Theme Sustainability and Eco-design of processes, products and services

RECYCLING CHAINS: A PROPOSAL FOR AN EXHAUSTIVE DEFINITION

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ABSTRACT

In the context of a circular economy, recycling presents as an interesting solution to reduce the impact of raw materials extraction and to reduce the quantity of waste that is incinerated or landfilled. However nowadays, there is no global and complete definition (which could be used as a common reference) of recycling chains.

Listing the parameters to be taken into account, such a definition would allow manufacturers and researchers to better assess the efficiency and the stability of supply chains (not only at the beginning of the product lifecycle, but also towards the next one), and to accurately compare them.

Therefore, we need a better definition of recycling chains, describing the system in its whole dimension (*i.e.* all internal and external factors) so as to improve (i) our understanding of the system and (ii) its inherent problems.

Firstly, the recycling chain will be defined and described as exhaustively as possible. Then, the second part will focus on the best way to integrate this information when analyzing and optimizing recycling chains. Lastly, perspectives of this preliminary work will be detailed.

INTRODUCTION

Before the 1970's, the recycling industry was faintly developed. Since then, this industry has experienced an important growth and has even reached industrial and economic maturity in some sectors (ADEME 2012). Indeed for some years now, the use of recycled materials has increased as they have become more and more attractive because of their always-better preserved mechanical properties, for still a profitable price. Integrating recycled materials thus becomes a strategic action for companies, while improving their image with consumers who seek more and more ecofriendly products.

Furthermore, regulations become stricter about the environmental impacts of products (*e.g.* Directives 2008/98/EC, 2012/19/EU, 2011/65/EU, 2000/53/EC, etc.). End-of-life goods must now preferentially be recycled than energy recovered or landfilled. In this context, availability of recycled materials increases and they are now real alternative to first extraction ones for manufacturing processes (ADEME 2015).

Nowadays, many approaches and many studies focus on improving waste management (*e.g.* reversed logistics, closed loop supply chain management, green supply chain management and sustainable supply chain management) (Seuring *et al.* 2008; Sarkis *et al.* 2011; Govindan *et al.* 2015). Nevertheless, recycling chains do not seem fully developed, neither well taken into account in industrial supply chains. The main problem actually lies in both quality and quantity variations of material flows. In order to better integrate recycled materials in industry (*e.g.* parts manufactured with 100% recycled materials, or at least partially integrated in high-performance products), stability and reproducibility of recycling processes, and more globally of all steps of the recycling chain, have to be ensured.

While recycling chains have been operating for quite a long time, there is still a lack of knowledge regarding the fundamentals of such systems. A complete definition and an exhaustive description of these treatment chains are needed as a common reference for future studies.

Firstly, the main steps of a component's lifecycle and its best end-of-life options will be detailed. Then focusing on the recycling option, a standard recycling chain will be defined and described as exhaustively as possible in all its dimensions. Lastly, perspectives of this work on (i) optimization of treatment chains, (ii) identifications of synergies between chains, and (iii) integration of ground realities in the product design phase, will be proposed.

COMPONENT'S LIFE AND END-OF-LIFE

1. Notion of *component*

Before broaching the lifecycle concept, the notion of *component* (that we chose to use rather than *product*) has to be clarified. Actually in this paper, this word will refer indifferently to:

- a whole product;
- a module or a unit (*i.e.* a product subset);
- an elementary part (*i.e.* a module subset), possibly

- a multi-material part (*e.g.* a composite, an architectured mix of polymers, etc.);
- or a homogeneous one (*e.g.* a mono-material or an alloy);
- or a part offcut in the manufacturing process;

as its properties can be assessed globally. However, the other terms can also be used if the scale of analysis is accurately defined.

In this way, depending on the chosen degree of precision, assessing the impacts of a component throughout its life and after is all the more difficult due to the fact that its structure is complex. The more a product contains modules and sub-parts, the more the factors to take into account to analyse its end-of-life.

2. The component's added value

The *added value* consists of any improvement provided to a component (*i.e.* elementary part, module or product) that makes it worth more.

Value is added at every step of the component's manufacturing process. However, it clearly depends on the component's own nature and function. In this way, the *material added value* must clearly be differentiated from the *functional added value*.

1. The *material added value* is mainly related to less complex components (as elementary parts). In this way, a component's added value results first from the material's own-value (*e.g.* strategic materials, rare earth metals, etc.). Nevertheless, value can also result from every process necessary to get the required material (*e.g.* plastics from crude oil, metals from ore, alloys, etc.) or from the manufacturing process itself (*e.g.* additive manufacturing).
2. The *functional added value* is mostly related to modules or to whole products. Here, it is the function of the component which must be preserved. Indeed, much more than its constitutive materials, the component's value results for example from its design (which ensures its efficiency) or from the complexity of assembly.
   However here again, a specific manufacturing process can even add functional value to a mono-material key part or a subset (*e.g.* complex gear train obtained by additive manufacturing).

