METHODOLOGY FOR MULTIPLE LIFE CYCLES PRODUCT ECODESIGN

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Abstract

Knowing how to design new production systems in order to better address sustainable development is a major stake. In this framework, designing new value networks that imply new products should integrate a lot of consideration such as technical performance of the product but also environmental impacts of the value network. This paper aims at contributing in design for system innovation and transition. It is based on mainly technical prospective analysis but in order to make people anticipate the main factors that will impact on environment on several product's life cycles as soon as possible when thinking the first life. The main question addressed is then how to define several product life cycles? What are the main technical factors that will influence environmental impacts? It proposes a methodology based on coupling design of experiment with Life Cycle Assessment for multiple life product ecodesign. The proposal is presented on a case study that aims at defining lithium-ion batteries for electric vehicles and home energy management systems.

Keywords: Ecodesign, Evaluation, Sustainability

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1 INTRODUCTION

Design for sustainability requires to consider social, economic and environmental aspects of the future life cycle of the product designed. Most of the time these aspects are evaluated on the basis of hypothetical deployment scenarios. However, in order to reduce waste or improve economic value of products, multiple use scenarios can be considered.

This paper proposes the use of a combination of Design of Experiments and Life Cycle Analysis to evaluate the key factors in judging the suitability of a second-life reuse. It also describes the use of this combination for second-life reuse of automotive traction batteries for energy storage in Home Energy Management Systems in order to reduce their whole-life environmental impact.

The research methodology is cut in 3 steps that also define the structure of the paper. Firstly, a state of the art on the design of multiple use products had been made. It leads to the need to better understand the main factors that will imply environmental impacts in order to define them first more deeply in a kind of robust design approach. Secondly, a design methodology based on the combined use of Life Cycle Assessment and Design of Experiments is proposed in order to identify and characterize the main influencing design factors on environmental impacts. More accurately, the purpose of the use of Design of Experiments is to identify situations to evaluate in a scenario analysis conducted using LCA. This methodology is illustrated on a case study that had been led with actors of automotive industry, thinking about electric vehicles' battery design in order to enable second life. Thirdly, based on the case study illustration and the analysis of the methodology limitations, a discussion is made and leads to further perspectives for the work.

2 STATE OF THE ART ON THE ECODESIGN OF MULTIPLE USE PRODUCTS

The design process of a product is described as a transition of a set of functional requirements into a complete product concept. The concept of designing a product to reduce the environmental impact during its lifecycle is known as eco-design and its integration into the design process has become an important focal point for future product developments. However; since this concept is not systematically incorporated from the early design phase, but rather considered as an afterthought, the initial value added through raw material extraction and manufacturing is decreased.

The perception of environmentally sustainable products has changed the focus from cradle-to-grave to cradle-to-cradle concept, as described by Go et al. (2015). A better option at the product end-of-life, from the reduction of the environmental impacts point of view, consists in the component reuse or, for the case it is not possible, in the component remanufacturing. Strategies like reuse and remanufacturing have indeed as principal goal: to prolong the product's life cycle. Using those strategies for the product end-of-life, is a means to preserve the value added during the product design and the product manufacturing (Williams and Shu, 2001) keeping the shape, characteristics and functionality of used parts/components. The implementation of those strategies also makes possible the reduction of raw materials extraction (Ferrer, 2001).

The model presented in Figure 1 inspired from Gehin et al. (2008), can be used to represent all the possible scenarios in a closed loop product lifecycle. The closed loop product lifecycle is obtained from the classical product lifecycle and a mix between end of life, reuse, remanufacturing and/or recycling scenarios. In addition to the conventional product end-of-life scenarios that permit the recovery of energy while generating non recoverable wastes, we considered in the present work three strategies to valorise products at its end-of-use (reuse, remanufacturing and recycling) Amaya et al. (2010). This model can be the basic framework for a Life Cycle Assessment of multiple use products.

