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Prerequisites for a high-level framework to design sustainable plants in the e-waste supply chain

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Abstract

Currently few attempts to properly structure knowledge that specifically supports a fully sustainable e-waste treatment system design have been proposed in literature. As a result, this paper sets up the prerequisites for a high-level framework to design sustainable plants in the supply chain of e-waste. The framework addresses production and environmental engineers mainly. The methodology grows out of literature studies, research project's outcomes and interviews with a group of sector experts. Stemming from this, a list of prerequisites was presented for the case study of an automated plant for e-waste sorting in order to design it while considering the triple-bottom-line of sustainability.

Keywords: e-waste; WEEE; sustainability; industrial system design; Key Performance Indicators; automation; sorting.

1. Introduction

The global weight of electronic waste (e-waste) is expected to reach 65.4 million tonnes in 2017, according to the forecasts drawn by the Solving the E-Waste Problem (StEP) Initiative [1]. This challenges the industrial design of plants supposed to take care of such volumes. This paper supports production engineers, environmental engineers and operations managers by addressing the development of a framework for sustainable plant design within the e-waste supply chain.

Waste Electrical and Electronic Equipment (WEEE) incorporates valuable materials (e.g., non-ferrous metals such as copper, iron, steel; precious metals like gold, silver, platinum), rare earth metals, but also hazardous substances (e.g., included in lead-containing glass, flame retardants) [2, 3]. Therefore, a proper treatment of WEEE prevents the release of substances hazardous to the human health and the environment, and enables cost savings by recovering valuable materials. As a result, aiming to meet the Triple-Bottom Line (TBL) goals of sustainability [4] may enable companies in the e-waste recycling to successfully compete in this market.

From an industrial design perspective, this means that all the facilities operating within the electronic End-of-Life (EoL) stages, ranging from collection centers to recycling facilities and disposal sites, should aim to become economically, environmentally and socially sustainable at the same time.

Embodying sustainability within plant design and impact assessment methodologies is a way to facilitate the fulfillment of such goals. Automation, when well-aligned to the manufacturing strategies, can also play a meaningful role in this sense. In fact, making identification and sorting of e-waste fully efficient and sustainable through automation is the main purpose of the WEEE ID project [5]. As a result, this work addresses the design of systems conceived to be automated.

Henceforward, the authors will refer to the electronics' EoL supply chain as "WEEE supply chain", whose actors and activities are depicted by [6]. Moreover, WEEE and e-waste are meant as equivalent concepts.

1.1. Background

Within the manufacturing field, extensive studies have been made on how to couple sustainability with production

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systems' planning and operations management [7, 8, 9]. Furthermore, [10, 11] addressed the design and management of a specific process within the WEEE supply chain (disassembly and recycling above all) with respect to efficiency and profitability objectives, whereas [12, 13] assessed the environmental impact from the local e-waste treatment. In addition to this, Wang et. al [14] reported how the good amount of research works they reviewed did make valuable contributions to the study of the technological details of treatment processes for a certain product, or to the value of the impacts from informal recycling activities. On the other hand they often do not target treatment solutions aiming to balance environmental, economic and social performances.

Notwithstanding, it can be said that studies that scope the WEEE supply chain, like [15, 16], rather than a single process or facility, are moving towards a more inclusive perspective by attempting to include TBL sustainability performances partially or fully. The conclusion from the performed literature review is that electronics' EoL has been studied in a manner that does not match plant design with the whole TBL of sustainability. Hence, developing a framework to design sustainable plants operating in the WEEE supply chain can capitally cover the just-presented research vacuum.

Nevertheless, such an aim causes extensive investigations into the different processes carried out by the e-waste facilities, for instance through the fulfillment of a reasonable number of case studies along the supply chain. Thus, the authors are tackling this goal gradually, by firstly looking for a framework which targets facilities in the WEEE supply chain from a high-level perspective. The framework will be fine-tuned later thanks to more case studies along with the application of modeling and simulation tools. This research sets the stage to achieve such a goal.

1.2. Goal, scope and structure of the paper

This paper proposes the prerequisites to drive a fully sustainable design of plants within WEEE supply chains.

The paper will present how the prerequisites are framed and how they have been developed within a case study.

Within this work, a prerequisite means the specification of a strategic or operational decision, activity, piece of information, factor, or even research method pertaining plant design and operations management usable to design a fully sustainable plant for e-waste treatment. The boundaries and the applicability of this research target all the facilities performing within the WEEE supply chain. Finally, with regard to the paper's outline, Section 2 presents the research methodology adopted in the study, Section 3 illustrates the theoretical form of the design prerequisites, Section 4 shows how the theoretical prerequisites were applied to the case study, and Section 5 provides the conclusion and future developments of this work.

