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Dynamic stock and end-of-life flow identification based on the internal cycle model and mean-age monitoring

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ABSTRACT

Planning of end-of-life (EoL) product take-back systems and sizing of dismantling and recycling centers, entails the EoL flow (EoLF) that originates from the product dynamic stock (DS). Several uncertain factors (economic, technological, health, social and environmental) render both the EoLF and the remaining stock uncertain. Early losses of products during use due to biodegradation, wear and uncertain factors such as withdrawals and exports of used, may diminish the stock and the EoLF. Life expectancy prediction methods are static, ignoring early losses and inapt under dynamic conditions. Existing dynamic methods, either consider a single uncertain factor (e.g. GDP) approximately or heuristically modelled and ignore other factors that may become dominant, or assume cognizance of DS and of the center axis of the EoL exit distribution that are unknown for most products. As a result, reliable dynamic EoLF prediction for both durables and consumer end-products is still challenging. The present work develops an identification method for estimating the early loss and DS and predicting the dynamic EoLF, based on available input data (production + net imports) and on sampled measurements of the stock mean-age and the EoLF mean-age. The mean ages are scaled quantities, slowly varying, even under dynamic conditions and can be reliably determined, even from small size and/or frequent samples. The method identifies the early loss sequence, as well as the center axis and spread of the EoL exit distribution, which are subsequently used to determine the DS and EoLF profiles, enabling consistent and reliable predictions.

1. Introduction

Consumer products and commodities accumulate in cities, homes and storage spaces until they reach the end-of-life (EoL) stage and are disposed of, as no longer usable; stocks of today are the discards of tomorrow. But when is tomorrow and how much is to exit every year? Accumulation depends on the exit flow, but stocks entail retention mechanisms macroscopically appearing as delays (Kleijn et al., 1999) – larger delay implies larger accumulation. The Extended Producers Responsibility (Directive 2000/53/EC) and the RCRA (USEPA, 2011) ushered a new era in remanufacturing by mandating collection, dismantling and reuse-remanufacture–recycle (RRR) above a minimum rate (e.g. packaging, vehicles, electronics). Directive 2008/98/EC set the reuse and recycling target at 50% by year 2020. On the other side, Truttman and Rechberger (2006) presented evidence that reuse of older products delays launching of ecologically more efficient designs, thus partially increasing the overall product footprint. Nonetheless, setting targets and measuring progress in sustainable use of resources and dematerialization via RRR is critical in view of the 50% global population increase by year 2050 (EEA, 2005).

RRR operations must be appropriately sized, sited, planned and operated, requiring prognosis of stocks, EoL exit time and returned flows to be processed. Planning and process design under raw material uncertainty may lead to improved results if key information is exploited (Gaustad et al., 2007). EoLF prediction is still evading however (ETCRWM, 2008), due to the volatile consumer behavior, affected by uncertain factors (fashion, trends, advent of technology, economic cycles, money supply and interest rates, income, ecological and health considerations, etc.). Another reason is the dynamic effect: annual production in year t will cause an increase of stocks if the exit is delayed. Suddenly, ecology or a technological advance (e.g. liquid crystal television) renders all stock (conventional tube television) ante-portas! A classical example is asbestos: a promising low-cost manmade thin insulator and waterproof material of the 1950–1960s installed in almost every building, has to be removed and safely disposed off, guilty of causing lung cancer. A similar fate may be envisioned for internal combustion automobile engines if the US Government target for fuel-cell engine cost target lower than \$30/kW is reached by 2015. EoL exit of building materials may rise significantly: innovative construction/insulation RRR elements are

