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Integration of end-of-life options as a design criterion in methods and tools for ecodesign

Yoann Le Diagon [1], Nicolas Perry [1], Stéphane Pompidou [2], Reidson Pereira Gouvinhas [3]

(1) Arts et Metiers ParisTech, I2M
UMR 5295
F-33400 Talence
France

Phone: +33 (0)5 56 84 53 27
E-mail: yoann.le-diagon@ensam.eu
n.perry@i2m.u-bordeaux1.fr

(2) Univ. Bordeaux, I2M
UMR 5295
F-33400 Talence
France

Phone: +33 (0)5 56 84 79 80
E-mail: s.pompidou@i2m.u-bordeaux1.fr

(3) Dep. de Engenharia de Produção
Univ. Federal do Rio Grande do Norte
Av. Senador Salgado Filho
3000 Campus Universitário Lagoa Nova
Br-59078 Natal
Brazil

E-mail: reidson@ct.ufrn.br

Abstract Ecodesigning a product consists (amongst other things) in assessing what its environmental impacts will be throughout its life (that is to say from its design phase to its end of life), in order to limit them.

Some tools and methods exist to (eco)design a product, just like methods that assess its environmental impacts (more often, *a posteriori*). But it is now well accepted that these are the early design decisions that will initiate the greatest consequences on the product's end-of-life options and their impacts. Thus, the present work aims at analysing traditional design tools, so as to integrate end-of-life possibilities in the form of recommendations for the design step.

This proposal will be illustrated by means of a wind turbine design.

Keywords Ecodesign, design for X, life cycle assessment, end-of-life, wind turbine

1- Purpose of the work

Ecodesign is an alternative approach to design a product with at least the same functional level, but (amongst other things) using less materials or fewer energy in the manufacturing process, favouring the use of higher renewable resources, optimising design for limiting maintenance operations, and improving product end-of-life treatments.

The goal of this paper is to show how traditional design tools can be used for *eco*designing a product. More specifically, it aims at integrating end-of-life options from the early stages of the product's design, to limit the environmental impacts due to this life phase.

A product's environmental impacts can quite easily be estimated *a posteriori* by a lifecycle assessment (LCA), even if some materials, constituents, processes or life stages are less known than others. On the contrary, it is more difficult to assess its impacts *a priori* in the early design phase, when the product definition is low-detailed. However, it is well known that the early to preliminary design decisions will initiate the greatest consequences in terms of impacts due to its end-of-life options, both environmentally and economically [FB1]. Indeed, some raw materials become strategic because of their decreasing availability: more and more constituents must be easily recycled. Lastly in a legislative point of view, regulations get stricter about the environmental impacts of a product. As a consequence, integrating ecodesign approaches becomes a strategic action for companies. Besides, they improve their image for consumers who seek more and more ecofriendly products.

In this framework, the present analysis aims at integrating end-of-life into previous studies that were rather focused on the implementation of the ecodesign approach, and its benefits on the development of tools for ecodesign.

This paper will start with a quick state-of-the-art of ecodesign approaches. The next section presents the product development cycle. Then, end of life and recycling criteria are introduced as key characteristics to evaluate. The fifth section describes the proposal linking end-of-life options into the product development cycle. Finally, the last section applies the proposal to a wind turbine design case study, before concluding.

2- Ecodesign framework

2.1- Overview

Ecodesign approaches can be applied to any product, that is to say a good or a service. However in the present analysis, we will mainly focus on the design of mechanical systems.

First of all, let us claim that assessing a product life cycle does not mean following an ecodesign approach. Even if LCA gives the most realistic environmental impacts' assessment for the designed product, this method is only practicable on a fully designed product. Indeed, the product definition (structure, material and manufacturing process) and its envis-

aged life scenarios (logistic, use phase and end-of-life option) must be as complete as possible in order to get the best assessment. So, how can this tool be used at the early design stages? To fill the gap between environmental assessment and analyses led by classical design tools, we propose to enrich design methods with criteria and systematic questions.
In spite of the potential benefits of the implementation of ecodesign, the method is not used yet in all design cases. On the one hand, collecting data is particularly difficult because the product lifecycle steps should be precisely known, including all stakeholders involved (*i.e.* raw materials suppliers, manufacturing stakeholders, transporters, consumers and recycling companies). On the other hand, some existing tools (see below) can be difficult to use and to implement for designing the product. Actually, the main barrier is the lack of know-how in the product design steps.