3. The component's lifecycle

The term *lifecycle* only refers here to the major activities in the course of the product's lifespan. A component lifecycle is usually divided into five main consecutive steps, as sketched in figure 1.

The dotted arrow depicts schematically the main principle of *circular economy* (etymologically by closing the loop): materials that stem from end-of-life components can be reinjected as raw materials in a next lifecycle. Usually called *secondary raw materials*, they will be used to manufacture a similar component or a new one.

The main steps of the lifecycle are briefly described in the next paragraphs (Le Diagon *et al.* 2004).

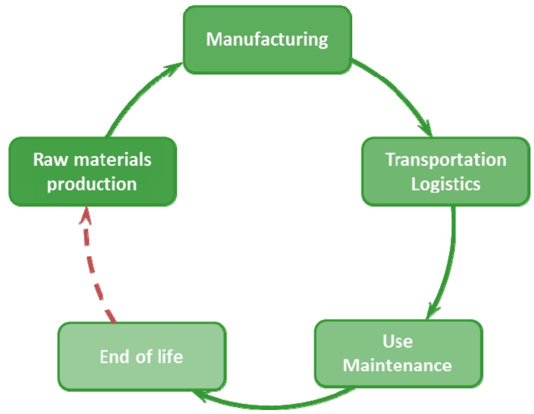

Figure 1: Simplified representation of a component's lifecycle

a. Raw materials extraction and processing

This first phase mainly consists of the extraction and transformation of natural resources (*e.g.* ore, petroleum, etc.) in *primary* raw materials.

This stage also includes the production of recycled materials (*i.e.* secondary raw materials; cf. below, § 4.3).

b. Manufacturing

The second step includes all manufacturing operations, such as raw materials transformation, production operations in the industrial process, thermal and mechanical treatments, assembly and packaging. These operations are specific for each component.

c. Transportation and logistics

This step includes all transport and logistics issues (acquisition, delivery, etc.) in relation to the component throughout its lifecycle. Consequently, these operations do not only concern the distribution phase as suggested by figure 1 (*i.e.* between the end of manufacturing and the purchasing sites), but can actually be found between or in all of the other stages.

d. Use and maintenance

This phase of the lifecycle focuses on the period in which the product is used, *i.e.* between its purchase and its end-of-life. It also includes all the maintenance operations needed for increasing its lifespan: curative and preventive maintenances, upgrading and reuse (resale, donation, sharing and pooling).

e. End-of-life

When the product becomes unused (*e.g.* because of a malfunction), it is taken for *waste*. However, several ways do exist to extend the life of either the whole product (and thus, to preserve part of its value) or of only some subsets. That's why it is generally more suitable to talk about the *end-of-life* phase.

Details of this key step of our study are given in the next paragraph.

4. The component's end-of-life

The five main options to treat an end-of-life component are listed below, from the most valuable to the least profitable solution (Le Diagon *et al.* 2004).

1. First of all, the *reuse* option mainly consists of the recovery of the whole product before it becomes waste. This option involves resale, donation, pooling, etc. The component will be reused for the same function for which it was designed.

   This end-of-life option is clearly the best in terms of maximising of the preservation of both functional and material added values. Nevertheless, it is more effective if the manufacturer himself implements and manages an economic model of services.

2. The second way is the *remanufacturing* process.

   When the end-of-life is managed by the manufacturer, it may consist of the product *refurbishment*. Here again, if an economic model of services is implemented, performances of this end-of-life option can be maximised.

   Nevertheless, this option more often consists in recovering modules (or in some cases parts) which will be reassembled as a same product or an upgraded one, during a later manufacturing process. However, it is only possible if previous design choices ensure an easy disassembly. Only then, modules may be cleaned, modified, adapted or simply reassembled; their functional value is preserved.

3. The *recycling* is the third possible way of treatment.

   Here, material valorisation is sought. It mainly consists in extracting materials (*e.g.* ferrous or non-ferrous metals, strategic materials, etc.) from the waste flow, and regenerating them in so called *secondary raw materials.* Then, they may be used for manufacturing the same product they came from or a different one. Secondary raw materials are usually more eco-friendly than primary ones, and theoretically have the potential for other recycling loops.

   It should be underlined that the recycling process consists of several steps such as collection, depollution, cleaning, dismantling, part and/or material identification, grinding, sorting (before or after grinding; recycling *with disassembly* then has to be differentiated from recycling *without disassembly*), etc. The reprocessing of materials is strictly speaking the last step of the recycling process.

   The process efficiency will be improved as a function of the dismantling and sorting quality (*e.g.* avoiding *downcycling* mainly due to a bad separability). Then, early design choices could obviously ease disassembly, improve accessibility to (sub-)parts and target materials, etc. In time, it will be guaranteed to supply better secondary raw materials for following manufacturing processes.

4. The fourth end-of-life option consists of *energy recovery*. Here, combustible waste is incinerated, with or without other waste, in order to recover heat.
5. Lastly, the worst end-of-life option consists of *landfilling* and *burying* (*e.g.* in old quarries) the inert waste that couldn't be treated by any of the previous ways. This treatment also requires pre-sorting in order to separate toxic from non-toxic waste, and inert materials.