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Nomenclature

a_t	market input flow (feed) of product in year t, t/y (tons per year), a = steady state level
b_t	market output flow of product in year t, b = steady state level (t/y) (=$R_t + W_t = E_t + \Omega_t$)
B_{t-1}, D_{t-1}	expressions of past inputs and past x, i.e. of x_{t-2}, x_{t-3}, ... in Eq. (23). (Given in Appendix A)
$C_{f,t}$	overall consumption (t/y) = annual amount reaching the consumer = annual sales
E_t; $E_t^{(k)}$	EoL flow (EoLF) in year t; age-k product vintage present in E_t (t/y)
$\overline{E}_t$	ensemble age of the EoL flow, years
EoL	end of life
DS	dynamic stock
F_{t-1}, G_{t-1}	expressions of past inputs and past x, i.e. x_{t-2}, x_{t-3}, ... in Eq. (22). (Given in Appendix A)
g_t	EoL exit probability mass function (g_t = probability to exit as EoL in year t)
I_{net}	flow of net imported product (unmounted or assembled) (t/y) = $I_t - E_t + I_{a,t} - E_{a,t}$, (t/y)
M	virgin raw material flow (t/y)
OM_t	recycled material from other products used to produce the specific product (t/y)
PD, PMF	probability distribution, probability mass function (=quantized probability density)
P_t	production flow of the product (t/y), (new items made from virgin or recycled material), (t/y)
R_t	overall recycle flow (t/y) (=$R_{s,t} + R_{E,t} = \text{Ro}_t + \text{Rp}_t$ = -$R_{s,t} + R_{E,t} = \text{Ro}_t + \text{Rp}_t = \text{Re}_t + \text{Rp}_t + \text{OP}_t$)
$R_{c,t}$	recycle flow from consumer discard, (t/y)
$R_{E,t}$; $R_{r,t}$	recycle flow from EoL exit; recycled EoL flow from the remanufacturer, (t/y)
Ro_t	recovered material leaving the external cycle as exports (exported recycle flow), or as recycle material used to produce different products than the specific product, (t/y)
Rp_t	recycle flow of product to produce the same product (t/y)
$R_{s,t}$	recycle flow from early loss, (t/y)
RU_t	reused product flow, (t/y)
s_t	early loss ratio (=$\Omega_t/(U_t + \Omega_t)$)
s	mean early loss ratio or steady state value of s_t
T	time (years) from production to center axis of the EoL exit (T = maximum lifetime for products with deterministic exit)
x_t	early survival ratio (=1 − s_t)
U_t	market accumulation: quantity present in the market at the end of year t (tons)
$U_t^{(k)}$	age −k product vintage present in the market at the end of year t, i.e. present in U_t
$U_t^{(T)}$	age T product vintage present in the market at the end of year t, i.e. present in U_t
$\overline{U}_t$	overall (ensemble) stock age, years
W_t	$W_{s,t} + W_{E,t}$ = total outflow to the environment due both to early loss and EoL exit = finally managed wastes (landfilled or incinerated, etc.) + other losses to the environment (t/y)
$W_{s,t}$	wastes from early loss flow, (t/y)
$W_{E,t}$	wastes from EoL exit flow, (t/y)
x	ean early survival loss ratio (=1 − s)

Greek

ε	EoL flow ratio = E/a, where a is the step input or step-trace level
η	stock mean age, steady state or average sample path value
θ	EoL flow mean age, steady state or average sample path value
μ	half spread of the EoL exit distribution, years
ν	full spread of the $2\mu + 1$, years
Ω_t	early loss flow (t/y) (=$b_t - E_t$)

Subscripts and symbols

t	t is time t = 1: first year the product under consideration is launched in the market
=:	equal by definition
E	part of the EoL flow
c	flow due to consumer discard
r	flow due to remanufacturer
s	part of the early loss flow
$\langle\rangle$	average sample path value

foreseen based on nanotechnology and carbon fiber structures (smart houses), along with optimized design/construction operations.

The intuitive way to predict the EoLF would be to assume that the dynamic profile of the EoL exit will be the same as the input profile delayed by the number of years the product stays in the market. Yet, besides uncertain socioeconomic factors drastically differentiating the EoLF from the input profile, the EoLF will be subject to whatever losses have occurred in the meanwhile: many products feature early exits (e.g. product withdrawals by manufacturers for safety reasons), others gradually loose mass due to wear (tyres appearing after 3–5 years of use and wear, Ferrao et al., 2007), degradation (e.g. biodegradable packaging – steadily replacing traditional more durable competitive products). In a national level, exports of used products or materials must also be included in early losses, since exports are not to appear as EoLF in the country of origin.

A challenging class for EoLF and DS identification may be fast cycling consumer end-products. They include fashion-type markets which feature exponentially increasing demand and input, the latter severely affecting the EoLF peak (Kleijn et al., 1999). Such inputs are randomly modulated, due to perpetually uncertain consumer behavior/demand. Thus, albeit for single use nondurables there is essentially no annual accumulation, faster identification is needed to predict monthly EoLFs and peaks. Multiple use products (e.g. refillable packaging) may feature fast dynamics resulting in higher than expected EoLF, due to the uncertain factors discussed above, subject also to losses in the intervening years.

Modeling and estimation of life expectancy, accumulated stock and discard flows for durables and commodities may follow conventional methods, which assume a given exit probability distribution (PD) over lifetime, with parameters tuned via extended databases (Meinen et al., 1998). Such static methods may hardly follow dynamic conditions, which prevail for consumer end-products. In addition, they do not account for early loss-essentially they presume that it is identically distributed with the EoL exit, which is not the case for consumer end-products. Taking a dynamic view, the notion of product metabolism was addressed in Fischer-Kowalski (1998),