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Sustainable networks for WEEE treatment: a case study

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Abstract

The paradigm of sustainable manufacturing equally implies the implementation of new technologies and their proper use within supply networks along product life cycle. In particular, this paper analyses the case of WEEE which requires the configuration of dedicated de/re-production networks to change the state-of-the-art processes thanks to the introduction of new production systems to improve capability of a region to treat this particular kind of waste. A modular approach is here proposed to evaluate the impact of each EOL process creating what-if scenarios for the network configuration. Using discrete-event simulation it was evaluated how the implementation of innovative de/re-manufacturing centers to re-work WEEE components (i.e. Printed Circuit Boards-PCBs) can change the sustainability of a certain geographical area taking into consideration the management of flows from pre-treatment centers to the new plants.

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Keywords: Supply chain configuration, Modular LCA, Green Supply chains;

1. Introduction

The consumption of electrical and electronic goods is increasing worldwide as is the speed at which they are disposed. Technological and functional improvements continuously lead to mounting replacement rates of this kind of appliances resulting in a growing volumes of End-of-Life (EOL) products which need to be properly treated. Due to the negative environmental impact and the valuable material content, legislation imposing recovery have been approved by many different countries in the Western World as well in the emerging economies.

This contribution addresses the problem of assigning the WEEE (Waste Electrical and Electronic Equipment) stored at pre-treatment centers to new plants for de-manufacturing as a step to improve the WEEE recovery process. The work is based on changing the existing WEEE network thanks to new technologies for WEEE processing influencing network configuration, transportation management and WEEE treatment process. The purpose of the study is to focus in particular on the treatment of one specific component of the WEEE which is the Printed-Circuit Board (PCB) as one of the most valuable component and provides a model to evaluate possible allocation configurations of new plants for PCB treatment.

The design of the new re/de-manufacturing (RDM) network starts from the assumption that a new generation of automated re/de-manufacturing plant can be established using advanced technologies for managing EOL components. In particular the following RDM phases are automated in a pilot plant established in CNR for PCBs treatment: disassembling by means of advanced robots, check and recovery of PCB components, shredding and dismissal for material recycling. The existing pilot plant is used as a reference for the definition of the parameters and the variables to be used in the present model. The aim of this work is to design the network based on facility location models providing a method to rank alternatives for RDM plant installations. The method is based on multi-criteria analysis to select location for disposal sites of municipal waste. The decision on the network configuration is based on the analysis of the processes that can be done with the new plant and the definition of important indicators (cost, time, production mix, etc.) which are necessary to give a dimension to the plants within the network. Different kind of WEEE is also considered and different type of plants are assumed to evaluate which is the best dimension of the plant

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according to the type of WEEE to be treated. The environmental impact of establishing this network is evaluated.

2. State of the art

2.1. Environmental sustainability of WEEE collection and treatment

According to literature review the proper eco-efficient management of the reverse chain in the WEEE sector represent a relevant driver in the sustainability of remanufacturing chains [1, 2]. Waste reduction and consumption savings are common registered effects [3-7] while the quantification of the network environmental implications is still a subject of debate [2, 8]. The eco-efficient management of networks is driven by a high number of operative variables ranging from the electronic item design, used technology, the product turnover and producer policy up to legal framework, general economic trends and raw material demand [7, 8] .

These works proposed a differentiated set of methodologies in order to manage such different operative variables to optimize the final environmental impact. Analysis framework included differentiated conceptual and descriptive types of modelling, linear and mixed integer programming, nonlinear programming methods, convex and concave programming, dynamic programming, queuing models, Markov decision process, graph theory, game theory, fuzzy logic, simulation modelling, multi-criteria decision making (MCDM) approaches and other approaches.

Environmental indexes are frequently integrated with other economic and social drivers within complex operative models. The environmental characterization approach is frequently not quantitative or it is aggregated in multi-objective indexes making scientific results hardly reusable. Another issue emerging as important is the analysis on data uncertainties and assumptions [1] which can seriously influence outcomes from application cases.

A limited focus seems also devoted to the impact of technological improvement. Few studies assess how a set of technologies can affect the recycling policy and which is the more effective operative tuning for the proper technology implementation [1].

Different work are focused on design criteria for the recovery network structure in terms of better location and transport set-up within a local districts are based for example on multi-objective economic optimization [9], ranking criteria [10], fuzzy logic [11], mixed integer linear program [12].

As far as environmental impact characterization, different works quantify the sustainability of recovery network within local districts by the use of environmental indicators. Criteria to address the environmental implication regards aggregated eco-indicators [13, 14], risk analysis [15], global warming potential [8, 14]. Few studies seem to have extensively characterized multiple impact categories [11, 16].

