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Pricing Decision for Short Life-Cycle Products in a Closed-Loop Supply Chain with 4

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.its.ac.id Abstract Remanufacturing is a product recovery process 115

that transforms a used product into "like-new" condition. It can extend the useful life of a product and help in reducing waste caused by a huge amount of short life-cycle products. Pricing decisions are an important aspect of successful remanufacturing and can secure the profitability of a firm. Remanufacturing for end-of-use products needs to cope with high uncertainties

in terms of the quality and quantity of the acquired product 31

returns. Therefore, after inspection, only a fraction of returns can be recovered through remanufacturing operations. This uncertainty in recovery yield influences the decisions impacting acquisition, wholesale, and retail prices. We propose a pricing model that accommodates the

random yield effect of product returns on pricing decisions for short life-cycle products in a closed-loop supply chain. 4

The system

consists of a retailer, a manufacturer, and a collector of used- 7

products. We apply a sequential decision approach to 1 determine the optimum pricing decision to maximize supply chain profit, according to a pricing game that places the manufacturer as a Stackelberg leader. The results indicate that an increase in remanufacturing costs and manufacturer shortage penalties increases the remanufactured product's price and decreases remanufactured product quantity and

the manufacturer's and retailer's profit. 6

The effect of recovery yield randomness on the system's profit can be mitigated by involving all

of the members of the supply chain in the 96

pricing decisions. Keywords: pricing, remanufacturing, short life-cycle product, yield of product return 1. INTRODUCTION Due to recent developments, product life cycle have been becoming shorter and shorter, especially for technology-based products. 8

Coupled with an increasing obsolescence in function and desirability, short life cycle products have created a huge amount of waste. Remanufacturing is a product recovery process that transforms used products into "like-new" condition. It can extend a product's useful life and help in reducing waste. There are three motives for remanufacturing that are often cited in the literature: ethical and moral responsibility, regulation, and profitability (Seitz, 2007). The first motive is relatively weak compared with the others, a fact that was originally noted by Ferrer & Guide (2002). The second motive relies on government regulation, which may not apply to some countries or states. The importance of profitability, however, is supported by Guide

et al. (2003), Guide et al. (2005), Atasu et al. (2008), and 52

Lund & Hauser (2010). There are three key activities

in the reverse supply chain, as 125

noted by Guide & Wassenhove (2009). They include the management of product return, issues in remanufacturing operations, and issues in remarketing the remanufactured product. Furthermore, these researchers find that the business perspective, including pricing, which is part of the market development activity, is an area that needs to be explored further. The pricing decision is an important aspect of a successful remanufacturing project and can secure the profitability of a firm. Atasu et al. (2010) find that cannibalization towards new products is not always occurred when remanufactured product is presented. Managers who understand the composition of their markets and use a proper pricing strategy should be able to create additional profit. In a similar manner, Souza (2013) notes that there are two implications when manufacturer offers remanufactured product alongside new product i.e.

a market expansion effect or a cannibalization effect; hence making the 93

pricing of the two products a critical issue. Therefore, pricing decision is very important in achieving economic advantages from remanufacturing practices. There are numerous studies on pricing remanufactured products for profit maximization. For instance, the studies by Ferrer & Swaminathan

(2006), Atasu et al. (2008), Ovchinnikov (2011), and Gan et al. (2015) 47
search for the optimal price and

quantity under a deterministic setting. However, unlike the remanufacturing of consumer and business-to-business (B2B) returns, the remanufacturing of end-of-use products needs to cope with high uncertainties

in terms of the quality, quantity, and timing of the acquired product returns. 31
After the

collected used products are inspected, only a fraction of the returns can be used in a remanufacturing operation. This uncertainty can influence pricing decisions. Moreover, neglecting recovery yields could hurt a firm, such as in Ford's attempt to enter the automotive recycling industry via Greenleaf LLC, which resulted in failure. A manager at Ford, James L. Richardson, stated that the value of the materials they bought was lower than the value for which they actually paid (Bakal & Akcali, 2006). Gan et al. (2015) focus on pricing

decisions in a closed-loop supply chain involving manufacturer, retailer 68
and

collector of used products (cores). They consider a monopolist of a single item with no constraint on the quantity of remanufacturable cores throughout the selling 3 horizon. Demand functions are deterministic and linear in price; and they represent the short life-cycle patterns along the entire phases of product life-cycle. The

objective of the proposed model is to find the optimal 104

wholesale and retail prices for both new and remanufactured products; 1
and the optimal acquisition

and transfer prices. Recently, Gan et al. (2017) propose a pricing decision model for a closed-loop supply chain 66

involving manufacturer, retailer, and collector, where the

remanufactured products are sold via separate sales channel. 112

However, both studies have not yet considered uncertainty in the recovery-yield while the returned cores are not always economically or technically feasible to remanufacture. Furthermore, they have not considered random demand, while the product life-cycle is short with an obsolescence effect that would increase the demand's uncertainty. This paper is an extension to Gan et al. (2015), where we accommodate the

effect of the random recovery yield of product returns on pricing decisions for short life-cycle products in a closed-loop supply chain. 4

A random recovery yield variable is introduced, which represents the fraction of returns that are remanufacturable. We considered

a closed-loop supply chain that consists of a manufacturer, a retailer, 1

and a collector in a pricing game under Stackelberg leadership with manufacturer as the leader. Hence, the

purpose of this study is to determine the 80

optimum wholesale price, retail price, and acquisition price and the relevant product quantities so that

the supply chain's profits can be 122

maximized. 2. LITERATURE REVIEW The importance of pricing strategy

in a closed-loop supply chain that concerns remanufacturing has been 30

previously explored in several studies (Guide & Wassenhove (2009), Atasu et al. (2010), and Souza (2013)). The results from these studies received positive responses, which can be ascertained through the ever-increasing number of studies on pricing decisions in remanufacturing practices, whether from the perspective of one member or several key members in the supply chain. 4 In many cases, remanufacturing is performed by the manufacturer, and so a hybrid system is applied. Pricing models in this setting have been discussed by several authors. Ferrer & Swaminathan (2006) study a problem where a manufacturer produces

new products during the first period and offers both new and remanufactured 55

products during subsequent periods by utilizing the returned number of used products. The

new and remanufactured products are not differentiated but 109

rather

are sold in the same market at the same price. Moreover, the proposed 41

models are developed for 2-periods monopoly and duopoly, more than two periods, and the infinite planning horizon. 1

