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Development of an Evaluation Tool for Engineering Sustainable Recycling Pathways

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Abstract

As the product end of life is becoming more and more complex, the recycling systems encountered many difficulties in valuing all the materials contained in the products. This involves not only recovering many materials but also getting the most economical way and the minimal environmental impact. The recycling industry is a new business sector that needs to be accompanied in its development and research of the most sustainable pathway to guarantee the resources circularity. That is why recyclers need robust assessment tools to make the right choices during the engineering of recycling pathways. This assessment, during the designing phase of the waste management line, should enable recyclers to choose the right recycling processes for a wide range of end of life products. In this article, we present how we develop a methodology for evaluating the performance of recycling processes and give relevant indicators during their design phase.

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Keywords: Recycling pathway, Evaluation tool, LCA, LCC

1. Introduction

1.1. General context

The rise of the world's population and its life conditions go hand in hand with the growth of energy and raw material consumption as well as the steadily growing CO_2 concentration in the atmosphere [1]. As the economy is mostly linear, the consumption's growth comes with an increase in the amount of waste produced annually [2]. Because the primary resources used are consumed and lost, the demand is not tenable in a long-term [3,4]. Wastes are not only more numerous, they are also more and more complex such as e-waste [5]. Following the status quo is not an answer to resource depletion. Therefore, it is essential to find solutions to maintain equivalent living standards while The circular economy offers a partial answer for decoupling resource use and demand [6–8]. The circular economy is defined as a global economic model that decouples economic growth and development from the consumption of finite resources. It is restorative by design, and aims to keep products, components and materials at their highest utility and value, at all times [9]. In this way, the recovery trough recycling lies at the heart of the circular economy [10,11]. Recycling aims to recover the materials contained in the products that are collected in waste streams [12].

To tackle the materials efficiency objectives producers and recyclers need to work hand in hand. In fact, the recycling industry is most often faced with new waste treatment issue. Without anticipating new types of waste, recyclers need flexibility in their recycling pathway. To achieve flexibility, they are looking to optimize their pre-recycling processes used for the recycling pathways. In this article, the term *recycling pathway* only concerns the steps

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downstream to the initial collection of the waste and before the material regeneration. The End-of-Life (EoL) segmentation is shown on Fig. 1. The more intricated the waste is the less obvious the pathway optimizations for will be.

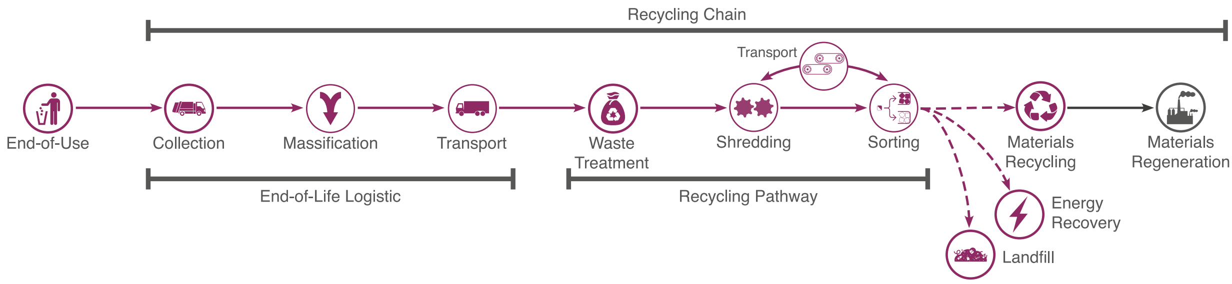

Fig. 1 Main stages of the End-of-Life chain including recycling pathway

1.2. Industrial Context

MTB is a French small size enterprise based at Trept a town near Lyon (France). Despite its size, MTB is a leading global player in the industrial waste management market. MTB designs, manufactures markets and installs machines, as well as complete recycling lines, worldwide. As an operator and manufacturer, its strength lies in the fact that they understand customers' issues and work to solve the issues by mastering recycling technologies. This give the fertile ground to offer innovative solutions tailored to the needs of each waste streams. With 35 years of experience, MTB has acquired a tremendous amount of expertise in the waste recycling industry. In 2005, MTB company has launched a sustainability strategy. Initially, this strategy resulted in eco-friendly purchases. For example, the choice of an exclusively renewable electricity supplier, or the relocation of manufacturing operations.

