressing these recommendations, the following points should be considered:

- In the frame of the project, a **glossary** was created to provide clear and precise definitions of the different terms and issues mentioned here. An equivalent in English was proposed when it existed. The glossary is not presented in this summary but is subject to a dedicated section in the study report.
- As previously stated, the recommendations presented here originate from a work of methodological literature analysis. The principal outcome of this study has been the thorough analysis of five publications of interest, presented in the following table and reported in the **methodology factsheet**.

Table 1 : Publications analysed in the frame of the project regarding the methods to include multiple lives in LCA.

Factsheet n°	**Title of the publication**	**Author(s)**	**Publication date**	**Approach used for the consideration of multiple lives**
1	Environmental trade-offs across cascading lithium-ion battery life cycles	Kirti Richa, Callie W. Babbitt, Nenad G. Nenadic, Gabrielle Gaustad	2015	Comparison between scope extension and allocation
2	Life cycle assessment aspects of reuse products	Andreas Pertl, Gudrun Obersteiner Stefan Salhofer	2011	Allocation based either on the function or on the economic value
3	Comparative life cycle assessment of smartphone reuse: repurposing vs. refurbishment	Trevor Zink, Frank Maker, Roland Geyer, Rajeevan Amirtharajah, Venkatesh Akella	2014	Extension of the system's boundaries
4	A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems	Leila Ahmadi, Steven B. Young, Michael Fowler, Roydon A. Fraser, Mohammad Ahmadi Achachlouei	2015	Extension of the system's boundaries
5	The environmental impact of technology innovation on WEEE management by Multi-Life Cycle Assessment	Bin Lu, Jingru Liu, Jianxin Yang, Bo Li	2015	MLCA (Multi-Life Cycle Assessment)

- A survey among the LCA community allowed us to complement the database of the identified studies.

Those different elements (namely the *methodological factsheets*), which served as a basis for the writing of the recommendations summarized below, are not covered in this summary but are presented in the study report.

Reading guide of the recommendations

The recommendations are given in the operational shape of a **decision tree**, and structured in the following way:

- The decision tree presented in §¬ enables the reader to follow the usual progression relative to the integration of multiple lives in the conception of the LCA.
- Section 2.3 (page 7) details the principal points in the decision tree. This summary focuses only on the blocks deemed relevant; all blocks are detailed in the study report.

2.2. Decision tree

The decision tree for the consideration of multiple lives in LCAs is presented on the following page. The blocks with a white background in a rectangular shape are “information” blocks, i.e. blocks to guide the practitioner in his decision making, while the rectangular blocks with folded edges are “question” blocks, from which two or more possibilities derive.

