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Accelerating Benders decomposition for closed-loop supply chain network design: Case of used durable products with different quality levels

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ABSTRACT

Durable products are characterized by their modular structured design as well as their long life cycle. Each class of components involved in the multi-indenture structure of such products requires a different recovery process. Moreover, due to their long life cycle, the return flows are of various quality levels. In this article, we study a closed-loop supply chain in the context of durable products with generic modular structures. To this end, we propose a mixed-integer programming model based on a generic disassembly tree where the number of each sub-assembly depends on the quality status of the return stream. The model determines the location of various types of facilities in the reverse network while coordinating forward and reverse flows. We also consider the legislative target for the recovery of used products as a constraint in the problem formulation. We present a Benders decomposition-based solution algorithm together with several algorithmic enhancements for this problem. Computational results illustrate the superior performance of the solution method.

1. Introduction

Landfilling of End-Of-Life (EOL) durable products that contain large quantities of precious and depletable raw materials is a major concern in terms of sustainability and environmental footprints. In recent decades, Original Equipment Manufacturers (OEMs) in several countries, such as Germany and Japan, have been facing with legislations on the take-back of their EOL products. Meanwhile, they have started recognizing the product recovery as an opportunity for saving production costs through reusing the recovered parts in their forward flow in addition to having access to the secondary markets. Hence, the OEMs have been forced to extend the scope of traditional logistics to incorporate the return flows from customers to manufacturer. As pointed out by Guide and Van Wassenhove (2002), OEMs that have been most successful with their reverse supply chains are those that closely coordinate it with the forward supply chain, initiating the closed-loop supply chain (CLSC). In a CLSC, the role of the reverse supply chain (RSC) is to collect used products from end-users, inspect and sort them as needed, ship them to various recovery facilities, and finally redistribute the recovered items into the forward supply chain or to the secondary markets.

This study is motivated by the recovery of durable products, such as aircraft, automobile, and large household appliances that are distinguished by their multi-indenture structure as well as their long life cycle. Such products can be disassembled into several components namely modules, parts, and precious raw materials. As opposed to simple waste, e.g., paper, carpet, and sand, that can only be recycled, each of the aforementioned components in the disassembly tree of durable products can be recovered by a particular recovery process. In the context of durable products with long life cycle, it can be expected that the majority of the return stream is composed of poor quality returns with a small number of recoverable modules and parts (Krikke, Bloemhof-Ruwaard, & Van Wassenhove, 2003). In other words, only a small portion of the return flows might belong to the warranty or damaged items involving a large number of high quality modules and parts. Since the remanufacturing cost increases as the quality of returns decrease, OEMs expect larger revenue through the recovery of high quality returns and thus might be less motivated for the acquisition and recovery of lower quality ones. However, the legislation, e.g., in Europe and Japan, sets targets for the

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Nomenclature

Sets

A	Set of disassembly centers
B	Set of bulk recycling centers
C	Set of collection centers
D	Set of disposal centers
E	Set of secondary markets for recycled materials
G	Set of material recycling centers
I	Set of manufacturing centers
J	Set of distribution centers
K	Set of end-user zones
L	Set of modules
M	Set of remanufacturing centers
P	Set of parts
Q	Set of quality levels of returns
R	Set of raw materials
S	Set of secondary markets for spare parts
U	Set of raw material suppliers
W	Set of secondary markets for modules
X	Set of module suppliers
Z	Set of part suppliers

Parameters

α_{rq}	The mass of recyclable material r in the returned product with quality level q shipped to material recycling centers from disassembly centers
β_q	The mass of residues in the returned product with quality level q shipped to bulk recycling centers from disassembly centers
δ_{lq}	The number of remanufacturable module l in the returned product with quality level q shipped to remanufacturing centers from disassembly centers
η_r	The ratio of recyclable material r shipped to material recycling centers from bulk recycling centers
γ_{pq}	The number of part p in the returned product with quality level q shipped to secondary markets and manufacturing centers from disassembly centers
μ_r	The volume of material r in each unit of product
ω_l	The number of module l in each unit of product
ϕ_p	The number of part p in each unit of product
ψ_q	The rate of return of each quality level q
σ_q	The ratio of non-recoverable returns with quality level q shipped to disposal centers from disassembly centers
τ_r	The ratio of non-recyclable material r shipped to disposal centers from bulk and material recycling centers
θ	The legislative target for recovery of the return stream
ca_{aq}	Processing cost per unit of the returned product with quality level q at disassembly center a
caa_a	Capacity of disassembly center a
cab_b	Capacity of bulk recycling center b
cac_c	Capacity of collection center c
cad_d	Capacity of disposal center d
cag_{gr}	Capacity of material recycling center g for raw material r
cai_i	Capacity of manufacturing center i
caj_j	Capacity of distribution center j
cam_{ml}	Capacity of remanufacturing center m for module l
cau_{ur}	Capacity of raw material supplier u for raw material r
cax_{xl}	Capacity of module supplier x for module l
caz_{zp}	Capacity of part supplier z for part p
cb_b	Processing cost per kg of residues at recycling center b
cc_{cq}	Processing cost per unit of the returned product with quality level q at collection center c
cd_d	Disposal cost at disposal center d
cg_{gr}	Recycling cost per kg of material r at material recycling center g
ci_i	Production cost per unit of product at manufacturing center i
cj_j	Distribution cost per unit of product at distribution center j
cm_{mlq}	Remanufacturing cost per unit of module l with quality level q at remanufacturing center m
cu_{ur}	Procurement cost per kg of material r supplied by raw material supplier u
cx_{xl}	Procurement cost per unit of module l supplied by module supplier x
cz_{zp}	Procurement cost per unit of part p supplied by part supplier z
de_{er}	Demand for material r at recycled material market e
dk_k	Demand the new product at end-user zone k
ds_{sp}	Demand for part p at spare market s
dw_{wl}	Demand for module l at secondary market w
fa_a	Fixed cost of opening disassembly center a
fb_b	Fixed cost of opening bulk recycling center b
fc_c	Fixed cost of opening collection center c
fd_d	Fixed cost of opening disposal center d
fg_g	Fixed cost of opening material recycling center g
fm_m	Fixed cost of opening remanufacturing center m
Pe_r	Unit price of material r at recycled material markets
Pk_k	Unit price of the new product at end-user zone k
Pr_q	Unit acquisition price of the returned product with quality q
Ps_p	Unit price of part p at spare markets
Pw_l	Unit price of module l at secondary markets
rd_{bd}	Shipping cost per kg of waste from bulk recycling center b to disposal center d
rg_{bgr}	Shipping cost per kg of recyclable material r from bulk recycling center b to material recycling center g
ri_{uir}	Shipping cost per kg of material r from material supplier u to manufacturing center i
sd_{gd}	Shipping cost per kg of waste from material recycling center g to disposal center d
si_{xil}	Shipping cost per unit of module l from module supplier x to manufacturing center i
ta_{ca}	Shipping cost per unit of the returned product from collection center c to disassembly center a
tb_{ab}	Shipping cost per kg of residues from disassembly center a to bulk recycling center b
tc_{kc}	Shipping cost per unit of the returned product from end-user k to collection center c
td_{ad}	Shipping cost per kg of materials from disassembly center a to disposal center d
te_{ger}	Shipping cost per kg of recycled material r from recycling center g to recycled material market e
tg_{agr}	Shipping cost per kg of recyclable material r from disassembly center a to material recycling center g
ti_{zip}	Shipping cost per unit of part p from part supplier z to manufacturing center i
tj_{ij}	Shipping cost per unit of the new product from manufacturing center i to distribution center j