In 2012, the company wanted to go further in its approach, by providing itself with the means to anticipate the requirements of an evolving industry. First, the aim was to reduce the environmental impact of its industrial activities. To do so, MTB started to evaluate its environmental performance with evaluation tools such as Life Cycle Assessment (LCA) and Material Flow Analysis (MFA). The first evaluation has been realised on an aluminium recycling process using only mechanical separation process instead of smelting. Results show the advantages of mechanical processes [13]. Based on the environmental assessment, MTB implemented corrective measures to increase the processes eco-efficiency [14]. Beyond optimising recycling pathways in operation, these results also helped us to guide the research for new recycling processes which have been designed to be more sustainable [15]. All these steps help to enrich the company's own knowledge, but the evaluation process is long and requires strong stakeholder involvement at each assessment stages.

The literature providing eco-design methodologies, good practices examples and tools based on experiments are numerous [16–18]. Nevertheless the available literature do not address methodology to eco-design industrial process. The guidelines for industrial processes are mostly focused on eco-efficiency [19]. Though these approaches are relevant, it reduces the scope of analyses and it provides narrow solutions for reducing the overall environmental impacts.

For the step forward, it is essential to implement this practice during the design phase of the recycling pathways. That is why, a methodology is required to integrate the Life Cycle Management (LCM) approach for engineering sustainable recycling pathways. The objective is to provide data relevancy to decision makers beforehand. For these reasons, our research team proposes an evaluation tool for engineering sustainable recycling pathways. The evaluation tool presented in this article attempts to provide a broader view of the efficiency of processes to move towards a comprehensive model considering all the potential impacts. As a starting point, our methodology concerns only pre-recycling processing solutions as define in Recycling Handbook [12].

2. Material and Methods

2.1. Unit Process Database

A first stage was to describe the EoL pre-recycling processes to propose an appropriate segmentation. We studied a wide range of EoL chain and as a conclusion we observed that they are mostly based on common elementary technologies [20]. Except for innovation breaks, pre-recycling processes use simple mechanical solutions [21]. The choice of technology and the order of that technology are the key aspects to implementing efficient recycling pathways. So, the assembly choices of common sub-processes are one of the key points to design efficient recycling pathways. The recycling process technology choices vary with the type of waste streams to achieve the desired purity targets. For example, the Fig. 2 shows different pathways for the same waste stream.

According to the literature [22] recycling processes can be classified in three families: shredding, separation and transport. In addition to these three families of process unit, there is a flow unit family that makes the link between unit process. These three types of processes are subdivided into subcategories. For the shredding processes, there are four subcategories: shredders, shears, granulators, micronisers.

Within these four subcategories there is a wide range of technologies that achieve the same objectives but for different materials, quantities, shape, etc. For all shredding technologies, their performance is defined by the fineness; i.e. the solution ability to shred the material well, producing little dust and with regular particle size. The same logic is applied to the separation processes, they are defined by purity and efficiency. The purity is specific to the separation criterion. The effectiveness considers the ability to extract the elements satisfying the separation criterion. The number of sub-categories is more important. We have listed at least nine subcategories: size, shape, weight, magnetic, eddy current separation, electrostatic separation, optical sorting, air buoyancy separation, wet buoyancy separation. Finally, transport processes are processes able to meet the material storage and progress constraints between two different technological processes. There are three subcategories: storage, pneumatic conveying and mechanical transport.

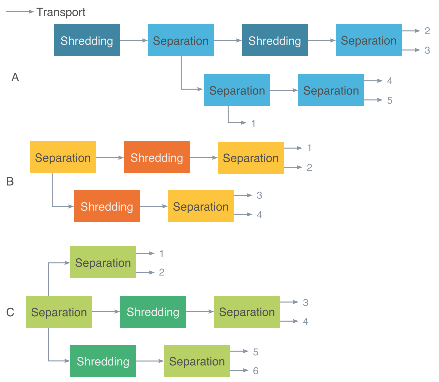

Fig. 2 Representation of pre-recycling processing pathway alternatives

This segmentation allows us to build a database (Fig. 3) to evaluate the performance of each recycling process insert in a recycling pathway. The database is divided into 3 levels of data. A first level includes all the fixed values of the processes characterization. These technical data are established as a function of the material flows. A second level of data makes it possible to consider the specificities of the recycling pathway. They are set by the engineering team and influence directly the first level of data. Finally, a last level regroups the performance data that are calculated based on the other two levels of data.

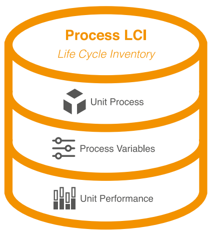

Fig. 3 Representation of the three-level unit process database

2.2. Environmental Technology Verification Program

Although the benefits of recycling are well established [23], the industrial processes need to be designed in regard with their environmental impacts. Yet the recycling pathways are multiple, and it is important to determine the best pathway according to different categories of indicators. With the help of indicators, it is possible to quantify and monitor the potential impacts, as well as the benefits of specific EoL scenarios [24]. For now, the environmental performance indicators are used only to justify the gains of recycled materials in comparison to virgin materials.

