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DEVELOPMENT OF A DESIGN FOR END-OF-LIFE APPROACH IN A STRONGLY GUIDED DESIGN PROCESS. APPLICATION TO HIGH-TECH PRODUCTS

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Abstract: In response to a growing concern for environmental problems and to waste management from mass production products, several regulations have appeared to tackle end-of-life (EoL) issues. They address for instance end-of-life vehicles or waste electrical and electronic equipment. EoL management mainly lays on both EoL industry and product design. Thus, new methods of design have already been implemented since the past decades to answer the regulation requirements, notably through material choices and product architecture. However, some high-tech products remain out of the scope of these legislations. But for some years, initiatives have emerged for these products, coming from governments, international programs or customers' requirements which become increasingly strict. This paper focuses on a new design approach that would allow taking into account EoL considerations for such type of products, based on EoL strategies and adapted to aeronautic and defence products.

1. INTRODUCTION

"Cradle to grave design" [1] is the actual common way for designing products. A product is made of first extraction raw materials and is rarely designed for a second life. In other words, reusing the whole product, remanufacturing it, or recycling its components are not yet promoted options. Indeed, end-of-life (EoL) considerations are not enough taken into account during the design process to ease its EoL treatments due to conflicting economic and environmental policies in a company.

However, some European directives tackle EoL issues of mass production products. One of the most advanced sectors in terms of waste management is the automotive one. End-of-life vehicles (ELVs) directive [2] aims at preventing the waste production from vehicles, by supporting recycling and other recovery processes, in order to reduce the waste disposal. According to this legislation, 85% of ELVs have been recovered in 2006, of which 80% recycled or reused. By 2015, these ratios will respectively rise to 95% and 85%. Tools and design methods have been developed to comply with this regulation.

Besides, other directives also deal with EoL: WEEE (Waste of Electrical and Electronic Equipment) [3], Disposal of spent batteries and accumulators [4] and Packaging and packaging waste [5].

Despite that, some high-tech products remain out of their scope. But for some years, initiatives have emerged for these products, coming from governments (*e.g.* French Department of Defence [6]) or international programs (*e.g.* European program *Clean Sky* [7]). Customers' requirements also become increasingly strict; designing more eco-friendly products is an important selling point, even in aeronautic, space and defence industries.

Taking into account the product's end-of-life during its own design process is not an easy task, especially for complex and high-tech ones. In this study, we will focus on products that require long development stages, undergo high levels of constraints, with long lifecycles and low amount of produced units. Our purpose is to propose and define a new design method that would better take into account EoL issues in the design process, and based on EoL strategies adapted to aeronautic and defence products. To do this, three topics have been investigated and will be developed in this paper: the design process, the standard profile and the EoL industry.

The first section will introduce the problem regarding high-tech products specificities. The second one will focus on our proposal: a method based on an EoL strategy adapted to defence and aeronautic products. Lastly, some aspects of the method will be detailed throughout a case study.

2. IDENTIFICATION OF THE PROBLEM

2.1. Context

2.1.1. The products

This article focuses on aeronautic and defence products from several classes of technologies: optics, electronics, mechanics, software, etc.

Firstly, these products require long development stages, undergo high levels of constraints, are developed for long lifecycles, but count a low number of produced units. In this way, the design characteristics result from their complexity, their lifecycle duration (from the beginning of the development process to the end-of-life strictly speaking), and the strongly guided process used for their development.

Moreover, these kinds of products are, most of the time, submitted to high confidential restrictions. As a consequence, companies have to track them in order to save these classified technologies. This leads to other EoL issues which differ from mass production products ([8], [9]).

In these conditions, it is difficult to implement other design constraints without a major impact on the product design: time, cost and spent resources.

2.1.2. Regulations

Regulations dealing with environmental issues in defence and aeronautic industries can be classified in two categories: the ones affecting product design (REACh [10], RoHS [11]) and those affecting EoL management (WEEE, Packaging and Packaging waste, Disposal of spent batteries and accumulators).