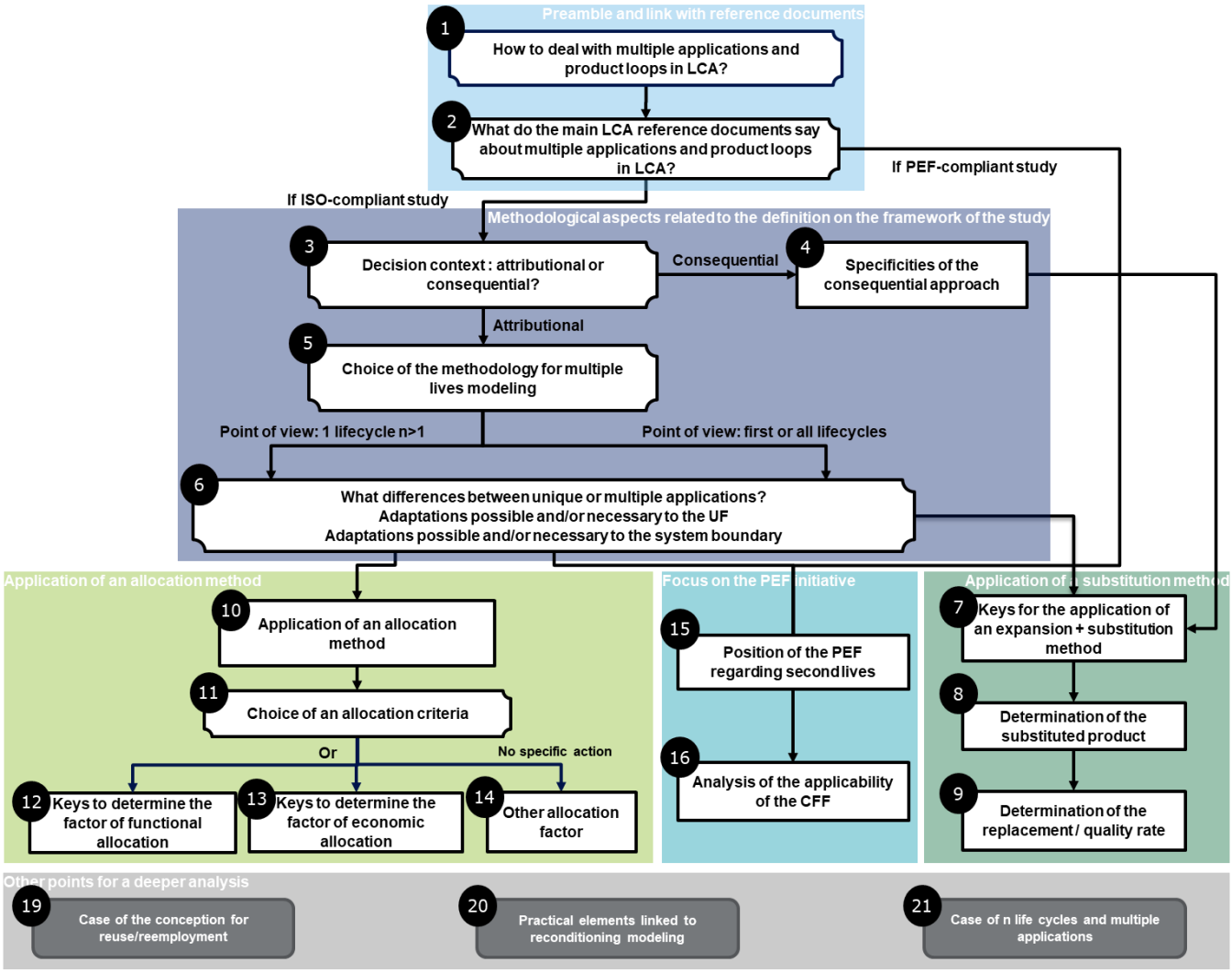


Figure 1 - Decision tree for the inclusion of multiple lives in LCAs

2.3. Recommendations

2.3.1 Preamble and link with the reference documents

❖ *#1 How to consider multiple application in LCAs and the products loops ?*

- **Case of similar use between the different lives of a single product**

From an LCA point of view, if the second life use is the same as the first one, then the total life cycle remains unchanged and it is possible to consider that the functional unit and the perimeter are extended. It appears that they are several ways of solving the problem linked to the extension of a product or a service's lifetime on a similar use: either by simple prolongation of its lifetime, or by allocation between two successive utilisations – which brings us back to the precedent case if the allocation is simply based on the length of use.

- **Case of different use between the lives of a single product**

If the second life involves a different product and/or a different use, for instance for an electric vehicle battery which will then be reused in a stationary use in a second life, then **it can be estimated that the modelling is similar to the concept of a multifunctional product.**

The specificity of the multiple lives issue, compared to the one of co-products, is that the state of the product at the end of its first life is not always known, nor at the end of its life *n*, nor the number of successive lives, nor the product's performance in its life *n*. The steps of repairing or reconditioning between two successive lives are also complex to evaluate.

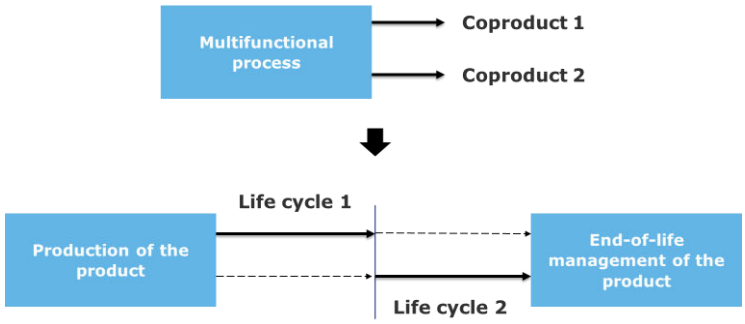


Figure 2: Illustration of the parallel between coproducts and multi-life cycle in the case of two successive lives

❖ *#2 What do the principal LCA reference documents say about multiple applications and product loops ?*

Once the parallel between multiple lives and multifunctionality is established, it is relevant to delve into the normative and reference texts, regarding the consideration of multiple lives, refurbishment and reuse in LCAs.

The ISO 14040 and 14044 norms prioritise the ways of considering multifunctionality in the following order:

- **System subdivision**: this case is not developed in this study. Indeed, the processes of reuse and refurbishment are by nature difficult to divide.
- **System expansion**: include the secondary functions and **substitution** of the impacts associated to the avoided coproduct.
- **Allocation** of the impacts between coproducts and functions.

The other documents (ILCD Handbook, PEFCR Guidance, EN 15804, Environmental display on consumer goods) globally provide a similar ranking to the one suggested by the ISO guidelines. Nevertheless, the PEF and the reference for consumer goods display in France simultaneously adopt an allocation-substitution method.

2.3.2 Methodological aspects linked to the definition of the study framework

Point #3 ("Decision context: attributional or consequential?") developed in the study report draws a distinction between the case of a attributional LCA and the one of a consequential LCA. A consequential LCA (see #4 "Particularities of the consequential approach" in the study report) which features reuse or refurbishment will favour a substitution method for its modelling of multiple lives.

❖ *#5 Choices for methodology and modeling of multiple lives*

The approach begins with the following questions: what is the point of view of the LCA practitioner? The goal of the study?

1. **"All life cycles"** point of view.

   If the LCA practitioner is looking to evaluate the impacts of the reuse or refurbishment of a product on a macroscopic level (**consequential approach**) it is recommended – following the proposed hierarchy of the ways to consider multifunctionality in LCAs[2] – to favour an **extension of the system's boundaries with substitution.**

   If that is not the case and the practitioner is looking to measure the precise impacts associated to each life in an **attributional approach**, before aggregating it on a life cycle level, then the recommended method is the **allocation** or the **Circular Footprint Formula (CFF)**.

2. **"First life"** point of view. This applies when the LCA practitioner seeks to evaluate the environmental impacts of a reused / refurbished product from the first life's point of view (upstream), i.e. from the viewpoint of the company responsible for placing the product on the market, on a microscopic level. In that case it is also recommended to use if possible **an extension of the system's boundaries with substitution**. Nevertheless, the **CFF is also relevant**, namely if the definition of the substituted product is imprecise. It is also possible to use an allocation method, but only if it does not take into account the following lives (for instance if the allocation factor is based on the total lifetime, the latter is not known / defined at the end of the first life).