2.2- Ecodesign tools

Ecodesign tools have been developed to ease and guide societies, team project and designers to implement associated approaches and processes. They especially help companies in assessing the environmental impacts of their products, and in defining the main improvement axes to (re)design them. More than 150 ecodesign and communication tools already exist for the design process; strategic tools can also be added to the list [BB1]. But they often turned out not suitable for SME companies [GC1], as they are too complicated to be useful for their daily work [GC2].
Among ecodesign tools [VM1], two types stand out: *assessment* and *recommendation* tools.

2.2.1- Assessment tools

Both *qualitative* and *quantitative* assessment tools can be taken in consideration [BJ1]:

- *Qualitative assessment tools* include streamlined life cycle assessment and complete monocriteria-LCA, matrix approaches as MET (material cycle, energy use and toxic emissions) [BH1], MECO (materials, energy, chemicals, others), ERPA (environmentally responsible product assessment).
- *Quantitative assessment tools* include all mono-criteria analyses (*e.g.* water footprint or carbon footprint) and multi-criteria LCA; they lead to an accurate evaluation of the product's environmental weak points.

2.2.2- Recommendation tools

In order to help design teams make decision [G1,GB1], all checklists, standards, guidelines and substances lists (*e.g.* REACH regulation and RoHS directive) can be used [L1]. Moreover, design for X [T1] (where *X* is for recycling, disassembly, environment [AZ1], reuse, remanufacturing or sustainability) are suitable in this case [RR1].

3- Formalisation of the product development cycle

In order to introduce end-of-life options from the design phase (cf. figure 1), that is to say either in classical design or ecodesign tools (depending on the available data at each step), the product development cycle has to be detailed.
As defined by Pahl *et al.* [PB1], it can be divided into the following main steps.

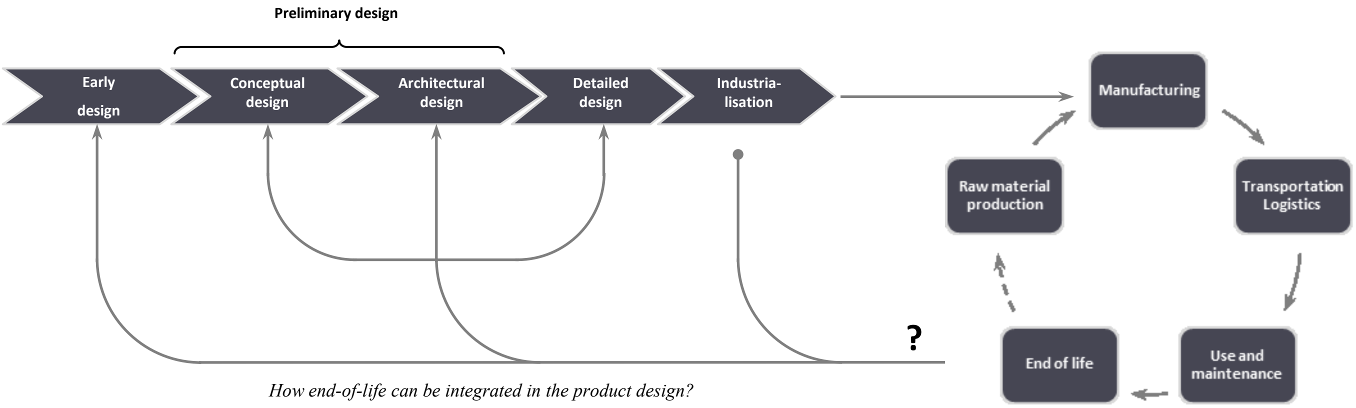
3.1- The early design

The early design phase is mainly based on the customer's needs. In this way, the product's major function is translated by designers in a technical requirements list that also takes into account the constraints related to the market, a business strategy, technology, legislation, etc. (see also figure 1.a)

