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Synthesis and Assessment of Waste-to-resource Routes for Circular Economy

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Abstract

The benefits of the circular economy paradigm have been proven during the past two decades, but its application poses some challenges that still need to be tackled. This contribution presents a systematic way to generate a list of potential waste-to-resource technologies based on the use of a semi-automatic ontological frameworks. The ontology is instantiated, giving the possibility to generate and assess a list of transformation processes alternatives, according to the potentially available waste streams and resource requirements in a specific area and/or sector. The resulting list is then analyzed and classified according to pre-established parameters, thus presenting which are the potentially best alternatives to close the material loops and recover chemical resources from available waste. The capabilities of the method to identify promising transformation technologies are assessed through an illustrative case study: the evaluation of different routes for the treatment of plastic waste materials, with the focus on chemical recycling.

Keywords: circular economy, product transformation, waste-to-resource, ontology, chemical recycling

1. Introduction

In the last years, there has been an increasing concern about the degradation of the environment due to the large amount of waste generated by the constantly growing world population. In this line, plastic waste deserves special attention, since it is one of the most abundant and lasting types of waste. Its manufacture entails a significant consumption of energy and resources considering its short average lifespan. Hence, there is a rising awareness on the need of not only treat waste, but also convert it into valuable feedstock for other processes, thus eliminating the problem of waste disposal and reducing the consumption of fresh raw materials.

Promising processes for chemical recycling have been proposed in the direction of closing the loop of materials, but most of them are still in development at lab scale. Hence, they are often disregarded, due to the lack of information on their cost, profitability and performance at industrial plant scale level. Furthermore, and opposed to traditional product-based processes, it is not always clear which is the best way to convert a specific waste stream into which added-value product(s), or even which specific waste streams will offer better economic or environmental potential to be reused or recycled.

Thus, systematic tools should be developed to address the generation of process alternatives that enhance resource upcycling. The aim of this work is to develop a method to synthesize and assess routes for waste-to-resource transformations.

The approach presented in this contribution is based on ontologies and knowledge modelling. An ontology is a formal, explicit specification of shared conceptualization (Studer R. et al, 1998). The extended use of ontologies has allowed the development of ontology-based engineering systems, providing a semantical environment and a knowledge management tool. Previous research has demonstrated the applicability of ontologies to circular economy and industrial symbiosis problems (Zhou et al., 2018, Cecelja et al., 2015, Rafaat et al., 2013).

In this work, a formal ontology that models the enterprise process engineering domain, so called Enterprise Ontology Project (EOP), has been used (Munoz et al, 2013). EOP model sets well-defined domain concepts encompassed by a taxonomic arrange, terminology, definitions and relations. The domain of this ontology is process system engineering including areas such as batch processes, control and automation, planning and scheduling, supply chain management and life cycle assessment. Thus, this ontology provides to process functionalities a consistent structure for explicit, shareable and reusable formal knowledge representation.

2. Problem statement

The problem addressed in this contribution can be stated in the following terms: ranging from a pre-defined ontology for the classification of waste-to-resource processes along with their specifications, and scientific documentation related to the domain of study. A list of tentative processes suitable to treat the considered waste with their specifications, such as operating conditions as well as economic and environmental data, should be determined.

Subsequently, given the previously obtained list, a set of characterized available wastes, potential products demand with quality requirements to meet, and data assessment criteria to analyze the adequacy of the process to the given waste, the objective is to determine a list of relevant technologies sorted by the criteria defined above.

3. Methodology

The methodology used in this work is described in Figure 1 and is divided into two main tasks; the first one consists of ontology selection and instantiation with information retrieved from scientific documentation, obtaining then a set of processes suitable for the domain of study. The second task consists of a reasoner that, starting from the potential transformation processes, would be able to obtain a list of processes and weight the best ones based on the assessment criteria mentioned below in section 3.2.

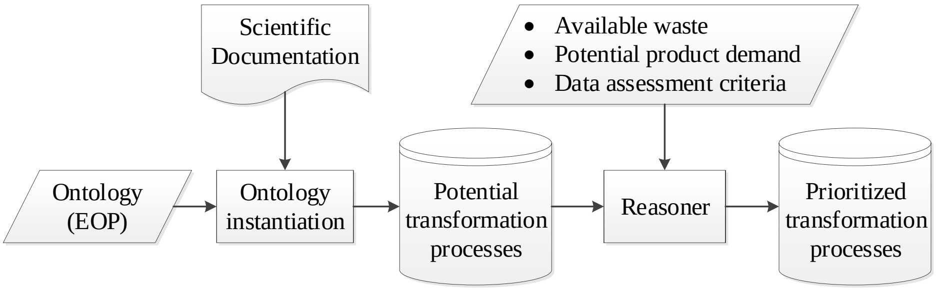

Figure 1. Methodology description

3.1. Ontological framework

An ontological framework is used to model resources, waste and potential transformation technologies considering their composition, characteristics and other specifications.