3. "**Any life *n* with *n*>1**" point of view. This applies when the practitioner seeks to evaluate the environmental impacts of a reused / refurbished product on the user's point of view (downstream) on a microscopic level. It is then recommended to apply an **allocation between the n life cycle covered** (if possible) or to apply **CFF**.

2.3.3 Application of a substitution method

❖ *#7 Advice on the application of a method of system's boarders extension with substitution*

The substitution method applied to reuse or refurbishment assimilates the whole life cycle to a monofunctional process, by removing the function of the previous life, which is not specifically studied here, from the system. The application of the substitution method for product loops does not fundamentally differ from the method for material loops.

❖ *#8 Keys for the determination of the substitued product*

The method of system expansion with substitution in the case of reuse or refurbishment consists in extending the boarders of the system, to include one (or several) successive life(s), and to deduct the impacts and benefits of the system that is substituted by this (these) successive life(s). Therefore, **the definition of the substituted system is of prime importance since it can have a strong influence on the results of the analysis.**

[2]This is not explicitly stated, but it is supposed that a subdivision of the multifunctional system in several equivalent monofunctional systems is not possible.

Two general cases can be identified:

1. **The extended system considered by the practitioner reflects an existing reality**. In that case, it is necessary to determine with the highest possible precision the functioning of the market and to compare truly equivalent systems.
2. **The extended system considered by the practitioner reflects a likely future situation**. This case is more complex since it implies to make prospective hypothesis on the evolution of the market. The research must then cover the definition of the future scenario as well as the associated data.

Generally, it is often difficult to precisely define the substituted system, and even more to collect the relevant associated data. It is however essential to conduct the research so as to identify the eventual areas that lack knowledge, namely for the purpose of the evaluation of the data's quality.

❖ *#9 Keys to refine the quality / replacement rate*

An essential aspect to define with precision the substituted system is to define the **replacement rate, i.e. the *quantity* of system that is actually substituted**. This replacement rate applies when it is possible to think in terms of number of reused products[3], or in terms of quality of the service provided by the product or service studied. For instance, the purchase of a reconditioned phone does not always substitute itself to the purchase of a new one, they are cases in which the purchaser ends up with two phones.

Therefore, it is essential to raise the question of the replacement rate and if possible to provide **an answer based on technical studies, as well as on the most reliable consumer data that is available**, such as user surveys.

2.3.4 Application of an allocation method

❖ *#11 Choice of the allocation criteria*

In the absence of a more precise or prescriptive methodological framework, the default choice is to follow the priority order recommended by the ISO 14044 according to the available data. A distinction should be drawn between on the one hand the economic and functional allocation, and on the other hand allocations such as 50/50, 80/20, 100/0, etc.

Indeed, economic and functional allocations are specific to the product since they account form a *measurable* reality, whether it is physical or economic. This way, the question to be raised is the following: **Through which parameters is the value of my product measured?** On the contrary, allocations in 100/0 (or 0/100), 50/50, 80/20 (or 20/80) are rather applicable in the use case related to a given methodological reference, or when the practitioner does not have robust enough data on his system to conduct a functional or economic allocation which would represent reality accurately.

❖ *#12 Keys to determine the functional allocation factor*

To determine the most relevant functional allocation factor, the practitioner can reflect on the following questions:

- What is the most relevant physical parameter to measure the quality / efficiency / performance degradation of the product during its existence (for instance the time it takes for a phone battery to discharge in sleep mode)?
- How does the use of the product influence this physical parameter (for instance the daily use time of the smartphone)?
- Do models exist to evaluate the variation of this parameter over time? Otherwise, is it possible to establish one?

To better portray the quality of a product over its whole life, and in particular between two successive lives, two principal approaches came from the literature review and the reflection carried out during the project:

[3] A comparison can be made between the quality rate of secondary data when a recycling process is studied, with the ratio Qs/Qp of the Circular Footprint Formula.

- **Delta approach**: if the performance degradation of the product is X% over its whole existence, then each user i responsible for the degradation x_i% of the product's performance is responsible for (x_i / X) % of the impacts of the activities that are "common" to the different lives. This means assigning the impacts of the activities "common" to the different lives prorated to the reducing of the different lives' performance.
- **Integrated approach:** this approach consists in integrating the functionality over the duration of each life and allocating the impacts common to each life prorated to the integrated functionality. This approach does not only take into account the evolution of the functionality over time, but also the duration of each life. This comes down to allocating the impacts proportionally to the amount of provided service (with a similar use case scenario between the different lives). The advantage of this approach, in addition to the fact that it deals with performance degradation, is that it also considers the length of each life through the integration of the functionality over time, therefore considering the immobilisation time of the product in each life.