These legislations introduce new design constraints to manage during the design stages in an already strongly guided process.

2.1.3. Specificities of the Department of Defence and Department of Aeronautics

Most of the time, defence and aerospace products are out of the regulations scope, and are not affected by the requirements previously listed, except for REACh and packaging. However, managing the product's end-of-life is a common problem which will impact further generations.

In the coming years, some products may become useless or obsolete due to regulation restrictions evolution [12] and materials scarcity [13]. Then, even if some industries are not directly affected by these situations, they may suffer from an indirect impact.

Moreover, legislations may evolve rapidly. It is not useless to be proactive on this matter. Indeed, it may be a strategic choice for a company to outpace the competition.

2.2. Highlighting the gap between requirements and aero-defence industries know-how

End-of-life is not a part of aero-defence culture. For this sector, it is a new subject because of the absence of regulations and the very few consumers' requirements in the past years. That leads to a lack of skills and knowledge to treat that kind of purpose.

However, many challenges can be faced by tackling EoL issues, as material rarefaction or protection of classified technologies, but designers are not enough aware of these challenges and the complexity of these new tasks [14].

2.3. Aero-defence industries actual practices

2.3.1. End-of-life form

End-of-life form is a recrudescent type of deliverable demand in aerospace and defence industry. This document is created to gather all the information required for the management of the product's end-of-life. It contains data about materials, hazardous substances, painting and surface treatment, etc. It also introduces the best end of life treatment associated to each part of a product, reminding the applicable EoL regulations and the dismantling procedures. The detail level of this document is discussed during the expression of the consumer's need.

For designers not trained to such purposes, it is not an easy task to find, sort and adapt relevant information coming from the definition of the product and manage such amount of information. Indeed, there is no existing tool or method to ease the edition of that kind of documents.

2.3.2. Guidelines

The Aircraft Fleet Recycling Association (AFRA) published in 2009 a collection of the best practices for management of used aircraft parts and assemblies [15]. But these guidelines are generic and theoretical; those make it hard to be directly applied on a product.

2.4. New issue: how to integrate end of life in design process?

2.4.1. State of the art: design for end of life and dismantling

According to the UNEP [16], the product or material end of life can be divided into two main phases. The first step is the collection (including dismantling, de-contamination and cleaning), and the second is the material recycling.

Several tools have already been developed in the literature [17]; they can be classified in three categories:

- Design for dismantling or design for recycling guidelines ([18], [19]): mostly dealing with materials, product structure, fasteners and connections;
- Indicators [21]: it may be every quantitative or qualitative data, useful for the EoL treatment of a product;
- Assessment methods ([14], [22]): they allow the designer to measure the EoL performances of a product, as for instance cost evaluation or assessment of the disassembly and dismantability.

In order to identify the ways to assess and propose relevant paths to integrate EoL into product’s design process, tools which have been identified above can be linked together.

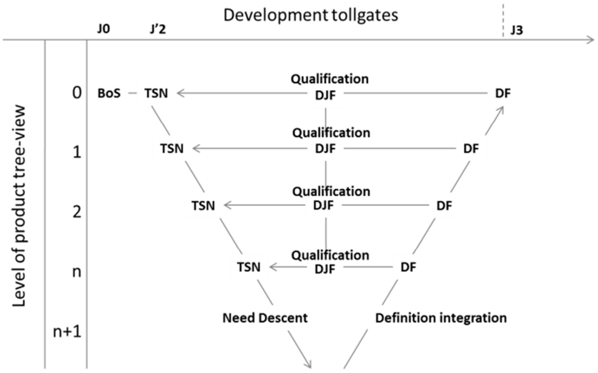
Assessment methods address particular sets of indicators to model end-of life characteristics.

According to different results, combinations and / or comparisons, general guidelines can be described in order to direct as easily as possible designers choices.

2.4.2. Limits of the existing tools and assessment methods: basis for the proposal of a new method

These tools allow the designer to take into account EoL during the design process, and assess it according to some criteria: all these tools have to be used together to correctly treat EoL, each one at the right moment during the design of the new product. But no proper link has been described between all these tools types in order to use them the best way as possible to integrate EoL design process.

