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Procedia Manufacturing 21 (2018) 502–509

Procedia MANUFACTURING

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15th Global Conference on Sustainable Manufacturing

An approach to favor industrial symbiosis: the case of waste electrical and electronic equipment

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Abstract

Waste management, in particular waste electrical and electronic equipment (WEEE), currently represents an important issue for the modern society. A transition toward circular economy and industrial symbiosis models is needed to mitigate the environmental problem and recover value from end of life (EoL) materials/products. This study aims to define an approach and a platform, dedicated to the WEEE sector, to favor the creation of industrial symbiosis opportunities. Through this structured approach, demand of virgin materials and components, and supply of EoL products are linked to find potential collaborations. In this way, EoL components/materials could be reused in different applications, thus closed-loop lifecycles can be created through industrial symbiosis. A case study focused on the reuse of plastics from electrical cables is shown to demonstrate that in the WEEE sector the implementation of industrial symbiosis models can lead to win-win scenarios for all the involved stakeholders.

Peer-review under responsibility of the scientific committee of the 15th Global Conference on Sustainable Manufacturing (GCSM).

Keywords: closed-loop scenarios; industrial symbiosis approach; End of life platform.

1. Introduction

In order to guarantee a livable planet for future generations, the most relevant environmental problems (e.g., water scarcity and pollution, air pollution, noise, etc.) need to be efficiently faced. Waste management is a primary issue for the modern society. Several reasons are behind this aspect, such as the continuous growing of the worldwide population, which is expected to reach 8,5 billion by 2030 [1]. The improvement of the overall economic

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2351-9789
Peer-review under responsibility of the scientific committee of the 15th Global Conference on Sustainable Manufacturing (GCSM).
10.1016/j.promfg.2018.02.150

conditions, together with an increment of the product discard rate, lead to an over-generation of waste and to an over-consumption of resources. The traditional linear consumption pattern ("take-make-dispose") is based on the assumption that "resources are abundant, available, easy to source and cheap to dispose of" [2]. According to this model, we are using more resources than nature can regenerate and we are emitting more carbon dioxide than forests can sequester [3]. This kind of economic model is not sustainable in the long-term perspective.

Among the waste flows, waste electrical and electronic equipment (WEEE) is one of the most critical flow to manage, since they represent a relevant percentage of municipal wastes (8% of the world municipal wastes in 2004 [4]). The WEEE are continuously increasing (about 5% per annum [5]), because the use of electronic devices leads to rapid obsolescence and decrease of product lifetime [6]. However, only a small percentage of WEEE are properly treated and recovered. According to Eurostat figures [7], the WEEE collected in 2014 was about the 50% of the total electrical and electronic equipment (EEE) put on the market in the three preceding years. The recycling rates vary from 11% to 60%, but most of the European (EU) countries had a recycling rate of about 30%. The majority of WEEE has a non-traced end-of-life (EoL) or are illegally exported to underdeveloped countries (particularly Central Africa) where they are treated with impactful processes [8], in unsafe and unhealthy conditions [9]. This means that only one third (in weight) of the EoL materials is reused, and a consistent residual economic value is lost.

In the traditional business model, companies or production chains operate as "isolated systems" that have no relationships with other companies/production chains. In this business scenario, it can happen that material/product wastes have no potential second-life applications. However, extending the perspectives and the business opportunities through the adoption of industrial symbiosis models, materials and components could be remanufactured or reused for different products and applications. In this context, the paper aims to demonstrate how the implementation of industrial symbiosis models in the WEEE sector leads to economic savings and new business opportunities for the involved stakeholders. The links and the inter-relations among different stakeholders belonging to different markets are provided by a structured web platform, which represents the means to achieve industrial symbiosis models. This is the main novelty of the proposed approach.

