Modeling sustainable recycling logistic network for batteries from electric vehicles in EU-27: A system dynamics approach.

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Abstract

Since the 2008 crisis, the automotive industry is shifting towards green mobility using mainly lithium batteries. Therefore, the issue of recycling batteries arises for ecological, economic and geostrategic reasons. In this contribution, we are concerned with the design and the analysis of a batteries recycling logistic network. The dynamics underlining the evolution of such a system are clearly shaped by the complex interaction between a set of heterogeneous factors. We advocate the use of System Dynamics (SD) as an appropriate tool for modeling and making explicit the complexity of this interaction. A SD model is given based on a joint work with a French car manufacturer. Further steps should lead us to deeply quantify some effects making it possible to build a quiet holistic comprehension of the dynamics of the future logistic network, in an evolving context. This comprehension is clearly useful for a strategic decision making aid.

Keywords: Recycling, System dynamics, lithium batteries

1. Introduction

Everyone agrees that we are at the beginning of a second automotive revolution, driven by the electro-mobility concept. Several technologies exist, including fuel cell technology. However, they are not yet marketable. Thus, the industry turned to hybrid or fully electric vehicles, using mainly lithium batteries. The challenge in the viability of the electro-mobility concept is that; the electric vehicle requires the establishment of a whole new eco-system (connectivity, charging infrastructure, battery processing, etc.) and offers new business opportunities (Vehicle 2 Grid, batteries 2\textsuperscript{nd} life use) which disrupts the classic automotive value chain and requires an efficient planning approach, in order to overcome technological and market uncertainties. In fact, the stakes about investments and value capture are huge; the use of prospective analysis tools might be of great help. These tools will provide insights and better understanding about the considered systems, which enhance the decision making process.

Given these new developments, the issue of recycling batteries arises for legal, economic and geostrategic reasons. The regulatory driver concerns the recycling targets to be achieved while recycling End-of-Life vehicles (ELV) and batteries. These recycling targets; 85% of ELV weight and 50% for batteries weight, are set by European directives 2000/53/EC (European Parliament, 2000) and 2006/66/EC (European Parliament, 2006), respectively. The economic stakes are induced by the possibility to repair batteries or extend their life out of the automotive industry. In fact, these batteries; when out of use for optimum automotive propulsion could be used as energy storage for stationary applications. The geostrategic issue concerns the supply of rare earth elements and strategic materials, such as lithium. Since the issues of lithium resource adequacy is resolved (Kesler et al., 2012), the challenge is to increase production capacity to meet the increasing future demand (Kushnir and Sandén, 2012). Miedema and Moll (Miedema and Moll, In
press) confronted the supply capacity of lithium to the needed demand from the automotive industry in EU-27. They concluded that undersupply can be expected in the near future, before a large scale recycling network of batteries is established.

Currently, partnerships are built between original equipment manufacturers (OEMs) and recycling companies. Due to low volumes in EV sales, the industrial recycling of these batteries is non-existent. Thus, an effective recycling network should be established (Hoyer et al., 2011). The related value chain to be created is considered as “not natural”, because it would not have appeared from a market demand. Therefore, there is a lack of common purpose between the actors. However, legislation is pushing towards more cooperation between the original equipment manufacturers (OEM), the ELV recovery infrastructure, the consumer, and other stakeholders. OEMs are shifting from traditional paradigms to innovative business models (Kumar and Sutherland, 2008).

The aim of this subject lies in the identification of a configuration of the logistic network associated to batteries at the end-of-life. This logistic network should be able to comply with regulations while controlling the overall cost and environmental impact of batteries. Even if we consider the whole recovery chain, we focus more on the role of the OEM, because they have the legal responsibility on the batteries. To achieve this, our research work consists of formalizing a methodology to help design a recycling logistic network for batteries from EVs, under uncertainty. In this paper, we focus on modeling the recycling network using an approach that capture the complex and evolving structure of the system to study, namely “System Dynamics” (SD).

In next section, we provide a background on end-of-life products recovery. We justify the use of SD as a modeling and analysis tool. The third section is dedicated to the SD modeling process; elaborated diagrams are explained in detail. Conclusions and perspectives of this work are outlined in the last section.

In this paper, “recycling” will be referred to as the treatment and recovery of batteries after the first automotive use, including: reparation, second life applications and materials recycling. The term EV includes: hybrid-electric vehicles (HEV), plug-in hybrid vehicles (PHEV) and battery-electric vehicles (BEV).

### 2. Why SD for a recycling logistic network design and analysis?

The issue of recycling end-of-life products is becoming a well studied subject, attracting attention from both academia and industrial worlds. Related work is found in several strands of literature: Environmental value chain management ((Ishii and A. Stevels, 2000), (Rose and Ab Stevels, 2000)), green supply chain management (Srivastava, 2007), and reverse logistics (RL). Regarding the recycling of batteries, a relatively substantial literature exists in the area of lithium portable batteries and lead acid batteries. However, the related networks are not adapted for EV batteries; given these latter’s characteristics (recycling drivers, weight, hazardousness and quantities). To the best of our knowledge, (Hoyer et al., 2011) is the unique developed work.