Another difference in environmental characterization of recovery network concerns the life-cycle perspective. Some authors extensively analyse the whole chain in a close loop perspective [8, 14] while other works examined partial optimization of the recovery chain [17, 12, 16] eventually including the secondary market. From one hand a partial chain analysis offer a limited view on product life-cycle while the higher complexity in the complete network design could not be properly supported by affordable life cycle data inventory to validate results.

2.2. Network configuration for WEEE management

There are already some works in literature on the logistics of the WEEE management. In Savaskan et al. [18] it is evaluated which is the best agent to collect WEEE considering three product take-back channel structures. Considering factors like retail price of the products, collection effort level, and total channel profits, the model defines that the best agent is retailer and shows that the coordinated system has the best performance for all parties, as the market demand and collection efforts are the highest, and the manufacturer and retailer pareto-optimize their profits in the coordinated system.

A methodology aiming towards optimal location of Units of Treatment and Recycling (UTR) taking into consideration economical together with social criteria is developed in Achillas et al. [19] where many different criteria are considered like local population, distance from existing UTR, land value, unemployed population, financial status of local population etc. With the development of additional UTR and their introduction in the WEEE reverse logistics scheme, transportation costs are expected to be significantly reduced.

In Queiriga et al. [10] a method for ranking of Spanish municipalities according to their appropriateness for the installation of these plants. Several criteria are considered like land costs, personnel costs, energy prices, facility access, etc. It results that large cities have advantages, e.g., with regard to agglomeration effects or number of inhabitants. Nevertheless, considering other criteria such as costs or availability of labour, other cities can also be suitable locations for recycling plants. In fact the results show that the large cities are not first in the ranking.

Kim et al. [20] discusses the remanufacturing process of reusable parts in reverse logistics, where the manufacturer has two alternatives for supplying parts: either ordering the required parts to external suppliers or overhauling returned products and bringing them back to ‘as new’ conditions. Criteria considered are: the number of collected products from customers, quantity of parts required by manufacturing plants, number of parts for assembling each product, products to go to the subcontractor for remanufacturing outsourcing, etc. A general framework for remanufacturing environment is proposed to determine the quantity of products/parts processed in the remanufacturing facilities/subcontractors and the amount of parts purchased from the external suppliers while maximizing the total remanufacturing cost saving. Some discusses about the pollution caused by different types of WEEE using 4 impact categories to find the most pollutant type of WEEE and compares the result with the pollution caused by fossil fuels used for the transportation of WEEE in a network[15].

Some of the parameters identified in these studies have been used also in our model and are the basis for the evaluation and comparison of different network scenarios.

3. The proposed model

The objective of the overall model is to compare the implementation of RDM plants for EOL PCBs processing within a territorial cluster. Through the creation of different scenarios where plant capacity, transportation type and rate of defectiveness of the PCBs can change from one scenario to another, the model helps to evaluate how these changes influence the environmental impact, the processing and transportation costs. The system boundaries for the environmental evaluation include inventory emissions and consumptions of the treatment centres (TC), transport systems and RDM plants up to recycling facilities processing.

3.1. The assumptions for the network configuration of RDM plants

While traditional production centres analyse demand, market and potential profits, promote products and establish plants near potential clients, WEEE treatment has different priorities and depends strongly on the quantity of returned EOL products and have a very limited influence on material input which is linked to waste production. To reduce costs of transportation, proximity and access to inhabited areas with large quantities of WEEE should be taken into account. Moreover while manufacturers order inputs from suppliers in the amount and for the time that they need it, recycling plants undergo procurement difficulties due to large fluctuations in quantity, state, and range of returned products. Therefore, these plants need to be very flexible with limited capacity to control the inflow. While manufacturers can affect the design, provision, performance and size of products, recycling plants have no influence on the characteristics of returned products, e.g., on the recyclability or content of harmful substances [10] and consequentially on the type of process to activate.

Regarding these special characteristics of RDM companies, the number and the infrastructure of WEEE collection points in the territory plays an important role on the input side for the establishment of these plants. Outputs of a recycling plant are materials that are strictly correlated to the status of the input (fully working, reusable PCB, reusable components, recyclable PCB) and for this work it is assumed that there are three main categories of output: metals, plastic and remanufactured PCBs.

In the model described in this paper, the state of the PCB is verified at the entrance of the plant since the flow from TCs to the plant is composed of mixed PCBs. Each type of state generates a different flow and a different processing time within the plant. The three outputs go to three different sinks located in the Region.