V-model in design is currently one of the most used design process type in aerospace and defence industry. This model corresponds to a succession of more and more detailed definitions of a product, all along the development progress. As represented in figure 1, the product definition at a given level is correlated to a set of validation and justification actions, like in a mirror, regarding reference documents [20].



BoS	Bill of Specifications
TSN	Technical Specification Need
DF	Definition File
DJF	Definition Justification File

Figure 1. *V-Model design (translated from [20])*

Our proposal, in order to match the design V-model, is to reverse the link we observed in bibliography between the three tools categories, as illustrated in figure 2.

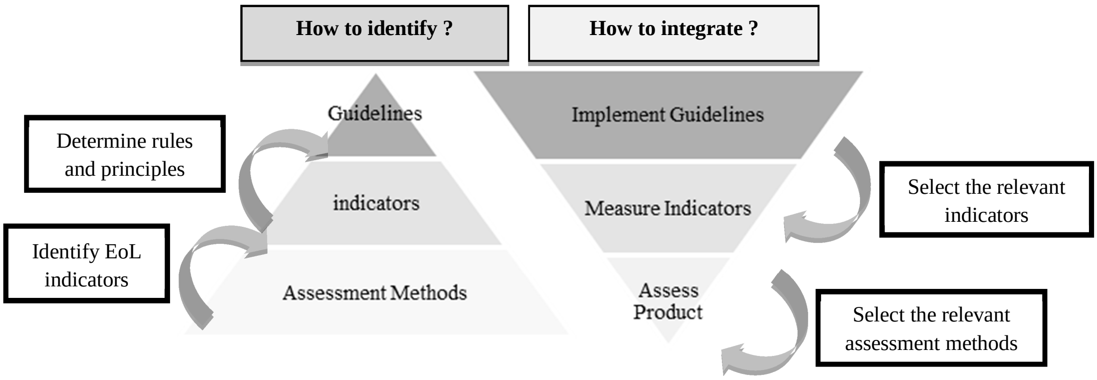


Figure 2. *EoL tools links: identification vs integration*

We propose to start with an end-of-life strategy according to one product (or a product family). This strategy lays on specific guidelines. In order to implement the chosen guidelines into design process, specific set of relevant indicators is defined. Assessment methods are then employed in order to evaluate indicators all along the design process. Indicators are used in order to monitor EoL integration during the process in the design choices. These indicators allow checking if the final “End-of-Life” performances comply with initial strategy objectives.

We develop this proposal in the next chapter.

3. PROPOSAL OF A METHOD BASED ON AN END-OF-LIFE STRATEGY ADAPTED TO DEFENCE AND AERONAUTICS PRODUCTS

In this section, we will propose a new method based on an EoL strategy adapted to defence and aeronautic products in order to integrate EoL issues during the design stages.

3.1. Introduction to the method

This method must be applied upstream of the product design, during the expression of the customers’ needs and the drawing up of the technical specifications. This method is composed of five steps (see also Figure 3):

1- An end-of-life strategy is defined for the product by both consumer and manufacturer. They have to choose the EoL requirements that their product must comply with (*e.g.* *x*% of recyclability, reuse of some parts, no hazardous substances, etc.).

2- The designer will refer a pair (standard profile/EoL industry). The *standard profile* is defined as the reference product in a product family, in order to gather all information regarding EoL, as materials or hazardous substances. Based on the *standard profile* and the knowledge of the *end-of-life industries*, the end-of-life performances of the new product can be estimated.

3- The designer checks if the EoL requirements previously defined are technically feasible, according to the end-of-life performances estimated at the previous step, and relevant regarding the needs and the evolution of the EoL treatment during the product life. This stage can be considered as a tollgate in the whole process, allowing continuing on step 4.

4- The product design can be launched: according to the EoL strategy chosen, relevant guidelines and associated indicators will be applied during the whole product development.