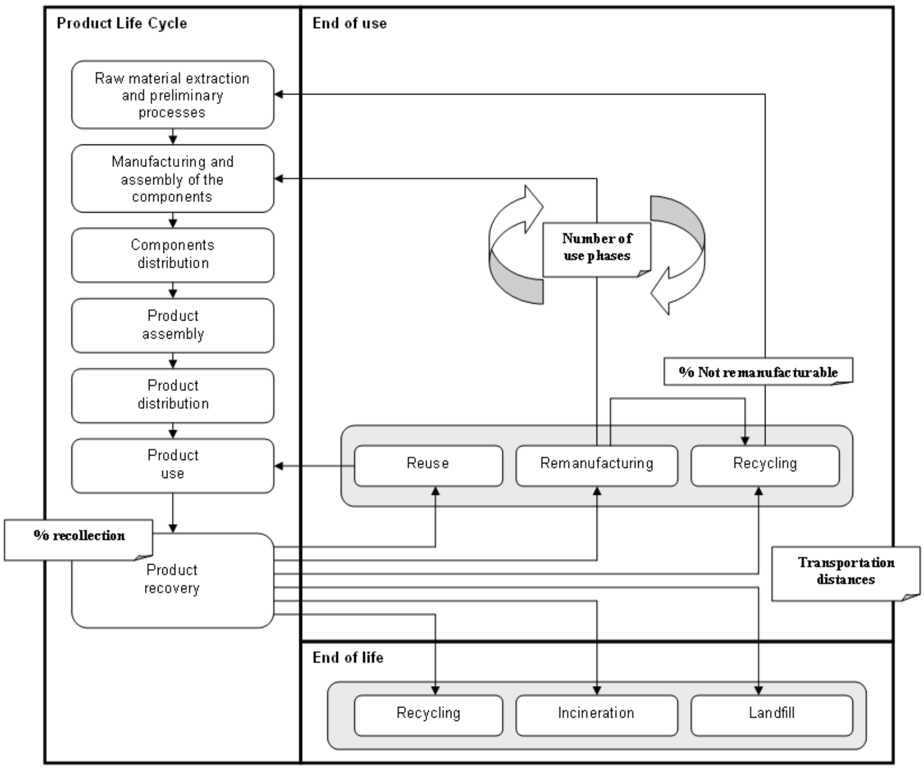

Figure 1. Product – multiple use approach [inspired from Gehin et al. (2008)]

This model implies the use of different factors that define the different life cycles. Eco-design of multiple use products requires to identify the key factors or key design parameters that influence the environmental impact of multiple use products. In this paper, it is assumed that the early choice of the value of these parameters for reducing environmental impacts will lead to eco-designed products.
As there is a lot of design parameters, we will focus on the ones that define the multiple use scenarios. We will evaluate the most influencing ones on environmental impacts in order to define them first and to reducing as much as possible environmental impacts of the multiple use products.

3 HOW TO IDENTIFY KEY DESIGN PARAMETERS TO ECO-DESIGN MULTIPLE USE PRODUCTS?

The first challenge to solve is then to identify the key design parameters of the multiple use scenarios and to identify the most influencing on environmental impacts. For that, we need to combine a methodology for environmental impacts assessment and especially Life Cycle Assessment (LCA, ISO 14040) with sensitivity analysis for multidimensional factors.

3.1 Life Cycle Assessment of multiple use product lifecycle

Life Cycle Assessment (LCA) and its use for potential impacts assessment have been developed to aid designers in evaluating the environmental impacts of their products. It determines the eco-efficiency of the designs of products which is defined as the product value per unit of environmental impact Fleischer et Schmidt (1997). Most of LCA tools determine the environmental impacts of a product by building a systemic model of the product life cycle, composed by a set of connected elementary process. This elementary processes are defined as input and output flows of resources, chemicals, energy… categorized by their provenance or destination in techno-sphere and ecosphere. These categorized flows are quantified and are linked to impact indicators, that can be calculates as characterisation of impacts or normalization if weights and aggregation model is used.
Closed Loop Environmental Evaluations is an eco-design approach that incorporates life cycle brick methodology with the objective to analyse products with multiple use cycles. It can be based on the modelling framework provided in Figure 1, and defining a set of bricks. This assessment requires the input of environmental impact indicators for each component raw material extraction, manufacturing, assembly, distribution, use, take-back and final disposition (multiple use scenarios) options to assess the

impact over the entire life cycle. Once bricks are defined, some rules have to be followed to build lifecycles of closed-loop systems (where product is made of several components):

