A robust optimisation model for hybrid remanufacturing and manufacturing systems under uncertain return quality and market demand

Han, S, Ma, W, Zhao, L, Zhang, X, Lim, MK, Yang, S & Leung, S

Author post-print (accepted) deposited by Coventry University's Repository

Original citation & hyperlink:
Han, S, Ma, W, Zhao, L, Zhang, X, Lim, MK, Yang, S & Leung, S 2016, 'A robust optimisation model for hybrid remanufacturing and manufacturing systems under uncertain return quality and market demand' *International Journal of Production Research*, vol 54, no. 17, pp. 5056-5072
https://dx.doi.org/10.1080/00207543.2016.1145815

DOI 10.1080/00207543.2016.1145815
ISSN 0020-7543
ESSN 1366-588X

Publisher: Taylor and Francis

This is an Accepted Manuscript of an article published by Taylor & Francis in Han, S, Ma, W, Zhao, L, Zhang, X, Lim, MK, Yang, S & Leung, S 2016, 'A robust optimisation model for hybrid remanufacturing and manufacturing systems under uncertain return quality and market demand' International Journal of Production Research, vol 54, no. 17, pp. 5056-5072 on 15th February 2016, available online: http://www.tandfonline.com/10.1080/00207543.2016.1145815

Copyright © and Moral Rights are retained by the author(s) and/ or other copyright owners. A copy can be downloaded for personal non-commercial research or study, without prior permission or charge. This item cannot be reproduced or quoted extensively from without first obtaining permission in writing from the copyright holder(s). The content must not be changed in any way or sold commercially in any format or medium without the formal permission of the copyright holders.

This document is the author's post-print version, incorporating any revisions agreed during the peer-review process. Some differences between the published version and this version may remain and you are advised to consult the published version if you wish to cite from it.

A Robust Optimization Model for Hybrid Remanufacturing and Manufacturing Systems under Uncertain Return Quality and Market Demand

Shuihua Han, Weina Ma, Ling Zhao, Xuelian Zhang＊, Ming K Lim

Department of Management Science, Xiamen University, China
Centre for Supply Chain Improvement, University of Derby, United Kingdom

Abstract: In remanufacturing research, most researchers predominantly emphasized on the recovery of whole product (core) rather than at the component level due to its complexity. In contrast, this paper addresses the challenges to focus on remanufacturing through component recovery, so as to solve production planning problems of hybrid remanufacturing and manufacturing systems (RMS). To deal with the uncertainties of quality and quantity of product returns, the processing time of remanufacturing, remanufacturing costs, as well as market demands, a robust optimization model were developed in this research and a case study was used to evaluate its effectiveness and efficiency. To strengthen this research, a sensitivity analysis of the uncertain parameters and the OEM's pricing strategy was also conducted. The research finding shows that the market demand volatility leads to a significant increase in the under-fulfilment and a reduction in OEM's profit. On the other hand, recovery cost reduction, as endogenous cost saving, encourages the OEM to produce more remanufactured products with the increase of market demand. Furthermore, the OEM may risk profit loss if they raise the price of new products, and inversely, they could gain more if the price of remanufactured products is raised.

Keywords: Production planning, Remanufacturing, Uncertainty, Robust Optimization Model

1. Introduction

Remanufacturing is *“an industrial process in which worn-out products are restored to like-new condition*” (Lund 1983); it is regarded as an environmentally and economically sound means to achieve some of the goals of sustainable development (Guide *et al.* 2000). Many firms have adopted core (and very limited on component) recovery in practice, such as remanufacturing of automobile components, single-use cameras, furniture, mobile-phone and personal computers. Although remanufacturing is more sustainable than the traditional way of manufacturing, it involves more uncertainty (Ilgin *et al.* 2011). The uncertainty is raised from the fact that end-of-use products are collected from multiple origins and forwarded to a single destination, which leads to both the quantity and quality uncertainties of the returned products (Gungor *et al.* 1999). Meanwhile, producers are facing market demand volatility caused by the competition of new and remanufactured products and the OEM’S pricing strategy (Ilgin *et al.* 2011), as well as customers’ tolerance for remanufactured products (Geraldo *et al.* 2006). As a result, the demand for both of the new and remanufactured products varies, which adds to the complexity of the manufacturers’ decision strategy.