These end-of-life options and their connections with the main steps of the component's lifecycle are sketched in figure 2.

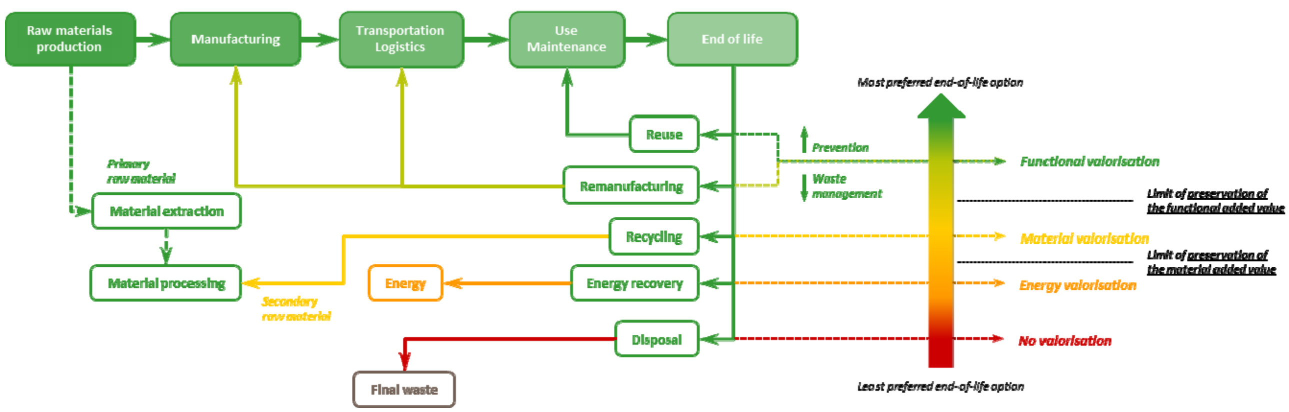

Figure 2: Major end-of-life options and their connections with the main stages of the component's lifecycle (left). Comparison of their relative interest in terms of added value (right).

Lastly, these options heavily depend on the nature of the component (*e.g.* from the material offcut to the whole product). We attempt to summarize the suitability of such and such option (cf. table 1). However, this simplified approach should be refined depending on the knowledge of both component functional and material values.

5. Towards a better recycling rate

a. Environmental impacts of the end-of-life

A component inevitably impacts the environment almost continuously, from the extraction of the raw materials, during the manufacturing process and all through its use phase (energy used for its working, associated substances rejected in water or in the air, etc.). But even in the end-of-life phase, the environment remains impacted by the landfilled parts (*e.g.* land occupation or constitu-

	Material	Mono-material part and offcuts	Multi-material part and offcuts	Module	Product
Reuse	*n/a*	+ + + +	+ + + +	+ + + +	+ + + +
Refurbishment	*n/a*	*n/a*	*n/a*	+ + +	+ + +
Remanufacturing	*n/a*	+ + +	+ + +	+ + +	+ + +
Recycling with disassembly	*n/a*	*n/a*	+ +	+ +	+ +
Recycling without disassembly	+ + + +	+ +	+	+	+
Energy recovery	- -	- -	- -	- - -	- - -
Landfill	- - - -	- - -	-	- - - -	- - - -

Table 1: Suitability of the five main end-of-life options depending on the nature of the component, from the most suitable (+ + + +) to the least suitable (- - - -).

ent 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 secondary raw materials in a following manufacturing process.

In order to improve design choices, a better knowledge of recycling chains could first help to reduce the impacts of end-of-life components by better taking into account the reality on the ground. Thus, more than just the processes involved in recycling, the whole chain itself has to be described listing:

- the recycling process (*i.e.* type of chain, main steps, processes, stakeholders, flows and specifications);
- the chain structure and organization;
- and all internal and external factors.

This is the aim of the following part.

THE RECYCLING CHAIN

1. Existing definitions

Firstly, one must notice that depending on authors, expressions like *recycling network*, *recycling system*, *recycling industry* or *recycling process* may all refer to a *recycling chain*. However, we still prefer to use the latter locution which echoes the *supply chain* (*i.e.* the management of the flows of goods and services).

Without proposing a definition of the recycling chain, most authors prefer to focus on defining recycling as a series of processes (Van Schaik and Reuter 2004; Chancerel *et al.* 2009). In the same logic but in the particular context of WEEE (waste electrical and electronic equipment), Hagelüken (Hagelüken 2006 a, b) states that “The [recycling] chain consists of different subsequent steps which are collection, dismantling, shredding/pre-processing, and end-processing of the various materials and metals. These steps are interlinked and interdependences are crucial”. This definition emphasises the importance of synergies between stakeholders.

According to Maudet-Charbuillet (Maudet-Charbuillet 2009), all elements that have an influence on the chain in some way must be identified. In this way, she specifies that valorisation chains are complex systems which depend on both internal characteristics (*i.e.* technical, structural and organizational) and external factors (*e.g.* comparison with raw materials, geographical and temporal variabilities, etc.). Thus, all these elements have to be taken into account when defining a valorisation chain.