Different level of defectiveness is assumed for each batch of PCBs arriving at RDM plants. Discriminant PCB states in plant consumptions and emission attribution are the following:

a) Fully working when the PCB does not register any loss in functionality. For these PCBs there will be only diagnostic and transport operations in the plant.

b) Reusable PCB when a limited number of PCB components does not work. In this case it is possible to recover PCBs through operations like diagnostic operations, remanufacturing and component substitution.

c) Reusable components when a relevant number of components do not work but a limited number of components can be disassembled and reused in other PCBs. In this case, after the functionality diagnosis, the PCB is sent to disassembly phase where working component are disassembled. The remaining part of the PCB is sent to shredding.

d) Recyclable PCB when the PCB is not remanufactured and it is directly sent to the recycling cell (diagnostic, internal transport and recycling operations are allocated to such PCB feature). According to such defectiveness level, the sequence for the plant operations can change as well as consumption and emissions for a specific de-manufacturing centre. Similarly output quantity and delivery to recycling centres are modified according to the processed outputs.

3.2. The features of the network configuration model

The examined scenarios for the network configurations concern with parameters like number of plants, type of products, type of transportation, level of defectiveness of the PCBs, inventory level etc. As a preliminary approach, the treatment centers belonging to the same city have been clustered according to a proximity criteria and the location of each plant has been based on centre of gravity approach in order to minimize the total transportation cost from the treatment centres to related RDM plant. Truck type can vary for size class categories and for each of them an average load factor correspond respectively to 1 ton, 3,2 tons and 5,8 tons loads. The truck type influences number of travels as well as the kind of routes. The specific environmental profile for each truck type has been separately assessed according to LCA rules. The truck type is identified in order to concurrently optimize truck utilization and number of trucks. Nevertheless, reduction of travels implies increase in buffer dimension at the entrance of the plant with a trade-off between the two dimensions. In addition, the model is inferred on the basis of the following assumptions:

- Processed-PCB features. The plant is set up to process PCBs with different features (different for dimension, number of components, commercial value, material composition etc.).
- Upstream network configuration. The treatment centres (TCs) are the source points in compliance with WEEE treatment centres displacement within the considered region.
- Downstream network configuration. The network endpoint are 3 warehouses for 3 different kind of output: mixed plastic material reprocessing, mixed metal flow and reprocessing and repaired PCB.
- Plant configuration. Different number of plants are assumed while processing capacity and plant utilization are the result of the discrete event simulation. Consumption of energy and other resources as well as emission on air, water and earth are assessed taking as unit measure the consumption and emission profile of the prototypal plant. Plant capacity has been set up in order to cover the amount WEEE stock in each treatment centres. Waste production, waste disposal and maintenance operations have been assessed for each tons of PCB processed by the plant.

- Transport configuration. When a threshold quantity is ready at treatment centre, an empty truck transports such quantity to the closest plant. When the truck arrives at the plant, it delivers the PCBs and it verifies if output (metal, plastic, etc.) is ready in the plant; in this case the processed waste is delivered to the related sink.

In order to calculate the time interval for TCs to prepare a certain amount of PCBs, the historical data for each treatment centre is used. Normal distribution is used by taking into account that the input to the plant does not have a uniform distribution along the year but can change on a daily basis according to the historical flow. The main goal of the model is to compare different network configuration based on important criteria calculated for each scenario. For each RDM plant and its treatment centres, the reduction of transportation costs along with the optimum plants capacity are considered as well as the buffer dimension and the environmental impact. Experiments are designed to find the optimum number of trucks (based on the analysis of truck utilization) and the maximization in the use of plant capacity.

3.3. *The environmental impact evaluation*

The model is based on the integration of the results of the modular LCA in the simulation routines in order to characterize the network environmental impact according to different scenarios and with different performance indicators. The current model does not consider impacts due to material recycling as well as to the reuse of PCB and secondary materials. Environmental impact is characterized through a set of impact categories which are compliant to the Environmental Product Declaration (EPD) system.

Modular LCA has been introduced by Rebitzer [21] to foster the application of LCA in an industry context. Independent information modules are assigned to a specific set of operations and configurations. A first generalization has been explored for manufacturing lines by Brondi et al. [22] and then applied to the supply chain context [23]. In this work a specific environmental profile has been assigned to each elements of the network configuration (transportation system, input and output materials, type of materials, overall plant, etc.). While the operations evaluation is based on results of the simulation, the unitary impacts are assessed through gate-to-gate LCA values in compliance with experimental evidences.