- A lifecycle is created as soon as the first component is created. The four product-level bricks are built as well as the four component-level bricks. The environmental impact of the product is the sum of the impacts of the bricks (only for weighted impacts or normalized impacts for certain methods).
- Each time the designer creates a new component, four new bricks of the component level are created and new impacts are added to the former ones for each lifecycle phase and for the whole product.
- The designers have to evaluate the number of usage cycles that the component can support at its maximum for the following closed-loop strategies (reuse, remanufacturing, recycling) and the component end-of-pipe strategy that will be adopted at the end. Because the strategy cannot certainly be 100% efficient due to the recovering process capability (quality of take-back parts, percentage of products recovered, efficiency of the remanufacturing process…), end-of-pipe scenarios have to be determined as well as the estimation of the percentage of components that will be effectively reused/ remanufactured.
- Once the model is ready for calculation, the environmental impacts are determined. Then, the impacts are brought back to one single usage cycle so that the designers can compare the different lifecycles alternatives they have envisioned.

The multiple use parameters developed in order to build the lifecycle model of closed-loop systems are described in Table 1.

Table 1. Parameters to consider in the Product Lifecycle Assessment (Gehin et al. (2008))

i	component (1 to n components).
ui	number of usage cycles (loops) that the components i can support.
Xi	percentage of components that can be effectively reused, remanufactured, or recycled in the loop, at the end of the usage phase. In a first approach, it is assumed to be the same at every loop (same end-of-life option and same percentage).
Bi,j	environmental impact of the component i for the lifecycle phase j (environmental impact of the brick (i,j)).
EoUi	end-of-usage option for the component i (reused, remanufactured, recycled).
EoLi	end-of-life option for the component i (recycled, incinerated, landfilled) and for the percentage of components that cannot be reused at the end of the usage cycle.
IEmati, IEmani, IEdisi, IEEoLi,	values of a component environmental impact, per unit of usage (the corresponding impacts of each loop are added and the result is then divided by the number of loops).
IEmat, IEman, IEdis, IEEoL,	environmental impact of the product for each lifecycle phase, per unit of usage.

The model proposed by Gehin et al. (2008) showed the need to consider products as an ordered assembly of components, which become the central entities in the construction of the model for the impact assessment. Indeed, the life cycle brick Gehin et al. (2008) are objects that can be manipulated by designers; those objects make possible to analyse in detail the data generated during the design process; finally, those data will permit designers to make calculations of the environmental impacts and work with them, to accomplish the redesign of the products.

So, at the moment, to promote the valorisation strategies and the duty to assess the impacts generated by those particular scenarios of end-of-life, the life cycle bricks could be used to model the life cycle of products in closed loop life cycles. It makes possible to observe the environmental performance of products in the long term.

However, it is important to identify which are the most important parameters among the multiple use parameters of Table 1 that influence the environmental impacts. The design of experiments presents an interesting support to analyse the influence of system parameters on different kind of performances (multidimensional parameters of complex systems).

3.2 Design of experiments

The design of experiments is increasingly practiced in companies, from the design to the manufacture. The use of experimental design allows to:

- Identify key factors in the design of a product or a process;
- Optimize the settings of a manufacturing process or a measuring device;
- Predict the behaviour of a process by modelling.

Experimental design falls within an approach of quality improvement, leading to a decrease of the production cost and increase of operational efficiency. Indeed, the success of this original approach is due to the possibility of interpretation of experimental results with minimal effort given to the experimental design: minimizing the number of required experiments enables time saving and cost efficiency.

The purpose of an experiment is to find the best combination of factors that are playing a key role into a process and that induce the best desired results: the most reliable and cost saving one.

There are three approach methods: the traditional, the full factorial and the fractional factorial approaches.

3.2.1 The traditional approach

The traditional approach consists in one single factor varying at a time. This method is the most spontaneously used. No specific experimental design is established: a new value of a factor is used given repeated trial and error.