Most researchers emphasized only on remanufacturing of whole product (i.e. core) rather than at the component level due to its complexity. Dong *et al.* (2011) and Han *et al.* (2013) are at the forefront of this research field by taking into account the production planning for hybrid remanufacturing and manufacturing systems (RMS) with component and product recovery in a multi-period environment. This paper further contributes to the literature by considering the uncertainties of product return’s quality, remanufacturing costs, and market demands. To address these uncertainties, this research developed a robust optimization approach, so as to assist the original equipment manufacturers (OEMs) to seek for an optimal solution to maximize their total expected profit while extensively considering the various uncertainties. Specifically, greater insights were developed in this paper by allowing the cores returned to be dissembled and the components obtained to be reused for remanufacturing. By further assuming components recovered from the same batch could be used in different periods, the proposed model in this study is more in line with the reality. Besides, the proposed model is also able to provide a more concrete production strategy when it comes to components planning problems and suggestions with regard to production and market condition changes.

The rest of this paper is organized as follows: In Section 2, the literature in relation to the remanufacturing problems is reviewed and Section 3 presents the conceptual model of a hybrid RMS. A robust optimization model for the hybrid RMS with component recovery is formulated in Section 4. In Section 5, a calculation is constructed to analyze the effectiveness and efficiency of the proposed model. Following that, the sensitivity analysis will be conducted in Section 6, and finally, the conclusions and future works will be given in the Section 7.

2. Literature Review

The literature review can be categorized into two streams. The first stream is related to the optimal policy for production planning of a hybrid RMS under uncertain environment. The second falls under the consideration of component recovery in remanufacturing production problems.

With regard to the first stream, some researchers take into account the uncertainties encountered during remanufacturing production planning (Fleischmann 1997, Dekker *et al.* 2004, Mula *et al.* 2006). To deal with the uncertainties in remanufacturing systems, a number of models have been proposed. Flapper *et al.* (2013) used Markov decision processes to investigate the optimal production policy at the minimal total costs (except for disposal costs and setup times), where manufacturing and remanufacturing operations are executed by the same single server. Reveliotis (2007) managed uncertainties in the context of optimal disassembly planning through learning-based strategies. There are other research works focusing on uncertain returns or demands (Wei *et al.* 2010, DeCrorix and Zipkin 2005, Depuy *et al.* 2007, Leung *et al.* 2007, Jin *et al.* 2011), stochastic quantity of product returns (Ferguson *et al.* 2009, Nenes *et al.* 2010, Denizel *et al.* 2010, Cai 2013), uncertain processing time (Depuy *et al.* 2007, Tang and Grubbstrom 2005) and random yield of recovery process (Bakal and Akcali 2006). However, these research works focused only on product (core) recovery. Çapraz *et al.* (2015) studied the best operational level decisions for a recovery facility to receive and handle waste electrical and electronic equipment (WEEE) and presented a mixed integer linear programming model to determine the recycling methods, types and quantities, and to provide the maximum bid price offer. Although assembly components are considered, the focus was to balance the use between different recycling methods. This proposed research inherits this stream by considering both production planning and remanufacturing operations.

In the second stream, while considering components recovered or new parts procured, the OEM has to balance on how many and when to either recover disassembled components or use new ones to produce remanufactured or brand new products in order to maximize their profit. Since end-of-use products are collected from multiple origins and delivered to a single destination, returned products incorporate both uncertainties of quantity and quality (Gungor *et al.* 1999). Some of the returned products with good conditions will directly be recovered (a.k.a. core recovery), while some with bad conditions will be disassembled to valuable components (i.e. component recovery). Although all the cores or components can be recovered to the same quality level, the recovery cost varies due to the uncertain qualities of returned products. Meanwhile, remanufactured products are the substitution of new products, but are usually sold at a lower price (Swaminathan, 2010). Due to the above complexity, most exiting papers considered only product recovery and very limited on component recovery (Whrbark *et al.* 2001, Franke *et al.* 2006, Depuy *et al.* 2007, Dong *et al.* 2011, Guo *et al.* 2014, Han *et al.* 2013). Whrbark *et al.* (2001) and Depuy *et al.* (2007) used the material requirement planning (MRP) approach to solve component recovery. Whrbark *et al.* (2001) focused on the production planning problems with component recovery under the situation of uncertain supply of used components and uncertain demand for remanufactured products. Depuy *et al.* (2007) predominantly considered the quality of returns and processing time variation at each production or assembly operation, and proposed a component purchase schedule model to avoid shortages in future periods with a low probability of meeting demand. However, MRP method is limited to highly uncertain returns and demands encountered in the remanufacturing systems. Guo *et al.* (2014) developed a multi-period stochastic dynamic program to study a firm’s disposition decision for returned end-of-use products, which can either be remanufactured and sold, or dismantled into parts that can be reused. However, they only consider the uncertain quantity of return goods, and neglected the lead time of recovery and customer segmentation. Franke *et al.* (2006) presented a remanufacturing system of mobile phones, which was similar to the system in this paper. The system included both core as well as component recovery. As they used linear optimization approach to solve the production problems, all the parameters were deterministic and the uncertainties in the system had not been explored. Dong *et al.* (2011) and Han *et al.* (2013) took into account the production planning for a hybrid RMS with production capacity constraints, the recovery of components and products, uncertain quality and processing time of return items in a multi-period setting. This research adopted their approach of classifying components according to whether they can be recovered and used in the current period or later period due to the components' different quality conditions. They include customer's preferences for new or remanufactured products and segment the customers into three groups, which are customers who accept new products only, buy remanufactured products only, and no preference for new or remanufactured products. This paper improves this aspect by introducing the utility function of customers with their preference for remanufactured products and the product price as input parameters, which jointly influence the market demand for new and remanufactured products. This paper also contributed to the literature by considering the uncertain quantity of product returns and remanufacturing costs, which are deterministic in Han *et al.* (2013) and Dong *et al.* (2011). Furthermore, this research is also able to provide justifiable suggestions to the OEMs with respect to component recovery arrangement and production plans when the production and market conditions changed.