2. Research methodology

To deliver the results of this research the authors adopted a qualitative research approach [17] which triangulates the building blocks depicted in Fig. 1. It pictures a matrix whose axes are the type of data (primary and secondary) and the field (manufacturing and e-waste).

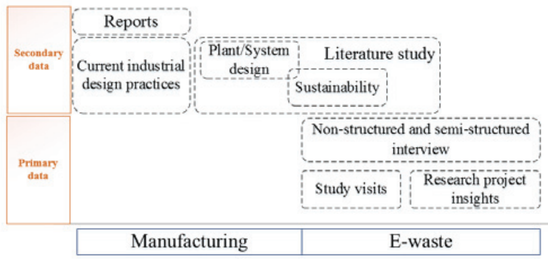

Fig. 1. Research methodology adopted in the study

Fig.1 shows that the knowledge about manufacturing systems' design established over the latest decades was combined with studies on sustainability's TBL in industrial systems, as WEEE facilities need to further embed it within design practices. With regard to the secondary data, a part of them consists in the conclusions from the literature review in Section 1, whereas the remaining part contributes to build the theoretical outcome of the study, thus it will be referenced in Section 3. Plant design for sustainability within the WEEE-supply chain context may demand a direct investigation in order to tackle the research gap argued in Section 1. To this end, the authors performed a collection of primary data and the development of a case study. In particular, semi-structured and non-structured interviews were carried out with three experts in e-waste management. To wisely use the inputs from the WEEE ID project, an automated plant for the identification and sorting of e-waste was selected as case study. The purpose of the interviews was to collect data about e-waste management's current state, validate the methodology to develop the prerequisites for the case study and validate the findings. Two study visits to Renova's Tagene recycling facility (Gothenburg, Sweden) and to El-Kretsen sorting facility (Arboga, Sweden) made economic, environmental and social issues about e-waste recycling bring out and supported the development of the prerequisites within the case study.

3. Theoretical prerequisites

Table 1 (next page) depicts the theoretical outcome of this work. It consists in prerequisites to lead a sustainable design of plants within the e-waste supply chain. The first column presents the theoretical prerequisites, engendered by the fields of industrial engineering, ICT, operations management and sustainable development. The second column presents the domain that defines the nature of the prerequisites, which sometimes was drilled down into the TBL of sustainability or equipped by bibliographical references.

Table 1: Theoretical prerequisites to design sustainable plants in WEEE supply chains and related bibliographical sources.

Theoretical Prerequisite	Domain and bibliographical sources
Setting goals with respect to TBL Sustainability	● Economic sustainability goals ● Environmental sustainability goals ● Social sustainability goals
Setting goals to comply the regulations	● Goals to comply the WEEE Directive [18] ● Goals to comply the RoHS Directive [19]
Identifying the stakeholders	● Company's management and engineers ● Actors of the electronics' supply chain [see 6, 14] ● Government and policy-makers [20]
Setting relevant Key Performance Indicators (KPIs) to be monitored and assessed	● Economic KPIs ● Operations management KPIs ● Environmental KPIs ● Social KPIs
Assessing the Information and Communication Technology (ICT) infrastructure	●Control systems, Computer-Integrated Manufacturing [21] Human-Centered Manufacturing (HCM) [22] ● PLM data, technologies and tools; Knowledge engineering systems [23]
Assessing physical equipment and layout configuration	● Equipment, physical components, workforce needed and their layout
Using research methods and research tools for plant design	● Discrete Event Simulation, Agent-Based Simulation, System Dynamics [24, 25] ● Digitalization, 3D laser scanning [26]

As the application of the theoretical prerequisites addresses a specific process within the WEEE supply chain (e.g., disassembly, recycling), the domain of each prerequisite includes bibliographical references only if they are not bounded to any particular stage of the EoL (as the case of sector regulations or ICT systems). As a result, TBL-Sustainability goals and KPIs do not reference any studies, since they are strictly dependent from the role played by the specific company within the e-waste supply chain.

Finally, it is worth to mention that the general prerequisites might support the design of not only automated systems but also manual systems, by supposing the use of non-automated or non-ICT-based equipment (see Table 1's sixth and seventh line). Despite of this, this paper did not explore this possibility and kept its focus on automatized systems.

4. Implementation of the prerequisites

Section 4 presents the results of this research as the application of the theoretical prerequisites to a case study. The case study is represented by the concept that the WEEE ID project wants to develop, that is a sustainable, automated plant for identification and sorting of e-waste. It is meant to be located in Sweden, according to the geographical boundaries in which the study and the WEEE ID project have been performed. These results stem from the implementation of the theory developed in Section 3 combined with the hints collected over the project's proceedings, the interviews and the study visits.