After this Introduction, the paper is structured as follows. Section 2 illustrates the state of the art about WEEE sector and normative, circular economy and industrial symbiosis. Section 3 presents the approach to favor the creation of industrial symbiosis opportunities. Section 4 describes the functionalities of the platform that implements the proposed approach. Section 5 reports the results obtained in the case study regarding the reuse of waste materials coming from electrical cables. Finally, Section 6 discusses conclusions and future developments.

2. State of the art

Environmental sustainability has been a popular issue in the recent years. Industries have been directly involved in this topic and have been developing strategic plans to cope the issues of environmental protection and resource consumptions [10]. In addition, the waste management and the possibility to make economic profits from EoL industrial products are pushing industries to investigate new possible business models based on the paradigm of circular economy [11]. From the industrial perspective, a strategic approach to pursue the circular economy pattern is the creation of an industrial symbiosis model [12]. The meaning of industrial symbiosis is "to connect the businesses of different industries/productions in a virtuous circle where wastes and by-products of a company become resources for another" [13]. In some case, these models lead to the creation of eco-industrial parks in which the network is limited, in space, to a specific region/site [14].

The regulatory framework in the WEEE sector establishes the minimum requirements for the management of EoL products and encourages the development of industrial symbiosis mechanisms. For electronic appliances, the standard extends the product responsibility far from the product manufacturing [15]. Looking at the proper management of e-waste, the most widespread scenario is the material recycling. In spite of the recycling process allows recovering valuable materials, the current technologies are not efficient; they consume a high quantity of energy and release emissions to air and water [16]. The adoption of more sustainable and cooperative strategies (such as reuse and remanufacture) [17] is driven by policy and legislative requirements, which create a favorable environment for the development of industrial symbiosis models in the e-waste sector [18]. However, only few practical implementations can be found in the market. For instance, Ricoh's business model offers direct sales/service infrastructures where EoL products are collected for remanufacturing purposes [19]. Even if this is a virtuous system, it only involves a single manufacturer and cannot be considered as an example of symbiosis.

In literature, some models for the implementation of industrial symbiosis and the development of eco-industrial park can be found. Bovea et al. [20] proposes a methodology to estimate the potential reuse of small WEEE, with the final aim to create a protocol to identify the potentially reusable appliances. Jin et al. [21] defined a systematic EoL management approach to handle WEEE considering economic and environmental aspects. Additionally, several eco-industrial parks are proposed at regional levels in particular in the Asian countries [22][23][24][25].

Considering the proposed examples, a lack in the market and literature analysis is pointed out. In particular, the potentialities of the industrial symbiosis business model are known, but the way to create a network for this model is not yet developed. The objective of this study is to favor the development of industrial symbiosis models focused on the efficient management of e-waste products/components. The approach proposed is supported by the development of a digital web platform which is the means for the interaction among different stakeholders involved in the whole lifecycle of EEE (e.g. producers, maintainers, recyclers). The developed approach is a step beyond the current state of the art for electronic products/components and provides a tangible example for the implementation of the industrial symbiosis paradigm, providing positive results in both environmental and economic sides.

3. An approach to favor Industrial Symbiosis

In this section, the approach for the implementation of industrial symbiosis models in the field of EEE is proposed. Indeed, this sector leads to a relevant amount of components and precious materials which can be shared at the products EoL creating new business opportunities. The approach is composed by six steps (Fig. 1).

Fig. 1. Industrial Symbiosis approach

The first step of the approach consists in identifying internal scraps and wastes of companies operating in the EEE sector or other ones which have a specific intention to seize the opportunities coming from this sector (e.g. automotive, etc.). This preliminary analysis allows companies (both dismantling centers and producers) in the identification of the material flows and their origin.

The second step enables the characterization and the classification of the retrieved information within a web platform properly developed for this purpose. The features of this web platform are debated in the next section. Within the platform, it is possible: (i) to start the identification of consistent links for a partner searching, and (ii) to analyze partnership opportunities (respectively step 3 and 4 of the approach).