In summary, this research extends the existing knowledge in production management of remanufacturing system. To the best of our knowledge, this research is at the forefront taking into account the production planning for hybrid RMS with components and products recovery under uncertain quality of returns and uncertain market demand for new or remanufactured products in a multi-period setting.

3. Framework of the robust optimization model

Robust optimization, first proposed by Soyster (1973), incorporates an uncertain data set to deal with uncertain parameters by considering worst cases. It has been successfully implemented to address with uncertain data on production management

(Mulvey *et al.* 1995, Bertsimas *et al.* 2004, Iyengar 2005). Robust optimization aims at finding optimal solutions that are robust to the final realization of any scenario a firm may face. In the basic term, several scenarios are specified according to the business environment, i.e. "*good*", "*fair*", or *"poor*" a firm would face. The probability each scenario would occur and the parameters, such as manufacturing cost and market demand characterizing each scenario, are based on the firm's historical data and prediction. For example, in a *good* scenario, a firm might face a boom in the market demand and a price reduction of a necessary material. Robust optimization is suitable for cases under which probabilities of different scenarios are relatively evenly distributed (e.g. $p_s = \{0.3,0.3,0.4\}$), and no scenarios dramatically dominate others while the difference between the scenarios will result in a significant yield.

Here, this paper briefly introduces the framework of robust optimization, and more details on robust optimization can be referred to Mulvey *et al.* (1995) and Yu and Li (2000). The basic robust optimization model is:

$$\mathrm{Max}\Phi = E(\xi) - \lambda E((dev(\xi))^2) - \omega E(z(\delta_s)) \quad (1)$$

$$s.t. \quad Ax = b \quad (2)$$

$$B_s x + C_s y_s + \delta_s = e_s, \ s \in \Omega = \{1, 2, \cdots, S\} \quad (3)$$

$$x \ge 0, \quad y_s \ge 0, \quad s \in \Omega \quad (4)$$

Φ is the objective function and s belongs to the scenario set Ω. Under each scenario s, the parameters related to the control constraints vary with probability p_s. ξ and $E(\xi)$ denote the net present value and the expected net present value respectively. $dev(\xi)$ denotes the deviation of the realized net present value from the expected value, and measures the solution robustness, namely how close the obtained optimal solution of this model will be robust for any realization of the scenario s. $z(\delta_s)$ denotes the infeasibility of the problem and measures the model robustness, i.e. the expected infeasibility of the obtained optimal solution for any realization of the scenario. The importance of these two robustness to the decision makers is reflected by λ, ω, which are the penalty parameters for the two robustness. x is the design variable set and Constrain (2) represents the certain aspects of the problem, i.e. the aforementioned structural constrain. y_s is the control variable set for scenarios s. Constrain (3) incorporates the uncertain parameters of the problem and allows for infeasibility with respect to the primary linear constrains by introducing auxiliary variables δ_s. In this paper, δ_s is mainly used in demand fulfilment constrains, which will be presented in Section 4.2.