The models aim to find the optimum quantities and

prices of new and remanufactured products that 9

will maximize profit. Extending their work, Ferrer & Swaminathan (2010) propose a similar scenario, but they differentiated

between the prices **of new and remanufactured products. Atasu et al. (2008)** 6

recognize three drivers from demand- related aspects which are competing with the Original Equipment Manufacturer (OEM) directly, having green segment as a the potential market from, and utilizing the speed of market growth. The results confirmed that these three factors have strong interactions and significant impacts on remanufacturing decisions. Furthermore, they manage to

show that remanufacturing can be an effective marketing strategy 70

and not merely a cost-saving strategy or an approach to achieving compliance with environmental regulations. In the competition with an OEM's strong brand image, the analysis shows that a remanufacturing strategy could draw more customers. Ovchinnikov (2011) proposes

a model for finding the **optimal** profit- maximizing **prices and** quantities **of remanufactured products when both new and remanufactured** 1

product are sold side by side. Customer switching behavior was also studied to understand their choices behind buying new or remanufactured products and to identify how large is the

fraction of customers who switch from buying new products **to remanufactured** 2

ones. Shi et al. (2011) propose a model

to determine the price and **quantities of new and remanufactured** product, **and the** used products' **acquisition price,** 11

which would

maximize the total profit of the supply chain. In this model, **the** price **of** 51

remanufactured products is not 5 differentiated from

new products, and both are **sold in the same market.** 29

Furthermore,

demand and return are both stochastic **and price-sensitive. The** 73

analysis shows that for a small market size, the optimal strategy is pure remanufacturing. However, for a large market, the best strategy is mixed manufacturing/remanufacturing. The effect of demand uncertainty significantly impacts the

production plan and the selling price of new **products.** Instead, **the** 26

uncertainty of return affects not only the

remanufacturing plan but also the manufacturing **plan of new products.** 26

Chen & Chang (2013) develop a

dynamic pricing model **for new and remanufactured products under** a constrained **supply of used** 1

products. The model is developed with a static environment as the benchmark and a two-period and multi-period setting over the product life cycle, to determine the optimum prices for maximizing profit. Although the products are differentiated, they are partially substitutable. Another study by Xiong et al. (2014) takes into account the lost sales and uncertain quality of used products in developing a pricing model for core product acquisition for remanufacturing companies. In this model, the demand is stochastic and the objective of the model is cost minimization over finite and infinite horizons. Several studies on pricing decisions from the remanufacturer's point-of-view are mainly focused on the

selling price of remanufactured products and the optimal acquisition price of used products 15

(Guide et al. (2003), Bakal & Akcali (2006), Liang et al. (2009), Li et al. 25

(2009)), in which the remanufacturer performs both collection and remanufacturing processes. Guide et al. (2003) claim that product recovery management is the primary driver determining the profitability of reuse activities.

They develop a model to find the optimal selling prices of remanufactured products and the acquisition prices 15

for each quality class of returns, which together maximize the manufacturer's profit. Liang et al. (2009) address the problem of collecting used products when there is a random fluctuation in remanufactured products' prices, given the condition that the remanufacturer is required to offer a certain core price to motivate customers to return the used products. The remanufactured products price is 6 presumed to follow the Geometric Brownian Motion.

A model is then developed to evaluate the acquisition price of used products. 11

Moreover, they use option principles to further

determine the selling price of the remanufactures products. 11

Remanufactured products' prices vary according to market sentiment, thus exhibiting the nature of stocks; hence, the core price shows the characteristics of the options. Other studies, rather than focusing on the effect of acquisition price

on the quantity and quality of product returns, focus on the effect of 28

random yield. For example, Bakal & Akcali (2006) develop a pricing

model to determine the acquisition and selling prices that maximize profit 75

when the

supply of used products and the demand for remanufactured parts are deterministic and price-sensitive. 45

They also investigated the effect of random yield by setting different timings for price decisions. The recovery yield refers to the

fraction of parts that are remanufacturable, and it can be 32

influenced by used products' acquisition price. The first setting takes the selling price decision after the recovery yield is calculated, and the second setting takes the pricing decision prior to the determination of the recovery yield. Hence, this model simultaneously determines the acquisition and selling prices. Later, Li et al. (2009) not only consider the effect of random yield but also random demand. They proposed an optimization model using two-step stochastic dynamic programming. First, they found the optimal selling price to maximize expected revenue and then calculated the collection price that maximizes the utility of the firm. This study is further extended in Li et al. (2014), and they study two

sequential decision strategies i.e. First- Remanufacturing-Then-Pricing (FRTP) and First-Pricing-Then-Remanufacturing (FPTR). 5

Therefore, these optimization models attempt to conclude not only the remanufactured product's optimal selling price but also the remanufacturing quantity 5

under conditions of random yield and random demand. 35

There are several approaches used in the literature that addresses random yield. Mukhopadhyay & Ma (2009) study the effect of random yield rates by comparing three cases: the

deterministic yield rate and the random yield rate with the 105

order placed both before and 7 after the actual yield is observed. Ferguson et al. (2009) propose the use of a grading system to tackle uncertainty in return quantity and uncertainty in the demand for remanufactured products. They develop a model with capacitated remanufacturing facilities for remanufacturing when returns have various quality levels. In Roy et al. (2009), the material for remanufacturing process is fed by the defective units from the production system, The rate of defectiveness is uncertain, and is approximated by a constant or fuzzy parameter. Teunter &

