Journal of Cleaner Production 81 (2014) 16–33

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Cyclic manufacturing: necessary and sufficient conditions and minimum rate policy for environmental enhancement under growth uncertainty

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ARTICLE INFO

Article history:
Received 4 December 2013
Received in revised form
22 May 2014
Accepted 10 June 2014
Available online 28 June 2014

Keywords:
Cyclic manufacturing
Sustainable production/consumption
Remanufacturing
Internal cycle model
Environmental policy

ABSTRACT

Economic development and rising consumption increase pressure on the environment. Sustainable production and consumption face the challenge of mitigating impacts under uncertainty in economic growth, trade, raw material availability and prices, variable consumer behavior and technological innovation. Necessary and sufficient conditions and a minimum rate policy for environmental enhancement under uncertainty are presented. They take into account variability in sales/consumption, in net product and material trade and in manufacturing technology and associated impacts. Three main criteria are considered. K1: reduced final wastes. K2: reduced extraction of virgin raw materials. K3: reduced impacts from manufacturing. The conditions are expressed in terms of the cycle rate, which is the generalization of the recycle rate and of readily monitored product flows, e.g. overall sales. Key advantages of the method are discussed. (A): simplicity and flexibility to simulate different growth conditions. (B): a readily determined, standardized rate policy, leading to reduced impacts in K1, K2 and K3. It is quantitatively established that for lower wastes, uncertainty in growth compels increase of the cycle rate larger than a threshold related to sales. For lower virgin material extraction, the threshold includes net product/material trade as well. Reduction of manufacturing impacts requires intensification of cleaner processes with adequately lower marginal impacts. In periods of economic austerity, the policy may be relaxed: enhancement is achieved via lower rate targets. It is concluded that cleaner production becomes all the more important as reuse/recycle flows increase and that such innovation may avert environmental degradation from manufacturing, even under significant growth.

1. Introduction

Sustainable production and consumption includes reuse, remanufacturing as products, modules or parts and recycling as material (RR) in a cyclic manufacturing (CM) scheme, for reducing the dependence of our affluent/throwaway society on extinguishing raw materials. Enacted legislation sets specific reuse and recycling targets (2004/12/EC, 2008/98/EC). It also allocates responsibility to manufacturers for many End-of-Life (EoL) products (USEPA, RCRA, 2011; Directives, 2000/53/EC, 2002/95/EC, 2005/32/EC). Several sectors are engaging in remanufacturing (Matsumoto, 2009), e.g., waste from electrical and electronic equipment (WEEE), (Sinha et al., 2009; Dindarian et al., 2012; Georgiadis and Bessiou, 2008). Transport equipment such as wind turbines (Ortegon et al., 2013) and vehicles (EoLV) are also a target for reuse and material recycle (Ferrao et al., 2006; Rathore et al., 2011; Saavedra et al., 2013; Jabbour et al., 2013; Martín-Peña et al., 2014).

Albeit in its early days, still reaping the low hanging fruits (environmental benefits), WEEE RR, recovers valuable metals (gold, silver, palladium, copper, aluminum, Fig. 1). Precious metals, occur at concentrations more than tenfold higher in printed wiring boards (PWBs) than in mined minerals (Cui and Forssberg, 2003; Betts, 2008). Swiss WEEE selective disassembly yields reusable parts and recycle materials. Included are metals at 56%, plastics at 18% CRT glass at 10%, glass, LCDs, paper, toners and wood 7%, PWBs at 1%, metal-plastics 6%, cables 1.5% and hazardous materials at 1%, (Wager et al., 2011). After recovering reused parts (8.9%ww), EoLV disassembly is followed by past shredder material (PSM) recovery -PSM makes up 18% of EoLV, with individual components distributed as follows: plastics 23%, polyurethane foam 15%, rubber 15%, textiles 27%, cellulose 1%, fines 17% and metals 8%. PSM recovery

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http://dx.doi.org/10.1016/j.jclepro.2014.06.028
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List of acronyms

BOD	biological oxygen demand
CM	cyclic manufacturing
CRT	cathode ray tube
EoL	end -of-life
ICF	internal cycle factor
LCD	liquid crystal display
RR	reuse/remanufacturing and recycling
PWB	printed wiring boards
PSM	post shredder material
WEEE	electrical and electronic equipment waste

raises recycling to 70% (metals: ferrous 56.6%, non Fe 3.2%ww) (Forton et al., 2006; Santini et al., 2011).

Skepticism about CM benefits hinges on three main issues: (1) Economic viability: the RR cost for a recycled material or a remanufactured product (= sum of all individual RR process costs) should be less than the value of the recovered material or product. (2) The advent of technology renders new products not only less expensive, but more material and energy efficient, reducing the benefits of reuse (Truttmann and Rechberger, 2006). (3) Impacts: in order for CM to be ecologically beneficial, the sum of similar impacts (e.g. atmospheric pollutants or BOD from waste water) in the various RR operations should be less than the respective releases from manufacturing a brand-new product from virgin raw materials. High environmental impacts are linked with informal recycling (Williams et al., 2008). Intensive RR operations may result in excessive energy consumption (e.g. transport and electricity for aluminum scrap and cans) or releases to the environment (e.g. water pollution or atmospheric pollutants from glass cullet). WEEE and EoLV operations are sources of environmental pollutants (Fig. 1): mercury from fluorescent lamps, batteries or switches, lead, (e.g. from broken or piled up CRTs), polychlorinated dibenzo-p-dioxins (PCDDs), dibenzofurans (PCDFs) and PBBs, PBDEs from plastics (Morf et al., 2005; Robinson, 2009). Cleaner production and RR processes may result in lower impacts; yet increasing demand, sales and overall consumption may quickly wither such benefits. Exponential growth featured by several fashion type markets may also result in rising impacts, despite meeting RR legislation targets.