The construction of our LCM approach has been broken up into several key stages. First, the evaluation tools (LCA, MFA) were used to characterize technologies and to identify the key impact category indicators. The results obtained allowed to complete the third level of the unit process database (Fig. 3). Next, the Environmental Technology Verification (ETV) was used to draw the evaluation framework for the recycling pathways. The ETV program was used by our research team to settle a robust comparison framework.

The ETV program is a new tool to help innovative environmental technologies to reach the market. The problem is that many clever new ideas that can benefit environment and health are not taken up simply because they are new and untried. Under ETV, if the *owner* of the technology wishes to, the claims about innovative environmental technologies can be verified by qualified third parties called *Verification Body*. The *Statement of Verification* delivered at the end of the ETV verification process can be used as evidence that the claims made about the innovation is both credible and scientifically sound [25]. One objective of the European commission with the ETV program is to promote environmental technologies by providing technology developers, manufacturers and investors access to third-party validation of the performance of innovative environmental technologies.

The EU ETV program just ended its pilot phase as the ISO 14034 standard was published [26]. All ETV verification steps combine together last six to eighteen months. In comparison, the average designing time is between three and six months. Although ETV verification time is too long for the design team to evaluate each recycling pathway, we have decided to launch a verification on a specific recycling process used by MTB at its recycling site. The aim is to implement the general requirements of the program into our methodological framework.

2.3. Performance Indicators Selection

As is shown on the Fig. 4, the performance evaluation is a three-part evaluation. For each performance category, we have selected three performance indicators that seems to be the most relevant for the recycling pathway evaluation. This selection was made in two stages. First, we have selected indicators that are necessary for the stakeholders and are currently missing or not robust enough [27]. On the other hand, we used the Environmental Technology Verification

(ETV) protocol [25,28] methodology to introduce a common claims basis for all recycling processes.

One of the information we want to get from the ETV verification is the general claims applicable to all recycling pathways. To do so, we also confront our claims with the claims arising from other ETV verification done on recycling technologies. Currently, in addition to our recycling technology only one recycling process is under ETV verification in Europe [29]. The claims from our two verification are similar and relate to the same performance indicators [30]. As a result, the ETV verification allowed us to establish both technical indicators for the characterization of unit processes which depended on technology choice, and operating setting definition. The ETV verification also help us to establish the Key Performance Indicators (KPI) for the global performance of recycling pathway proposals. After the discussion with the stakeholder, three technical KPI and two other KPI, one for sustainable performance and one for economic performance were established using the ETV verification. On the other hand, we used the Environmental Technology Verification (ETV) protocol [25,28] methodology to introduce a common evaluation claim basis for all pre-recycling processes.

For each performance category, we have selected the three most relevant performance indicators based on the stakeholders' needs. The calculating formulas for these indicators are available in the literature. However, the robustness is need due to the lack of accuracy for the data used. That is why we work to improve the quality of the results with a strong database. We chose to not aggregate these indicators. This will allow to establish a panorama and helps stakeholders to start a discussion about each performance regarding to the other one. It is not a question of producing a classification of recycling pathway subject to caution. In line with these observations a three-part performance evaluation was set up (Fig. 4).

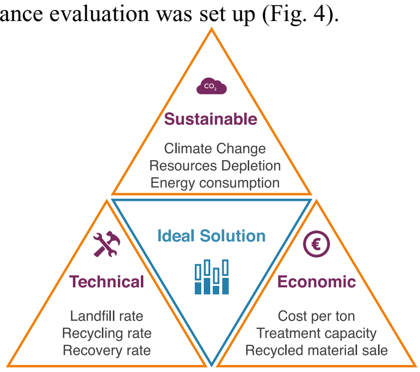

Fig. 4 Three-part key performance indicators (KPI)

The technical performance indicators are oriented towards the capacity of the pathway to recycle the waste, so each unit process is described by three indicators. The calculation of these rates is done according to the pre-recycling processing scope [27]: recycling rate, recovery rate and landfill rate.

For the economic dataset, data is easily accessible through the information provided by manufacturers and recyclers feedback. The Life Cycle Cost (LCC) analysis is used to determine the economic performance of each unit process. The LCC methodology used to consider both the costs of each system in addition to the profit from the sales of the sorted materials. However we do not include the costs of the environmental impact [31]. The economic performance is described by using three results: initial investment costs, operating costs (cost per ton) and profit from recycled materials sales.

On the contrary, environmental data are rare and not available in the current Life Cycle Inventory database (ELCD, Gabi, Ecoinvent). Inventory data remains to be collected and assessed to build a strong dataset. Our team has started to build an environmental database for recycling processes. The result of environmental performance is given with one inventory indicator and two impact factor indicators using ILCD methodology [32]: total energy consumption, climate change and non-renewable resource depletion.