The identification of consistent links, defined as “the matching results (score) between two or more stakeholders using specific rules and algorithms”, is a prerequisite for the creation of potential partnership opportunities and thus of an industrial symbiosis model. The formalization of “consistent links” is based on different entities, such as market sector, keywords about materials input/output, geographical position and distances among companies, etc. (see section 4 for details).

Companies that show single or multiple matchings based on the proposed entities are candidate to be in touch and evaluate potential sharing of materials/components. Before creating the circular economy model, the analysis of the different partnership opportunities (step 4) with different stakeholders (if exists) is provided by the platform.

Successively, a cost-benefit analysis is performed to investigate different closed-loop scenarios. Among them, the platform highlights the ones with the most relevant benefits in terms of economical profits (step 5). In this way, the proposed model encourages not only new business partnership but it allows understanding the most profitable ones.

Lastly, after the business model validation, companies can decide to start the collaboration with other companies and thus to practically develop the proposed industrial symbiosis scenario (step 6).

4. The industrial symbiosis platform

As described in previous section, the proposed approach is based on a specific web platform that enables connections among industries/stakeholders. Stakeholders are companies that exploit the approach and web platform to establish an industrial symbiosis model. Company's information needs to be entered and stored in the web platform, afterwards, the outputs of a company A could become the inputs of a company B. The platform supports the creation of a network within the same market sector, even if possible collaborations among different markets are explored to identify all the most promising inter-relations.

The platform consists of two main modules: (i) the data entry module, and (ii) the assessment module. Data entry permits to fill the platform repositories in a structured way. The assessment module allows performing the cost benefit analyses for all the identified potential opportunities (economic profitability). Partners matching is also part of the assessment module. The identification of consistent links is based on the following entities (Fig. 2):

- Market sector. This is the most important entity of the platform. Each market sector is characterized within the platform with specific items. Currently, the platform is customized for EEE sector but it can be updated, including other sectors with the relative data.
- Keywords about materials input/output. This entity concerns the input/output materials treated by a company during the daily activities. It allows to track the materials coming from recycling processes and to find the right collocation.
- Keywords about components input/output. This entity concerns the components or by-products treated by a company during the daily activities. It allows tracking components and by-products which can be used in a remanufacturing scenario.
- Keywords about products input/output. This entity concerns the flows of products (usually EoL products) to implement all the necessary actions (cleaning operations, refurbishment, repair, part substitution, etc.) to create second-hand markets.
- Keywords about processes and equipment. This entity list all the manufacturing processes made available by a company with its internal assets.
- Geographical position. This entity refers to geographical localization of the company. It allows to understand which companies are located in the same geographical region for the promotion of industrial eco-parks.
- Distances among companies. This entity is linked with the geographical localization and it allows to calculate the cost of transportation if an industrial symbiosis model occurs.
- Research / Innovation. This entity characterizes the long-term vision and research plan of companies, in order to identify the most interesting links with other companies that have the same vision.

Each company will fill entities depending on its own needs and features. When a match of the entity records among two or more companies is highlighted, the platform proposes a potential symbiosis opportunity to the interested stakeholders.

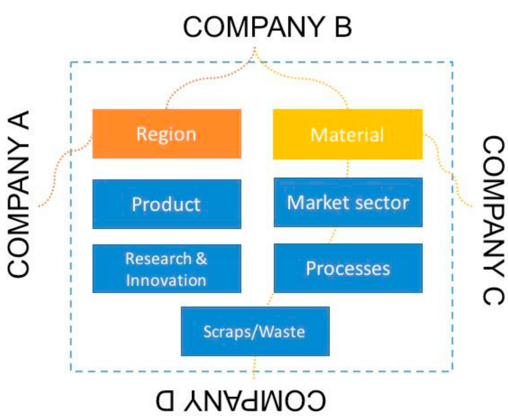

Fig. 2. Platform entities interaction flows

As discussed above, the approach and the proposed web platform have been developed within the specific case of EEE sector. Fig. 3 shows the data structure in the case of EEE, with a focus on the electrical cables/wiring. The items highlighted in the picture are the required data that are used by the platform to characterize the different entities for each company (components produced/treated, materials used/recycled, available equipment and technologies for materials/components processing). They have to be inserted by each company in the platform repositories during the first phases of the approach implementation (step 2), and are successively used by the platform algorithms and rules to identify the industrial symbiosis opportunities and finally assess benefits for each involved stakeholder.

