The Optimal Product Disposition Decision for Product Returns towards Sustainable Manufacturing

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***Abstract*— Due to the substantial growth of used product disposal and recovery, product remanufacturing has drawn significant attention by many practitioners in the last two decades. One of the major concerns is the feasibility for product recovery, which is to meet the stringent worldwide environmental requirements. In recent years, product recovery is considered as one of the appropriate approaches for achieving efficient and effective post-use life management. However, producers have to examine and determine optimal recovery plan, which is to maximise the recovery value for a remanufactured product in order to gain significant financial and environmental sustainability. This article presents a decision disposition model to examine two types of the proposed recovery configuration selections to make the comparisons of their possible recovery utilisation value of a remanufactured product. In this study, an optimization model is developed and solved using binary programming. The results obtained for numerical application in product recovery plan showed that the proposed Type-II remanufactured product with base parts to be remanufactured is practically more desirable than the Type-I remanufactured product with base part to be de-manufactured via recycling.**

***Index Terms*—sustainable manufacturing, product recovery, product remanufacturing, sustainable supply chain**

I. Introduction

The commercial market for buying remanufactured products have increased significantly due to the recent changes in environmental legislative regulations and as well as the used commercial product disposal requirements [1-3]. Consumer are now willing to consider for purchasing various types of the remanufactured products [4, 5]. In the past decades, the product remanufacturing markets have been expanding rapidly [1, 2, 6, 7]. There are also numerous consumer products that are being produced using mixed-remanufactured components and/or parts in a recoverable manufacturing system, such as remanufacturing and/or de-manufacturing via recycling only [8, 9]. An overview of the product recovery with a closed loop system is illustrated in Fig. 1 [1]. In practice, there are four alternative disposition decisions, such as those used components and/or parts from returns streams are to be reused, remanufactured, recycled and totally disposed for landfills [1, 6, 10]. Remanufactured product usually consists of multiple parts and/or components to be reused, rebuilt and recycled [2, 7]. These product recovery strategies have been proven as most effective way to decrease virgin materials usage, as well as to reduce waste disposal treatments. For example, those currently available remanufactured products include the air conditioners, heavy machineries, power bearings, water pumps, electrics motors, etc. [11-13].

In recent years, global market competitiveness has also emphasised the minimisation of recovery processing costs and manufacturing lead-time as well as the maximisation of recoverable weight contents and the total reliability of a remanufactured product. To meet these requirements, there is a need to examine the possible trade-off recovery decisions of various types of remanufactured products for establishing a sustainable manufacturing system.

For utilising remanufactured products, most customers are uncertain for their actual performance and physical reliability within post-use lifecycle stage. Producers also currently focus more on operational improvement for product recovery operations and reliability that may help increase customers' confidence level and attain market competiveness [11, 13, 14]. In recent years, many users and/or customers are keen to purchase the remanufactured products without any trouble. Johnson et al. [13] stated that one of the significant operating expenses for producing a consumer product would be product returns and recovery costs in a post-use stage. In addition, Kuik et al. [2] and Nagalingam et al. [7] emphasised on the appropriate selections of used product destinations that can reduce landfill burden significantly. Therefore, EPR strategy on any part and/or product remanufacturing is one of the significant research areas in product redesign improvement.

A. Product Returns and Recovery

In reverse supply chain management, the product recovery strategy is usually established based on various kinds of parts and/or components reuse, remanufacture and recycle. This has become an increasingly common research focus for the last 20 years, in response to higher costs of waste treatment and increased landfill burdens [4, 13, 15]. In the lifecycle management, the aim of recovery is to rebuild consumer products for sales upon receiving from returns streams.