Flapper (2011) consider multiple quality classes and multinomial quality distribution for acquired lots and 19

find that it is necessary to obtain additional used products as safety stock to avoid cost errors. Robotis

et al. (2012) consider the random quality of returns as the source of uncertainty in 61

remanufacturing costs and propose an inspection environment setting based on the firm's ability to perform a reliable inspection of used products. Wang et al. (2011)

study a hybrid manufacturing remanufacturing system for a short life-cycle product with stochastic demand and stochastic returned products 20

to get a minimum total cost for the hybrid system. Qiang et al. (2013) provide a finite dimensional variational inequality problem as the governing equilibrium condition in the existence of stochastic demand and a returns yield rate. Ahiska & Kurtul (2014)

study a stochastic hybrid manufacturing/ remanufacturing system with substitution using a 39

discrete-time Markov Decision process,

with stochastic demand and returns. A 39

product substitution strategy and its profitability are studied, and it can be shown that profitability is significantly affected by the remanufactured-product price to manufacturing cost ratio. The pricing models within a supply chain that involve several members of the supply chain were also discussed in several studies. Qiaolun et al. (2008)

consider a supply chain that consists of a manufacturer, a retailer, and a 17

collector. These companies are involved in selling new products, collecting used core products, remanufacturing, and reselling the recovered products. The

manufacturer is the Stackelberg leader, and he determines the 118

wholesale price, whereas the retailer and collector decide on the retail price and the acquisition price of the 3

used 8 products. The return rate is influenced by end-customer's willingness, and willingness is affected by the collecting price. 57

Wei & Zhao (2011) consider fuzziness in customer demands, remanufacturing costs,

and collecting costs in a closed-loop supply chain and 64

use

fuzzy theory and game theory to find the 111

optimal retail price, wholesale price, and remanufacturing rate. There are 3

two scenarios considered, namely, centralized and decentralized decision scenarios. Wu (2012) uses game theory

to investigate the OEM's product design strategy and the remanufacturer's pricing strategy. 36

The OEM has

to consider the level of interchangeability in its product design and needs to 67

find the optimal level because

increasing the level of interchangeability would decrease the OEM' s manufacturing cost and the remanufacturer's cost in 1

the attempt to cannibalize the

OEM's product. The remanufacturer evaluates its pricing strategy and decides on either low or high pricing. 1

In this model, the demands for new and remanufactured products 87

are both linear and sensitive to price. Wu (2013), similar to Wu (2012), applies game theory to compute equilibrium decisions when determining the prices of

new and remanufactured products and the degree of the disassemblability of the 18

OEM's product design. The OEM risks price competition with the 113

remanufacturer because when the degree of disassemblability is high, it not only reduces the

OEM's production cost but also reduces the remanufacturer's recovery cost. 23

The model is constructed for two-period and multi-period problems. Moreover, the demands for

new and remanufactured products are both linear and price-sensitive. However, the 9

above studies consider only deterministic or fuzzy demand and do not consider randomness in the demand function. Jena &

Sarmah (2014) study **optimal acquisition price management in a remanufacturing system,** considering three schemes **of** 48

collection: direct, indirect, and coordinated. The model involves

a remanufacturer and a retailer and aims to **determine the** optimum core **price** 81

that maximizes profit within a single period. This study considers random demand, but only

for the remanufactured product. It is **our** goal to **study** 119

pricing decisions with random demand for both

new and remanufactured products within **a closed-loop supply chain.** 1

9 Our study focuses on the random recovery yield and random demands, and we consider all of the key members of the

closed-loop supply chain: the manufacturer, the retailer, and the 56

collector. Therefore, we consider

both new and remanufactured products and the pricing **decisions** 28

made by the above-mentioned members. A sequential decision approach is used in this study to calculate the optimal prices. The

rest of this paper is organized as follows. In section 3, **we provide a** description **of the** 14

problem, which includes the process flow, the variables involved, the demand pattern, the definitions of multiple functions, and the decision flows. The development of optimization models for each of the three key members

in the closed-loop supply chain 3

is discussed in section 4. In section 5, we provide **numerical** 65

examples and discuss several important factors in the pricing decisions. Finally, our conclusions are presented in section 6. 3. PROBLEM DESCRIPTION As depicted in Figure 1, we considered

a closed-loop supply chain that **consists of** three members: **a manufacturer, a retailer,** and a collector. **The** closed-loop system **is** 1

initiated by the production of new product, which is

sold at a wholesale price to the retailer according to **the** 90

quantity ordered. The new product is then released on the market at a retail price . After a certain period of time, some products reach their

end-of-use and become **the** objects **of** used products collection. **The** used **product** 13

is acquired by the collector at a certain acquisition price and in a quantity of . The collector performs inspection, sorting, and cleaning tasks under a random recovery yield . The portions of the collected products that are remanufacturable are then transferred to the manufacturer at a price as the inputs for the remanufacturing process. The quantity of remanufactured products made by the manufacturer is dependent on the retailer's original order quantity ( ) and the availability of the remanufacturable items. The 49

remanufactured product is then sold to the retailer at a wholesale price 12

and released on the market at a retail price . , , Figure 1. Framework of the closed-loop pricing model with a random yield The

product considered in this model is a single short life-cycle 1

item with an obsolescence effect after a certain period, in terms of obsolescence in function and desirability. The demands are random with four time frames that represent the short life-cycle pattern; this is true for both

new and remanufactured products, and they have linear prices. As 8

depicted in Figure 2, there are four time-frames considered in this model. The first time frame