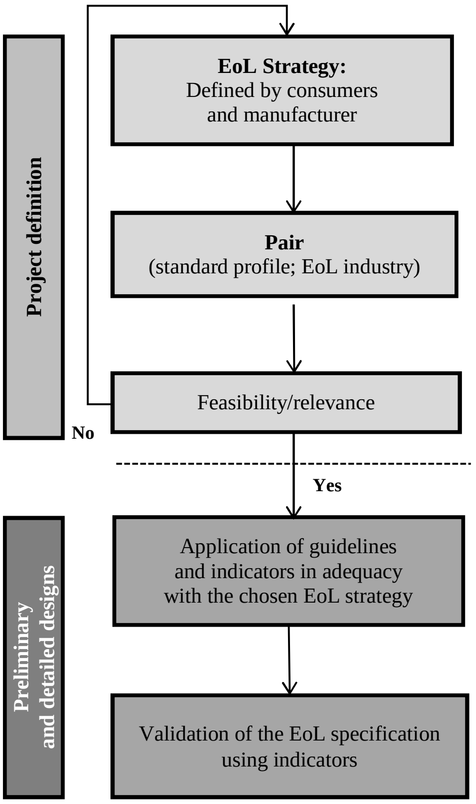


Figure 3. *Method principle*

5- At the end of the design steps, indicators and assessment methods will allow the designer to check if the product complies with initial requirements.

The following sections will investigate three topics: (i) the standard profile, (ii) the end-of-life industry and (iii) the design processes. End-of-life strategies may be correctly defined combining these three axes: it ensures that rules and indicators used for a given product are relevant for the chosen recovery options [20] keeping in mind that EoL treatments will obviously evolve throughout the product’s life.

3.2. Pair (Standard profile / EoL industry)

3.2.1. Definition of a standard profile

As most of new designed products are actually new generations of older ones, a product profile can be defined for a same product family (same functionality products composed of same classes of technologies); it will be called *standard profile*.

This profile is the basic reference to assess EoL recoveries solutions. Based on this reference, a new generation of product can be compared, only, theoretically, to the oldest one, from the EoL point of view.

The data families which constitute such standard profile have been chosen regarding EoL industry actual requirements in order to perform a relevant disposal process.

The standard profile consists in a new type of product tree-view, especially made for EoL study, and which data mainly proceeds from definition and maintenance tree-views. It is an inventory of materials, fasteners and components of the product, as listed below:

1. Structural Materials
   1.1. Steel
   1.2. Aluminium
   1.3. Magnesium
   1.4. Plastic
   1.5 …
2. Functional components
   2.1. Electronic Components
      2.1.2. WEEE RoHS
      2.1.3 WEEE not RoHS
   2.2. Optical components
      2.2.1. Lens
      2.2.2. Restitution (LCD)
   2.3. Others
3. Fasteners and connections
   3.1. Screws
   3.2. Glue
   3.3. Clips
   3.4. Seal
   3.5 Wires
   …

All components and sub-parts are listed in a table regarding their proportion (percentage by mass), the presence and quantities of hazardous substances, and strategic materials.

Defining a standard profile for each family of products in a company, regarding EoL applicable topics (design and EoL treatment processes) should be useful to capitalize the work done on the EoL issues, and helpful to estimate the gain linked to the design choices (comparing a new product profile to the older one).

3.2.2. EoL industry

Having a good visibility over EoL treatment processes can allow us to rightly answer to the needs and requirements of dismantling companies, without giving them useless information, and keeping in mind the evolutions of the dismantling processes during the product's lifecycle.

In this paper, we will base on the assumption that no specific EoL industry has been developed for a product, but that companies rely on existing EoL industries, less effective than an EoL network specifically developed for a product. Some of them already exist mostly set up under the pressure of regulations:

- WEEE;
- Packaging wastes;
- Batteries and accumulators wastes.

Moreover, some specialized EoL industries also begin to emerge due to the high value of materials or the scarcity of others. Such EoL industries can be taken into account in the study (for example composite recycling network).