Lastly, Rosu and Tilloy (Rosu *et al.* 2013) proposed a more complete definition: “[A recycling chain involves] the whole set of internal and external stakeholders implied in the conversion of waste into recycled raw material as well as the exchanges of material, money and knowledge in accordance with legislations, in order to limit the impact of raw materials extraction on the environment”. However, what this definition comes down to say is that reducing raw materials extraction is the main drive for recycling (which is usually not the case). It also implies that involved stakeholders exchange more knowledge about their own know-how, skill, etc., rather than information about the components they treat (*i.e.* products specifications and properties, performance indicators, etc.).

2. Our definition of recycling chain

Mainly based on the definition of Rosu and Tilloy (Rosu *et al.* 2013), we propose the following definition:

“A recycling chain is an industrial system that involves the whole set of processes and internal and external stakeholders implied in the conversion of waste into recycled material (*i.e.* secondary raw materials) as well as the exchanges of material, money and information, in accordance with legislation, in order to:

- reduce the impact of raw materials extraction;
- reduce the quantity of waste that is incinerated or landfilled;
- and primarily, keep the material added value of the product’s components.”

Independently of the other differences mentioned above, this definition emphasises the fact that a recycling chain is an *industrial system*, and should be considered as such in order to become competitive and to reach an economic stability.

3. Schematic depiction of a recycling chain

A component lifecycle (previously sketched in figure 1) is detailed in figure 3, with a focus on its end-of-life and specifically on the recycling chain. It aims to identify the main stakeholders, pro-

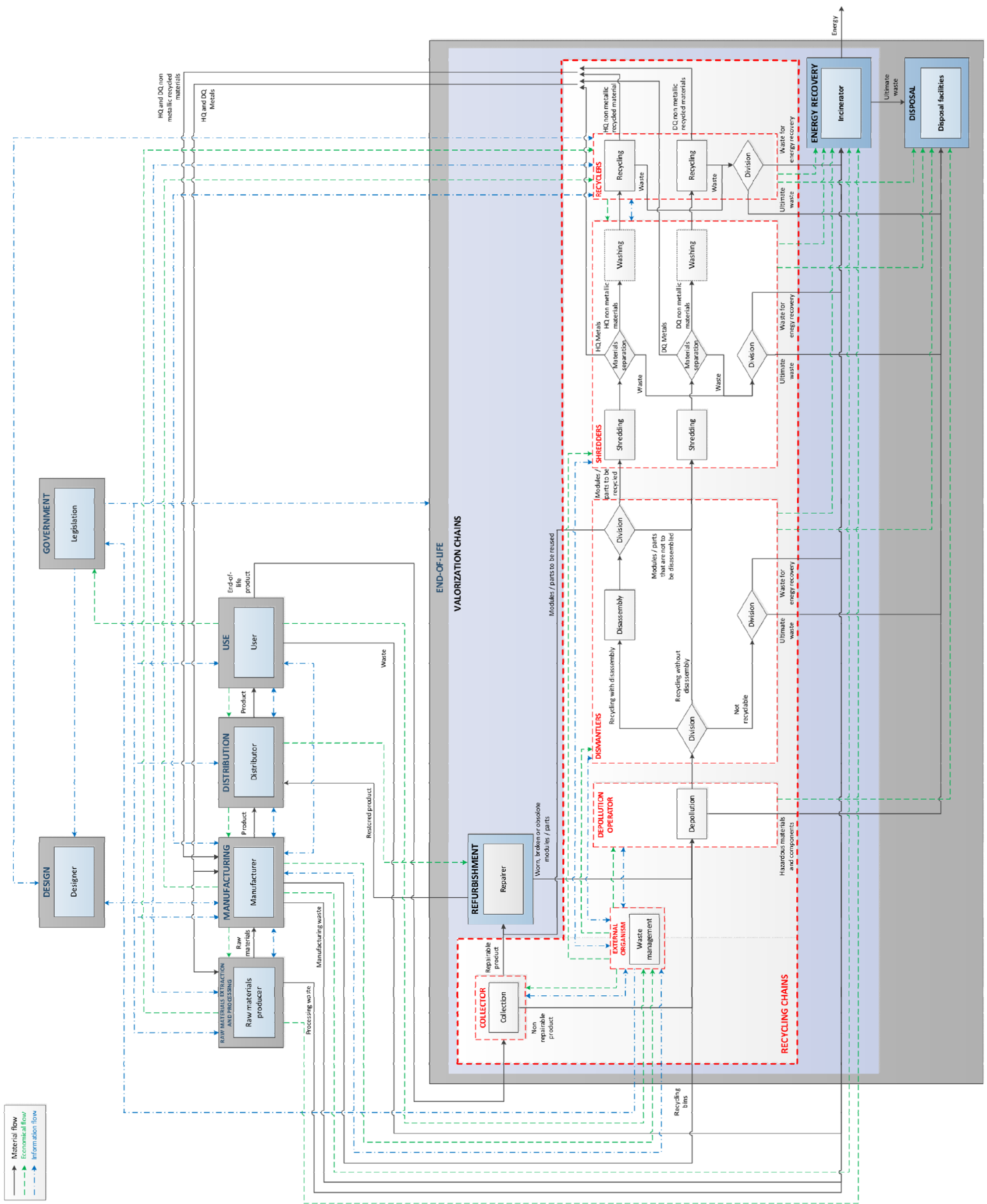

Figure 3: Schematic depiction of a recycling chain within the component's lifecycle.

cesses and flows of material, information and money of the recycling chain, as well as their interaction with the other stages of the lifecycle including the other end-of-life options.