3.2- The preliminary design

The preliminary design usually involves the two following steps:

- *conceptual design* that aims at defining the functional structure. Many concepts are developed to answer the needs previously listed, then compared to assess issues that could stem from every choice. A *solution principle* is thus selected;
- *architectural design* that consists in assessing the previous proposal. The most suitable structure from technical and economic points of view is chosen, including components (shapes and materials), pre-sized or nonstandard constituents, etc.



a. Product development process **b.** Product lifecycle

Figure 1: Integration of the end-of-life options as a design criterion in the product development process

3.3- The detail design

In the detail design step, the selected architecture is mocked up by CAD, optimised and finally approved. A definition file containing all sized parts and assembly drawings is provided (the *definitive layout*).

3.4- The industrialisation

Lastly, the industrialisation phase aims at choosing the best manufacturing process, optimising the supply chain, drafting a quality plan, and eventually implementing a prototype to be tested.

4- Formalisation of the product's lifecycle and focus on its end-of-life

The product lifecycle is usually divided into the following main consecutive steps, as sketched in figure 1.b.

4.1- Raw materials production

This first phase mainly consists in the raw materials production; they can either be first extraction or recycled ones (usually called *secondary-raw materials*).

4.2- Manufacturing

The second step includes all manufacturing operations; that is to say, amongst others, raw materials transformation, production operations previously chosen for the industrial process, thermal and mechanical treatments, and packaging.

4.3- Transportation and logistics

This step includes all transport and logistics issues in relation with the product throughout its lifecycle. Consequently, these operations do not only concern the distribution phase (*i.e.* between the manufacturing and the purchasing sites) as suggested by figure 1.b, but can actually be found between all the other phases.

4.1- Use and maintenance

This phase of the lifecycle focuses on the period during which the product is used, *i.e.* between its purchase and its end-of-life (*e.g.* when it becomes a cause of failure). This step also includes all the maintenance operations needed for increasing its lifespan.

4.2- The end-of-life

When the product becomes unused, it is generally more suitable to talk about its *end-of-life* phase, rather than to consider it as a *waste*. Indeed, this last expression would imply an absolute loss of value, while several ways exist to extend the life of either the whole product (and thus, preserve part of the worth) or only some parts (components, constituents or constitutive materials).

4.2.1- Ways of treatment of an end-of-life product

The five main options to treat a life-ending (sub-)product are listed below, from the most valuable to the less profitable solution.

- First of all, the *reuse* option mainly consists in the recovery of the whole product. It can be reused for the function it was designed, or another one. This end-of-life treatment is clearly the best in terms of maximisation of the product value.
- The second way is the *remanufacturing* process. It more often consists in recovering parts that will be reinserted in a new product, during a later manufacturing process. However, this option is possible if previous design choices assure an easy disassembly. Only then, parts may be modified, adapted, or simply reassembled in a second generation product; their value is preserved.
- The *recycling* is the third possible way of treatment. It mainly consists in extracting strategic materials from the waste flow, and regenerating them in new ones, usually called *secondary raw materials.* They are more eco-friendly, and theoretically have the potential of other recycling loops. However, this reprocessing path requires firstly the preparation of the waste; it includes collect, depollution, cleaning, dismantling, part and/or material identification, sorting, etc. Early design options would obviously ease the product disassembly, the accessibility to the (sub-)parts and then, the materials separation.
  With respect to the recycling process (specific for each nature of material), performance indicators will be varied as a function of the dismantling quality. Again, early design choices thus impact the recycling ratio (*e.g.* ease/difficulty to reach target materials), the efficiency of the recycling process (*e.g.* downcycling likelihood due to a bad separability), and then, the availability of good secondary-raw materials for new manufacturing processes.
- The fourth end-of-life option mainly comes down to an *energy recovery* by burning the product (manifestly likened to a waste).
- Lastly, the worst end-of-life option consists in *landfilling* and *burying* the inert waste that couldn't be treated by one of the previous ways.