However, the readiness level of the existing industries can hardly be assessed for a company due to the difficulty to anticipate the short and long term evolution of the EoL treatment processes.

3.2.3. The pair

When matching the knowledge of the EoL industry and the standard profile data, we can ascertain what EoL strategy is really compatible with a new product development, what improvement has to be done to enhance the product's EoL performances to reach the objectives defined by the consumer. To do this, each element contained in the standard profile has to be checked regarding the existing recovery options and relevance must be evaluated.

3.3. Guidelines, indicators and assessment methods associated to an EoL strategy

According to the EoL strategy chosen, different guidelines and set of indicators will be used to design and assess the EoL performances of a product. Currently, a product must respect one EoL strategy but it may happen that the strategy can be different from one part to another, in a same product.

	End-of-life strategy				
Indicators	**Reuse**	**Remanu-facturing**	**Recycling**	**Heat recovery**	**Disposal**
Disassembility	•	•	•		
Dismantability	•	•	•		
Adaptability	•				
Reliability	•	•			
Traceability	•	•			
Fatigue	•	•			
Deterioration		•			
Structure		•			
Separability			•		
Composition			•	•	•
Contamination			•		
Economic viability			•		
Risk				•	•
Efficiency				•	
Material evolution					•

Table 1. *EoL strategies and associated indicators*

Table 1 lists pertinent EoL indicators regarding the main EoL strategies.

Various design guidelines already exist for industrial products for dismantling, disassembly, or recycling. Most of them are compatible with aeronautic and defence products. The next list introduces relevant guidelines for design for recycling, taken from “Guidelines for designing for disassembly and recycling” [23]:

1. **Materials**
    1.1. Minimize the number of different types of material;
    1.2. Make subassemblies and inseparably connected parts from the same or a compatible material;
    1.3. Mark all plastic and similar parts for ease of identification;
    1.4. Use materials which can be recycled;
    1.5. Hazardous parts should be clearly marked and easily removed.
2. **Fasteners and connections**
    2.1. Minimize the number of fasteners;
    2.2. Minimize the number of fastener removal tools needed;
    2.3. Try to use fasteners of material compatible with the parts connected;
3. **Product structure**
    3.1. Minimize the number of parts;
    3.2. Make designs as modular as possible, with separation of functions;
    3.3. Locate parts with the highest value in easily accessible places.

Moreover, most suitable design stages to implement both rules and indicators must be identified in order to maximize the efficiency of the process. Sooner the end-of-life aspects will be taken into account, better the EoL performances will be [24]. But, designers must keep in mind that uncertainties will be high in early design.

Then, after the application of guidelines and the measurement of indicators, the end-of-life performances of a product will be assessed through methods based on the indicators and product data. These methods are directly related to the recovery options. For instance, a company can assess technical performances (recyblability, dismantability) or economic performances as EoL costs. Meißner [25] proposed a model to assess these cost according the following equation:

EoL costs = Dismantling costs + Disposal costs - Reuse and Recycling Profits

But, due to variability of the material courtyard and difficulty to quantify workload, it will be most relevant to assess these costs for example in number of hours, which present less fluctuation and can be multiplied by an updated cost factor.

4. CASE STUDY: BINOCULARS PRODUCT FAMILY

4.1. Product presentation

The chosen product for case study is a medium-range infrared multifunction military binocular. These compact and light binoculars are based on uncooled infrared technology, with all the functions essential to combat operations in a single housing: thermal vision, telemeter and magnetic compass.

This product has been chosen to test the proposed methodology because of its complexity and the diversity of technologies it owns: optical, electronic, and mechanical; and also because of the high number of produced units.

Figure 4. *Binocular*

We can assume that the binocular is representative of the binocular family in term of:

- performances (medium range);
- technologies;
- materials.

4.2. Standard profile: required data

Establishing the standard profile of a product requires some knowledge about the type of technologies, the product mass and materials repartition, hazardous substances and strategic materials presence and traceability.