DESCRIPTION OF A RECYCLING CHAIN

As previously expressed, recycling chains are complex systems. In order to better analyse them, it is necessary to describe chains with both internal and external parameters. This description will allow us to fully understand these systems as they are reflecting the current situation.

1. Internal characteristics

Internal characteristics can be divided into (a) technical, and (b) structural and organizational.

a. Technical

These characteristics refer to all aspects related to methods, techniques, know-how and requirements, within the recycling chain.

1. *Chain type*. First of all, three types of recycling chains can be differentiated (Maudet-Charbuillet 2009), depending on the nature of the component to recycle. In this way, if the component is
   - a *product*, the recycling chain only focuses on the treatment of a specific one (*e.g.* ELV (end-of life vehicles), WEEE (waste electrical and electronic equipment), etc.);
   - a *part*, the chain aims to preserve functional and/or material values (*e.g.* PCBs (printed circuit board) must be treated separately in a specific recycling chain);
   - a *material*, each chain only integrates a specific material (*e.g.* cardboard, glass, etc.), independently of the product it comes from.
2. *Valorisation circuit*. Each step (and sub-step) characterises the chain. Recycling process can usually be divided in:
   - *Collection*. Waste is collected from houses, dumpsters, collecting points, industries, etc. and conveyed to treatment centres;
   - *Depollution*. Hazardous materials are removed from the waste in order to be safely treated and to avoid contamination of materials later in the recycling process;
   - *Disassembly*. Each component that can be reused or need to be treated separately (in order to preserve its value or because of a too complex recycling process) is removed;
   - *Shredding*. The objective is to grind the component into small particles, before separation (*e.g.* ferrous and non-ferrous metals, plastics, etc.);
   - *Recycling*. Lastly, this process transforms recovered materials into secondary raw materials.
3. *Stakeholders of the valorisation*. They can be collectors, depollution operators, dismantlers, shredders, recyclers, etc. But one may be charged with multiple operations.

4. *Input characteristics*. These are the characteristics of the waste entering the recycling process. This is key information because the effectiveness of the recycling process is tightly linked to waste properties. Some of these characteristics are listed below:
   - Origin of components (*i.e.* nature of the last user, *e.g.* individual or industry);
   - Complexity (*e.g.* product/module assembly, mono or multi-material, etc.);
   - Localisation (*e.g.* waste coming from surroundings, from a remote area within the same country or from another country, etc.);
   - Valorisability (*e.g.* disassemblability, separability, recyclability, etc.);
   - Deposit characteristics (*e.g.* weight, volume, toxicity, economic value, etc.).

   These characteristics can induce important choices in the valorisation circuit (*e.g.* choosing if some parts need to be dismantled or not), and then in the efficiency of the recycling process.
5. *Output product characteristics*. This refers to the final product characteristics (*e.g.* mechanical properties, physical form, etc.). These characteristics are usually required by the purchaser (*i.e.* the market).

b. Structural and organizational

Structure and organization of the recycling chain are as important as the technical characteristics previously listed. Indeed, these features will directly impact flows of material, information and money.

1. *Financial organization mode*. It specifies who administrates and finances the recycling chain. Three main financial organizational modes can be found (Maudet-Charbuillet 2009).
   - *The manufacturer's administration*. In this organization mode (cf. figure 4.a), the producer organises and finances the recycling of his own products, at least until the last step of waste conditioning. In other words, the manufacturer treats waste until it is no longer considered as such (thanks to one valorisation chain), or ensures its disposal.
   - *Administration by an external organism*. In this organization mode, an external organism (private or public) organises and finances the recycling chain. Several organisms may interact in the chain and each one can treat many products (cf. figure 4.b). While material flows do not change (compared to manufacturer's administration), the external organism is now responsible for managing the waste.
   - *The free market*. This is more a scenario than an organization mode. It consists of a set of independent stakeholders who all seek to valorise waste, with a maximum profit. In contrast with both previous financial modes, there is no responsible for the end-of-life. As a consequence, each actor is supposed to find his own balance without the influence of either the state or the manufacturers (cf. figure 4.c).
2. *Structure*. This feature relates to the principle of a circular economy; more specifically it refers to the final destination of products to be recycled. In this way, structure can be:
   - *opened-loop*: the recycled materials do not return to their original application;
   - *closed-loop*: the recycled materials do return to their original application.