This work addresses the problem of assessing the trend of environmental impacts from CM via a robust and nifty procedure, which would allow assessment of alternative CM processes and eco-efficiency of operations under various growth scenaria. Growth and rising consumption constitutes the main pressure on the environment. Sustainable policy should avert proliferation of impacts under real market conditions by reducing wastes to sinks, extraction of virgin materials and energy consumption and pollutant releases from manufacturing. Yet, sales and markets are ubiquitously evolving, affected by random consumer behavior, social factors, fashion, lifestyles, reordered priorities, economic cycles, money supply and interest rates, advent of technology, grassroots and niche innovations, product design, health considerations and ecological footprint (Vergragt et al., 2014). Hence, along successive economic cycles, several markets feature exponential sales growth followed by decline, or resurgence. For instance, the rapidly increasing demand for the lead, cadmium and mercury containing CRT monitors in the 1990s (Menad, 1999) is fading away due to the

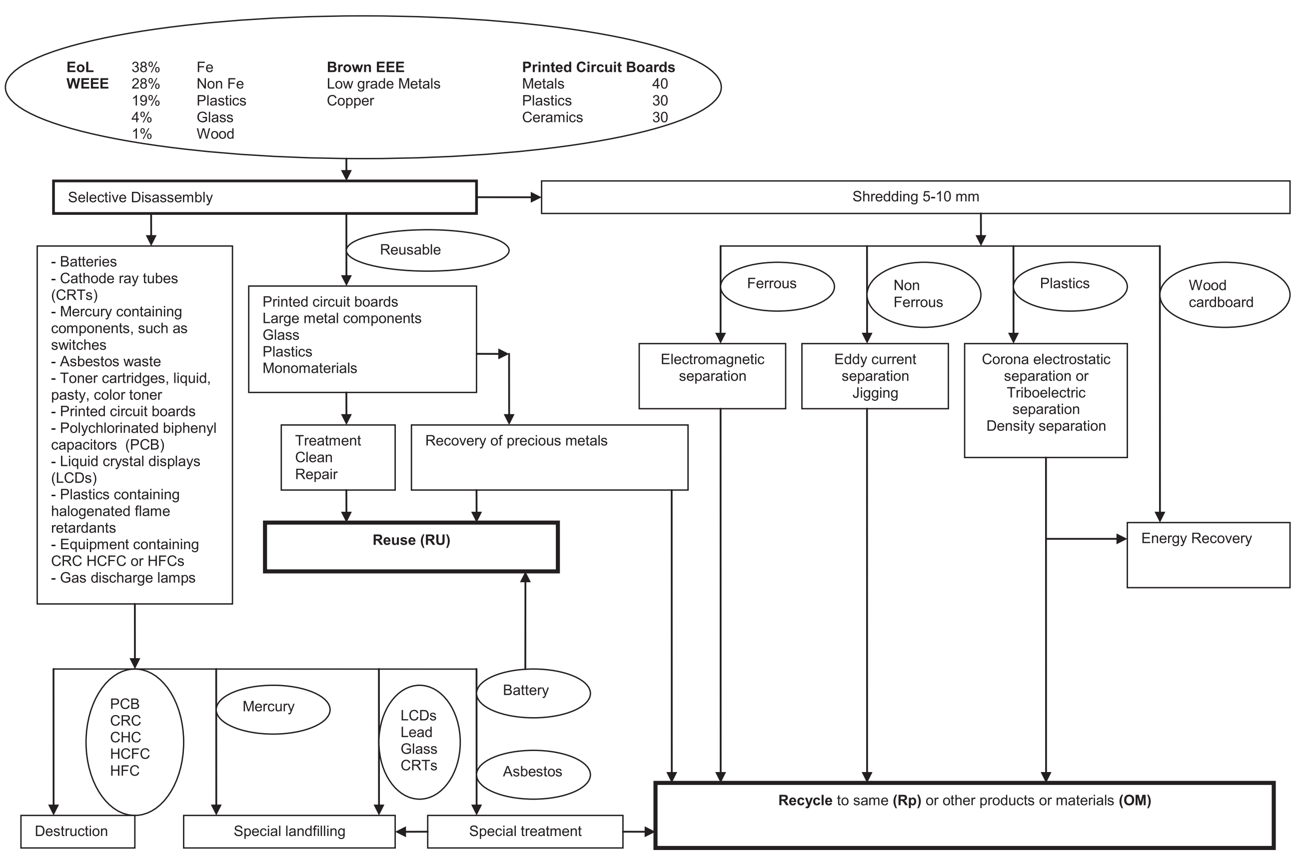

Fig. 1. WEEE processing (Sweden).