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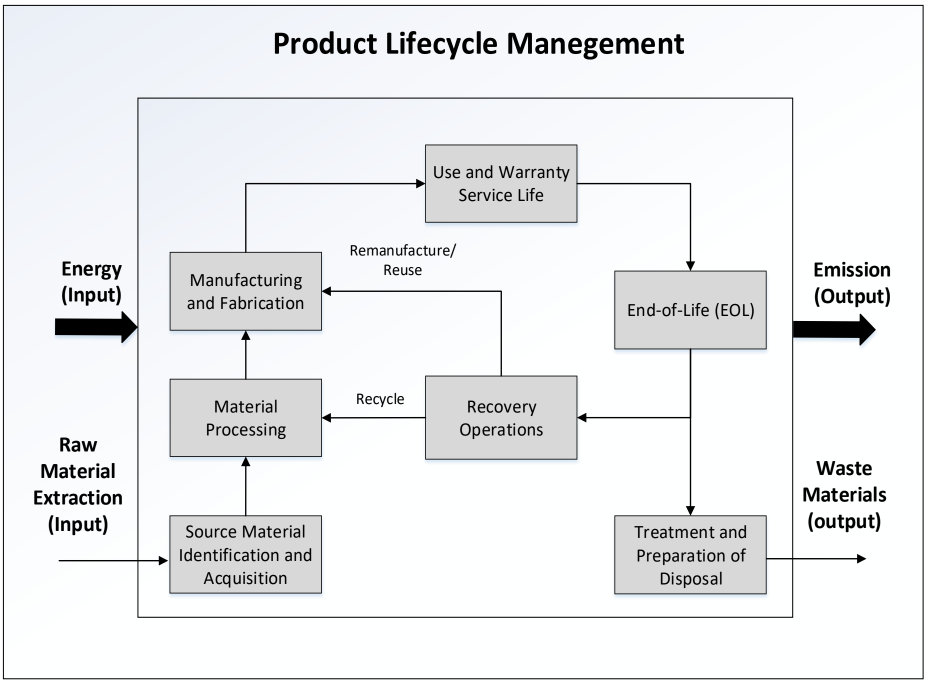

Fig. 1. An overview of the manufactured product with recovery operations [1]

Despite the good product recovery strategy to minimise used product disposal and treatment, there are many shortcomings that have been identified by researchers. One of the most critical facts is indeed product reliability and recovery operations that have been faced by most producers for improvement [2, 7, 16].

B. Product Lifecycle Management

One of the important obstructions to the profitability of product designs and recovery operations for producers is the uncertainty and variation of returns and collection rate of used products in the market. Further, the product returns management is usually focused on the bridge between reverse logistics system and remanufacturing production planning as a whole. Another significant factor is the demand fluctuation due to consumer confidence level using remanufactured products [1, 6]. Till today, a large number of consumers' preference is still on purchasing a new product, which is fabricated by use of virgin materials and/or partially recycled materials than recovery due to the reliability and quality issues [2, 7, 10].

In recent years, producers are still concerned with the increased recovery values for producing remanufactured products in the market and at the same time, maximise product reliability and manufacturing lead-time [2, 7]. Researchers also stressed on the increased returns incentive and implementation of the effective transparent returns procedures by producers that could improve used product returns management. European environmental sustainability committee has now emphasised on the extended producer responsibility (EPR) [17]. The EPR policy may stimulate producers to focus on the recovery value within returns streams when remanufactured products are produced.

Several research studies [4, 7, 11, 18] also considered the modelling of product recovery problems, including the optimization of design for assembling and/or disassembling, maximization of recovery weight upon returns, minimization of operating costs for second-hand products, and maintenance strategies for used products [2, 7, 17]. However, most of them focused on the deterministic and simplified model scenario in product returns with recovery operations [19, 20, 21, 22].

In addition, the increased value of recovery savings may not increase on the actual gained profits for producers as the technical constraint is also one of the most significant factors within a recoverable manufacturing system during its post-use stage [1]. Therefore, there are numerous research studies that focus on the used products recovery to gain market competiveness but none of them focuses on how the recovery configuration option may impact on the relationship of product recovery values, recoverable weight rate, product reliability and manufacturing lead-time [2, 7]. This research area still remains as a less focussed issue in current literature.