First, a set of transformation processes available in the domain of study are populated and implemented in the ontology framework mentioned above. These transformation processes have to be well defined and all the relevant parameters must be registered in the ontology.

In order to connect the available wastes with the final marketable products, an input-output matching method has to be applied, thus being able to generate different process paths (or routes) with their eventual outcomes and taking into consideration eventual intermediate products, which will enforce specific sequencing constraints.

Finally, end-of-life treatment processes for any non-marketable by-product, such as incineration for energy recovery or landfill, should be included in the proposed process network, if necessary.

3.2. Sorting and classification of instances (reasoner)

For each one of the transformation processes routes available in the ontology, a list is created and a ponderation is applied in order to sort them out, seeking the maximum economic and environmental profit, as well as promoting the use of simpler and more mature processes.

The process characteristics to be analyzed are sorted in three main categories: economical, environmental and matureness. Main economic aspects are: products selling price (including energy recovery benefits), waste purchase price, and processing cost. The environmental impacts of the feedstock, products and process are obtained (and eventually monetized) according to the life cycle impact model ReCiPe2016 (Huijbregts et al, 2016). And finally, the matureness of the technology is assessed with the Technology Readiness Level (TRL) as defined by the EU Horizon 2020 (European Commission, 2014).

Products prices are obtained from the Prodcom Annual Data 2018 (European Commision, 2018), waste prices and processes cost for the case study are taken from scientific literature review.

Then, the economic and environmental profits for every process path (the letter j is used to represent the set of processes to be studied) can be calculated as shown in Eq. (1) and Eq. (2).

$$P_{eco,j} = V_{products} - C_{waste} - C_{process} \tag{1}$$

$$P_{env,j} = EI_{products} - EI_{waste} - EI_{process} \tag{2}$$

Additionally, weighting factors are calculated in order to prioritize paths with higher economic and environmental profits against those with lower values, as shown in Eqs. (3, 4).

$$f_{eco,j} = \frac{P_{eco,j} - \min_j \left\{ P_{eco,j} \right\}}{\max_j \left\{ P_{eco,j} \right\} - \min_j \left\{ P_{eco,j} \right\}} \tag{3}$$

$$f_{env,j} = \frac{P_{env,j} - \min_j \left\{ P_{env,j} \right\}}{\max_j \left\{ P_{env,j} \right\} - \min_j \left\{ P_{env,j} \right\}} \tag{4}$$

And another factor will be calculated from the TRL in order to promote the use of more mature technologies, as seen in Eq. (5):

$$f_{TRL,j} = \frac{TRL_j}{\max_j \left\{ TRL_j \right\}} \tag{5}$$

Finally, an objective function can be calculated as shown in Eq. (6), which has to be maximized, that is to say, the routes with the greatest O.F. will be at the top of the list and the ones with lowest will be at the bottom.

$$OF_j = \left(P_{eco,j} + P_{env,j} \right) \cdot f_{eco,j} \cdot f_{env,j} \cdot f_{TRL,j} \tag{6}$$

4. Case study

With the purpose of illustrating the methodology, a case study has been proposed for the treatment of plastic waste, such as polyethylene waste (PEw). A list of tentative processes has been obtained from scientific literature and other public domain sources. Other alternatives have been added, such as, direct mechanical recycling, direct downcycling, landfilling and incineration for energy recovery. A list of processes suitable for PEw recycling has been obtained and schematized in Figure 2.

