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A fundamental law relating stock and end-of-life flow in cyclic manufacturing

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ABSTRACT

Cyclic manufacturing (CM) emerges as a sine-qua-non for sustainability. Consumer product stocks of today are the end-of-life flows (EoLF) of tomorrow in circular economy. Enacted legislation fosters reuse/recycle of EoL consumer products, of chemicals, raw materials and hazardous products and components (batteries, brake fluids, printed circuit boards, cellular phones, computers). But when is tomorrow and how much of the stock will appear as EoLF? Efficient CM operations depend on cognizance of EoLF and accumulating stock, the pool from which EoLF emanates. Consumer uncertainty, personal income, economic cycles, advent of technology, social and health reasons, stricter eco-standards and random early product losses during use, render EoLF and product stock uncertain and unobservable. Conventional identification methods based on regression, sequential least squares, or actuary science methods presuming specific residual life distributions, may not provide reliable estimates under uncertainty and non-stationarities. An appealingly simple constitutive law is revealed, relating the mean stock and EoLF in terms of stock mean-age and EoLF mean-age, which are scaled, readily and reliably monitored variables, even from relatively small, decentralized samples. Valid under random lifetime early losses, the law encompasses any EoL exit distribution, enabling stock and EoLF identification, data consolidation and assessment. Being a linear algebraic expression between stock and EoLF, the law reduces computational burden and evades presumption of any survival or exit probability distribution, or cognizance of early loss history, or ex-post fitting of stochastic parameters. The results may prove useful in planning/sizing EoL facilities and recycling operations and in environmental policy or compliance assessment.

1. Introduction

The chemical industry has long been implementing reuse/recycle of products and materials including hazardous materials, by recovering and reusing by-products, solvents, reactants and catalysts (regeneration), in order to increase yield and productivity and reduce releases to the environment. Examples include mining industry, oil refineries, pharmaceutical, paint and plastics industry (Ally et al., 2001; Flapper et al., 2005; Rockwell Automation, 2009). Cyclic manufacturing (CM) of consumer end-products is nowadays heralded as the means for waste prevention, dematerialization and reduced impacts from manufacturing processes towards sustainability. CM includes the forward supply chain (extraction of virgin raw materials, manufacturing of primary, manufacturing of end-product) and the reverse supply chain (return/recovery of products, reuse of whole products, modules or parts, in manufacturing new end-products and recycling as materials for production of primary). Enacted legislation (Directives 2000/53/EC; 2002/95/EC, 2002/96/EC; 2005/32/EC; 2008/98/EC; 2004/12/EC; USEPA, 2011) views CM, as a means to reduce wastes directed to landfills, impacts from manufacturing and virgin raw material extraction. CM encompasses consumer end-products and hazardous materials, since most industrial processes include assembly lines in which hazardous materials are incorporated into the end-product. Such products, e.g. electronics that contain heavy metals (switches, printed wiring boards PWB, CRTs, cell handsets, LCDs) and plastics containing halogenated organic compounds (Cui and Forssberg, 2003; Betts, 2008; Williams et al., 2008; Robinson, 2009; Khetriwal et al., 2009; SENS, 2010; Wäger et al., 2011; Rathore et al., 2011; Dildarian et al., 2012; Leigh et al., 2012) are removed in the early stage of selective disassembly for reuse or safe disposal. Batteries and brake fluids are recovered in vehicle disassembly for remanufacturing or recycling of transportation