This article is organised as follows: in Section II, the model formulation is presented. Section III discusses the numerical example to demonstrate its usefulness of the developed model for assessing various types of the recovery configurations for a remanufactured product. Section IV presents the results and discussions for two different proposed recovery configuration for a remanufactured product. Furthermore, a comparative study is also presented. Finally, the contribution and future work are discussed briefly.

II. MODEL FORMULATION

This section presents the model formulation for product remanufacturing and redesign in the recovery decision making if the product technical specifications and its related recovery processes are known. In this study, the recovery destinations for discarded products is classified into four disposition alternatives, such as parts and/or components for a manufactured product to be reused, rebuilt, recycled and disposed entirely. A summary of the indices and parameters used for formulating optimisation model is presented in the following sub-sections.

A. Notations

The mathematical notations used in this study to formulate the optimisation model for product redesign decision for remanufactured product are summarised [20] as follows:

Decision variables:

- n — *Number of components*
- i — *Index set of product component where* $i = 1, 2, 3, ...n$
- r — *Index of virgin component,* $r = 1$*; reused component* $r = 2$*; rebuilt component,* $r = 3$ *and recycled component,* $r = 4$
- $X_{r,i}$ — *= 1 if component,* i *is virgin, reused, rebuilt, or recycled, otherwise it is 0*

Indices and parameters:

- V_{REC} — *Achievable recovery value for a manufactured product*
- op — *Cost associated with* op^{th} *operational process for a product*
- s — *Cost associated with* s^{th} *collection related activity for a product*
- TC_{REC} — *Total cost for recovery for a product*
- TC_{VIR} — *Total cost without recovery for a product*
- $C_{1,i}$ — *Raw material acquisition cost for component, i*
- $C_{2,i}$ — *Manufacturing cost for component, i*
- $C_{3,i}$ — *Assembly cost for component, i*
- $C_{4,i}$ — *Direct reuse associated cost for component, i*
- $C_{5,i}$ — *Disassembly cost for component, i*
- $C_{6,i}$ — *Rebuilt cost for component, i*
- $C_{7,i}$ — *Recycling cost for component, i*
- $C_{8,i}$ — *Disposal cost for component, i*
- $TC_{collect}$ — *Collection related costs with recovery for a product*
- $C_{1,collect}$ — *Financial incentives for a product incurred by manufacturer*
- $C_{2,collect}$ — *Administrative cost for a product incurred by manufacturer*
- $C_{3,collect}$ — *Sorting cost for a product incurred by manufacturer*
- $C_{4,collect}$ — *Transportation cost for a product incurred by manufacturer*
- MLT_{REC} — *Manufacturing lead-time with recovery for a product*
- MLT_{VIR} — *Manufacturing lead-time without recovery for a product*
- g — *Lead-time associated with* g^{th} *operational process for a product*
- μ_{MLT} — *Lead-time ratio in recovery against manufacturer's target*
- $T_{1,i}$ — *Lead-time for manufacturing of component, i*
- $T_{2,i}$ — *Lead-time for assembling component, i*
- $T_{3,i}$ — *Lead-time for direct reusing component, i*
- $T_{4,i}$ — *Lead-time for disassembling component, i*
- $T_{5,i}$ — *Lead-time for rebuilding component, i*
- $T_{6,i}$ — *Lead-time for recycling of component, i*
- $T_{7,i}$ — *Lead-time for processing disposable component, i*
- W_{REC} — *Weight recovery proportion for a product*
- W_{TOT} — *Weight proportion for a product*
- μ_W — *Weight recovery proportion ratio against manufacturer's target*
- $Z_{r,i}$ — *Weight for virgin/reused/rebuilt/recycled component, i*
- QR_{REC} — *Quality in terms of reliability characteristic with recovery for a product*
- QR_{VIR} — *Quality in terms of reliability characteristic without recovery for a product*
- μ_{QR} — *System reliability ratio against manufacturer's t target*
- $b_{r,i}$ — *Weibull parameter for component, i*
- θ_r — *Characteristic life for component, i*
- l — *Allowable lifecycle before wear-out for reused or rebuilt component, i*
- $\delta_{r,i}$ — *Mean operating hours for component, i*

In the following, the mathematical notations to be used for the optimisation model for product redesign plan is discussed in details.