4.2.2- Environmental impacts of the end-of-life

A product inevitably impacts the environment almost continuously, from the extraction of the raw materials, and all along its use phase (energy used for its working, associated substances rejected in water or in the air, etc.). But even after, environment remains impacted by the landfilled parts (*e.g.* land occupation or constituent toxicity), or by the reprocessing or recycling treatments (*e.g.* energy consumption, supplies needed for the process, etc.). However, as previously mentioned, design choices may assure an easier disassembly of the product, a better materials separability, or a greater reintegration of the secondary-raw materials in a next manufacturing process.

As a consequence, we propose to assess how the end-of-life step could be integrated as a design criterion, while controlling potential transfers of pollution.

5- The proposal

The goal of this part is to display, for each design step, (i) the tools that can be used and (ii) the questions to ask for integrating end-of-life options as design criteria, in order to provide indicators which could help the design phase. Both aim at improving the performance of the end-of-life product. But before that, it is important to differentiate, in terms of scale of treatment, the management of the production waste (*e.g.* unused constituents, off-cuts, rejected parts, etc.), and the end-of-life products. Moreover, there is no added value for a production waste. Thus, efforts have to be kept to minimize production wastes in an ecodesign context.

Our analysis will be linked to the three main steps of the design phase.

5.1- Early design

It has been previously seen that the earlier the end-of-life is taken into account in the design process, the better the economic and environmental impacts of the associated valorisations are. However at the early design step, the product is still an idea, or at best a customer's requirement (cf. § 3.1-); in all cases, available data are extremely limited.

Despite that, questions about the strategic position of the manufacturer (*i.e.* a company) must be taken into consideration. A first level of thought must be led about existing regulations, and legislation to come. Some regulations already limit the use of materials and chemicals, or will require a minimum recycling rate at the end-of-life. As an example, this first analysis of legal texts will force designers and manufacturers to limit the use of hazardous substances that will be difficult to treat at a later stage.

The second focus for reflection is related to the company's management strategy. Usually, the company favours some end-of-life options (*e.g.* recycling or thermal recovery) for internal processes (*i.e.* production waste) and external ones (*i.e.* when user feels/reckons the product reaches its end-of-life). This will enable to choose the most suitable materials and constituents to fit in the more easily treatment sectors.

Both questions directly influence the design possibilities. For example, if the company gives priority to recycling (and so to recycling rates), then mass and volume will be key design criteria. Giving priority to reuse, the design will have to be modular, and each sub-system will only fulfil one function. In this case, number and nature of functions, and then number of sub-parts to disassemble will be the key parameter.

In order to integrate end of life criteria at this step, the work focuses on functional analysis tools: tools called (in a mundane way) *octopus diagram* (or *functional interactor diagram*) and *bull chart*, technical specifications, SADT (structured analysis and design technique), FAST (functional analysis system technique) and FBD (function block diagram), etc.

The *functional interactor diagram* enables to find all external interactors to the product for all its living phases. Analysing end-of-life emphasis the functions linked with this step. Then, technical specifications allow matching functions with criteria (*e.g.* a recycling rate required by regulations). In the context of an eco-*re*design, FAST diagram allows putting emphasis on the materials choice regarding the end-of-life (*e.g.* recycled or recyclable material, strategic material, chemicals and assembly methods). The BFD, which depicts flows and links between components, enable to determinate sub-systems and their imbrication.

Lastly, only two end-of-life indicators can guide designers: a composition indicator (if design is monitored by legislation) and a separability/disassembility indicator which can fix objectives in terms of accessibility and ease for the associated end-of-life options.

5.2- Preliminary design

In the present part and the next one, we will only focus on the *recycling* option because of the lack of knowledge and available data, as already mentioned.