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Nomenclature

a_t $=P_t + I_{net,t}$, product inflow in period t, e.g. year t, (tons/year), a = steady state level
b_t $= E_t + \Omega_t$, outflow from internal cycle stock in period t, (t/y), b = steady state level
$C_{f,t}$ overall consumption (t/y) = amount reaching the consumer in period t, e.g. annual sales
CRT cathode ray tube
E_t end of life (EoL) flow in period t, e.g. year t, (tons/year, t/y), EoLF = EoL flow
$E_{xu,t}$ exports of used
$g_{i,t}$ EoL exit probability distribution ($g_{i,t}$ = probability to exit as EoL in year $t = t^* + T - \mu + i$, i = 0,1,2,..,ν−1, of an originally manufactured product in time period t*)
I_{net} flow of net imported original parts and products $= I_{part,t} - Ex_{part,t} + I_{prod,t} - Ex_{prod,t}$, (t/y)
LCA lifecycle analysis
LCD liquid-crystal display
V virgin raw material flow to produce the specific product, (t/y)
MRT, MEoLF Mean retention time = mean lifespan, time periods, e.g. years, mean EoL flow, (t/y)
OEM original equipment manufacturer
OM_t recycled material from other products used to produce the specific product, (t/y)
P_t original production flow (t/y), (original items made from virgin or recycled material with no reused parts or components)
PD, PMF probability distribution, probability mass function
PIM perpetual inventory model
PWB printed wiring board
R_t $=Ro_t + Rp_t = Re_t + Rp_t + OP_t = R_{\Omega,t} + R_{E,t} = R_{c,t} + R_{R,t}$ (t/y)
$R_{c,t}$ recycle flow from early or EoL discarded product, by consumer, (t/y)
$R_{E,t}$; $R_{r,t}$ recycle flow from EoL exit; recycle flow from the remanufacturer, (t/y)
Ro_t $=Re_t + Rp_t$ recovered material leaving the external cycle as exports (recycle exports flow), or as recycle material used to produce other products, (t/y)
Rp_t recycle flow to produce the same specific original product, (t/y)
$R_{\Omega,t}$ recycle flow from early loss, either from consumer or from remanufacturer, (t/y)
RU_t actually reused returns in the internal cycle, flow, (t/y)
$RU_{x,t}$ exports of remanufactured
s_t early loss ratio $= \Omega_t/(U_t + \Omega_t)$ = probability of early loss (before EoL exit) in year t
T time (e.g. years) from production to center axis of the EoL exit (T = maximum lifetime for products with specified period of exit)
U_t net market accumulation: quantity present in the internal cycle at the end of year t (tons)
$U_t^{(k)}$ age-k product present in the internal cycle at the end of year t, i.e. present in U_t
W_t $=W_{\Omega,t} + W_{E,t} = W_{C,t} + W_{R,t}$ total outflow to the environment = finally managed wastes (landfilled or incinerated, etc) + other losses to the environment (t/y)
$W_{\Omega,t}$ =wastes from early loss flow, (t/y)
$W_{E,t}$ =wastes from EoL exit flow, (t/y)
x_t $=1-s_t$ = retention ratio = probability of remaining in the internal cycle in period t.

Greek

ε =mean EoL flow to inflow ratio or EoL rate, (time average)
η =stock mean age (ensemble average)
θ =EoL flow mean age (ensemble average)
μ half spread of the EoLF exit distribution, time periods (e.g. years)
ν $=2\mu + 1$ = spread of the EoLF exit distribution, time periods (e.g. years)
τ =U/a, mean residence time (MRT) or mean lifespan, (time or sample path average)
Ω_t $=b_t - E_t$ = total early loss (t/y)

Symbol

= equal by definition

Subscripts

t t is time period t = 1: first period the product under consideration is launched in the market.
E part of the EoL flow
c flow due to consumer discard
R flow due to remanufacturer
Ω part of the early loss flow

equipment (Morioka et al., 2005; Ferguson, 2007; Santini et al., 2011; Ortegon et al., 2013; Jabbour et al., 2013; Saavedra et al., 2013; Martín-Peña et al., 2014).

Reuse/recycle of consumer end-products via CM is realized either in the premises of the original equipment manufacturer (OEM), or in special EoL facilities (e.g. for EoL vehicles, EoLVs, or for waste from electrical and electronic equipment, (WEEE), that supply OEMs. Planning and sizing of EoL operations and facilities depends on the EoL flows which are highly uncertain due to unpredictable consumer EoL return and discard, stemming from economic cycles, varying personal income, money supply, interest rates, reordered priorities, fashion trends, social status, health considerations, ecological and energy efficiency features of the product, etc. Uncertainty is intensified by the distributed nature of consumer returns and final discard, with the EoL exit turning up several years after sales, a fact macroscopically appearing as EoL exit delay. Besides return and EoL exit time uncertainty, early mass losses of product due to use and wear during lifetime (Fischer-Kowalski, 1998; Tsiliyannis, 2005, 2008), affect stock and EoLF level. After whatever early losses during retention, the EoL exit in year t, E_t, may include product items manufactured several years ago, which have accumulated in the market. More specifically, it consists of the overall contributions of product manufactured during several years in the past, with each contribution subject to early loss in the elapsed years (Tsiliyannis, 2011, 2012).

CM has been analyzed in a number of closed loop supply chain (CLSC) industrial engineering works (Fleischmann et al., 1997; Toktay et al., 2000; Guide and Van Wassenhove, 2003; Dekker et al., 2004) focusing on profitable use of the recovered products (Guide and Van Wassenhove, 2006, 2009; Dempsey et al., 2010) and including issues such as return inventory management, time value of returns, competition of new and remanufactured products