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Process planning for closed-loop aerospace manufacturing supply chain and environmental impact reduction ☆

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ABSTRACT

A considerable amount of work has recently been applied to the development of processes to reduce negative environmental impacts of disposal products. Different waste reduction options such as direct reuse, repair, refurbishing, cannibalization, and remanufacturing were introduced to overcome these shortages. This paper studies an integrated system of manufacturing and remanufacturing using a capacitated facility in the aerospace industry, where products are returned after certain flight hours or cycles for overhaul. A mixed integer linear programming model is developed to maximize profit considering manufacturing, remanufacturing set-up, refurbishing, and inventory carrying costs. The model was tested through a set of experimental data. Further sensitivity analysis was conducted aiming at revealing the effects of certain factors on inventory carrying cost, profit, amount of scrap, and inventory turnover ratio.

1. Introduction

In recent years, increasing environmental concerns, the price of raw materials, and government legislations, aiming at conservation of energy and natural resources, landfill reduction, pollution reduction, and creating new jobs and skills (Gray & Charter, 2006; Mcconocha & Speh, 1991), have resulted in companies to reduce their material wastes. The earlier approach, which was introduced in the 1970's, was the recovery/recycling of materials such as waste paper, glass and metals. Wastewater treatment and waste-to-energy (WTE) are reestablishing themselves as attractive technology options to promote low carbon growth among other renewable energy technologies (Amoo & Fagbenle, 2013; Kusiak & Wei, 2011). However, recycled products lose their added values; most of the time closed-loop recycling is not possible because of the purity of the recovered materials. Also, many energy taking activities would be required to transform a recycled product into raw materials. To overcome these deficiencies, different waste reduction options such as direct reuse, repair, refurbishing, cannibalization, and remanufacturing were studied (Thierry, Salomon, Van Nunen, & Van Wassenhove, 1995). Remanufacturing is "a process of recapturing the value added to the material when a product was first manufactured" (Gray & Charter, 2006). In order to have a successful remanufacture, the following parameters are required: market demand for remanufactured products, technology to remanufacture, stable product technology, standard interchangeable parts, and a lower remanufacture cost than the price of a new product (Lund, 1998). Dowlatshahi (2005) identifies strategic factors in the remanufacturing system and Guide (2000) lists the characteristics that make remanufacturing complex. Ijomah (2009) introduces a paradigm shift from product sales to service business model where a company's needs are much more closely tied to customers' needs. The new model looks at the following factors differently: product price, quantity of spares, reliability, customer expectation, source of profit, and incentive to overhaul. It also lists the difference between the new and old business model for aircraft engine life cycle costs.

Companies create different strategies to encourage customers to buy remanufactured products. For example, up to 40% of part price is reimbursed by Caterpillar to the dealers that return parts and engines depending on their conditions (http://www.product-life.org/en/archive/case-studies/caterpillar-remanufactured-products-group). In aerospace industry, where safety and performance are the main concern and repairs are highly regulated, the general opinion is that remanufacturing has the least appeal. However, considering high price of raw materials and the low tolerance for manufactured components in aerospace which causes high