This method is effective only to determine if a particular factor affects the results. But it remains ineffective to quantify and model the cause and effect relationship. This method is not enough viable to establish a predictive model as it is not possible to determine if one factor combined with another has an influence on the response. The reproducibility of the results in real conditions where other factors can be modified in the same time cannot be guaranteed. This method is not recommended as it does not reflect reality.

3.2.2 The full factorial design;

The full factorial design takes all the possible factors combinations into account. This method is the only one taking into consideration all interactions between factors. The number of required experiments can be calculated: $N=n^k$

Where N = number of experiments required; n = number of level per factor; k = number of factors.

The full factorial design method is theoretically perfect. But the limit is quickly reached when the number of tests to be performed is too high. Waiting time and experimentation costs become prohibitive as soon as 3 or 4 factors are tested.

3.2.3 The fractional factorial design.

In the full factorial design method, all combinations of factors do not have the same practical value. In other words, some tests bring more efficient information than others. A fractional factorial design only takes into account these tests. They are carefully selected. This design method leads to a minimalist number of tests.

Several designs and interpretations methods have been defined. We studied three methods:

- Plackett and Burman’s method (Goupy, 2005);
- Taguchi’s experimental design (Alexis, 1995);

The full factorial design method is theoretically perfect. But the limit is quickly reached when the number of tests to be performed is too high. Waiting time and experimentation costs become prohibitive as soon as 3 or 4 factors are tested.

When a dispersion or instability characteristics are observed while manufacturing or using a product, we usually look for the causes to reduce or eliminate them. But the means used to remove them could be very expensive. Instead of eliminating the confounders (also called “noises”), Taguchi suggests to

reduce their impact. In concrete terms, the method consists in identifying the combination of factors that reduce the effects of causes, but without acting directly on the causes.
Taguchi managed to popularize the experimental design by putting a wide variety of standard experiment plans at users' disposal. The users can adapt these plans to fit their real needs. A great part of the statistics aspect is simplified or eliminated, turning the experimental design into a tool easy to use. The Taguchi's plans are called "tables" and referred as Lg (mf). "g" stands for the number of lines (or runs), "m" stands for the level of the factors and "f" stands for the number of columns (equal to number of factors + number of interactions).
Taguchi's is the most appropriate method to apply in our case as the aim of this study is to determine the combination of factors that gives the lowest environmental impact and improve the model. Plus, the Taguchi's method is one of the most used method in the industry.
It is possible to split the application of the Taguchi's method into four steps:

- Step 1: Determination of factors and interactions to be tested. This step is crucial as taking into account additional interactions could lead to a larger table with a number of tests increased.
- Step 2: Determination of the level of the factors. If the factors have a non-linear evolution, usually, the level is greater than 2.
- Step 3: Choose the table among the tables with the number of selected levels, those which respect the number of factors, the number of selected interactions. The choice is made with line graphs. The vertices of the graphs indicate the factors and the arcs indicate the possible interactions between factors. Adapt the table to the number of factors if needed.
- Step 4: Interpretation of the results given by the experimental plan.