Let us remind that the preliminary design step firstly consists in translating technical specifications in a concept, then in an architecture with pre-sized components (cf. § 3.2-). Taking into account end-of-life options from this step, requires looking at two main parameters: the assembly (in order to anticipate the components separation) and the nature of materials (that will have to be recycled). Thus, the present analysis focuses on several tools: CAD, simulation and materials choice tools, decision matrix, physical rules, etc.

Firstly, design must be managed to take into consideration an easy disassembly, of parts or components, but also, with a view to recycling, of materials.

Disassembling difficulty is tested by assessing means and time needed; degree of linkage standardisation and accessibility to the joint (which is important for both end-of-life and maintenance operations) are deduced. Indeed, a FMECA (failure mode, effects and criticality analysis) can highlight critical components which can easily be repairable or replaceable. The second reflexion axis relates to the assembly process because welding or riveting for example, can introduce filler material which can be a pollutant for the recycling process. Then, CAD tools and kinematic drawings enable to give a first evaluation of the separability performance.

Otherwise, analysing the used materials is a requirement to improve the end-of-life treatment. Obviously, they are mainly chosen in accordance with their mechanical properties; however, it is important to evaluate the recycled ones, depending on the treatment industry. Another key point is the identification of constituents. Indeed, in order to choose the better way of treatment, materials have to be easily identifiable, particularly for high-value materials. Lastly, materials can have an incidence for technical intervention (*i.e.* maintenance or lubrication), so these choice criteria must be taken into consideration at the same level. A decision matrix is suitable to compare them.

Previous indicators also guide designers and become more and more accurate, especially thanks to the increase of available data due to the knowledge of the product. Another indicator assesses the pollution due to the recycling process, that is to say chemicals or materials which will have a negative or hazardous impact on the process. Quantification of this indicator will depend on the recycling option.

5.3- Detailed design

One of the goals of the detailed design is to optimize shapes and materials, for example with CAD tools (cf. § 3.3-). At this stage, the involved tools are overall the same as in the previous one.

A new way to optimise end-of-life lays in searching alternative materials with (at less) the same mechanical properties that would balance environmental performances (*e.g.* with CES software).

Another reflexion must be led about the choice between different grades of material. Indeed, some can be more or less desirable depending on the recycling process and the quality of the recycled material. In this sense, one must take a close look on surface treatments; as an example, tinplating or copper plating reduce the mechanical performances of a recycled steel [CR1]. Coatings have to be taken into consideration for the same reason.

Moreover, it is essential to compare all the possible alternatives of assembly. With an eye to recycling, joints easier to disassemble are more desirable. On the contrary, if a rigid linkage is required, the main problem remains the polluting effect of one constituent on the other in the recycling process, and the degradation of the material (*i.e.* downcycling); a less efficient recycling way could be chosen.

Lastly, other constituents' properties can be taken into account. As examples, ferromagnetic materials can be easily sorted in a waste flow, just like materials of different density floating in a fluid. Use of such materials will ease their separation and orientation in the recycling process.

In an economic point of view, it is essential to know if the ratio (by mass or volume) recyclable constituent/total waste is likely to be profitable to recycling industries [RS1].

6- Case study: wind system

This part aims at showing how end-of-life option can be integrated in the design of a wind turbine.

6.1- Legislative framework

The present work matches with two improvement points identified by the French Ministry of Ecology, Sustainable Development and Energy in June 2012. The first one gives priority on ecodesign approaches and the research on alternative materials in place of rare or strategic ones. The second point forces designer to use ecodesign approaches not only throughout the main mechanical system lifecycle, but also to all annex components and structural parts (*e.g.* foundations, etc.).

6.2- Material composition and treatment performances

6.2.1- Material composition study

This part aims at studying the arrangement of a horizontal-axis wind turbine (HAWT), with a 85m high tower and a 90m in diameter rotor. Mass of components are classified in table 1.

Figure 2 details the contribution of these components to its overall cost. These data are also classified in table 2 to highlight the economic impacts of the two possible end-of-life scenarios we propose for the wind system. The first one is an assumption of what could be considered as end-of-life options; the second one is an alternative version that favours the reuse of some parts instead of their only recycling. This leads us to ask three questions.