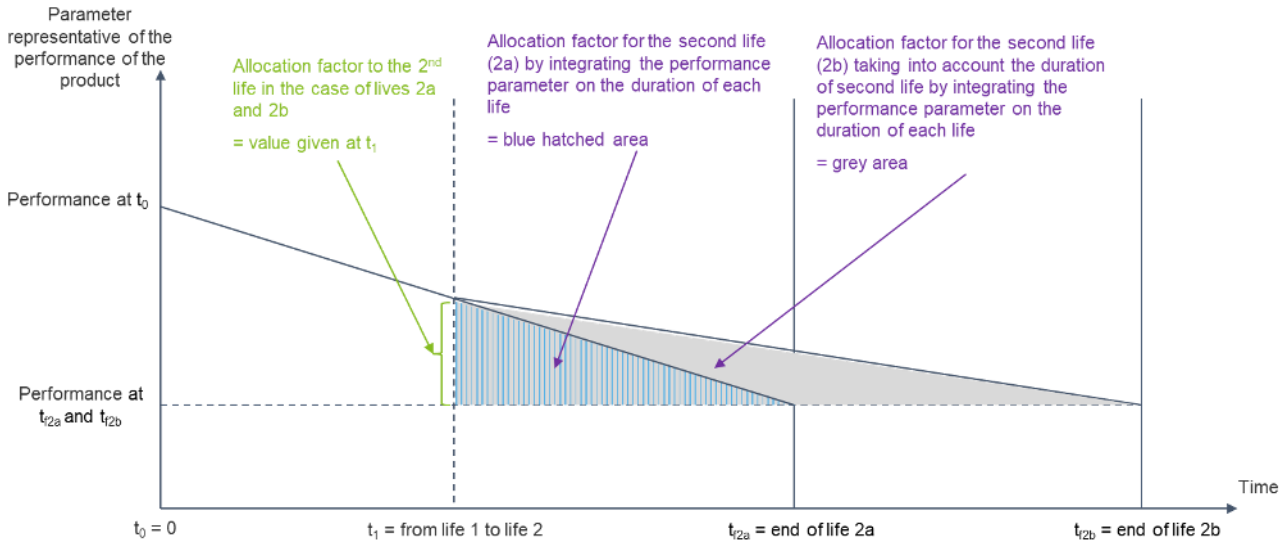


Figure 3 - Illustration of two allocation approaches: "Delta" in green; "Integrated" in purple

❖ *#13 Keys for the determination of the economic allocation factor*

If the economic allocation may at first seem easiest than the functional allocation, it remains a complex issue. Indeed, the value of a product over time can be measured in several ways: either the market prices are known and accurate, or they are not (if the market is not established yet, for confidentiality reasons, etc.). If the prices are known, then the economic allocation is rather straightforward to carry out. Otherwise, the practitioner needs to find trustworthy economic prediction models or data for extrapolation. In general cases or if no relevant data is available, it is possible to consider that the product's value decreases at each time step by a factor X%, X being fixed or fluctuating.

One can also note that usually, in the case of products with several successive lives, the economic value already takes into account the decrease in the product's functionality.

2.3.5 Focus on the Product Environmental Footprint

❖ *Positioning of the PEF referential regarding refurbishment, reuse and second life*

The PEFCR Guidance does not diverge from the ILCD Handbook or the ISO norms regarding the proposed hierarchy for the ways to deal with multifunctionality. In section 7.8 "Extension of a product's life time" of the PEFCR Guidance, two cases are mentioned:

1. Identical applications. In this first case, it is recommended to include the life time prolongation due to refurbishment in the scope of the study.

2. Multiple applications. They are to be treated in the same way as recycling, through the application of the Circular Footprint Formula.

Another important point to make is that the issue of refurbishment and reuse was barely covered in the "Technical Secretariats" of the PEF's pilot phase. The understanding of the subject will be deepened when PEFCRs will be initiated for product categories in which refurbishment / reuse are of prime importance. As stated in several parts of the PEFCR Guidance on material loops, it is judicious that the parameters to model the second life, e.g. the allocation factor, the parameters linked to substitution, etc., would be framed in the PEFCRs, in order to improve the comparability of the products in the same category. Finally, another current limitation of the PEFCR is the lack of a deeper analysis on the application of the CFF in the case of refurbishment or reuse, which is the subject of the following paragraph.

❖ *Analysis on the applicability of the Circular Footprint Formula in the case of refurbishment or reuse.*

The Circular Footprint Formula (CFF) is the formula to apply in the PEF frame to distribute the environmental impacts of energy or material valorisation between the upstream and the downstream of the system studied. The PEFCR puts reuse on the same level as recycling. It is a substitution and allocation formula[4]. The terms of interest in the CFF, under the modular form (CFF-M), are presented below, namely the terms linked to the benefits and costs linked to the secondary inputs (given at life *n+1*).

Impacts associated to production	$(1- R_1) E_V + R_1 \times E_{reused}$	• Allocation factor between upstream and downstream • Refurbishment / reuse rate • LCI of refurbishment. • LCI of the "new" / "original" product • LCI of the product (virtually) substituted • Quality factor
Impacts and benefits linked to a product's reuse	$-(1 - A) R_1 \times (E_{reused} - E_V \times Q_{Sin}/Q_p)$	
Impacts and benefits linked to reusing a product	$+(1 - A) R_2 \times (E_{reuslingEol} - E^*_V \times Q_{Sout}/Q_p)$	

Figure 4: CFF terms linked to the production of the product and to the material/product valorisation in end-of-life (the terms linked to energy valorisation and end-of-life without valorisation)

The following comments can be made regarding the application of CFF to refurbishment / reuse:

- R_1 and R_2 correspond to the refurbishment and/or reuse rate of the product studied.
- **+/-(1 – A)** corresponds to the allocation factor between the life cycles. It is defined by convention in the PEFCR. The choice of A raises questions in the case of refurbishment or reuse.
- Q_s/Q_p is the equivalent to the replacement rate (see item #9) and account for the nature and the quality of the substitution.
- E_V et E^*_V correspond to the production LCI of the substituted product. The building of this LCI is not necessarily straightforward according to the type of product studied.
- $E_{recycled}$ et $E_{recyclingEol}$ correspond to the LCI of the preparation for refurbishment / reuse. The building of this LCI is also complex to establish.