B. Optimisation Model

This section discusses the development of optimisation model for product recovery decisions. An objective function is formulated to maximise total recovery value based on the total costs for a remanufactured product as shown in Eq. (1).

$$\text{Maximize } V_{REC} = TC_{VIR} - TC_{REC} - TC_{Collect} \tag{1}$$

where

$$TC_{VIR} = \sum_{i \in I} \left[X_{1,i} \left(C_{8,i} + \sum_{op \in \{1...3\}} C_{op,i} \right) \right] \tag{2}$$

$$TC_{REC} = \sum_{i \in I} \left[\begin{array}{l} X_{2,i} \left(\sum_{op \in \{3...5\}} C_{op,i} \right) + X_{3,i} \left(\sum_{op \in \{3...6\}} C_{op,i} \right) \\ + X_{4,i} \left(C_{7,i} + \sum_{op \in \{2...5\}} C_{op,i} \right) \end{array} \right] \tag{3}$$

$$TC_{Collect} = \sum_{s \in \{1...4\}} C_{s,collect} \tag{4}$$

subject to

$$\frac{MLT_{REC}}{MLT_{VIR}} \le \mu_{MLT} \quad (5)$$

$$\frac{W_{REC}}{W_{TOT}} \le \mu_{W} \quad (6)$$

$$\frac{QR_{REC}}{QR_{VIR}} \le \mu_{QR} \quad (7)$$

$$X_{2,i} + X_{3,i} + X_{4,i} = 1 \quad (8)$$

$$X_{1,i}, X_{2,i}, X_{3,i}, X_{4,i} \in \{0,1\} \quad (9)$$

where

$$MLT_{REC} = \sum_{i\in I}\left[\begin{array}{l} X_{2,i}\left(\sum_{g\in\{2..4\}} T_{g,i}\right) + X_{3,i}\left(\sum_{g\in\{2..5\}} T_{g,i}\right) \\ +X_{4,i}\left(T_{6,i} + \sum_{g\in\{1..4\}} T_{g,i}\right)\end{array}\right] \quad (10)$$

$$MLT_{VIR} = \sum_{i\in I}\left[X_{1,i}\left(T_{7,i} + \sum_{g\in\{1,2\}} T_{g,i}\right)\right] \quad (11)$$

$$W_{REC} = \sum_{i\in I}\left[X_{2,i}\left(Z_{2,i}\right) + X_{3,i}\left(Z_{3,i}\right) + X_{4,i}\left(Z_{4,i}\right)\right] \quad (12)$$

$$W_{TOT} = \sum_{i\in I}\left[Z_{1,i} + Z_{2,i} + Z_{3,i} + Z_{4,i}\right] \quad (13)$$

$$QR_{REC} = \prod_{i\in I}\left[\begin{array}{l} X_{2,i}\left(e^{-\left(\frac{\delta_{2,i}}{\theta_{2,i}}\right)^{b_{2,i}}}\right) + X_{3,i}\left(e^{-\left(\frac{\delta_{3,i}}{\theta_{3,i}}\right)^{b_{3,i}}}\right) \\ +X_{4,i}\left(e^{-\left(\frac{\delta_{4,i}}{\theta_{4,i}}\right)^{b_{4,i}}}\right)\end{array}\right] \quad (14)$$

$$QR_{VIR} = \prod_{i\in I}\left[X_{1,i}\left(e^{-\left(\frac{\delta_{1,i}}{\theta_{1,i}}\right)^{b_{1,i}}}\right)\right] \quad (15)$$

In this model, Eq. (2) is expressed as the total associated cost using virgin components and/or parts that is the summation of operational processes for producing a manufactured product. Eq. (3) is also expressed as total recovery associated cost for producing a manufactured product according to the reused related processing costs, rebuilt processing costs, and recycle processing costs and collection related costs. Eq. (4) is the collection activity related costs for a manufactured product. Meanwhile, Eqs. (5) and (6) are established based on technical constraints, including manufacturing lead-time, weight recoverable proportions, and quality in terms of reliability characteristic for a remanufactured product.