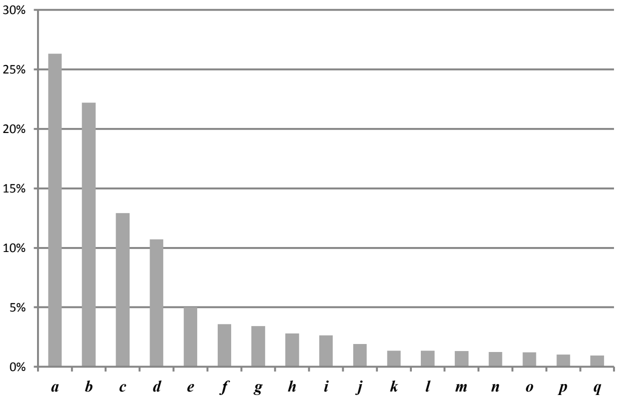
First, blades are made of glass reinforced plastic. But to date, there is no industrial solution to recycle such composites. Consequently, the end-of-life option currently led is the thermal recovery, although blades are high added value components (about 20% of overall cost of the HAWT).

Secondly, the electrical components remain difficult to recycle. Indeed, generator includes a copper-steel mix difficult to treat. As previously explained, copper is a pollutant for steel in terms of quality of the secondary raw material.

Lastly, foundation is a huge buried structure. Consequently, it also has to be dismantled when the HAWT reaches its end-of-life. Otherwise, a repowering could be planned with the same foundation. Thus, designer have to wonder if it is better profitable to extract it (if it is not required), or if it is well enough sized for fixing a new wind system.

Components	Concrete	Steel	Alu.	Copper	Glass reinf. plastic
Hub		18 t			
Blades		1 t			19 t
Gearbox		25 t			
Generator		13 t		7 t	
Frame, machinery and shell		21 t	2 t	1 t	1 t
Tower	3 t	145 t			
Foundation	480 t	2 t			

Table 1: Material composition of the studied HAWT [AV1]



Caption: ***a***: tower; ***b***: rotor blades; ***c***: gearbox; ***d***: others (foundations; grid connections); ***e***: power converter; ***f***: transformer; ***g***: generator; ***h***: main frame; ***i***: pitch system; ***j***: main shaft; ***k***: rotor hub; ***l***: nacelle housing; ***m***: brake system; ***n***: yaw system; ***o***: rotor bearings; ***p***: screws; ***q***: cables

Figure 2: Contribution of wind turbine components to the system overall cost [E1]

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These three points have so to be taken into account from the design stage in order to (i) anticipate the components' end of life, and (ii) avoid a loss of the added value with a treatment which wouldn't be effective enough.

6.2.1- Treatment performances

Designers now have to focus on the loss of added value due to the choices of end-of-life treatments. Indeed, components of a wind system represent about 90% of the overall cost.

In order to highlight the loss of value in the end-of-life phase, two scenarios are proposed:

Scenario 1: Only electrical components are reused;

Scenario 2: Electrical components, gearbox and main shaft are reused.

In both approaches, rotor blades and nacelle housing are burned; non-quoted materials are supposed to be recycled.

The table 2 compares these scenarios in terms of allocation of value. In this economic-only point of view, we have already mentioned that recycling is more attractive: it leads to a new material, when burning option is just elimination, admittedly with an energy gain, but leading to wastes difficult to make more attractive.

Firstly as already mentioned, the treatment of composite parts lead to a 24% loss of the overall value (even if energy can be recovered). Secondly, since gearbox and main shaft can be reused, 20% of the system value could be preserved.

As a conclusion, to enhance end-of-life performances, two points have to be studied: (i) develop recycling methods for composites, or substitute composite parts in the blades design, and (ii) better control mechanical fatigue of some components in order to reuse them.