A further step is based on the location of the facilities in the territory taking into consideration the existing treatment centres. Inventory flows for plant consumption and emissions changes with the item type (the PCB features) while transport routes change with plant location in a geographic context. The environmental modelling has been assessed for network types with different plants within the examined geographic area. In this case the number of network nodes coincides with the number of plants in the network. Such gate-to-gate network environmental profile can be assessed according the following equation:

$$\boldsymbol{N}_{b,M,P} = \left(\sum_{l=1}^{L} \boldsymbol{u_l} \cdot \left(\sum_{i=1}^{I} m_i^l(p) \cdot d_i^l(p)\right)\right)_{Transport} + \left(\sum_{p=1}^{P}\sum_{j=1}^{J} \boldsymbol{v_{p,j}} \cdot (b_j \cdot m_p)\right)_{Processing} \quad (1)$$

Variable	*Explanation*
N	Network Environmental Profile (NEP): vectoral array of data representing Environmental Impact at time *t* with *p* plants.
B	Batch type produced with *p* plants.
u	Vectoral array of environmental impact for a specific transport type *l*. The vector is assessed for 1 ton*km and for a set of predetermined impact categories.
v	Vectoral array of the environmental impact for a specific plant type *p* to process item *j*.
M	Total quantity of transported item within the network
b	Average percentage of family item type j within the transported item
L	Total number of transport types
l	Transport type for which the unitary profile is modelled.
P	Total number of plants in the network
p	plant *p* within the network.
I	Total number of arcs within the network
i	Arc *i* between two points.
m	Mass of transported items by a truck type *l* to an element.
d	Overall covered distance by a truck type *l* for transporting an item .
J	Total number of workable items within the plant for a certain item family
j	*j* type of items (e.g. fully working, not working, recovery)

Environmental burden of the RDM network is examined according to the two decisional drivers:

- the logistics depending on the load sizing as well as the network capillarity (n. of plants) and the transport type.
- the environmental contribution due to item processing depends on internal technologies for each object as well as from the item type.

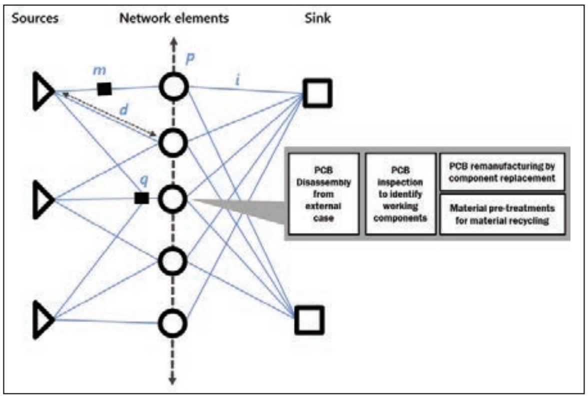

Figure 1. Network allocation problem

The vectoral arrays in this equation have been evaluated through the use of the independent modular LCA and have been used in the simulation together with the distances and processed quantities to assess the overall performance.

4. Results

The geographical area under consideration (i.e. Lombardy Region) is characterized by more than 800 collection centers and 21 treatment centres where WEEE are separated in components like plastic, metal, glass, PCBs. The flow of PCBs of the Region is roughly estimated to be 2.000 ton with different concentration of WEEE collection in the different cities.

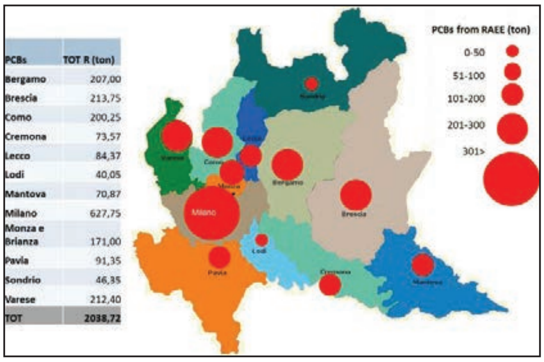

Figure 2. Map of the PCBs flows in the Region

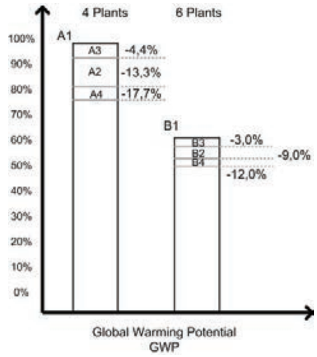

Figure 3. GWP allocation among different scenarios

The amount of PCBs collected in the cities is very different from each other and is strictly correlated to the concentration of people living in each city. The new RDM plants can receive the PCBs from the treatment centres assigned to it.