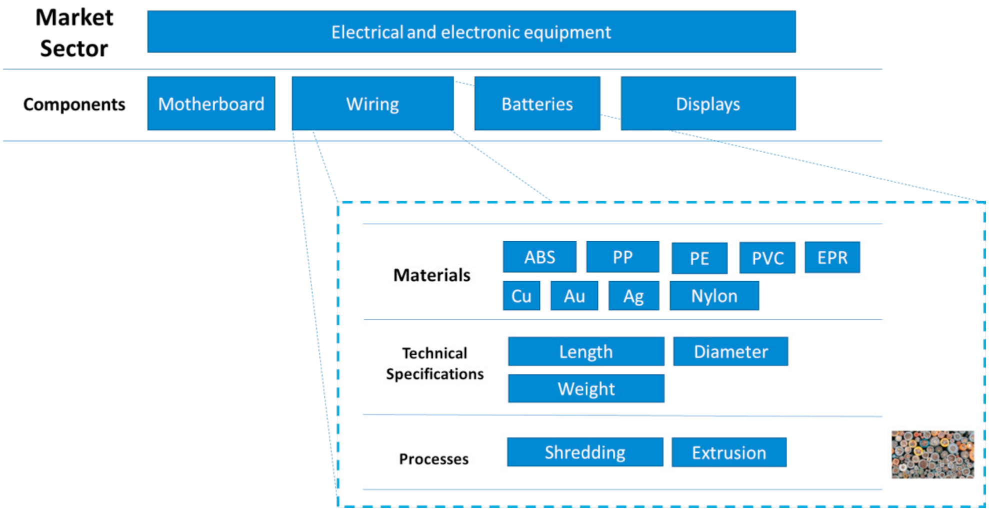

Fig. 3. Data structure for the EEE market

5. Case Study

Since the platform functionalities, interfaces and databases have not been yet fully developed, the case study presented in this section describes the "manual" experimentation of the proposed approach and platform in the WEEE Italian context.

As described in section 3, the first necessary steps concern the characterization of each involved company, in terms of localization, materials, scraps, processes, etc. More than 15 companies located in the Central Italy have been involved in this test. They belong to different product markets, among them: product dismantling, product remanufacturing, material recycling, material production, etc. In particular, the approach allowed identifying a potential relation between the following three companies described here below:

- Company A is a small enterprise located in the Marche Region, authorized as WEEE treatment center. It receives EoL household appliances in input, disassemble the product and separate the different materials (metals, plastics, etc.) through manual or semi-automatic processes. A relevant activity is related to treatment of electrical cables (both power and data cables) that are shredded through specific mills to separate copper from the plastic insulation. This latter is generally composed by mixed polymers, such as PVC, PE, rubbers, etc. At the end, the copper is sold to specialized recyclers, while the mixed plastics (containing a residual small percentage of impurities and copper) are commonly landfilled or incinerated and rarely exported.
- Company B is a material recycler located in the Marche Region. It receives in input industrial plastic and rubber scraps, which are used to produce plastic and rubber granulates or powders to be reused in second-life applications (filler for compounds or asphalts, insulation applications, etc.). They own specific equipment for the grinding and pulverization of all the most common plastic and rubber typologies.
- Company C is a compound producer located in the Marche Region. They mainly produce PP and PE based compounds to be used for the realization of extruded or molded products.

