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Sustainability by cyclic manufacturing: Assessment of resource preservation under uncertain growth and returns

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ABSTRACT

Resource preservation (RP) and homeostasis is a key aspect of sustainability and a prime target of policy considerations. Heralded as an efficient means towards sustainable production and consumption of manmade products, cyclic manufacturing (CM) is fundamentally different from traditional open loop manufacturing: raw materials are not merely resources extracted from the natural environment, but products returned by the consumer as well. RP via CM strongly depends on the quantity and quality of returns. Affected by several factors (economic cycles, income, technological innovation, energy efficiency, social trends, etc.), the majority of returns, including end-of-life (EoL) returns, are random and unobservable. The present work reveals the intricacies of RP under real market conditions, including uncertainty in growth, stock and returns. It is shown that the recycling rate, the reuse rate and key parameters, including mean lifetime, number of reuse cycles and cyclic frequency, may not discern RP enhancement. A simple dimensionless rate is proposed and shown suitable for RP assessment. Its efficacy is demonstrated under leveled consumption/sales, growth or contraction: the minimal rate for reduced virgin material demand is higher under rising sales/consumption and lower in periods of economic austerity. The results may be useful for RP monitoring and proactive sustainable policy.

1. Introduction

Amidst traditional benchmarks of withstanding competition and adopting technological advances, manufactured products are nowadays challenged for sustainability. Recent legislation (USEPA, 2011; 2005/32/EC; 2004/12/EC; 2000/53/EC; 2008/98/EC) requires production and consumption to be associated with reduced wastes and virgin material extraction from the natural environment. Driven by economic growth and 50% global population increase by year 2050 (IEA, 2008), extraction is anticipated to triple (UNEP, 2011). A pillar of dematerialization (Allwood et al., 2011), cyclic manufacturing (CM) aims at counteracting the detrimental effect of manufacturing based solely on virgin raw materials and thus, reverse the trend for natural resource extinction. To promote CM, embedded innovation in product design aims at efficient disassembly besides product quality while effective recovery systems are adopted (Um et al., 2008; Selcuk et al., 2015; Mahmoudzadeh et al., 2013; Ardente et al., 2015).

CM (Lund, 1983; Cho and Parlar, 1991; Flapper and Wassenhove, 2005; Eckelman and Chertow, 2009; Kissling et al., 2012) includes return of original products by the customer, acquisition of returns by the (re) manufacturer, selective disassembly, repair and refurbishing to reinstate products, modules or parts to like-new condition, reassembly and distribution to the same or segmented markets (Majumder and Groenevelt, 2001; Tibben-Lembke, 2004; Zhang et al., 2011). No-further-reusable returns are sent for material recycling. Main cycles operating concurrently within the bifunctional closed loop supply (CLS) are: (a) the internal reuse/remanufacturing cycle that allows meeting demand/consumption, by a lower level of originally manufactured products and (b) the external, material recycle loop that further reduces the need for natural resources, including energy (Allwood et al., 2011; Gutowski et al., 2011; Woolridge et al., 2006), by substituting recycled for virgin materials.

Due to market and consumer volatility (Guide and van Wassenhove, 2006, 2009; Dekker et al., 2004), implied by economic cycles, varying interest rates, money supply and personal income, technological innovation and shifting social penchants, both returns and market-stock, from which returns originate, are chance variables, essentially unobservable. The emerging CLS chain is more volatile than traditional open loop manufacturing, due to the random arrivals and quality of returns (Souza et al., 2002; Teunter et al., 2009; Toktay et al., 2000) that affect resource preservation (RP) as well. Scarcity of special resources (e.g. metals and rare

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earths) and rising prices render the forward supply chain highly volatile as well, intensifying overall CLS uncertainty. Full understanding of the return motives is still eluding research (Guide and van Wassenhove, 2009; Atasu et al., 2008). At first, returns are affected by the varying sales of originally manufactured products: this is evident even in the few cases where returns can be predictable, e.g. end-of-lease returns. In addition, sales of the same manufactured lot of original products may appear as returns at various future time instants (diffusion of original sales in the returns), whilst others may never reappear. Such losses from the internal CL (Kleijn et al., 2000; Domingos, 2008; Elshkaki et al., 2005; Niza and Ferrao, 2006), occurring early in the product cycle, may be due to consumer discards (Tsiliyannis, 2005), to wear (tires), to losses to the environment due to biodegradation (biodegradable packaging) etc. Furthermore, the diffusion profile of the returns (Toktay et al., 2000; Atasu et al., 2008), i.e. the return distribution, may be shifting (Atasu et al., 2008; Geyer et al., 2007; Steffens, 2001). A symmetric return distribution may be left tilting under economic expansion-earlier returns, or right tilting under economic austerity, or even structurally varying; the fractions of the return distribution may be randomly varying as well. Field evidence of product lifetimes (Mueller et al., 2007; Murakami et al., 2010; Oguchi et al., 2010; Kagawa et al., 2006) brings out great shades of difference between residual life expectancy methods of actuarial science (Meinen et al., 1998; OECD, 1982) and EoL exit of manufactured products, indicating the bearings of the subject on non-stationary processes. Such changes are a consequence of consumer volatility and the ubiquitous variation of overall product sales. It is evident that the five strands of CLS uncertainty, that is uncertain demand, random early loss, diffusion of sales into the returns, shifting characteristics of the return distribution, and varying fractions of the return distribution are interwoven, inducing a striking richness on CLS dynamics. As a result the flows of reusable returns, actually reused/remanufactured items, end-of-life (EoL) returns, recycle, final wastes and resource extraction are randomly varying.