	Scenario 1			Scenario 2		
	Reuse	Recycling	Burning + ER	Reuse	Recycling	Burning + ER
Tower		26.30%			26.30%	
Rotor blades			22.20%			22.20%
Gearbox		12.90%		12.90%*		
Power converter	5.00%			5.00%		
Transformer	3.60%			3.60%		
Generator	3.40%			3.40%		
Main frame		2.80%			2.80%	
Pitch system	2.70%			2.70%		
Main shaft		1.90%		1.90%*		
Rotor hub		1.40%			1.40%	
Nacelle housing			1.40%			1.40%
Brake system		1.30%		1.30%*		
Yaw system		1.30%		1.30%*		
Rotor bearings		1.20%		1.20%*		
Screws		1.00%		1.00%*		
Cables	1.00%			1.00%		
Total	**15.70%**	**50.10%**	**23.60%**	**35.30%**	**30.50%**	**23.60%**

Table 2: Economic-based analysis of two possible end-of-life scenarios for a wind turbine (ER: energy recovery) [E1]. Data are the contribution of the wind turbine components to the system overall cost [E1]. The second scenario (optimisation of the first one) favours the reuse of some parts instead of their recycling (data marked with an asterisk)

Structural choices	**Consequences for recycling**	**Involved indicators**	**Decision tools**		
			Early design	*Preliminary design*	*Detailed design*
Nacelle rotation	Yaw drives reuse/recycling Yaw gears disassembly Yaw system constituents Maintainability	Disassembly Composition Separability	Characterisation of functions	FMECA Simulation	
Blades orientation	Hub size Hub complexity Maintainability and reuse of pitch cylinders Blades disassembly	Disassembly Composition Economic viability		FMECA Simulation	
Number of blades and constituents	Quantity of material to treat Disassembly Hub complexity	Disassembly Composition Separability Pollutant Economic viability	Client demand (personal choices) Characterisation of functions	FMECA Simulation	Optimisation (production gain)
Driving system	Quantity of material to treat Number of components Maintainability	Disassembly Separability Composition	Strategic positioning of the company	FMECA Simulation	
Rotor size	Quantity and nature of materials to treat Size of the main frame (dimensioning) Size of the tower (dimensioning)	Composition Disassembly Economic viability	Legislation Characterisation of functions	Simulation	Optimisation (production gain)
Tower size	Type of material	Composition Disassembly Economic viability Pollutant	Legislation Characterisation of functions	Simulation	Optimisation (production gain)

Table 3: Impacts of structual choices on the only recycling

6.3- Integration of the recycling option as design criteria

Since we assume to favour recycling option, consequences of the preliminary structural choices must now be studied, and connections between choices, end-of-life indicators and tools must be underlined.
Our analysis deals with six main structural choices for a HAWT: nacelle rotation, blades rotation, number and material of blades, drive system (with or without gearbox), rotor size and tower size. The table 3 displays a first proposition to show how end-of-life indicators can be linked with a design step. Thus, it is important to note that preliminary design is the step where end of life criteria are the more likely to be taken into account. Before, it is difficult to constraint some functions by end-of-life options, even if a wide range of hypothesises can be adopted regarding recycling rates, material composition and facility for disassembly, which will all be affined in preliminary design and optimized in detailed design, in order to balance production gain and end-of-life performances.

7- Conclusions. Application and limits

The purpose of this paper is to analyse how end-of-life options can be integrated as a criterion in the design process. For that, we propose to integrate questions about end of life or indicators in each design steps. It enables to see what step is the more suitable to consider end-of-life issues and to also highlight the role that tools can play to improve the end-of-life performances of a product. These examples of very simple reflexions can be led in all design cases. Currently, the main limit is the case per case quantification of indicators, and the study of how they can be precisely be integrated into tools (*e.g.* how can designers link a recycling rate to FMECA? To what extent can indicators influence the use of tools?)
These questions deserve to be solved because, as shown in the wind system example, the improvement of the design by the consideration of end-of-life issue, may preserve a lot of the invested value. Indeed, taking into account the analysis of the end-of-life scenarios, 20% of invested value could be reused in order to save the investment, rather than recycling parts.

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