Theoretically, CFF is indeed applicable in the case of refurbishment / reuse. In practice, to our knowledge, this has not yet been done, and it is one of the objectives of the LCA case study presented in the following section: to test the applicability of CFF to the case of refurbishment / reuse.

[4] As well as the end-of-life formula of other referential such as the one related to environmental display in France.

3 LCA of batteries with a second life

3.1. Bibliography

Bibliographic research covers all major electric battery technologies, mature (Li-Ion, PbA) and in development (Li-silicon, Vanadium Redox Flow), for any kind of application. As of today, only car batteries appear to have been studied through multiple lives applications. In this case, first automotive application is limited by a minimum charging capacity under which the battery mass becomes too energy demanding to propel the car. Most studies agree on a 20 % charging capacity loss (Kons13), up to 30 % (Faria14). Otherwise, stationary applications should allow complete capacity loss. However, a total capacity loss of 50 % (Cicc12) is observed.

The bibliographic study showed what key parameters are considered in LCA:

- Charging capacity (needed to separate multiple lives)
- Depth of discharge (DoD)
- Battery life span (in years, cycles, km driven)
- Energy efficiency (kWh provided/kWh stored) which is critical in use phase.

A wide range of values can be given to each parameter across all studies:

- Distance driven: 100 000 km (Kons13) - 200 000 km (Zack16)
- Stationary life span: 4 years (Kons13) - 20 years (Cicc12).

Besides that, no 3 consecutive applications study was found. As it is experienced in our LCA study (see 3.2), the possibilities to model variations is limited by the lack of data on remanufacturing as well as stationary energy storage and consumption strategies (“peak” / “off peak” hours).

Multiple life cycles modelling limits arise from the current state of the art. On the one hand, battery degradation laws are various. Capacity loss depends on the chemistry and can be related to numerous variables:

- LFP – Elli14: average capacity loss of 0,008 % per cycle
- $LiTi_4O_5$ – Casa15: exponential law with several variables: time, voltage, temperature, current etc.

Our attempts to apply these laws show it is difficult to manage all parameters at the same time.

On the other hand, remanufacturing stage is essential to model second and third lives. In particular, the replacement of failing cells is critical in the legitimacy of multiple lives scenarios. But cell failure rate is not considered in any article. Instead, the remanufacturing stage in Ahma14 accounts for 50% of battery manufacturing.

As a conclusion, multiple lives studies of electric batteries only apply to car batteries (1^{st} use phase). Despite the growing concern and promotion for batteries, few data from manufacturers is available. This lack of data is also true for user experience, which leads to difficulties to draw solid scenarios that could arguably show environmental benefits resulting from battery reuse. Even if NMC battery technology is spreading out, notably in Renault and Nissan cars, study cases are in minority, LFP battery being the best covered technology. After all, the identified key parameters (life span, charging capacity, energy efficiency, DoD) were evaluated coherently in the LCA model. It is described in part 3.2 below.

3.2. Life cycle analysis

The aim of the study is to test three multiple lives modelling methods in LCA based on the bibliographic research carried out in part A. There are two major goals:

- To identify what are the difficulties of multiple lives modelling in LCA though case studies
- To illustrate variations depending on the chosen environmental impacts allocation methods used.

This focus is on the methodology more than variations in environmental impacts of the product under study.

3.2.1 Allocation methods

Boundary extension (BE)

System Boundary Extension method (BE) consists in including all lives together and subtracting the life cycle of the new product replaced by the reused product. In our case, NMC battery used in the car replaces, in its second stationary application (in solar farm or in household) a new LFP battery. The production of the new LFP battery is avoided (see figure 1). Its impacts are subtracted from the whole system.

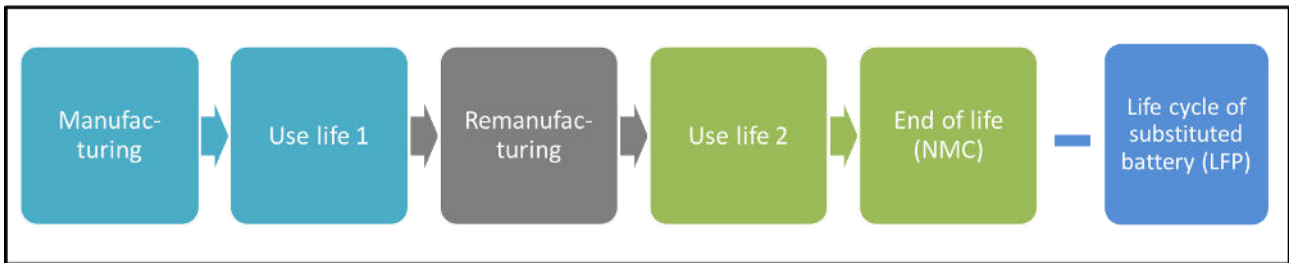


Figure 5: Boundary extension method (avoided impacts)

Integrated functionality (IF)

Integrated Functionality method (IF) consists in splitting environmental impacts based on the level of service delivered (functionality) by the product over time, through each life. In our case, two parameters define the functionality level at each life *i*: quantity of energy delivered (Q_i in kWh) and the average charging capacity remaining ($\Delta C\%_i$). Allocation factors are then evaluated according to the following formula:

$$FI_i = \frac{Q_i * \mathbf{\Delta C\%}_i}{\sum_i Q_i * \mathbf{\Delta C\%}_i}$$

The figure below presents the evolution of charging capacity for NMC811 battery. The calculation of $\Delta C\%_i$ is also represented.