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Nomenclature

i, k	index for component i, $k \in I$, $I = \{1, 2, 3\}$
j	index for product $j \in J$, $J = \{1, 2\}$
l	index for parts $l \in L$, $L = \{1, 2, 3, 4, 5\}$
t	index for time period $t \in T$, $T = \{1, 2, 3, 4, 5\}$
α	percentage of demand for new spare components
γ	upper bound of disposal rate for component i
BOM_{ij}	bill of material for product j
$BOM2_{li}$	bill of material for component i
Ct_i	manufacturing cost of component i
CT_j	aggregated cost of assembly, material handling, and packaging of product j
$Ctcan_{li}$	cannibalization cost of disassembled component i
$Ctr1_i$	repair (type I) cost of component i
$Ctr2_i$	repair (type II) cost of component i
$Ctrm_i$	remanufacturing cost of component i
$CtShortp_j$	shortage cost of product j
$CtStucan_{li}$	set-up cost of cannibalization of disassembled component i
$Ctstum_i$	set-up cost of manufacturing of component i
$Ctstur1_i$	set-up cost of repair (type I) of component i
$Ctstur2_i$	set-up cost of repair (type II) of component i
$Ctsturm_i$	set-up cost of remanufacturing of component i
$CtstuRZ2_i$	set-up cost of assembly of parts l to produce component i
$Ctstutrm_{ik}$	set-up cost of transforming of component i to component k
$Cttrm_{ik}$	transforming cost of component i to component k
Def_{it}	number of defective components i produced at period t
$Defrat_i$	defect rate of manufacturing of component i
$Demp_{jt}$	demand for product j at period t
$Dems1_{it}$	demand for new spare component i at period t
$Dems2_{it}$	demand for used spare component i at period t
H_i	holding cost for one unit of component i
$H2_l$	holding cost for one unit of part l
Hrm_i	remanufacturing hours of component i
$Hrm1_i$	remanufacturing hours of non-repairable disassembled component i
Hrp_i	manufacturing hours of component i
$Hrr1_i$	repairing (type I) hours of component i
$Hrr2_i$	repairing (type II) hours of component i
HRS	summation of labor hours available for certain processes
$Hrtrm_{ik}$	transforming hours of component i to component k
$Invn_{it}$	inventory of new component i at period t before assembling the product j
$Invnf_{it}$	inventory of new component i at period t after assembling the product j
$InvSubpr_{lt}$	inventory of part l at period t
$Invu_{it}$	inventory of used component i at period t
P_i	disposal cost of component i
Pr_{it}	number of component i produced at period t
$Prc1_i$	price of new spare component i
$Prc2_i$	price of used spare component i
$PRCP_j$	price of product j
$Prcz1_i$	price of customer's repaired component i (Rz)
$Prcz2_i$	price of customer's remanufactured component i (Ry)
PRP_{it}	number of product j assembled at period t
Q_{it}	1 if component i is manufactured at period t, otherwise 0
$R1_{it}$	1 if component i is repaired (type I) at period t, otherwise 0
$R2_{it}$	1 if component i is repaired (type II) at period t, otherwise 0
$RCtSturm_i$	set-up cost of remanufacturing of disassembled component i
$RCtSturm1_i$	set-up cost of remanufacturing of non-repairable disassembled component i
$RCtStur2_i$	set-up cost of repair of disassembled component i
$RCtrm_i$	remanufacturing cost of disassembled component i
$RCtrm1_i$	remanufacturing cost of non-repairable disassembled component i (Ry1)
$RCtr2_i$	repair cost of disassembled component i
$RDef_{it}$	number of defective component i disassembled at period t
$RDefrat_i$	defect rate of disassembled component i
$RPro_{jt}$	returned product j at period t
Rm_{it}	1 if component i is remanufactured at period t, otherwise 0
$RR2_{it}$	1 if disassembled component i is repaired at period t, otherwise 0
RRm_{it}	1 if disassembled component i is remanufactured at period t, otherwise 0
$RRm1_{it}$	1 if non-repairable disassembled component i is remanufactured at period t, otherwise 0
$RRz2_{it}$	1 if component i is produced of cannibalized part l at period t, otherwise 0
RS_{it}	1 if component i is cannibalized at period t, otherwise 0
$Rw1_{it}$	returned component i sent for salvage at period t
$Rw2_{it}$	returned component i sent for cannibalization at period t
$RW1rat_i$	lower bound for disposal of component i after disassembly
$RW2rat_i$	lower bound for cannibalization of component i after disassembly
Ry_{it}	remanufactured component i of repairable disassembled components at period t
$Ry1_{it}$	remanufactured component i of non-repairable disassembled components at period t
Rz_{it}	repaired component i of disassembled components at period t
$Rz2_{it}$	used component i produced of cannibalized parts l at period t
$R2Ctr2_i$	cost of assembling component i of parts l
$Salrat_l$	defect rate of part l during cannibalization
$Short2_{it}$	shortage of used component i at period t
$ShortP_{jt}$	shortage of product j at period t
$Subpr_{lt}$	part l produced as a result of cannibalization at period t
t_1	lead-time of manufacturing
t_2	lead-time of remanufacturing
t_3	lead-time of repair (type I)
t_4	lead-time of repair (type II)
t_5	lead-time of transforming
t_6	lead-time of repair of disassembled component
t_7	lead-time of remanufacturing of disassembled component i
t_8	lead-time of cannibalization of disassembled component i
t_9	lead-time of assembly of cannibalized part
t_{10}	lead-time of remanufacturing of non-repairable disassembled component i
t_{11}	turn-around time of overhaul of product
t_s and t_e	start and end period of labor hours restriction
T_{ikt}	1 if component i is transformed to component k at period t, otherwise 0
V_{ikt}	component i transformed to component k at period t
w_{it}	component i scraped at period t
$Wrat_i$	lower bound of disposal for component i
$Xrat_i$	maximum percentage of repair (type I) for component i
x_{it}	number of component i repaired (type I) at period t
y_{it}	number of component i remanufactured at period t
z_{it}	number of component i repaired (type II) at period t