This section includes also an excerpt of the current status of e-waste sorting, whose investigation was necessary to understand how design can meet the needs of this process with respect to the TBL of sustainability. Hence, the case study focuses on a pre-processing stage of the WEEE supply chain, which precedes the disassembly processes. The effectiveness of pre-processing deeply affects the recovery of a specific substance over the entire WEEE supply chain, as it determines which fractions of WEEE are driven forward the different end-processing streams. As a result, if any specific substance ends up into the "wrong" output stream it is likely that this substance will be lost in the final recovery step (see [2]). Moreover, sorting is accountable for carefully separating acid-resistant-bearing items from non-hazardous WEEE items, as in case of error the formers would contaminate downstream recycling processes that are not supposed to deal with acid-resistant substances.

Today e-waste sorting activities are performed mostly by humans, as up to now they are the most flexible and self-learning resource available. These manual activities currently not supported by automation and ICT not only deny a socially sustainable work for operators (as they are exposed to toxics from electronics' segregation), but also do not allow to store workers' knowledge and WEEE items' data into a structured data management system which companies in WEEE supply chains would benefit from. Therefore, introducing the use of an intelligent sorting equipment, as the WEEE ID project aims, reduces the exposition of operators to acid-resistant substances and enables to meet the increasing WEEE collection rates established by regulations, thanks to an increased process efficiency. Ultimately, automation combined with human manufacturing interfaces (HMI) and product lifecycle management (PLM) technologies enables process and product statistics collection and a wise use of product data within a decision support tool for intra-company and inter-company decisions. The background just presented gives the key to understand the results of this study, depicted in Table 2 (next page). Table 2 reproduces Table 1's structure: the second column contains each prerequisite being developed, whereas the third column recounts complementary details of it from primary data collection.

Table 2: Prerequisites and support knowledge to design a sustainable, automated plant for e-waste sorting.

Theoretical Prerequisite	Prerequisite's definition for the case study of automated e-waste sorting	Complementary knowledge from primary data collection
Setting design goals with respect to Sustainability	***Economic sustainability goals*** ● Setting the return on investment or the payback time of the investment ● Improve the financial yield of sorting/recycling efficiency	To assess such goals: comparing design alternatives with respect to both short-term and long-term economic indicators, and with respect to both economy objectives and environmental impact simultaneously
	Environmental sustainability goals ●Separating each item containing acid-resistant material from those that do not contain acid-resistant material (reducing as best as possible sorting errors) ● Containing the environmental impact from plant's running (e.g. electricity consumption)	To assess such goals: evaluating the environmental pay-off of building and using the automated equipment compared to the manual, as-is sorting system
	Social sustainability goals ● Protecting operators from contamination from acid-resistant materials ● Retaining and motivating the operators; improving work satisfaction through ICT and data-driven operations	●As operators handle waste, they need to be carefully protected from dirt and toxics. Hence, retention and motivation are hot topics. ● Currently operators perform monotonous tasks: automation can shifts operators' tasks towards knowledge-and-data-driven activities
Setting design goals to comply the regulations	***Goals to comply WEEE Directive*** Supporting the current collection target (45% of electronics put on the market (POM)) and the future collection target set from 2019 (65% of electronics POM)	System's size and yield must support the achievement of WEEE collection targets (upstream) and WEEE recycling targets (downstream) established by the Directive
Identifying the stakeholders	***Company's management and engineering*** Company's top/middle management, production and environmental engineers, designers, logistics managers	Communication among these actors is crucial to make sure to include TBL goals within plant design
	Actors of electronic products' supply chain ● Final customers of electronics ● Producers, retailers and recyclers of electronics, recyclers of metals and plastics ● Municipalities, local communities	Artificial intelligence can enable the collection of statistics to add knowledge about process performances and products' life-cycle within a decision support system in WEEE supply chain (e.g., feedback to producers about use phase)
	Government and policy makers EU policy-makers and regulators, Swedish government	System design must support compliance schemes and anticipate regulation breakthroughs.
Setting relevant Key Performance Indicators (KPIs) to be monitored and assessed	***Economic KPIs*** ● Break-even point and payback time of the investment ● Sorting or recycling efficiency	An automated equipment guarantees a faster sorting if compared to the manual one, which leads to higher economical and operational KPIs and higher recycling rates downstream
	Operation management KPIs ● Lead time, cycle times ● Total throughput, throughputs of output fractions ●Number of reusable and recyclable components upon processed WEEE	Flexible, artificially intelligent sorting leads to increased productivity and, if integrated with sensor-technology and scanning, enables a smart update of sorting criteria to meet variable segregation needs or specifications
	Environmental KPIs ●CO2 emissions from electricity consumption to run the equipment ●CO2 emissions from transports ●Ecological and Human toxicity (Life Cycle Impact Assessment Indicators)	●Electricity consumption is one of the main source of environmental impact from plant running ●Broken lamps and some WEEE items can release toxics jeopardizing the environment and human health
	Social KPIs ●Rates of injury, lost days, absenteeism, personnel turnover ●Satisfaction from working environment	Automation can improve working conditions, safety, and satisfaction, provided that its introduction is supported by the proper training
Assessing the Information and Communication Technology (ICT) infrastructure	***ICT systems in production*** ●Sensors to feed the equipment and keep up speed ●PLC, control automated parts; HMI, ●Infrastructure for use of PLM data, methodologies and tools	Matching HMI with PLM is a way to facilitate the collection of WEEE data and statistics, as well as to facilitate the creation of collaborative platforms in WEEE supply chains
Assessing physical equipment and layout configuration	***Physical components, workers and layout*** Flexible, reconfigurable equipment allows to add/remove work stations or change the number of sorted fractions	A flexible equipment and layout meets the challenge of the huge variability of input streams in terms of amount and material contents of the WEEE items
Using of research methods and research tools for plant design	● Discrete Event Simulation (DES), Process flow simulation ● 3D Scanning of plant and of WEEE items	A combined use of such tools allows to assess sustainability of system's design and operations