Different “consistent links” have been highlighted by using the approach to create industrial symbiosis scenarios:

- Both Company A and Company B belong to the WEEE market sector. While the first one realizes pre-treatments and disassembly of WEEE, the second one is specialized in material recycling.
- The three abovementioned companies are located in the same production district (Marche Region) at a distance of about 50 kilometers.
- The output materials (mixed plastic from electrical cable insulation) of Company A are very similar to the input materials (plastic and rubbers scraps) of Company B.
- Company B has the necessary equipment (pulverizers) to treat the scraps of Company A.
- Company C is currently using fillers (rubber and mineral powders) to realize its PP based compounds.

Based on the data provided by each company, the approach suggests the possibility to create an industrial symbiosis scenario between Company A and Company B. In addition, a correlation between Company B and Company C is highlighted. As a consequence, an indirect relation between Company A and Company C can be established. The following Fig. 4 illustrates the new industrial symbiosis scenario, involving the three companies, in comparison with the baseline scenario, in which Company A does not collaborate with the other partners belonging to the same production district.

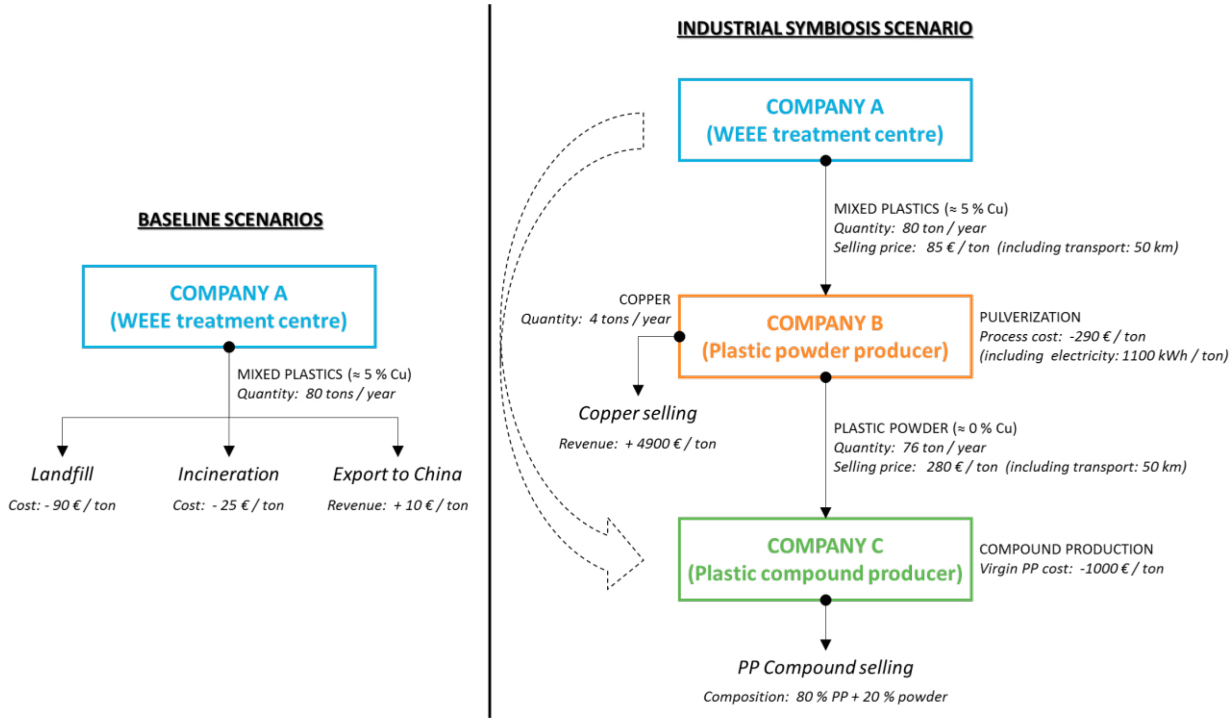

Fig. 4. Baseline vs Industrial symbiosis scenarios.