In the table 1, a preliminary list of scenarios is presented. Each scenario is characterized by a certain number of RDM plants and different defectiveness share of PCBs for each batch. As mentioned above, the PCB defectiveness requires different kind of steps along the RDM process which means different processing time, production costs, etc.

Table 1. Definition of the scenarios

Sc.	N° plants	PCB status*	Working PCB	Reusable PCB	Reusable components	Recyclable PCB
A1	4	1-LD, HR	30%	40%	10%	20%
A2	4	2-LD, LR	45%	10%	25%	20%
A3	4	3-HD, HR	5%	35%	10%	50%
A4	4	4-HD, LR	10%	10%	20%	60%
B1	6	1-LD, HR	30%	40%	10%	20%
B2	6	2-LD, LR	45%	10%	25%	20%
B3	6	3-HD, HR	5%	35%	10%	50%
B4	6	4-HD. LR	10%	10%	20%	60%

*L=Low, H=High, D= defectiveness, R= Reparability

The comparison among scenarios is based on performance indicators derived from previous literature studies. These indicators are influenced both by the level of defectiveness of the input PCBs as well as by the number of plants and the transportation mean considered.

Environmental impact evaluation is calculated applying the modular LCA mentioned above to consider the impact of transport, production, inventory and it is based on the following criteria: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Depletion Potential (ODP) and Photochemical Ozone creation potential (POCP). Analysing the results of the scenarios, in general terms, the environmental impact caused by transport accounts for a limited quantity for all the examined impact categories (0,8% to 21,8%). The only exception is the transport weight for the Ozone Depletion Potential for which transport can accounts up to the 95,1% of the total CFC_{11} equivalents produced by the network.

The figure 4 shows the variation of impact for the considered scenarios only for the GWP indicator. The results of the analysis for the other impact categories (AP, EP, POCP) shows a percentage impact partition similar to this. Such similar partition seems to result from the high relevance of energy consumptions compared to other consumption or emissions (e.g. transports, solid waste etc.) for all the examined categories. In particular, the item defectiveness variance affects only energy consumption in a limited way. Only the ODP indicator shows a reversal of such partition: the four-plants scenarios provide lower quantities of CFC_{11} equivalents compared to the six plants scenarios. This effect comes out from the RDM process in the ODP category.

In the table 2 the most important indicators resulting from the simulation of the scenarios are reported. The scenario A1 is taken as a reference and all the other scenarios are evaluated as differential compared to it.

Table 2. Results of the preliminary simulation

			Performance indicators			
Sc.	N° plants	PCB status*	Processing costs	Travel costs	Buffering costs	GWP
A1	4	1-LD, HR	0%	0%	0%	0%
A2	4	2-LD, LR	-4%	5%	-6%	-4%
A3	4	3-HD, HR	12%	-7%	10%	-13%
A4	4	4-HD, LR	5%	-4%	11%	-17%
B1	6	1-LD, HR	10%	-33%	26%	-32%
B2	6	2-LD, LR	15%	4%	-6%	-41%
B3	6	3-HD, HR	-8%	5%	12%	-35%
B4	6	4-HD. LR	7%	6%	15%	-44%

The four performance indicators here selected are influenced both by the number of RDM plants and by the status of the PCBs. The choice of one network scenario is based on the priorities given by the decision maker on the considered indicators as well as on the level of defectiveness of the entering PCBs.

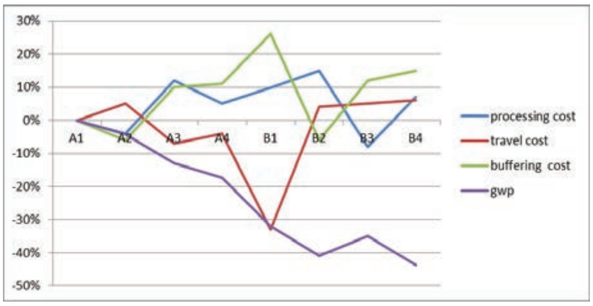

Figure 4. The trend of the performance indicators

5. Conclusions

A methodology has been set-up to combine discrete event simulation with modular LCA and was tested to evaluate the problem of network allocation for the implementation of a prototypal RDM network for PCB recovery. Simulation results allowed to compare eco-efficient configuration for different plant size and transport types to meet a given demand which is highly variable along the considered time horizon. The trade-off between different performance indicators requires the decision maker to define priorities among them in order to choose the best solution. Future developments include the analysis of other scenarios and the implementation of other performance indicators for a comparison based on a larger amount of criteria.

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