Within the WEEE ID project, the results sprung from this case study are to provide the knowledge necessary for the development of a new concept of automated identification and sorting of e-waste, which will be followed by the realization of the related prototype.

Most of the outputs collected in Table 2 are currently being used and assessed within the investment planning of the system, particularly the sustainability goals that the stakeholders want to reach, the KPIs to measure them, the necessary equipment and ICT infrastructure.

For instance, DES has been selected as the tool to assess plant design alternatives, where proper KPIs will allow a fair comparison among the alternatives with respect to economic and environmental objectives simultaneously.

Plant dimensioning and the development of the impact assessment methodology are underway. A hypothesis of the layout of the sorting line is graphically presented in Fig.2.

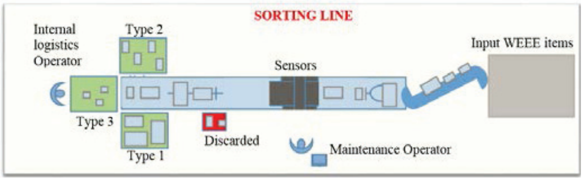

Fig. 2. Hypothesis of layout and components of the automated sorting line.

As Fig. 2 shows, dedicated workforce takes care of WEEE items' loading and unloading and possible machine stoppages or general maintenance services. After the identification, the actuators split the input stream up into three "good" fractions, and separate the hazardous items in another fraction. Engineering design and implementation stages of the line are currently underway and carried out also with the help this study.

With the aim to tackle social sustainability goals, a collection of related KPIs might be performed through questionnaires and reporting initiatives before and after the realization of the system within a real production environment. Moreover, Agent-Based Simulation might model operators' behavior [27] to figure and forecast the impact of the system in terms of ergonomics and safety.

5. Conclusion

This research work develops the prerequisites for a sustainable design of plants for e-waste treatment and targets its outcome towards production and environmental engineers, industrial designers, and operations managers, mainly.

A list of prerequisites to design an automated plant for e-waste sorting was developed, according to the data and the information currently available. This supported the realization of a concept of an intelligent sorting line, which is the purpose of the WEEE ID project. Thus far the results of this work have been applied within the investment planning in equipment and ICT, and used to evaluate the layout configuration. As a result, this study contributes also to guide the realization of the prototype following the concept.

The results of this research open the discussions about benefits and limitations of introducing automation and artificial intelligence in processes that are traditionally performed by humans.

Possible future developments of this work have been planned. The main ones are listed as follows:

- Fine-tuning the proposed methodology through several activities: e.g., including new prerequisites or modifying the existing ones by updating the literature study and enlarging the panel of the experts on e-waste management to be interviewed;
- Applying the methodology to the case study of e-waste disassembly plants and e-waste recycling plants;
- Developing the high-level framework to aptly guide the design stage of plants for a more sustainable e-waste management. In particular, developing a framework to design the system of the reported case study after integrating more knowledge and data from the remaining stages of the WEEE ID project;
- Investigating how PLM tools, data management systems and collaborative platforms can affect and improve sustainability of WEEE supply chains;
- Assessing whether operations and strategies implemented within the designed facility are well-aligned with its mechanical and informational level of automation.

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