[0, t1] only offers new product on the market, while the second and third 1

time frames, [t1, ?] and [?, t3], offer

new and remanufactured products. Both new and remanufactured products are 54

in increasing phase during the second time frame, but are in opposite directions during the third. In the fourth time frame [t3, T], new product is no longer manufactured, and remanufactured produce is entering its decline phase. The demand pattern over those time frames

are constructed for both the new and the remanufactured product, and the governing 1

functions follows Gan et al. (2015) i.e. dn (t) ? ??dn2d(tn

)1(?t)U?/ U??/U ?1(?t ?ke ???)U?t?? ?;0 ?;?t 97

?? t?? t3 ? dr(t) ? ???ddr2r1((tt))??VV//???1V?(hte???tV3)(t??t1?)?? ;;t1t3??tt??t3T where ? ?1?ke k? U/d0???U1? ………(3.1), where ?h ?? 1V?/ hder0???V (1t3 ?t1) ……… (3.2), where dn(t) and dr(t)

are the demand patterns for the new and the remanufactured products. 82

U is

maximum possible demand for the new product, ? is the time of 1

highest demand, λ is the 11 speed of the change in demand. Parallel definitions are applicable for V, t3, dr0, and η, respectively,

for the remanufactured product. As the demands for the 10

new and the remanufactured products are random and both depend on the price of the new product and the price of the remanufactured product, the 9

demand functions

can be expressed as: (, ,) = ()(121

1 − +) · ....(3.3) (, ,) = ()(1 − +) · ....(3.4) where and are random variables with density

functions f(x) and g(x), respectively, and cumulative distribution functions F(x) and G (x), 46

respectively. The random variable can take an additive form, as in Petruzzi & Dada (1999), Shi et al. (2011), and Jena & Sarmah (2014), or multiplicative forms,

as in Li et al. (2009), Cai et al. (2010), and Li et al. 1

(2014).

In this study, we use a multiplicative form because the 99

random variable is a non-negative number (as opposed to a real, zero-mean, random variable in the additive form). Furthermore, the random term in a multiplicative form only affects the magnitude of the demand, not the price elasticity of the demand.

The demand function information is shared to and by all members of the supply chain. The 1

pricing game mechanism begins

with the manufacturer, as the Stackelberg leader, releasing the 89

wholesale prices. This information is used by the retailer, along with an observation of the market demand, in deciding optimal retail prices and product order quantities. Similarly, the collector observes the market

demand for the remanufactured product and decides on the optimal acquisition 13

price, taking into consideration the random recovery yield. The remanufacturable-acquired products are then transferred to the manufacturer, who (re)calculates the

wholesale prices for both the new and remanufactured products. 8

Demand t1 ? t3 T time Figure 2.

Demand pattern for a product with a gradual obsolescence over time 1

List of Notations Decision variables: All variables are non-negative. : wholesale price of the new product; ≤ : retail price of the new product; ≤ : wholesale price of the new product; ≤ : price of the remanufactured product; ≤ : collection or acquisition price; ≤ Parameters: All parameters are non-negative. : collector to remanufacturer transfer price for the remanufacturable core product : retailer's order quantity for the new product : retailer's order quantity for the remanufactured product : collection quantity 12 : demand potential of the new product, excluding price sensitivity 34 : demand potential of the remanufactured product, excluding price sensitivity : new product's price sensitivity, i.e., the

sensitivity of the demand for the new product 43

to

a change in the price of the new product : remanufactured product' 21

s cross-price sensitivity, i.e., the

sensitivity of the demand for the new product 43

to

a change in the price of the remanufactured product 13 : remanufactured product' 21

s price sensitivity,

i.e., the sensitivity of the demand for the remanufactured 32

product to a change

in the price of the remanufactured product : new product's cross -price 2

sensitivity, i.e., the sensitivity of the

demand for the remanufactured product to a change in the price of the new product 13

:

random variable as the multiplicative uncertainty of the demand for the 37

new product; [0,1] :

random variable as the multiplicative uncertainty of the demand for the 37

remanufactured product; [0,1] : random yield of the product's return; [0,1] : unit shortage penalty applied to the collector by the manufacturer : unit shortage penalty applied to the manufacturer by the retailer : unit salvage value : unit raw material cost of producing the new product :

unit manufacturing cost of producing the new product : unit remanufacturing cost of producing and selling the remanufactured product : unit collection cost 34

: coefficient in the return rate function : exponent of the power function in the return rate function, which determines the curve's steepness; [0,1] 4. OPTIMIZATION The optimization model uses a sequential decision-making approach under the condition of

a Stackelberg game, with the manufacturer as the leader. The objective of the 50

pricing model is to maximize the profits of all of the 94

key players through the payment flows, shown in Figure 3. 14 4.1 Retailer's Optimization The retailer's pricing decision is very important because the demands are random and price-sensitive, which applies to the

prices of both the new product and the remanufactured 84

product. Hence, in our proposed model, the retail prices, together with the demand's random variables, are the determinants of the quantity of demand. As the Stackelberg leader, the manufacturer makes the first move in the game by releasing the initial wholesale prices and . The retailer then optimizes its retail prices through a sequential approach, as presented in (4.1) and (4.2). First, the retailer computes the optimum

quantities of new and remanufactured products (,) that maximize its profit 1

under the conditions of random demand for each product, given the predetermined retail prices, (,). Then, the optimum quantities are utilized to calculate the optimal retail prices. Figure 3. Flow of payments

in the closed-loop supply chain As the demands for 79 the

new and remanufactured products are random and price- sensitive, the 9

retailer's pricing decision significantly impacts the respective price of each product. Furthermore, the

retail prices of both products will 8

determine the size of the demands. 15 As the Stackelberg leader, the manufacturer makes the first move in the game by releasing the initial wholesale prices and . The retailer then optimizes its retail prices using a sequential approach, as shown in (4.1) and (4.2). First, the retailer calculates the optimum

quantities of new and remanufactured products (,) that maximize its profit 1

under the conditions of random demand for each product, given the predetermined retail prices (,). Then, the optimum quantities are utilized to determine the optimal retail prices. Optim 1: max, Π((,)|(,)) = (−) + (−) ………………(4.1) where (,) is the solution of Optim 2 Optim 2: max, Π((,)|(,)) = ma,x {[· min((),)] + [· min((),)] − − } ………………(4.2) where () is the total demand over [0, 3]

for the new product, which is a function 3

of the random variable , and () is the total demand over [1,T] for the remanufactured product, which is a function of the random variable . Therefore, () = ∫0 1+− (1 − +) · + ∫3 (−)+ (1 − +) · = 12(1 − +) · ……………………………………… (4.3) () = ∫13 1+ℎ−(−1) (1 − +) · + ∫3 (−3)+ (1 − +) · = 34(1 − +) · ……………………………………… (4.4) where 12 = 1 ((1+)−) ((3−)+) ……………………………………… (4.5) 34 = 1 ((1+ℎ)−(3−1)) ((−3)+) ……………………………………… (4.6) Proposition 1 The retailer's expected order quantities

for new and remanufactured products to maximize its profit 110

(4.2) under the given (retail) prices and are: = 12(1 − +)−̅1 () …………………………………… (4.7) = 34(1 − +)̅−1 () …………………………………… (4.8) Proof: First, let = 12(1−+) , which is the value of the random variable when () = , and = 34(1−+) , which is the value of the random variable when () = . These variables are similar to the stocking factor that is proposed by Li et al. (2009). The first term in (4.2) can be expressed as [· min((),)] = · [min((),)]= · {∫0 ()() + ∫1 ()} = · {∫0 ()() + ̅()}.