III. Numerical Example

This section presents the numerical example for comparing the proposed Type-I and Type-II remanufactured product configurations with their base to be remanufactured or de-manufactured via recycling. The detailed interpretation of the model are listed in Table III and IV for reference. Table I illustrates an analysis of proposed types for product recovery configuration selections with base part to be remanufactured and de-manufactured via recycling for comparison using binary programming in Matlab solver.

Table I. Data analysis of the Type-I and Type-II configurations

Configuration	*Type-I*	*Type-II*
V	*$61.36*	*$69.18*
MLT	*25.19%*	*22.13%*
WM	*52.32%*	*55.90%*
QR	*0.9747*	*0.9891*

In this typical scenario, a producer aims for comparing these two proposed types of recovery configuration selections for producing a remanufactured product in a recoverable manufacturing system. This study focuses on the analysis for those separate components that can be practically reused, rebuilt, de-manufactured via recycling for base part. The obtained results from these proposed types of the recovery configurations, which are named as “Type-I” and “Type-II”, are tabulated in Table I. The comparative result shows that Type-II is more desirable than Type-I as producer can achieve maximised recovery value by considering product remanufacturing.

IV. Results and Discussions

In this study, we consider the proposed “Type-I” and/or “Type-II redesign recovery decisions. There are A-Comp (6 components), B-Comp to be remanufactured (5 components), C-comp (5 components), D-comp (4 components) and E-base (5 components) for producing a remanufactured product. By comparing with both types of the recovery configurations, Type-I recovery value (i.e. about $61.36) was slightly lower than Type-II recovery value (i.e. about $69.18). Therefore, the proposed Type-II configuration is more desirable than Type-I for implementation.

Product returns with handling management, which requires close relationship among members of supply chain, is an important aspect of a reverse supply chain. In recent years, product recovery decisions for product remanufacturing is also regarded as a critical aspect in manufacturing industries. Especially, the virgin material supply associated costs, and used product disposal treatment costs have been increased significantly in the past decades. In order to achieve sustainable manufacturing, organisations need to work closely and collaboratively as well as aim to achieve realistic financial benefits that could be directly applicable within multiple stages of the product returns and recovery operations. However, management commitment and strong leadership on sustainable manufacturing is necessary to achieve significant improvement activities in product returns and recovery operations.

V. Concluding Remarks

In conclusion, this analytical study has demonstrated the recovery product redesign decisions for remanufactured products based on Type-I and Type-II configurations. Both are considered as very efficient and effective approaches for recovery improvement towards sustainable manufacturing. By comparing both types of the recovery configuration selections, Type II configuration is the better option for producer as its recovery value is higher than Type-I.