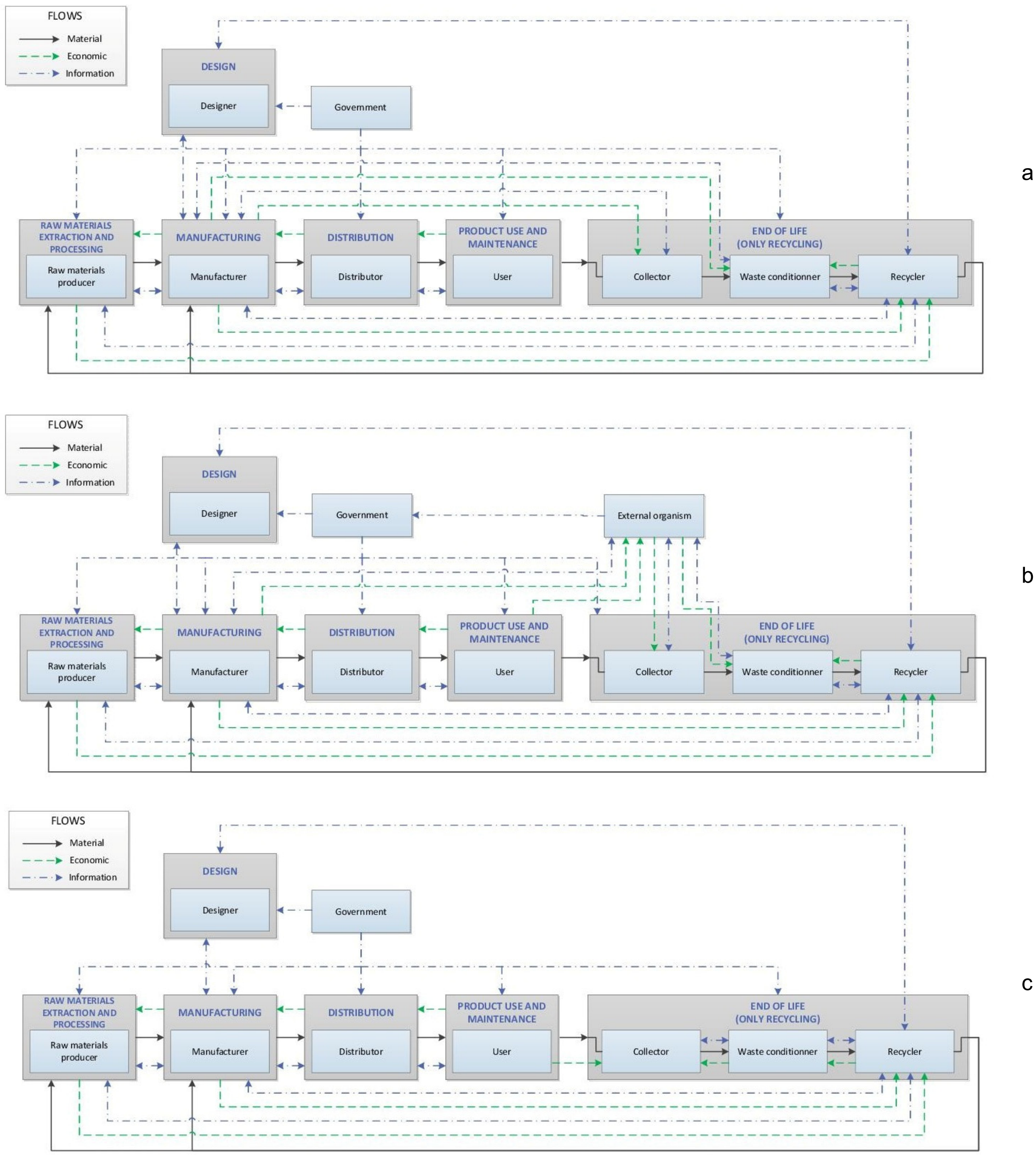

Figure 4: Financial organization mode.
(a) Manufacturer's organization. (b) Administration by an external organism. (c) Free market.

3. *Motivation*. This characteristic expresses the main driving force of the recycling chain. It can be:
   - *Legislation*. The recycling chain was created with an environmental motivation, specifically to respect legislation;
   - *Business*. The recycling chain was created with an economic motivation, *i.e.* to generate profits.