4 ILLUSTRATION OF KEY DESIGN PARAMETERS IDENTIFICATION TO ECO-DESIGN SECOND LIFE OF ELECTRIC VEHICLES' BATTERIES

Our proposal is then to use design of experiments and especially Taguchi's method to structure the identification of design parameters and structure the LCA that should provide the evaluation of environmental impacts for each numerical experiment to achieve.
We applied this methodology on a case study for the use of lithium ion batteries for electric vehicles. In the case of electric vehicles, Neubauer et al. (2011) had estimated the impact of battery second use on the initial cost of PHEV/EV batteries to automotive consumers and exploring the potential for grid-based energy storage applications to serve as a market for used PHEV/EV batteries. It is found that although battery second use is not expected to significantly affect today's PHEV/EV prices, it has the potential to become a common component of future automotive battery life cycles and potentially to transform markets in need of cost-effective energy storage. Based on these findings, the authors advise further investigation focused on forecasting long-term battery degradation and analysing second-use applications in more detail. In the same time, Viswanatan et al. (2011) explored optimality for the replacement of transportation batteries to be subsequently used for grid services. This analysis maximizes the value of an electric vehicle battery to be used as a transportation battery (in its first life) and, then, as a resource for providing grid services (in its second life). The results are presented across a range of key parameters, such as depth of discharge (DOD), number of batteries used over the life of the vehicle, battery life in the vehicle, battery state of health (SOH) at the end of life in the vehicle, and ancillary services rate. The results provide valuable insights for the automotive industry into maximizing the utility and the value of the vehicle batteries in an effort to either reduce the selling price of EVs and PHEVs or maximize the profitability of the emerging electrification of transportation.
The AbattReLife project is based on a European consortium including automotive industry partners and focus on the study of end-of-life scenarios for lithium-ion batteries. A reference scenario of lithium-ion battery end-of-life had been built considering a second life for Home Energy Management System. In order to eco-design second-use scenarios, we applied the 4 steps of Taguchi's method and evaluate the design of experiments by the way of a LCA model implemented on Gabi software.
The reference scenario modelled in Gabi software is illustrated in Figure 2.

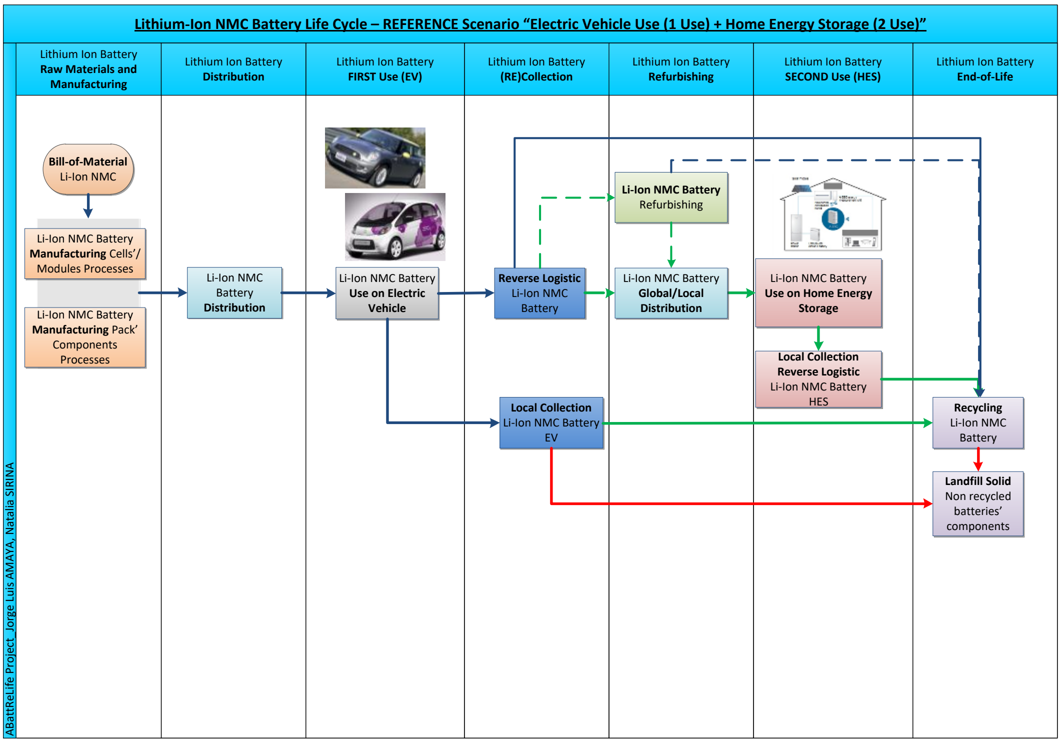

Figure 2. The LCA reference scenario

The final key factors and the range of expertise is defined by the high and low levels of each factor illustrated in Table 2. The level 1 and 2 corresponds to minimum and maximum values of each factors provided by experts from automotive industry and consolidated with experts of the possible business models for second life for HEM. These two levels are used in the design of experiments in order to evaluate the influence of each factor on environmental impacts.