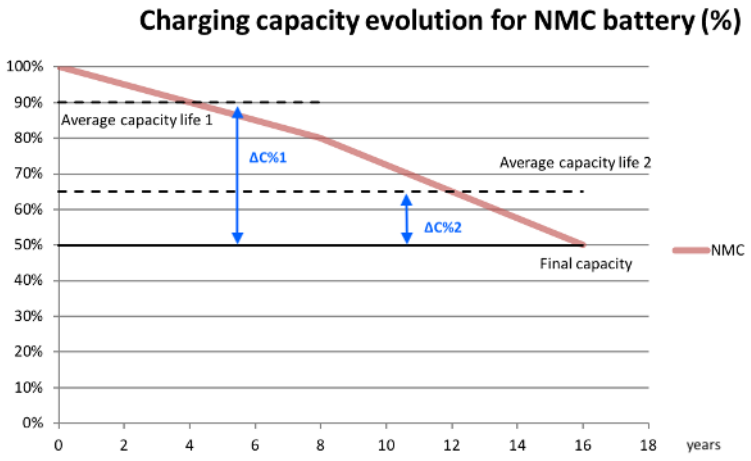


Figure 2: Charging capacity evolution over time (lives 1 & 2) – Scenarios A & B

The end of life after the last use phase is modelled according to the Circular Footprint Formula (CFF) method. In IF method, impacts over the whole life cycle are equally shared between each life. Each user is charged with some impacts from all other stages of the life cycle, including remanufacturing.

Circular footprint formula

CFF method aims at allocating impacts between consecutive life cycles. Allocation factors are based on recycled materials quantities (R) and quality (Qs) and market supply and demand trends (A) of those materials. CFF can be applied to any material or to the product in case of reuse. In this case study, quality factors Qs were determined for the battery product with the same parameters as for the integrated functionality approach;

capacity and efficiency, evaluated at the point of substitution. The figure below shows the energy efficiency values estimated at each point of substitution.

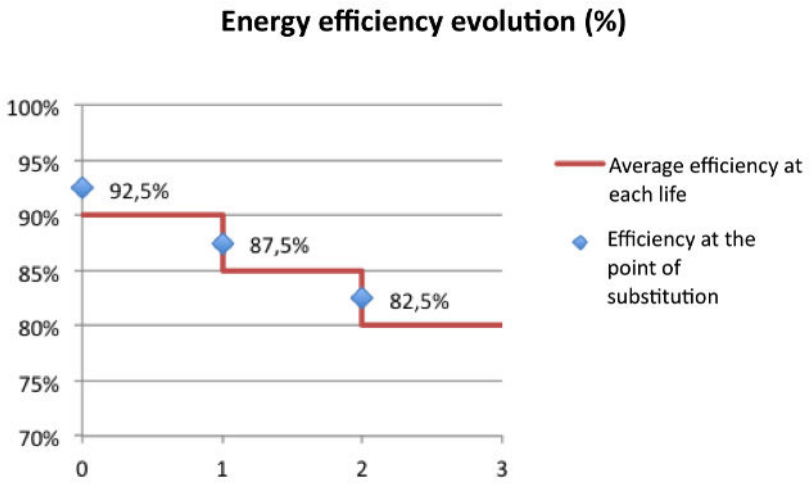


Figure 3: Evolution of the energy efficiency of the NMC battery

3.2.2 Assumptions and limits

Modelling the life cycle was difficult due to lack of available data at each stage of the life cycle. At production stage, bills of materials are barely public. Since car batteries have been commercially available for only a few years, user experience data and real condition measurements are also lacking. Then, end of life treatment (pyrometallurgy and hydrometallurgy) data and CFF factors can only be found in PEFCR on batteries.

Several hypotheses were initially made on key parameters. They are listed in the table below.

Table 2: LCA hypotheses and associated level of criticity

Parameter	Stage	Criticity on results
Temporal constraint on charge/discharge cycle	Use (stationary)	**High**: the functionality is defined by the amount of energy delivered.
Charging capacity loss	Use	**High**: Delivered Energy quantity and allocation factors (IF, CFF) are proportional to the capacity.
Energy efficiency	Use	**Mild**: efficiency varies in smaller range compared to capacity. However, it has a higher uncertainty.
Cell failure	Use - remanufacturing	**Mild**: cell failure rate is set to 0.
Remanufacturing process	Remanufacturing	**Mild**: battery pack modification and cell refurbishment can be significant over the whole life cycle. BMS alone is changed in our study.
Metal recycling	End of life	**High**: only PEFCR for batteries gives data on metal recycling. This determines avoided impacts (BE) and allocations (CFF).
Transport	Life cycle	**Low**: not including transport is a reasonable simplification regarding the methodological goal of the study.

3.2.3 Results

General results and results at each life

Firstly, methods are compared over the whole life cycle. Figure 4 shows climate change results.