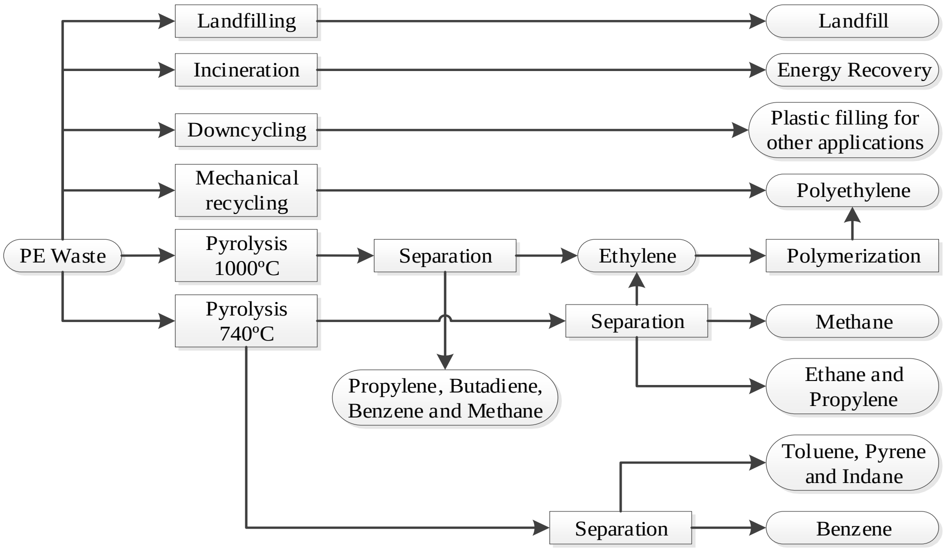

Figure 2. Possible alternatives for PE waste treatment.

According to the structure obtained in Figure 2, there are 7 different paths that can be followed for the conversion of waste into valuable products, each one of them leading to a different outcome. For simplicity purposes, the number of processes in the path generation has been limited to a maximum of 3. Tables 1 and 2 show the studied paths and their main specifications.

5. Results and discussion

Economic and environmental impacts of the processes are calculated in order to sort them out from the most profitable economically and environmentally to the less. The result is shown in Table 3, which is sorted by the objective function. Based on these results, the most profitable process would be PEw pyrolysis at 740ºC, followed by pyrolysis at 1000ºC, along with the separation of the resulting gas and oil fractions in each case; while landfilling is found to be the less profitable option.

Chemical recycling appears to be a very promising way of treating waste and closing the materials loop, thus obtaining raw materials that can potentially be used instead of fresh raw materials. Additionally, these processes are economically and environmentally far more profitable than the traditional way of treating this kind of waste, namely landfill or incineration.

Table 1. Economic specifications for the analyzed processes.

Process path	Total Cost (€/t)	Waste purchase price (€/t)	Products Value (€/t)	Economic Profit (€/t)
Pyrolysis 740ºC + Separation	216.61	307.98	698.47	173.88
Pyrolysis 1000ºC + Separation	215.15	307.98	695.63	172.50
Pyro. 1000ºC + Sep. + Polymerization	320.60	307.98	709.93	81.35
Direct Downcycling PE	0.00	307.98	307.98	0.00
Direct Recycling PE	106.66	307.98	528.03	113.39
Incineration	128.20	307.98	493.12	56.95
Landfill	97.53	307.98	0.00	-405.51

Table 2. Environmental impact (E.I.) specifications and TRL of the analyzed processes.

Process path	E.I. Process (€/t)	E.I. Feed (€/t)	E.I. Products (€/t)	E.I. Profit (€/t)	TRL
Pyrolysis 740ºC + Separation	79.27	13.23	292.13	199.63	7
Pyrolysis 1000ºC + Separation	105.27	13.23	185.47	66.97	6
Pyro. 1000ºC + Sep. + Poly.	141.37	13.23	221.57	66.97	7
Direct Downcycling PE	0.00	13.23	13.23	0.00	9
Direct Recycling PE	139.68	13.23	125.87	-27.04	8
Incineration	209.35	13.23	162.37	-60.21	9
Landfill	19.10	13.23	0.00	-32.33	9

Table 3. Results and weighting parameters for the different process paths

Process path	Economic factor	Environment. factor	TRL factor	O.F.	Global position
Pyrolysis 740ºC + Separation	0.98	1.00	0.78	1041.90	1
Pyrolysis 1000ºC + Separation	0.98	0.64	0.67	516.69	2
Pyro. 1000ºC + Sep. + Poly.	0.89	0.64	0.78	510.35	3
Direct Downcycling PE	0.82	0.46	1.00	376.03	4
Direct Recycling PE	0.92	0.39	0.89	344.85	5
Incineration	0.87	0.30	1.00	258.48	6
Landfill	0.44	0.37	1.00	92.88	7

6. Conclusions

This work presents a methodology for the systematic generation of a list of potential waste-to-resource technologies based on the use of ontologies. Thanks to this method, new technologies can be identified and compared to others that are well-established, and a manageable list of technologies can be obtained for further optimization and superstructure analysis, as well as a more profound development.

The growing application of circular economy principles entails the emergence of new waste-to-resource technologies, such as chemical recycling. A fair evaluation of the potential technologies has to consider its TRL, as its application is riskier than the one of well-established alternatives. Thus, the proposed objective function includes a factor to assess the maturity of the technology.

The framework also allows the generation of routes based on linking consecutive processes in a building-blocks approach. This method leads to flexible product compositions, aiding decision-makers to identify the most economically and environmentally beneficial solutions.

With the aim of ensuring that the list of alternatives includes the most up-to-date transformation technologies, future work will address the development of a procedure for the systematic search of waste-to-resource processes.

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