Similarly, the second term in (4 .2) can be written as 16

[· min((),)] = · {∫0 ()() + ̅()},

where ̅() = 1 − () and ̅() = 1 − (). 16

The optimization problem (4.2) thus becomes max, Π = m,a,x [· {∫0 ()() + ̅()} − + · {∫0 ()() + ̅()} −] ………………………… (4.9) As = 1 12(1−+) and 1 = 34(1−+) , then Π = · (12(1−+)() 12(1−+) + ̅() − 12(1−()+)) − = 0 ……. (4.10) Π = · (34(13−4(1−++))() + ̅() − 34(1−(+))) − = 0 ……. (4.11) Simplifying the equations, we find: 17 ̅(12(1−+)) = …………………………………… (4.12) ̅(34(1−+)) = …………………………………… (4.13) so that the optimal quantities are , where = 12(1 − +)−̅1 () and = 34(1 − +)̅−1 () [qed]. Proposition 2 The optimal retail prices that maximize the retailer's profit (4.1) on the order quantities of and are and , which satisfies the nonlinear system: 12(1 − 2 + +)Φ () − (−) (2) Φ′ () + 34Ψ () (−) = 0 …………………… (4.14) 34(1 − 2 + +)Ψ () − (−) (2) Ψ′() + 12Φ () (−) = 0 …………………… (4.15) where = 12(1 − +), and = 34(1 − +); Φ() = −̅1() and Ψ

() =̅−1(); and Φ ′() = (−̅1()) and Ψ ′() = (̅−1()). 58

Proof: Substituting and in (4.1), the optimization problem becomes: max, Π((,)|(,)) = 12(1 − +)−̅1 () (−) + 34(1 − +)̅−1 () (−) …………………… (4.16) Thus, the first derivative conditions are: Π = 12(1 − 2 + +)−̅1 () + 12(1 − +)(−) [−̅1 ()] + 34̅−1 () (−) = 0, and Π = 34(1 − 2 + +) ̅−1 () + 34(1 − +)(−) [̅−1 ()] + 12−̅1 () (−) = 0. As [−̅1 ()] = − (2) Φ′ () and [̅−1 ()] = − (2) Ψ′(), the resulting linear system is (4.14) and (4.15) [qed]. The optimal retail prices and are influenced by the price elasticity and the uncertainty of the respective

demands for both the new and remanufactured products. 12

However, when ascertaining the optimal retail prices, it is difficult to provide closed-form solutions. Thus, we utilize a computational approach and leave the analysis to the numerical study. 4.2. Collector's Optimization The collector's problem is significantly influenced by the random recovery yield, as only a portion () of the returned

used products meets the input requirements of the remanufacturing process. In our model, the quantity of 78

returns is influenced by the acquisition price ; an approach that has been used in several previous studies, including Qiaolun

et al. (2008), Li et al. (2009) and El Saadany & Jaber (2010). 71

The collector inspects and sorts the acquired returns and then transfers the remanufacturable items to the manufacturer at a transfer price of . Returns that do not meet the quality requirement are discarded. Because the collector determines the collected quantity of remanufacturable items before the random recovery yield is realized, the actual quantity of remanufacturable items may be higher or lower than the manufacturer's order quantity . Therefore, a shortage penalty and a salvage value are incorporated in the model. The recovery yield is a

random variable with the density function ℎ () and the cumulative distribution function (). 38

The governing equation for the collection

quantity, as a function of the acquisition price, 95

is given as: = Θ() = , ... (4.17) which is similar to the return rate used in Qiaolun et al. (2008), where is a positive, constant coefficient, and ?[0,1] is the exponent of the power function, which determines the curve's steepness. Therefore, the collector's optimization problem can be expressed as: Optim 3: max Π() = · [min(,) − [−]+ + [−]+] − (+) .... (4.18) Proposition 3 The optimal collection quantity for the collector's optimization problem (4.18) is , which satisfies: (+ −) ∫0⁄ ℎ() + () − (1 + 1) () − = 0 1 ...... (4.19) and the optimal collection price is = () 1⁄ Proof: Let = , which represents the value of when = ; thus, replacing with () 1⁄ according to the collection function (4.17), the optimization problem Optim 3 becomes: max Π() = (+ −) ∫0(−)ℎ() + (−) + () − (() 1⁄ +) .... (4.20) Applying the first derivative condition, we find: Π = (+ −) [(−)ℎ() + ∫0 ℎ()] + () − (1 + 1 1) () − = 0 .... (4.21) As = and = − 2 , the equation becomes (4.19) [qed]. The optimal collection quantity and price depends on the recovery yield's randomness, the parameters of the collection function, the order quantity of the remanufactured product, and the transfer price, as well as the shortage penalty and the salvage value (if applicable). Because

a closed-form solution is difficult to obtain, we 117

will use

a numerical study to analyze the effects of several important parameters, such as the 69

parameters for , , , and the yield's randomness. 4.3. Manufacturer' Optimization During the third stage, the manufacturer tracks the prices set and the quantities ordered by the retailer, as well as the actual quantity of remanufacturable items supplied by the collector, after the random recovery yield has been realized. Therefore, the manufacturer

is not necessarily always able to supply the retailer's order quantities of the 77

remanufactured product because the ability of the manufacturer

to meet the retailer's order-quantity is dependent on the ability of the 29

collector to meet the quantity requirements. Consequently, a shortage penalty may be imposed on the manufacturer by the retailer to increase the level of order fulfillment. Thus, the manufacturer's optimization problem is expressed as: Optim 4: max, Π = (− −) + [min(,) ·(− −) − [−]+] .... (4.22) where and are the unit raw material cost and the unit manufacturing cost, respectively, for the new product, 60