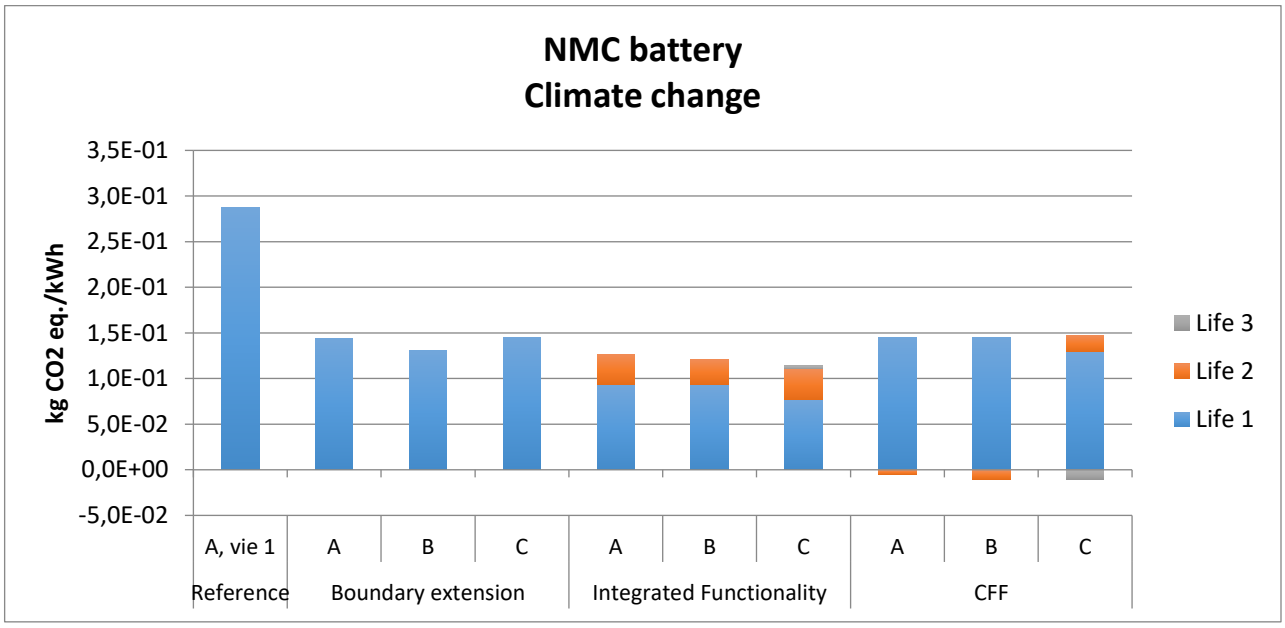


Figure 4: Résultats globaux, changement climatique (/kWh)

This graph reveals similar trends for other impact categories:

- acidification
- photochemical oxidation (smog)
- eutrophication.

Manufacturing and end of life (final disposal) are the main contributors to these impact categories.

Regarding mineral resources and energy consumption, comparative results are particularly affected by remanufacturing (rare earth elements contained in the BMS) and household energy consumption.

Secondly, lives from different scenarios are compared for each method (figure 5). All impact categories are shown in one graph so as to analyze how methods allocate impacts.

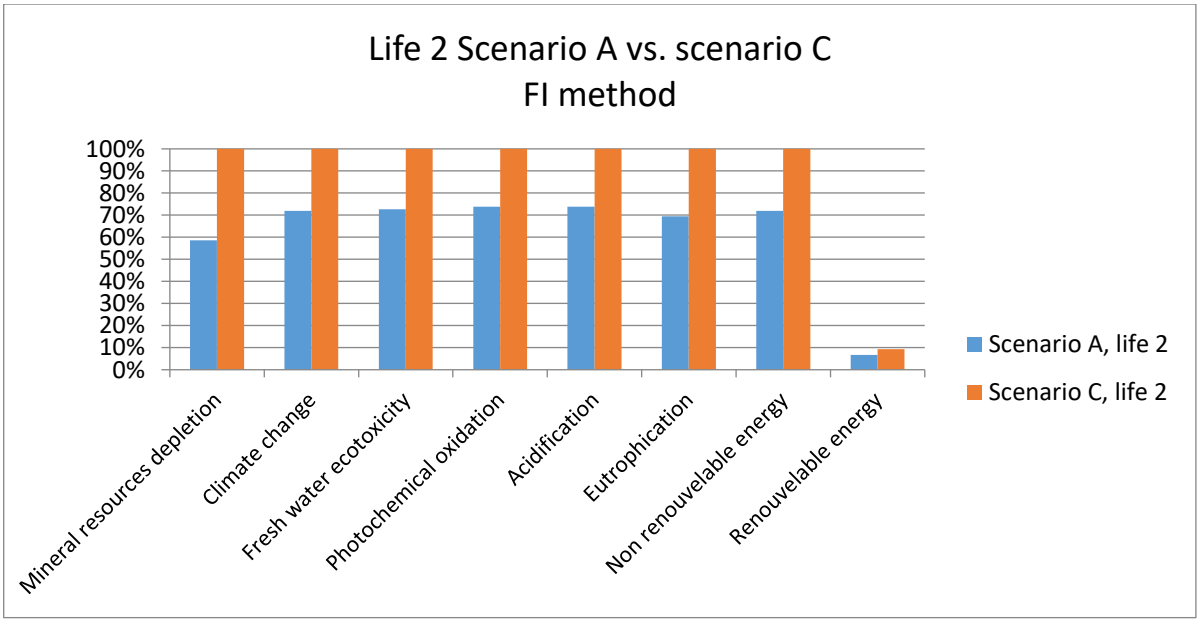


Figure 5: Comparative results (%) 2nd use stage – Integrated functionality – Scenario A vs. scenario C

Note: Renewable and non-renewable energy consumption indicators are represented in relative proportion to the overall energy consumption.

That type of graph stresses the importance of service level delivered. “IF method” allows to share more impacts between three lives. The amount of energy being delivered in 2nd life of scenario C being smaller than in scenario A, impacts are 40 % greater for similar allocation factor.