Apart from the amount of returns, quality is also a decisive factor for viable CM, since it determines the fraction of reusable returns (Dekker et al., 2004; Guide and van Wassenhove, 2006, 2009; Atasu et al., 2008). The difficulty in accessing sufficient volumes of good quality returns is a prime inhibitor of CLS penetration (Kissling et al., 2013). For instance, older returns equipped with older technology may be valuable in remanufacturing of power tools or industrial equipment, whilst in remanufacturing of electronic products they may be worthless. In practice returns are (a) commercial (or customer) returns, within a few weeks from purchasing, usually within warranty and of the highest quality, (b) end-of-use (EoU) returns, at the end of a use cycle, that include older technology, the majority still being reusable and (c) EoL returns with either obsolete technology or extensive wear and tear, rendering them no further reusable, that are directed to material recycling. EoU returns include trade-ins, buy-backs, or acquired in the open market. EoL are mainly customer take-backs and are often recovered together with EoUs, separated at the stage of selective disassembly (Zikopoulos and Tagaras, 2008). Even if the return flow is fairly constant, quality may be shifting due to uncertain factors as above, manifested by a time-varying age distribution of returns.

It is evident that RP induced via the internal and the external CM loops, crucially depends on the uncertain amount and quality of returns. This very feature renders assessment of RP a challenging task, thus far accomplished only a-posteriori, based on actual resource extraction data. RP prediction and early assessment of environmental policy efficacy is advantageous however, for timely and preventive action towards sustainability.

The present work investigates actual preservation of resources effectuated by CM. It aspires to fill a dearth in sustainability assessment in the emerging circular economy, by assessing RP under constant, varying or growing pressure from consumption and sales. It focuses on bringing forth the key parameters that may provide swift and reliable assessment under realistic market conditions, e.g. high variability of stock and sales, including exponential markets of high-tech products, random early losses and uncertain, highly varying returns.

2. Modeling resource preservation in cyclic manufacturing

The model in this section represents the dynamic evolution of stock and main flows of the internal (reuse/remanufacturing) and the external (recycle) loops. It serves for simulating various scenaria and assessing the efficacy of parameters that do not depend on the model or CLS uncertainty, for RP monitoring, including a proposed simple rate, ρ_M, defined in Section 3.1. Monitoring and assessment of resource preservation is in discrete time, (time t: $t = k\delta$, where $k = 1,2,3\ldots$, δ = discretization interval), appropriate to the nature and cycling frequency of the product, e.g. annually, quarterly, monthly.

Table 1
Modeling of resource preservation in closed loop supply.

Virgin material extraction:	$M_t = P_t - Rp_t - OM_t$	(1)
Production of original products, P_t, from virgin or recycled material, a_t =overall inflow of originally manufactured products	$P_t = a_t - I_{net,t}$	(2)
	P_t = fraction of $a_t = \phi_{P,a} a_t$	(3)
Recycled material from the product directed to manufacturing the same product:	Rp_t = fraction of $R_t = \phi_{Rp,R} R_t$	(4)
Recycle, R_t, originates from early loss, Ω_t and from end-of-life (EoL) flow, E_t:	R_t = fraction of Ω_t + fraction of E_t	(5)
	$R_t = \phi_{R,\Omega} \Omega_t + \phi_{R,E} E_t$	
Material from other products entering production of originals of the specific product, OM_t:	OM_t = fraction of $P_t = \phi_{OM,P} P_t$	(6)
The parameters ϕ_i in Eqs. (2)–(6) are between zero and one:	$1 \geq \phi_i \geq 0$	
Waste generation: if b_t is the overall outflow from the internal cycle (see Eq. (11))	$W_t = b_t - R_t - RU_{e,t}$	(7)
Recycle directed to other products or exported material: $Re_t + OP_t$. Re = exported recovered material, OP = portion of the product's EoL material directed to other products, Rp = material directed to manufacturing the same original product.	Recycle balance: $R_t = Re_t + OP_t + Rp_t$	(8)
Overall sales = inflow of original products to the internal cycle + actually reused returns (remanufactured products from original inflow a_t):	$C_{f,t} = a_t + RU_t$	(9)
T = the center axis of the EoL exit distribution. If N is the overall number of cycles, the mean return frequency, f and the mean cycle-time, f^{-1}, satisfy:	$N = fT$ or $f^{-1} = \frac{T}{N} = \kappa$	(10)
Output from the internal cycle:	$b_t = \Omega_t + E_t = RUe_t + R_t + W_t$	(10)
Early loss ratio (Tsiliyannis, 2008):	$s_t = \Omega_t / (U_t + \Omega_t)$	(12a)
Internal cycle retention ratio:	$x_t = 1 - s_t = U_t/(U_t+\Omega_t)$	(12b)
If U_t is the overall stock at the end of time period t, due to original inflow a_t, EoL exit E_t, in the	$U_t = U_{t-1} + a_t - \Omega_t - E_t$	(13a)
beginning of time period t, and losses Ω_t during the time period t, then	$U_t = U_{t-1} + a_t - RUe_t - R_t - W_t$	(13b)