whereas is the remanufacturing cost and is the unit shortage penalty. Proposition 4 The optimal wholesale prices are and , which satisfies: Φ′ () (− −) + Φ () = 0 ………………..…………… (4.23) 1   Ψ′ () [(− −)̅() + ()] + (+ ∫0(−)𝑓()) = 0 …………………………………………… (4.24) Proof: As the retailer's optimum quantities are given in (4.7) and (4.8), the optimization problem becomes: max, Π = Φ () (− −) + [min (Ψ () ,) · (− −) − [Ψ () −]+] …………… (4.25) Let = 34(1−+)−̅1() Ψ(), which represents the value of the random recovery = yield when = . Therefore, the optimization problem can be expressed as: max, Π = Φ () (− −) +   (− −) + (− − +) ∫0(−)𝑓() …………… (4.26) As is a function of , taking the first derivative of can be accomplished by applying the chain rule with = Ψ′()   1 . Therefore, the first derivative conditions are: (1) Π = Φ′ () (− −) + Φ () = 0, which yields (4.23). (2) Π = (− −) +   + ∫0(−)𝑓() + (− − +)   [∫0(−)𝑓()] = 0, which can be simplified into (4.24) [qed]. The optimal

wholesale price for the new product depends on the retailer' s price, the raw material and 3

manufacturing unit costs, and the cumulative

distribution function of the random variable governing the randomness of the 91

new

product's demand function. It is interesting that even though the 101

demand for the

new product is sensitive to the retail price of the remanufactured product, 2

the optimal wholesale price does not depend on any parameter in the remanufacturing process flow. As for the optimal wholesale

price of the remanufactured product, along with the parallel factors in the new product's optimal wholesale price calculation, the 42

quantity of the collection, the recovery yield randomness, and the penalty factor all affect the optimum, as well as the

new product's retail price. The retailer' 3

s order quantity may change in response to the optimal wholesale prices, which are decided by the manufacturer. However, increases in wholesale prices, compared with the respective original wholesale

prices of the new and remanufactured products, will reduce the retailer's order quantities 24

under this responsive system. Furthermore, as

it is difficult to obtain closed-form 44

solutions, we will use a

numerical approach to study the effects of 44

several important factors. 5. NUMERICAL EXAMPLE The price sensitiveness of the demands for

new and remanufactured products are given as 8

= 0.003, = 0.0001, = 0,004, and = 0,0002. The demand capacity of the new product contains the parameters , 0, and , such that 12 = 4000, whereas the demand capacity of the remanufactured product involves the parameters , 0, and , such that 34 = 1500. The unit raw material

cost for the new product is = 50; the **unit** manufacturing **cost** is = 40; **the** 2

unit remanufacturing cost is = 20; and **the unit** collecting **cost is** 102

0 = 4. The parameters of the return rate function are = 0.1 and = 0.7. The collector's shortage penalty and salvage value are = 5 and = 8, respectively, whereas the manufacturer's shortage penalty is = 50. The transfer price is = 40. The initial

wholesale prices released **by the manufacturer are** 8

= 120 and = 80

for the new and remanufactured products, respectively. We use **a** uniform distribution for **the** 24

random variables in the demand functions and the recovery yield. This type of distribution is previously applied in Li et al. (2014) and Mukhopadhyay & Ma (2009). Furthermore, , , and are random variables with a uniform distribution that have finite support [0,1]. The optimization problems are solved using Matlab. We performed sensitivity analyses for several factors that are important for the pricing decision, namely, the unit remanufacturing cost, the manufacturer's shortage penalty, and the parameters of the random yield. The results are shown in Tables 1 – 4. The

existence and uniqueness of the solution to the 107

optimization problem is revealed using a graphical approach, whereby we plot the profit functions over the domain of the decision variables. These

plots can be seen in Figure 4, Figure 5, and Figure 6 for **the** retailer's, **the** collector's, **and the** 33

manufacturer's profit functions, respectively. Table 1 shows that

an increase in the remanufacturing cost will lower **the** 5

profits of the retailer and the manufacturer, although **the** 83

collector's profit is unaffected by remanufacturing cost changes. Moreover, the remanufacturing cost

does not affect the retailer's 124

or the 24 collector's pricing decisions, as shown in the analytical model, but it does affect

the wholesale price of the remanufactured product. As **the** remanufacturing cost increases, **the** 22

manufacturer responds by increasing the

wholesale price of the remanufactured product rather than decreasing **the** 108

quantity produced, as shown in Figure 7. Therefore, both the retailer and the manufacturer receive lower profits, although the manufacturer's profit decreases twice as quickly as the retailer's. Similarly, as shown in Table 2, when the manufacturer's shortage penalty increases, the

retailer's and the manufacturer's profits 6 decrease, whereas the collector's profit is again unaffected. In this scenario, the manufacturer reacts by simultaneously increasing

the wholesale price of the remanufactured product (enough to cover **the** risk **of**	22

it receiving shortage penalties)

and decreasing the produced **quantity of the remanufactured** product. Although both **the**	5