Beyond the technical, economic and environmental indicators selection, the tool aims to correlate the indicators to balance the results. We chose not to aggregate these indicators. This will allow to establish a panorama and helps stakeholders to start a discussion about each performance regarding to the other one. It is not a question of producing a classification of recycling pathway subject to caution.

3. Results

3.1. Step by Step Evaluation Methodology

To support our assessment methodology and provide a coarse result in early design phases to promote sustainable solutions. The methodology can be divided into several key steps. First, with the specifications and the customer need the general framework can be built. This step allows to determine the specific constraints, delays and costs of the project to draught the initial specifications. In the continuity, the customer provides his main orientations for the recycling process purpose. The customer defines purpose and objectives for the recycling pathway. And the engineering team validate or not main orientation of the recycling chain. Next using a case database and the expertise from MTB engineering team the operating settings are set for each unit process. From this orientation, the engineering team starts working on the recycling pathway proposal. The aim is to provide: treatment synoptic definition, selection of the main steps, choice of technological bricks.

For each step of the recycling pathway, MTB commercial team needs to select the appropriate technology and thanks to the expertise from MTB engineering team the operating variables are selected. Next the database makes it possible to calculate the unit performances. All the elements filled up so far make it possible to establish the technical, economic and sustainable performance of each unit process. The Fig. 5 presents the modelling of the interconnections between each unit process and its associate in/output flows. To obtain the KPI for recycling pathway every unit process performance is summed up to obtain the final result. On the one hand, a synthetic evaluation is provided to the customer to initiate a discussion. On the other hand, the results help the engineering team to optimize the initial pathway proposal.

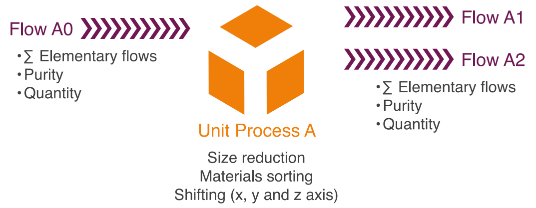

Fig. 5 Modelling of a recycling pathway step with a unit process and its related flows

3.2. Characterization for Recycling Unit Process

To enable the three-part performance evaluation (Fig. 4), the database includes technical, environmental and economic dataset. On the one hand, for each data a part of the values is fixed. These are the invariant data regardless the type of transformation performed by the unit process. This is mainly the impact of manufacturing, its price without the options or the weight of the equipment. On the other hand, in addition to these fixed values, the engineering team can set value for adjusting unit processes to customer needs. These are the operating settings. These actions will have a direct effect on the performance of the recycling pathway.

For the three families of unit process, the Table 1 gives the associate operational details and the technical process characterization define using the ETV program. For each specific unit process, technical characterization will help to define the most suitable process for each purpose of the recycling pathway step.

Table 1 Variables and characterization for each unit process family

Type	Operational Details	Characterization
Shredding	Type of technology (constraint)	Reduction rate/ Fineness
	Cost of purchase	
	Substance losses	
	Capacity	
Separation	Type of technology (constraint)	Effectiveness Separation quality
	Cost of purchase	
	Substance losses	
	Capacity	
Transport	Type of technology (constraint)	Flow rate
	Environmental characterisation	
	Cost of purchase	
	Substance losses	
	Capacity	
Elementary flow	Flow composition	Purity
	Physical properties	
	Input or Output	
	Market price	

4. Conclusions

The decision tool aims to help the design team to implement more sustainable recycling pathway. It is not a matter of providing a comprehensive assessment for each recycling pathway during the design phase, but it is to communicate to industrial customers the performance indicators in addition to the economic indicators. These additional performance indicators should allow designers to propose optimization on recycling pathways and give a quantified result of the improvements. With an iterative approach, designers could optimize the flows and processes to contain impacts.

Although recycling lines are not new, industrial optimization has not been fully conducted [33]. The unconstructive approach, the complexity of waste, the toxic composition and the lack of control over incoming flows limit the drafting of theoretical principles. The increasing interest in waste recycling and the evolving regulations in force steer the waste sector to adopt an increasingly industrial approach. To accompany this transition, it is a question of advancing the design methods with specific tools.

Even though plenty of technical options exist for developing recycling products, the recycling solutions selecting motivations are too often led by the pursuit of profit growth which leads to a greater inefficiency [34,35]. By communicating additional performance indicators, we are convinced that this approach can evolve. And that new issues will be introduced in trade negotiations for recycling pathway.

As a next step, we need to build a sufficiently complete and robust database to support the evaluation of recycling pathway. This approach must be enriched in the future. It is also required to facilitate the improvement of the quality of results during the refining process variables and input parameters.

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