Table 2. Multiple use parameters considered

Tested factors	Units	Level 1	Level 2
Factor A: Capacity left in the battery cells after the first use	%	50	70
Factor B: Proportion of products that are recovered by the reverse logistics	%	90	100
Factor C: Distance from dealers to warehousing/reconditioning (refurbishing) facilities	km	200	1000
Factor D: Type of transport used on the recollection of used lithium-ion according to European emission standards		Euro 4	Euro 6
Factor E: Performance of the reconditioning	%	30	80
Factor F: Distance from the reconditioning facility to the customers	km	1500	200
Factor G: Distance from the reconditioning (recollection) to the product end-of-use site (recycling) or end-of-life site (waste treatment)	km	200	1000
Factor H: Energy storage capacity for HEM (House Energy Management)	kWh	1.2	6

From this identification, the influence of each key factor on environmental impacts had been evaluated on the basis of the reference scenario model with a design of experiments where the factors had taken the extreme values provided in Table 2. A numerical design of experiments had been executed where each line of the design of experiments is a specific instance model of the reference model that had been parameterised in Gabi Software. It should be noticed that no allocation had been made but stock method had been used. Then, from the results, the influence of each factor on the different environmental impact categories had been evaluated and the interaction between factors studied. These evaluations enable to classify the importance of each defined parameter of the implementation scenario on environmental impacts. The results are summarised in the following table (Table 3) for influence results. In other words, Table 3 provides the influence of the factors on each considered environmental impact evaluated using a parametric LCA. The impact category had been chosen to fit both the first and second use (i.e. energy for electric vehicles and energy storage for HEM). It consolidates usual impact categories used by professional and those recommended in ILCD Handbook.

Table 3. Synthesis of the influence of each key factor of prospective scenario definition on chosen environmental impact categories

5 DISCUSSION AND CONCLUSION

In Table 3, the importance of the influence is provided by the height of the vertical bar relative to each factor, and this for each environmental impact category. It appears clearly that, whatever the considered impact, the most influencing factor is the definition of the value for energy storage capacity in second application (factor H), i.e. HES (Home Energy Storage). This parameter of the prospective scenario design has been evolving in value and is still defined under uncertainties. This result underlines the fact that it should be accurately defined first to reduce the environmental impact of the implementation scenario.

Another important factor is the performance of reconditioning (factor E) that also has the second most influence on all the chosen environmental impact categories. It is then very important to have a sufficient reconditioning performance, which means a good rate between the batteries that are used in the first life and those that are usable and used in the second life. Therefore, it is necessary to adjust the end of first life to fit the second life features of the batteries for second use in HEMS.

Finally, the less important factors to define that affect the environmental impacts are the distances (Distance from dealers to warehousing/reconditioning (refurbishing) facilities and distance from the reconditioning facility to the customers). Than we can conclude that the definition of the reverse logistics to come from the first application to the second one is not very important with respect to environmental impacts.

It provides valuable information for decision making early in multiple use scenario design but, further works should be developing in order to include in the same framework the cost estimation in order to evaluate the influence of these choices on the economic value of the scenarios.

As the proposed methodology is based on the description of prospective scenarios, a lot of uncertainties are included in the LCA and limit the interpretation that had been done on the influence analysis. The work should be completed with an uncertainty analysis into the LCA framework or in the Design of experiments including noise factors or in both.

It would be interesting to see if considering the uncertainty will change the design parameter definition for second use of Lithium ion batteries.

Extension of the approach can be envisaged considering that material stocks are generated in the simulation (no allocation had been made in LCA but stock method is used) and can provide additional economic value. The way to consider this secondary material is to assess the material flow in LCA (tracked flows in Gabi software) and economic value of this secondary material should be included in the cost and economic evaluation of the second use scenarios.

To conclude with, the paper proposes the use of a combination of Design of Experiments and Life Cycle Analysis to evaluate the key factors in judging the suitability of a second-life reuse. It also describes the use of this combination for second-life reuse of automotive traction batteries for energy storage in Home Energy Management Systems in order to reduce their whole-life environmental impact. It provides first basis for an initial framework to eco-design multiple use products.

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