manufacturer and the retailer are hurt by the lowered profits, in this scenario, the retailer's profit decreases slightly faster than the manufacturer's (see Figure 8). Retailers profit function x 10 4 10 8 Retailers profit 6 4 2 0 250 200 300 150 250 200 100 150 pr pn Figure 4. The Retailer's Profit Function Collectors profit function 1000 500 0 Collectors profit -500 -1000 -1500 -2000 2 1 Manufacturer profit 0 -1 -2 -3 -4 20 40 60 80 100 120 140 160 180 200 qc Figure 5. The Collector's Profit Function Manufacturers profit function x 10 4 -5 200 180 160 140 120 100 200 300 prw 80 60 100 pnw Figure 6. The Manufacturer's Profit Function Table 1. Effects of changes to the remanufacturing cost 30 20 10 5 Wholesale price of new product () 171.09 171.09 171.09 171.09 Retail price of new product () 252.19 252.19 252.19 252.19 Quantity of new product () 337.62 337.62 337.62 337.62 Wholesale price of remanufactured product () 150.93 148.46 146.12 144.99 Retail price of remanufactured product () 190.44 190.44 190.44 190.44 Quantity of remanufactured product () 73.11 76.56 79.73 81.21 Acquisition price of used product () 8.26 8.26 8.26 8.26 Quantity of used product collected () 241.20 241.20 241.20 241.20 Manufacturer's profit (Π) 32,458.81 33,207.42 33,989.07 34,391.43 Retailer's profit (Π) 30,267.95 30,592.69 30,912.68 31,070.33 Collector's profit (Π) 1,207.78 1,207.78 1,207.78 1,207.78 Total system's profit (Π) 63,934.54 65,007.89 66,109.53 66,669.54 Table 2. Effects of changes to the manufacturer's shortage penalty 70 50 30 10 Wholesale price of new product () 171.09 171.09 171.09 171.09 Retail price of new product () 252.19 252.19 252.19 252.19 Quantity of new product () 337.62 337.62 337.62 337.62 Wholesale price of remanufactured product () 151.35 148.46 144.99 140.65 Retail price of remanufactured product () 190.44 190.44 190.44 190.44 Quantity of remanufactured product () 72.51 76.56 81.21 86.64 Acquisition price of used product () 8.26 8.26 8.26 8.26 Quantity of used product collected () 241.20 241.20 241.20 241.20 Manufacturer's profit (Π) 32,855.83 33,207.42 33,616.15 34,391.43 Retailer's profit (Π) 30,213.35 30,592.69 31,070.17 31,692.54 Collector's profit (Π) 1,207.78 1,207.78 1,207.78 1,207.78 Total system's profit (Π) 64,276.96 65,007.89 65,894.10 67,001.09 The shift in the mean value of the random yield influences the profits received by all three parties in a positive direction, as presented in Table 3. As the expected value of the random yield increases, a larger portion of the collected used products will meet the remanufacturing requirements. Hence, the probability of supplying less than the order quantity

decreases, and the total quantity of the remanufactured **product increases.** Furthermore, **the**	10

collection price also increases to escalate the collection quantity as a response to the higher order

quantities of the remanufactured product. All of **the**	10

members' profits increase as the expected value of the random yield increases, as a result of increased order fulfillment and reduced or fewer penalties. Consequently, the collector's percentage profit increase is significantly higher than those of the others because the recovery yield of product returns is isolated to the collector's inspection and sorting process. Table 3. Effects of changes to the mean value of the random yield U[0.1,0.7] ~[,] U[0.2,0.8] U[0.3,0.9] Wholesale price of new product () 175.84 175.84 175.84 Retail price of new product () 251.69 251.69 251.69 Quantity of new product () 318.56 318.56 318.56 Wholesale price of remanufactured product () 152.77 152.50 152.50 Retail price of remanufactured product () 193.43 193.43 193.43 Quantity of remanufactured product () 35.44 35.75 36.06 Acquisition price of used product () 6.01 6.14 6.14 Quantity of used product collected () 194.07 197.12 197.12 Manufacturer's profit (Π) 26,685.70 26,702.54 26,719.45 Retailer's profit (Π) 25,601.45 25,623.28 25,645.37 Collector's profit (Π) 801.20 957.67 1,116.61 Total system's profit (Π) 53,088.36 53,283.49 53,481.43 A similar argument applies for the variance of the random yield, as shown in Table 4.

It is interesting to note that an **increase** in **the** variance **of**	63

the random yield is responded to by a lowering of the wholesale and collection prices and that this action increases the remanufactured product's quantity, which, in turn,

increases the supply chain's profits, as shown **in**	123

Figure 9 and 10. However, the effect of the decrease in the wholesale and collection prices according to the increase in the variance of the random yield is more notable than that of changes to the mean value.

We find that the wholesale price of **the** remanufactured product **and the** 76

collection price are more robust against a shift in the mean value of the random yield rather than against a change to the random yield's variance. Table 4. Effects of changes to the variance of the random yield U[0.2,0.8] ~[,] U[0.1,0.9] U[0,1] Wholesale price of new product () 175.84 175.84 175.84 Retail price of new product () 251.69 251.69 251.69 Quantity of new product () 318.56 318.56 318.56 Wholesale price of remanufactured product () 152.50 149.23 146.94 Retail price of remanufactured product () 193.43 193.43 193.43 Quantity of remanufactured product () 35.75 39.66 42.55 Acquisition price of used product () 6.14 5.45 4.97 Quantity of used product collected () 197.12 181.25 169.83 Manufacturer's profit (Π) 26,702.54 26,914.92 27,067.62 Retailer's profit (Π) 25,623.28 25,913.33 26,138.30 Collector's profit (Π) 957.67 1,723.15 2,218.29 Total system's profit (Π) 53,283.49 54,551.40 55,424.21 The effects of the remanufacturing cost and the shortage penalty are consistent with Li et al. (2014), who demonstrated that an increase in the parameters of the remanufacturing cost and the shortage penalty

decreases the optimal **quantity of the remanufactured** product, reduces **the** 10

manufacturer's profit, and increases the

wholesale price of the remanufactured product. However, in **Li et al.** 12

(2014), the effect of the shortage penalty on the remanufacturing quantity is not conclusive, and, unfortunately, such a situation does not occur in our model. In addition to the above results, by analyzing the whole

supply chain, we find that the 6

retailer's profit is also affected by changes to **the** 86

remanufacturing cost, in terms of the extended effects of the change in remanufacturing quantity, although the collector's profit remains unaffected in this situation. Figure 7. The effect of changes to the remanufacturing cost

on the supply chain's profit Figure 8. **The** effect **of** 27

changes to the short- age penalty

on the supply chain's profit Figure 9. **The** effect **of** 27

changes to the yield's randomness on the wholesale price profit

Figure 10. The **effect of changes** to **the** yield's variance **on the** 106

supply chain's The price elasticity of the remanufactured product also has a consistent effect, as previously demonstrated in Li's work (Li et al., 2009; 2014), which showed