Table II. Model Type-I Remanufactured Product

Sub-assembly	*part*	*decision variables*				*Interpretation of output*
		$X_{r,i}$	$X_{r,i}$	$X_{r,i}$	$X_{r,i}$	
A-Comp.	*A*	*Entire part remanufactured*				
	A1	*0*	*1*	*0*	*0*	*Reuse*
	A2	*0*	*1*	*0*	*0*	*Reuse*
	A3	*0*	*1*	*0*	*0*	*Reuse*
	A4	*0*	*1*	*0*	*0*	*Reuse*
	A5	*0*	*0*	*1*	*0*	*Rebuild*
	A6	*0*	*0*	*1*	*0*	*Rebuild*
B-Comp.	*B*	*Entire part remanufactured*				
	B1	*0*	*0*	*1*	*0*	*Rebuild*
	B2	*0*	*0*	*1*	*0*	*Rebuild*
	B3	*0*	*0*	*1*	*0*	*Rebuild*
	B4	*0*	*0*	*1*	*0*	*Rebuild*
	B5	*0*	*0*	*1*	*0*	*Rebuild*
C-Comp.	*C*	*Entire part remanufactured*				
	C1	*0*	*0*	*1*	*0*	*Rebuild*
	C2	*0*	*0*	*1*	*0*	*Rebuild*
	C3	*0*	*1*	*0*	*0*	*Reuse*
	C4	*0*	*1*	*0*	*0*	*Reuse*
	C5	*0*	*0*	*1*	*0*	*Rebuild*
D-Comp	*D*	*De-manufacture via recycling*				
	D1	*0*	*0*	*0*	*1*	*Recycling*
	D2	*0*	*0*	*0*	*1*	*Recycling*
	D3	*0*	*0*	*0*	*1*	*Recycling*
	D4	*0*	*0*	*0*	*1*	*Recycling*
E-Base	*E*	*Entire part base de-manufacture*				
	E1	*0*	*0*	*0*	*1*	*Recycling*
	E2	*0*	*0*	*0*	*1*	*Recycling*
	E3	*0*	*0*	*0*	*1*	*Recycling*
	E4	*0*	*0*	*0*	*1*	*Recycling*
	E5	*0*	*0*	*0*	*1*	*Recycling*

Table III. Model Type-II Remanufactured Product

Sub-assembly	*part*	*decision variables*				*Interpretation of output*
		$X_{r,i}$	$X_{r,i}$	$X_{r,i}$	$X_{r,i}$	
A-Comp.	*A*	*Entire part remanufactured*				
	A1	*0*	*1*	*0*	*0*	*Reuse*
	A2	*0*	*1*	*0*	*0*	*Reuse*
	A3	*0*	*1*	*0*	*0*	*Reuse*
	A4	*0*	*1*	*0*	*0*	*Reuse*
	A5	*0*	*0*	*1*	*0*	*Rebuild*
	A6	*0*	*0*	*1*	*0*	*Rebuild*
B-Comp.	*B*	*Entire part remanufactured*				
	B1	*0*	*0*	*1*	*0*	*Rebuild*
	B2	*0*	*0*	*1*	*0*	*Rebuild*
	B3	*0*	*0*	*1*	*0*	*Rebuild*
	B4	*0*	*0*	*1*	*0*	*Rebuild*
	B5	*0*	*0*	*1*	*0*	*Rebuild*
C-Comp.	*C*	*Entire part remanufactured*				
	C1	*0*	*0*	*1*	*0*	*Rebuild*
	C2	*0*	*0*	*1*	*0*	*Rebuild*
	C3	*0*	*1*	*0*	*0*	*Reuse*
	C4	*0*	*1*	*0*	*0*	*Reuse*
	C5	*0*	*0*	*1*	*0*	*Rebuild*
D-Comp.	*D*	*De-manufacture via recycling*				
	D1	*0*	*0*	*0*	*1*	*Recycling*
	D2	*0*	*0*	*0*	*1*	*Recycling*
	D3	*0*	*0*	*0*	*1*	*Recycling*
	D4	*0*	*0*	*0*	*1*	*Recycling*
E-Base	*E*	*Entire part base remanufactured*				
	E1	*0*	*0*	*1*	*0*	*Rebuild*
	E2	*0*	*0*	*1*	*0*	*Rebuild*
	E3	*0*	*0*	*1*	*0*	*Rebuild*
	E4	*0*	*0*	*1*	*0*	*Rebuild*
	E5	*0*	*0*	*1*	*0*	*Rebuild*

For future research, we will consider different recovery configuration decisions with a focus of the product quality and reliability.

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