While designing supply chains, (Kibli et al., 2010) argue that it is important not to assume a static deterministic behavior, by modeling appropriately uncertainties and developing methodologies to overcome them. Several theories and methodologies such as stochastic programming and fuzzy programming might be used to tackle uncertainty (Sahinidis, 2004). When it comes to selecting the right approach in supply chain modeling, there is no general framework allowing the identification of the most appropriate one. In the health context, Brennan et al. (Brennan et al., 2006) provide a number of criteria, including: system characteristics and complexity, presence of interaction due to constrained resources and the decision makers’ requirements, in order to guide the choice of the appropriate modeling technique.

Within the reverse logistics and closed-loop supply chains context, operational research tools are widely used (Georgiadis and Besiou, 2008) to solve problems such as network design ((Nickel et al., 2012), (Cardoso et al., 2013), (Pishvaee et al., 2011), (Pishvaee et al., 2010), (Ramezani et al., 2013), (Lee and Dong, 2009)) and inventory control (Choi et al., 2007). Sterman mentioned that “whenever the problem to be solved is one of choosing the best from among a well-defined set of alternatives, optimization should be considered. If the meaning of best is also well-defined and if the system to be optimized is relatively static and free of feedback” (Sterman, 1991). In these papers indeed, the structure of the studied systems is considered as well defined and static, and uncertainty is mostly assumed at the demand level (Nickel et al., 2012). In (Hoyer et al., 2011), the ELV recovery infrastructure, the consumer, and other stakeholders. OEMs are shifting from traditional paradigms to innovative business models (Kumar and Sutherland, 2008).

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2011), a framework for the design of recycling networks for Li-ion batteries from EVs is developed. It involves three steps: analyzing problem characteristics; description of actors and requirements that need to be considered and an integrated planning approach of the network. The planning approach falls into strategic network planning literature, using mathematical multi-objective optimization. Uncertainties are tackled by the mean of scenarios techniques and sensitivity analysis. As in (Hoyer et al., 2011), coupling simulation and optimization may lead to efficient approaches to tackle uncertainty ((F. Glover et al., 1999), (Fu et al., 2005)).

As highlighted earlier, the challenge of the present work is to design a sustainable value creating recycling network, in the context of a value chain emergence. In this context, products return volumes, potential markets for recycling materials, interaction between virgin and recycled materials markets, feedbacks while remanufacturing / recycling, maturity and configuration of recycling processes, change in legislation and reuse opportunities are such evolving and uncertain factors that make it difficult to assume a static behavior both for the considered network and its context. Indeed, a static behavior is rarely present in environmental management systems (Bloemhof-Ruwaard et al., 1995).

In this paper, a SD based approach is adopted to model the factors defining the system under study as well as its context and their dynamics.

SD is a powerful methodology suitable for analyzing large-scale complex management problems, it provides a conceptual framework useful in the assembly of non-linear differential equations with complex feedbacks (Forrester, 1961). It encompasses analytical modeling and simulation, taking roots from the System Thinking theory. The objective is to analyze, understand and predict the behavior of complex systems over time, by analyzing its changing factors(Sterman, 2000). A good example of the SD’s interests is the Meadows report (Meadows et al., 1972), a report that confronted the global growth to the limited resources on earth, also widely considered as the first reflection on sustainable development. Seadon (Seadon, 2010) emphasized on the necessity to implement a systems approach including system dynamics tools to achieve sustainability in waste management systems, because of the multiplicity of interaction between its components and its adaptive evolutionary nature. Georgiadis and Besiou ((Georgiadis and Besiou, 2008). (Georgiadis and Besiou, 2010)) studied the environmental and economical sustainability of WEEE closed loop supply chains with recycling, by incorporating factors such as green image, legislation, availability of natural resources and design for environment. Farel et al. (Farel et al., 2013) used a SD model to estimate the costs and benefits of end-of-life vehicles glazing recycling in France. These papers illustrate the interest of SD, whenever it is necessary to go beyond the classic economic factors, usually well quantifiable and homogeneous.

Two key words, mentioned above, justify and legitimize the SD approach, namely: Complexity and feedbacks. Donnadieu and Karsky (Donnadieu and Karsky, 2002) identify three kinds of complexity: Space complexity, “unpredictable” Complexity and dynamic complexity. SD approach has been developed to overcome the last one. Feedbacks are the major manifestation of the dynamic complexity. There are two types of feedback loops: Positive (self-enforcing) and Negative (self-correcting, balancing). The feedback loops may encompass delays and nonlinearities, they may also occur simultaneously or sequentially, making it possible to predict the behavior of the corresponding system over time (Donnadieu and Karsky, 2002).

3. System Dynamics modeling

The SD approach is an iterative process that starts from the problem definition (system boundaries, important factors, time horizon). It consists of formulating the dynamic hypothesis using Causal loops diagrams and Stock & flow diagrams for simulation and validation. Once the model is validated, it is used for policy formulation and evaluation (Sterman, 2000).