that an increase in the price elasticity **of the remanufactured product** decreases **the** 23

optimal remanufacturing quantity, the wholesale price, the **selling price, and the** 5

used product collection price,

which, in turn, decreases **the** total profits **of the supply chain.** 88

Table 5 shows these results. However, we observed that the effect of an increase

in the price elasticity **of the remanufactured product** on **the** 2 collector's profit is not conclusive because the collector' profit is significantly influenced by the transfer price. The determination of the transfer price should be a coordinated decision, not one that is decided by one party and then imposed upon the other, as the calculated

values of the optimum **transfer price** for **the** manufacturer **and the** 19

collector conflict. When the problem is addressed only

from the point-of-view of **the manufacturer'** s problem, **the** conflict between **the** 25

optimum transfer price values for the manufacturer and the collector may not be observed. Moreover, the effect of the remanufactured product's elasticity in relation to the new product's pricing can be studied under this model. For example, an increase

in the price elasticity **of the remanufactured product** decreases **the new product's** 2

wholesale and retail prices, as well as 114

its optimal quantity, which, taken together, result in new product pricing rates that are significantly lower than those of the remanufactured product. The development of a pricing model that involves three members of

a closed-loop supply chain shows **a** discriminated effect **of the** 92

recovery yield's randomness. A higher degree of uncertainty in the recovery yield results in a lowering of the

wholesale price of the remanufactured **product,** which leads to **increases** in **the** 3

optimal remanufacturing quantity and the manufacturer's **profit.** 5

Although Li et al. (2009) find that recovery yield randomness does not influence the manufacturer's expected profit, Li et al. (2014) show that an increase in the recovery yield's variance can

lead to an increase in the price **of the** remanufactured **product,** which then decreases **the** 53

expected quantity

and the manufacturer's profit. By 6

involving all

of the supply chain members in the pricing decisions, **the** effect **of** 17

recovery yield randomness can be mitigated and, further, can even slightly improve the total profits of the system. Table 5. Effects of changes to the price elasticity of the remanufactured product 0.003 0.004 C 0.005 0.006 Wholesale price of new product () 171.91 171.09 170.61 170.29 Retail price of new product () 253.82 252.19 251.22 250.58 Quantity of new product () 338.72 337.62 336.84 336.23 Wholesale price of remanufactured product () 179.74 148.46 129.08 115.75 Retail price of remanufactured product () 238.57 190.44 160.88 140.75 Quantity of remanufactured product () 86.64 76.56 59.72 45.75 Acquisition price of used product () 10.43 8.26 6.43 4.89 Quantity of used product collected () 285.55 241.20 201.76 166.13 Manufacturer's profit (Π) 38,018.70 33,207.42 30,619.36 29,094.53 Retailer's profit (Π) 33,453.26 30,592.69 29,051.39 28,139.37 Collector's profit (Π) 483.10 1,207.78 1,483.51 1,473.85 Total system's profit (Π) 71,955.06 65,007.89 61,154.26 58,707.75 6. CONCLUSION The

pricing decision problem facing **a closed-loop supply chain** 100 that includes remanufacturing processes

under conditions of random yield and random demand 35

is an important problem for which an acceptable solution needs to be determined because this problem significantly affects the profitability of all of the members of the supply chain. Unlike many previous studies, which generally only consider one member of the supply chain, we developed a model that involves three key members—a manufacturer, a retailer, and a collector—of a supply chain that produces, sells, collects returns, remanufactures, and resells a short life cycle product. The results show that the remanufacturing cost and the manufacturer's shortage penalty influence

the wholesale price of the remanufactured **product and** impact **the retailer'** s and **the** 59

manufacturer's profits. Decreases in the remanufacturing cost and the manufacturer's shortage penalty

increase the supply chain's total **profits.** 120

On the other hand, the mean value and variance **of the** 62

random yield have positive

effects on the supply chain's profits; the **higher the** 103

mean value and the variance of the random yield, **the** 72

higher each member's profits. We also find

that the wholesale price of the remanufactured **product is more** 30

robust against a shift in the mean value of the random yield than against a change in the random yield's variance. Whereas

previous studies found **the effect of the** shortage penalty **on the** 98

remanufacturing quantity to be inconclusive, we find that an increase in the shortage penalty is responded to by a decrease in the remanufacturing quantity and a reduction in the

profits of the manufacturer and the retailer. Moreover, we find **the** variance **of the** recovery yield **to** 18

have a 33 different effect compared with that of previous studies, as a higher variance responds by lowering the price of the remanufactured product. Hence, higher quantities result in stable and slightly higher manufacturer profits. Pricing decisions involving

a manufacturer, a retailer, and a collector working together **in** one system result **in** 14

significant improvements

to the total **profits of** the **supply chain** 116

compared with pricing decisions made solely by a manufacturer. Therefore, coordinated decisions accompanied by

information sharing among the supply chain **members** can improve **the supply chain'** 85

s performance in making pricing decisions that maximize profits for all

of the supply chain members. Finally, **this** 6

model could be extended to include coordinated decisions, which would be an important future research step. 7. REFERENCES Ahiska, S. S., & Kurtul, E. (2014). Modeling and analysis of a product substitution strategy for a stochastic manufacturing/remanufacturing system. Computers & Industrial Engineering, 72, 1-11. Atasu, A., Guide, V. D. R. J., & Wassenhove, L. N. Van. (2010). So what if remanufacturing cannibalizes my new product sales? California Management Review, 52(2), 56–76. Atasu, A., Sarvary, M., & Wassenhove, L. N. Van. (2008). Remanufacturing as a marketing strategy. Management Science, 54(10), 1731–1746. Bakal, I. S., & Akcali, E. (2006). Effects of Random Yield in Remanufacturing with Price-Sensitive Supply and Demand. Production and Operations Management, 15(3), 407–420. Cai, X., Chen, J., Xiao, Y., & Xu, X. (2010). Optimization and coordination of fresh product supply chain with freshness keeping effort. Production and Operations Management, 19(3), 261–278. 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