Fig. 4 also reports flows of materials between the different involved companies, together with the relative quantities and costs/revenues. Economic assessments have been realized to understand the feasibility and convenience of the identified industrial symbiosis scenario for each involved partner. In addition, by considering material savings and reuse, transport and energy consumptions, environmental assessments have been carried out by using the Life Cycle Assessment (LCA) methodology [26]. LCA allows to quantify the environmental impacts/benefits in terms of Global Warming Potential indicator that is largely used and simple to understand also for non-experts. Results of the assessments relative to one year of operations are reported in the following Table 1, where economic costs are reported with negative values, economic revenues with positive values, environmental impacts with positive values, and environmental benefits with negative values (according to the LCA standard).

Table 1. Economic and environmental balance of both the baseline and industrial symbiosis scenarios.

Baseline scenario			
Output Material	MIXED PLASTIC: 80 tons / year	-	-
Costs	Landfill: - 7200 € / year Incineration: - 2000 € / year	-	-
Revenues	Export: + 800 € / year	-	-
Industrial symbiosis scenario			
Output Material	MIXED PLASTIC: 80 tons / year	PLASTIC POWDER: 76 tons /year	PP COMPOUND
Costs	-	Mixed plastic: - 6800 € / year Process cost: - 23200 € / year	Plastic powder: - 280 € / ton Virgin PP: - 1000 € / ton
Revenues	Mixed plastic: + 6800 € / year	Copper selling: + 19600 € / year Plastic powder: + 21280 € / year	PP compound (20% powder): + 144 € / ton
Balances (Industrial symbiosis vs Baseline)			
Economic balance	+ 14000 € / year + 8880 € / year + 6000 € /year	+ 10880 € / year	+ 144 € / ton compound sold
Environmental balance	- 7656 kgCO2eq. / year - 39400 kgCO2eq. / year - 13048 kgCO2eq. / year	+ 33268 kgCO2eq. / year	- 2090 kgCO2eq. / ton PP avoided
	Company A	**Company B**	**Company C**

Results reported in Table 1 highlights that the industrial symbiosis potentially represents a win-win scenario for all the three involved companies. Company A can realize consistent revenues (sum of avoided costs and revenues) by selling its mixed plastic scraps to Company B. This latter is able to treat the mixed plastic material with its equipment, in order to produce powder and thus to add a new product in its portfolio. In addition, the pulverization allows Company B recovering the residual copper (about 5%) contained in the mixed plastic purchased from Company A. The economic assessment highlights that the revenues from copper selling almost cover the additional process costs. Company C can use the powder, supplied by Company B, as filler for its PP compounds, by preserving the material performances and with a relevant economic saving for each ton of compound produced.

Concerning the environmental assessment, results are quite different since the industrial symbiosis scenario does not always lead to a global reduction of impacts. Company A and Company C can decrease their respective environmental loads, while Company B certainly increases its impacts. This is mainly due to the high quantity of electricity consumed by Company B in the pulverization process of the mixed plastic purchased from Company A.

6. Conclusions and future work

This paper presents an approach and a web platform to favor the implementation of industrial symbiosis scenarios between companies operating in the same or different market sectors. The study is focused on the WEEE sector, which currently represents an important criticality for the modern society due to the low recycling rates. Through the mapping of company characteristics (called "entities"), the proposed approach and platform are able to identify possible opportunities of collaboration between stakeholders, and thus to favor the sharing of EoL materials/components. The idea beyond is to link the demand of virgin materials with the offering of EoL products in order to maximize the material recovery rates, while minimizing the loss of value.

The case study focused on the reuse of waste materials coming from the treatment of electric cables, demonstrates the usefulness of the approach in supporting companies of the same geographical region to identify opportunities for future collaborations. Relevant economic savings and enlargement of the product portfolio have been demonstrated for all the involved enterprises.

Future work will be focused on the implementation of the EoL platform, with the development of all the modules, databases and interfaces, to deeply evaluate the platform in more complete case studies. Moreover, additional efforts are needed to develop more robust algorithms and rules for the identification of a larger set of potential industrial symbiosis opportunities.

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