Sensitivity analyses

Sensitivity analyses were performed to further investigate the CFF methodology. Three sensitivity analyses were done:

1. Including 15 % recycled metal (Ni, Mn, Co) at manufacturing
2. CFF factor “A” lowered from 0.8 to 0.5
3. CFF factor “Qs” expressed only with charging capacity at points of substitution (instead of the product charging capacity x energy delivered).

Recycled metals incorporation

The share of secondary nickel reduces photochemical oxidation and acidification impacts by 10 %. Recycling credits are not significant for other impact categories. Recycling remains uncertain regarding currently available data and future technological progress.

Even if metals within battery cells are critical for resource depletion, the manufacture of one BMS for each life also contributes significantly to resource depletion.

CFF factor: A

Decreasing A from 0.8 to 0.5 results in allocation ratios for stationary lives 2.5 times greater (proportional to 1-A).

In the CFF method, the variation of A affects allocation share between lives. The lower A is, the more battery manufacturing impacts are allocated to the second life. End of life credits in second life are overcome if more than 15 % of battery manufacturing are allocated to the second life. Thus, making A an important variable regarding the relevance of multiple lives in LCA.

CFF factor: Qs

Changing the definition of Qs reduces manufacturing impacts allocated to stationary lives by almost 50 %.

3.2.4 Conclusions

Scenarios and parameterization

Only BE and CFF methods require to define a reference product life cycle, which is substituted by the remanufactured product. This is explicit in BE method, where reference product life cycle is subtracted to the system under study. For “IF” method, the initial product consecutive lives are known and there is no substitution.

The choice of this reference needs to be justified because it determines the final results. The issue is to know whether the reused product replaces another new or refurbished product, or more. For example, we modelled the case where, in 3rd life, battery acquisition in household is opportunistic. No other battery would have been invested in otherwise.

Moreover, the nature, quantity and quality of the substituted product should be carefully evaluated. These parameters should be discussed due to their uncertainty. BE method is particularly affected since it has no allocation between lives.

Boundary extension method

BE method requires to set a point of view. This method leads to include all life cycles of the product and to subtract part of the life cycle of the substituted product depending on the user's point of view (see figure 1). Three options are possible:

- From user 1 point of view, life cycle of the product substituted in 2nd life is withdrawn, which gives impacts for the 1st life
- From user 2 point of view, life cycle of the product in 1st life with classical end of life, i.e. without reuse, is subtracted, which gives impacts for the 2nd life
- Relevance of reuse evaluation: life cycles from both uses separately are subtracted.

Integrated functionality

"IF" method presents the following specificities:

- **Every consecutive life cycles of the product need to be known**
- **Duration and performance for each life of the product must be known** or evaluated to parameterized impact allocation between lives. This method is therefore not relevant for immature technologies, where future lives are still hypothetical.
- **First user can be more or less charged with impacts from following users**, even if he is not necessarily responsible for it. This is not true for CFF method.

CFF method

Even if "CFF" method is framed and applied in PEF battery study, the large number of market trends and recyclability parameters make it difficult to apply to new technologies. The major learnings from the testing of this method, developed through sensitivity analyses, are:

- **Advantage compared to "IF" method**: only lives N-1 to N+1 need to be known. LCA of consecutive lives is done with parameters detailed in PEF guidelines. It can be adjusted to new technologies.
- **Waste allocation in last life**: waste is only allocated to the last application. This shows the risk for user 1 to download waste impacts towards end user.
- **Need to know how product is prepared for reuse** in order to decide whether to use modular CFF version to the product or to its sub-systems: whole battery or separately for each component.

3.2.5 Conclusion on the three methods tested

The application of all three methods reveals a high sensitivity to allocation factors (IF, CFF) and reference for substitution (BE). The lack of primary data and critical metals modelling add another level of uncertainty.

General results show that increasing the number of lives is not always environmentally better. A balance between delivered service and remanufacturing process in second life has to be found. Indeed, the latter remains an aspect to improve in the LCA model of batteries.

4 Conclusion and Outlook

This study has been able to structure the different steps that are needed to conduct an LCA study including refurbishment or reuse. In this context, drawing a parallel with multifunctionality provides a scope for this issue and makes it possible to prioritise the different possible solutions.

Three principal methods to deal with these issues are identified thanks to the methodological literature review: the extension of the system boundaries with substitution, the allocation, and the application of a substitution and allocation method (for instance the Circular Footprint Formula (CFF) used in the frame of the PEF).

The conduction of an LCA of a battery with a second life made it possible to test the applicability of these different methodologies (including the CFF) and their advantages and limitations.

Several aspects of these methods were developed, specifically in the case of product loops. It can namely be stated that it is necessary to identify the market dynamics between products of second and first hand, or to base the study on specific technical studies to determine the functional equivalence between a new product and a refurbished / reused one. Specifically, in a context of circular economy, it seems fruitful to deal with the issue of multiple lives, refurbishment or reuse in a joined vision between environmental, economic and technical challenges.

In this project it has been discussed that the issues are different between products with a long lifetime (buildings for instance), products reused many times (for instance medical tools), and products limited to two or three lives (such as batteries). It has not been possible in the frame of this project to define recommendations by type of products – however, a next SCORELCA study on product loops will likely make it possible to complement these aspects, and why not as a complement to the methodological guide established here.

More generally, we apprehend, with a reflection on the modelling of successive lives of a product in LCA, the broader issue of the modelling of resources and consumption. Indeed, recent works put the emphasis on the inconsistency of a modelling of resources use under the shape of a consumption, and on the need to distinguish the conservative use from the dispersive use, or even to count the “concentrating” use, which can for instance allow the provisioning of metals from low concentrated ore.