2. External factors

The external factors refer to all elements that impact the efficiency of the chain or affect it in any way.

a. Raw materials price

Price of primary raw materials directly impacts the recycling chain. Indeed, recycled materials are in constant comparison with first generation ones (ADEME 2015), not only from a physical or mechanical point of view, but also economically. Consequently, it is usually expected that secondary raw materials must be cheaper than new ones, even when both have the same quality.

b. Geographic variability

Recycling chains' stakeholders are usually spread over large territories as chains are usually
- decentralized (a same process is carried out at different locations);
- and multilevel (recycling processes may be subsequently carried out at different locations);

systems. As a consequence, the chain is highly impacted by geographic variability (Mathieux 2002). Depending on their location, differences between stakeholders of the same chain can be found in (1) legislation, (2) economic and material resources and (3) in the community' attitude to recycling practices. These differences are shortly detailed below:

1. *Legislation*. Laws differ between states, and even from one area to another in the same country, but they all constrain recycling chains ;
2. *Resources*. Economic resources vary from one country to another and even between cities. Taking this into account, one must note that available logistic resources (*e.g.* number of collecting points) and their distribution (*i.e.* variability in density) may benefit or limit the operating mode of the recycling chain;
3. *Community attitude to recycling practices*. Some communities are more eco-friendly than others. Thus, it is important to see how to encourage less environmentally conscious ones to participate to the recycling process.

c. Temporal variability

Product life expectancy (1) and product evolution (2) are the most important factors of temporal variability; they both impact the recycling chain (Mathieux 2002).

1. *Product life expectancy*. The efficiency on recycling of the (re-)design of a component can only be assessed when it reaches its end-of-life and not before. This can be problematic for long-life products. Indeed, the longer a component is used, the harder it is to improve the chain and to implement effective eco-design strategies. It results from the difficulty to link design to end-of-life.
   Life expectancy can be split in three categories:
   - *Short life*. A product with a short life expectancy will stop being useful rapidly and will be binned quickly (*e.g.* packaging and disposable products);
   - *Average life*. The meaning of *average* could obviously change from product to product; however, we propose to set the limit at two years (*e.g.* electronic devices, kitchenware, etc.);
   - *Long life*. This category addresses all products used for more than two years (*e.g.* cars).
2. *Product evolution.* Products are in constant evolution. Sometimes, it only consists of minor changes (*e.g.* changes in food packaging). Nevertheless, it can also significantly affect the products design (*e.g.* composition of electric cars). Thus, recycling procedures must anticipate these changes in order to prevent the impact of these evolutions.

d. Interaction with other existing chains

This characteristic refers to the degree of integration of a chain with other existing chains (Fleischmann *et al.* 2000). It aims at checking if other chains already treat the same materials or have similar processes that could eventually be applied to the chain so we can take advantage of existing knowledge in order to better meet market expectations and demands. The only two possible options are:

1. *New system*. There is no other similar system;
2. *Extension of an existing system*. There is a similar system which must be studied.

e. Interaction with other end-of-life options

Other end-of-life options which interact with the assessed recycling chain can be identified. For example, there may be interactions with remanufacturing, energy recovery, and/or disposal (cf. figure 3). These interactions must be identified in order to be improved.

3. Synthesis. Multidimensional representation

Figure 5 is a multidimensional representation of a recycling chain which seeks to include all the axes needed to take into account when characterizing these systems. Its main objective is to show that a recycling chain is not only defined by internal characteristics but also by external elements that affect it in a positive or negative way.

Figure 5: Multidimensional representation of a recycling chain.

PERSPECTIVES

1. Evaluating the efficiency of a recycling chain

The main perspective of the present work is to provide *one* index (or if not, as few as possible) characterizing the efficiency of all or part of a recycling chain, taking into account the internal and external factors previously listed. But above all else, it should be mentioned that an *index* results from the aggregation of several *indicators*.

a. Concept of an *indicator*

An *indicator* is a state or an evolution assessment tool which may be used as support for a decision.

An indicator must convey a causal relationship with a measured (*i.e. indicated*) quantity. It then expresses a synthesis of information, potentially from different types. Hence, the indicator enables knowledge exchanges between several stakeholders from different worlds. The more it reflects reality and it is understandable, the more it is usable.

Assuming that n internal or external factors have been clearly identified and defined (cf. above), let P_i be the i^{th} evaluated quantity $(1 \le i \le n)$. Then, n indicators must be built to characterize the n P_i; they are called r_i and constitute the n-tuple $r = \{r_i\}_{1 \le i \le n}$.

We propose that they are all built as dimensionless ratios (*e.g.* value of the property reduced to a reference datum) in order to be easily combined. As an example, r_i could be built as:

$$r_i = \frac{P_i}{P_i^*}$$

where P_i^* is a reference quantity of the same physical nature as P_i.

b. Notion of *index*

An indicator which results from the aggregation of n others is called an *index*.

Like so, the efficiency index of the recycling chain will result from the aggregation of the n indicators r_i. Let R be this index.

In that case, we aim at defining the map f such as:

$$R = f\left(r_1, r_2, ..., r_i, ..., r_n\right)$$

which reflects as best as possible the reality of the chain.

f is an aggregation function of the n-tuple $r = \{r_i\}_{1 \le i \le n}$. The choice of this map is *a priori* complex. For example, f must be

- independent of the order of the r_i;
- invariant by permutation of the r_i;
- monotonic;
- etc.

All these assumptions will have to be argued by examining the consequences of each decision on the R index.

1. Improving recycling chains and developing synergies between them

Armed with the R-index, it will be easier to compare the efficiency of all or part of a recycling chain, to another one. As a consequence, we aim to:

- identify the least effective part of a recycling chain in order to improve it;
- optimize the recycling of a component by referring it to the best recycling chain (or the most effective stakeholder);
- propose new end-of-life options for a component by better preserving its added value.