As explained in the section 3.2.1, the standard profile presents an inventory of structural materials, components and fasteners of the product. This profile has been established Table 2, mainly regarding data taken from definition and maintenance tree-views.

4.3. Pair Construction

Table 2 introduces the pair (standard profile, EoL industry).

Most suitable options for the whole product or for each of its components are determined when

Product composition	**Quantity (Mass %)**	**Hazardous Substances (e.g. annex XIV REACh regulation)**	**Strategic materials [13]**	**Reuse**	**Remanufac turing**	**Recycling**	**Energy recover**	**Disposal**
Structural Materials:	**20%**							
- Magnesium	16%	-	Mg			x		x
- Aluminum	3%	-	-			x		x
- Plastic	1%	-	-			x	x	x
Functional composants:	**76%**							
1. Electronic Components								
- DEEE RoHS	50%	-	-			x		x
- DEEE not RoHS	5%	Cr VI, Pb	-			x		x
- Wires	10%	-	-			x		x
2. Optical components								
- Lens	1%	-	Ge	x	x	x		x
- Restitution (LCD)	3%	-	-			x		x
3. Others								
- Strap	1%	-	-			x	x	x
- Battery	10%	-	-					x
Fasteners and connections :	**4%**							
- Screw	3%	-	-					x
- Glue	/	-	-					x
- Clips	0.5%	-	-					x
- Seal	0.5%	-	-					x

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Table 2. *Pair (Standard profile, EoL industry)*

matching the existing recovery option with each data of the standard profile Thus, the result will be extended for the entire binocular family.

4.4. Proposal of an EoL strategy compatible with the binoculars family

For every elements of the standard profile, designers must check what the possible EoL strategies are, regarding the existing treatments and recovery options. First it is preferred to select a strategy highly valuing the product or parts of it, then the materials and finally the energy.

In this example, according to pair examination, recycling the whole product or reusing some parts seem to be the best EoL strategies to choose.

In a theoretical calcul, assuming that first the recyclability of each part of the product compatible with recycling operations is about 100%, and secondly the efficiency of the full recycling process is at 100%, the recyclability rate reaches a theoretical level of 86% according to the pair. This result represents the amount of product recyclable (sum of the mass percentage of the parts compatible with this end-of-life strategy). A more realistic evaluation could reach an objective of 50%, due to the lack of compatibility of the product with the existing recycling process or the emerging recycling solution for the very specific material of such products. At the components scale, it may be more interesting to reuse or remanufacture some high-value components, like lens. Moreover, that kind of components is rarely subject to wear or soiling, thus reuse seems to be the best strategy.

As described on table 1, specific set of indicators could be chosen by the designers in order to follow the good integration of the chosen strategy.

According to the table, two indicators should be monitored in both ways: disassembility and dismantability.

This approach enables to describe, between manufacturer and customer, some kind of relevant objectives for binoculars EoL, and determine which metrics, linked to indicator monitoring, would be relevant to assess product EoL performance.

5. CONCLUSION AND DISCUSSION

Our proposal method is a new way to integrate end-of-life in the design process, taking into account what the company is able to do and what the requirements of the EoL industries are, in order to propose a relevant products's EoL management.

However, having a good visibility on the EoL industries is the hardest part, due to the lack of communication between these two actors and the permanent changes in the EoL industries.

Hence, a company must be an actor of the EoL treatment of its products. Even if a company integrates design for end-of-life and manufactures wholly recyclable products, this does not mean that products will effectively be recycled. A synergy has to be created between companies and end-of-life actors in order to (i) enhance the recovery processes and (ii) harmonize the work done earlier by designers and the recovery requirements given by the EoL actors.

Ideally, in order to maximize the product recovery rate, a product and its own EoL industry have to be designed together.

In this paper, we focus on the product development. However, the method should also be adapted and applied to the technology development, based on the Technology Readiness Level (TRL).

Further investigations are planned in order to improve the whole cycle, from strategy definition to indicators identification and integration in design process.

TRL links will also be an important field of inquiries.

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