Constructing a SD model is a subjective work. However, the process above should always be respected. In order to identify the system of interest, we tried to highlight the supply chain related to recycle batteries from EVs. This will enable the use of reverse logistics literature, which enhance and ease the modeling of recycling activities. Based on the RL characterization provided in (Fleischmann et al., 2000), “Fig. 1” illustrates the system of interest, its boundaries and subsystems.

As explained earlier, we identified three major drivers for recycling lithium batteries from EVs, which concern the two recovery options: reuse (refurbishment at product level, reuse “as is” at product level and reuse at component level) and
materials recycling. These macro factors are split according to their perimeters to deduce exploitable variables. Regarding the time horizon, we choose to simulate our system between 2010 and 2050. This is consistent with the early sales of EVs and existing literature (Miedema and Moll, In press).

![Fig. 1. System boundaries and subsystems.](image)

3.1. Causal loop diagrams:

In the second step of the process described above, SD approach requires constructing the “causal loop diagrams”. Causal loop diagrams are used to capture the influences (cause-effects) between variables. The variables are linked by arrows (causal links) which may have either a positive (+) or a negative (-) sign (Chaerul et al., 2008). These signs have the following meanings:

- A positive link means either one variable is adding to the other one, or they change in the same direction.
- A negative link means either one variable subtracts from the other one, or they change in opposite directions.

In order to assess the sustainability of the recycling network, the identification of the appropriate performance indicators is a critical task. Other than the obvious economic indicators, there is a multicity of environmental indicators (energy efficiency, greenhouse gas emissions, waste generated, waste recycling rate, etc.). In the other hand, there is a lack in social metrics, which rises a challenge on how to measure the impact of SC on people/society (Tang and Zhou, 2012). There is no consensus or study addressing the three dimensions of sustainability (Hassini et al., 2012). In the absence of such a framework, we identified the metrics that seem to be most relevant to our topic, namely the economic and environmental criteria. The economic criterion is shown by a cost-benefit analysis. It is important to notice that we consider the economic balance of the whole recovery chain. This assumes a cooperative recycling network, which raises questions about role-play definition and profit redistribution. To quantify the environmental performance of the considered recovery chain, we chose the following indicators: the carbon footprint and the energy used. These will highlights the benefits, or possibly the disadvantages, for recycling instead of producing from raw materials, which is also consistent with the existing literature (Dunn et al., 2012), (Gaines et al., 2011).

Starting from the flow activities diagram introduced in “Fig. 1”, causal loop diagrams have been developed; their main parts are described in the following.

**Interaction between virgin and recycled lithium:** This interaction refers to the mechanisms that enable lithium recycling, which is today not beneficial. In order to upgrade the recycling process (invest in hydrometallurgy facilities) to recover lithium, two mechanisms could trigger that; the undersupply in virgin lithium (supply gap), or the shifting advantage to the recycled lithium (Price gap) (see “Fig. 2”). Supply gap translates the inability to keep up with the demand rate. Price gap translates the increase in virgin lithium price, caused by scarcity of reserves and the necessity to exploit more expensive deposits.
The amount of available lithium for recycling and required lithium in EU is defined by the development in EV market.

The different costs: The overall cost comprises collection / inspection cost, repairing cost and recycling cost (see “Fig. 3”). Each of these specific costs is dependent on the volume and transportation distance for treatment (inspection, repair or recycling). In addition to the classic trade-off in network design, between transportation costs and investments in treatment facilities, used batteries are considered hazardous. Therefore, their cross-boarding transport is submitted to an European regulation “According for dangerous goods by road”, which induces additional costs.

The Carbon footprint: To model the environmental impacts, we choose three indicators: CO2 emissions and used energy. “Fig. 4” illustrates the carbon footprint of the whole supply chain, in order to highlight possible saved emissions from extracting virgin materials. The same reasoning as for the costs is used here.

Overview: “Fig. 5” illustrates the different parts explained above. The whole economic and environmental balances are also included.

4. Conclusion and perspectives

The recycling network for batteries from EVs will be implemented, mainly for legal, economic and geostrategic reasons. The developments in batteries’ technology as well as the maturity of recycling processes and the evolution of legislation are a significant burden in this study. To overcome this complexity and get useful insights about an evolving system which is at the emergence phase, we use SD to model and predict the recycling network’s behavior.

The exposed model has so far been validated by the car manufacturer. To yield the next step, which is the simulation phase, all necessary data will be gathered through interviews of experts within the car manufacturing company and its main partners and using further reading of similar studies.

The resulting model would be of great interest for a strategic decision making aid and policy design of the main industrial actors concerned by the emergence of such a logistic network and would make it possible to predict effects of complex interactions within the supply chain, which would otherwise stay out of reach of any foresight.
Fig. 3. The different costs of the recycling network

Fig. 4. The carbon footprint of the recycling network
Fig. 5. Overview of the recycling network

Acknowledgment

This work was benefited from the support of the chair “PSA Peugeot Citroen Automobile: Hybrid technologies and Economy of Electromobility. So-called Armand PEUGEOT Chair”, led by Ecole Centrale Paris, ESSEC and SUPELEC, and sponsored by PEUGEOT CITROEN Automobile.

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