2. Taking into account the best end-of-life option from the design phase

Lastly, a better knowledge of the real effectiveness of each end-of-life option expressed by a numerical index could easily be taken into account from the design phase.

a. Formalization of the design phase

The impact of the design of a component on the preservation of its added value (namely on the choice of the best end-of-life option) has previously been underlined.

In order to introduce a better vision of the end-of-life reality from the design phase (*i.e.* in design tools), the component design cycle has to be detailed.

As defined by Pahl *et al.* (2007), it can be divided into the following main steps.

1. *Early design*. The early design phase is mainly based on the customers' needs. In this way, the products' main 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.
2. *Preliminary design*. The preliminary design usually involves the following two steps:
   - the *conceptual design* aims to define 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;
   - the *architectural design* 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.
3. *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*).
4. *Industrialisation*. Lastly, the industrialisation phase aims to choose the best manufacturing process, optimising the supply chain, drafting a quality plan, and eventually implementing a prototype to be tested.

b. Areas of improvement of the design step

The R-index being a mathematical tool, it could be quite easily taken into account either in classical design or in eco-design tools, depending on the available data at each step. But the best phase to integrate this knowledge will have to be discussed as an outlook of our preliminary work (cf. figure 6).

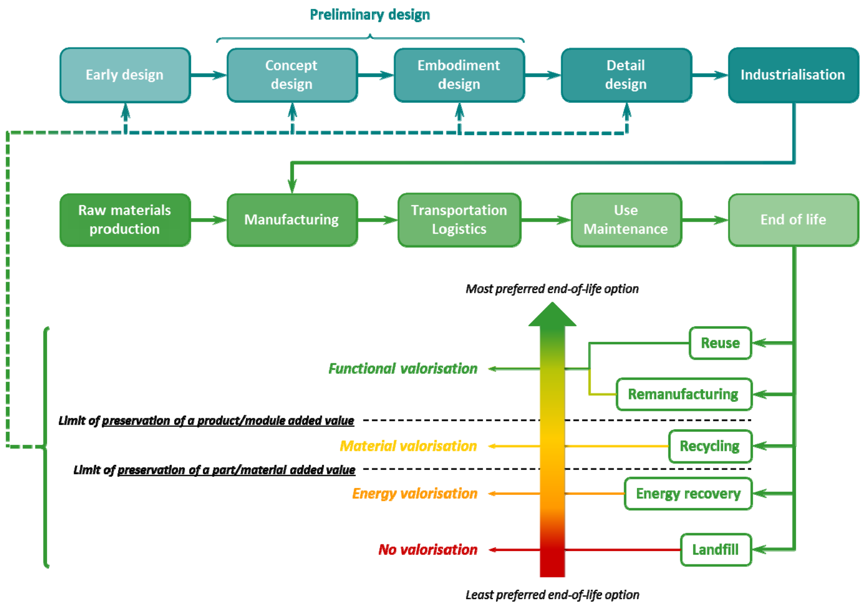

Figure 6: Component development process (blue boxes) and its connection to its later lifecycle (green boxes). The end-of-life options are listed from the most to the least preferred. We now aim to connect knowledge of recycling chains (and more generally of end-of-life), from the design phase (dotted arrows)

CONCLUSIONS

Recycling chains have been operating for quite a long time. Nevertheless they are still not fully developed. It is mainly due to the complexity of such systems (as schematically shown in figure 3), but also to the lack of theoretical principles on this area.

Our proposed definition and description of a recycling chain are the first step on the way to a complete analysis and full comprehension of these systems. Indeed, it gives a preliminary perspective of the subject at hand.

Firstly, the definition fully describes a recycling chain; it regroups the most basic information such as stakeholders, processes and flows (material, information and money) and also takes into account important elements such as legislation and motivation. In that regard, one must pay special attention to the motivation. On one hand, our definition emphasises the environmental motivation when it specifies that recycling chains reduce the impact of raw material extraction and the quantity of waste which is going to be incinerated or landfilled. On the other hand, it also considers the economic motivation when it is specified that these chains seek to preserve material added value, and primarily when it emphasises that a recycling chain is an industrial system. This duality of motivations is important because both need to be considered and satisfied so that a balance can be found.

The description of recycling chains has been split into internal characteristics and external factors. The first aims to subdivide the recycling chain into simple identifiable and sometimes quantifiable elements and to specify the way in which they are related to each other. The second aims to list the extra-chain elements which are in constant interaction with the chain. These descriptions can be used as a preliminary support for any chain analysis.

The next step of this work is to fully characterise the recycling chain (using an index or indicators) in order to improve both the chain itself and the component design, always taking into account current situation and legislation and end-of-life evolutions to come.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to the ADEME (French Environment and Energy Management Agency) for their financial support and the EcoSD Network (French association which encourages collaboration between academic and industrial researchers in the ecodesign fields) for its aid and support.

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