It is worth noting that this research will emphasize more on the solution robustness measurement, i.e. the second term in the objective function. Its quadratic form requires a good deal of computation work for solving the robust optimization model. Yu and Li (2000) verified an efficient method to replace the quadratic term and the objective function can take the following form:

$$\max\Phi = \sum_{s=1}^{S} \boldsymbol{p}_s \xi_s - \lambda \sum_{s=1}^{S} \boldsymbol{p}_s \left\{ \xi_s - \sum_{s'=1}^{S} \boldsymbol{p}_{s'} \xi_{s'} + 2\theta_s \right\} - \omega \sum_{s=1}^{S} \boldsymbol{p}_s \delta_s \quad （5）$$

$$\text{s.t. } \xi_s - \sum_{s=1}^{S} \boldsymbol{p}_s \xi_s + \theta_s \geq 0, \text{for all } s \epsilon \Omega$$

$$\theta_s \geq 0 \text{ for all } s \epsilon \Omega$$

As it is decided by the decision makers, the penalty parameter ω with a zero value may lead to an infeasible solution, while if it is large, the infeasibility will decrease and may lead to a lower objective value.

In this case, the OEM needs to find a trade-off among the procurement cost, production cost, remanufacturing cost in a hybrid system, and the customer satisfaction to deal with uncertainties, in order to ensure that their production plan is optimal as a whole for any realization of the scenarios.

4. Robust Optimization Model for Hybrid Remanufacturing and Manufacturing Systems (RMS)

4.1 Conceptual model

The production and inventory system which was considered in this paper has been successfully implemented in a large manufacturer of mobile phone in China. Used mobile phones are collected at the customer site and transported to a disassembly plant for disassembly into components. The components, such as batteries, plastic housings, that satisfy certain specific quality requirements, are remanufactured in a remanufacturing plant. The components that do not satisfy the quality standards for remanufacturing are either used as spare-parts for the second-hand market or being disposed of. Owing to the local legislation or other reasons, some components, e.g. liquid crystal displays, are not allowed to be remanufactured. Taking the facts above, this paper classified all components into two groups: remanufacturable component group (RCG), which consists of components that can be either remanufacturable or new components (e.g. batteries, plastic housings, printed circuit boards in the mobile phone); un-remanufacturable component group (UCG), which refers to new components only (e.g. liquid crystal displays in the mobile phone).

The production planning model of a hybrid RMS is shown in Figure 1. The stages are as follows: (1) Upon arrival of the returned products, they are subject to a preliminary quality inspection; (2) If the quality of the returned products is in good conditions, they can be stocked for future use or renewed as a remanufactured product after core refurbishing, which are relatively simple and time saving; (3) Disassembling – the remaining returns will be split into remanufacturable components (unusable components are then being disposed); (4) Component recovery - considering the uncertainties of quality and recovery time of splitting components, this research classifies two types of remanufacturable components, Type A and Type B, in the hybrid RMS. Type A components, which may come from a rather new return, can either be stored or recovered to be used or resold in the current period. However, Type B components, which come from reasonable old returns with poor quality, will subject to longer time for recovery and to be used or resold in the future period; (5) Assembling – if a product is all assembled by new components, it is regarded as a new product, else if there is more than one remanufactured component in the assembled product, it is then regarded as a remanufactured product; (6) Finally, both new and remanufactured products will be released to the market in the current period.

In general, the market demand for new and remanufactured products is influenced by the customers with different preferences and willingness to pay for remanufactured products; remanufactured products are only partial substitutes for new products, namely $0 < \sigma < 1$ (Ferguson 2006). Let variable τ characterize the type of consumers according to their valuation of the new product, the willingness-to-pay of customer type τ for a remanufactured product is $\sigma\tau$. Two extreme cases exist when the customer will only buy new products ($\sigma = 0$), and new and remanufactured products are perfect substitutes ($\sigma = 1$). The demand of new and remanufactured products can be identified as a pricing function of p^n and p^r. The utility function of customer type τ choosing a new product will be $U_n = \tau - p^n$, and choosing a remanufactured product will be $U_r = \sigma\tau - p^r$. When $U_n > U_r > 0$, which means that $\tau > \frac{p^n - p^r}{1-\sigma}$, the customer will buy a new product. Then, the demand function of new products can be expressed as $Q_t - \frac{p^n - p^r}{1-\sigma}$; when $U_n < U_r$and $U_r > 0$, which means that $\frac{p^n - p^r}{1-\sigma} > \tau > \frac{p^r}{\sigma}$, the customer will buy a remanufactured product. The demand function of remanufactured products can be expressed as $\frac{p^n - p^r}{1-\sigma} - \frac{p^r}{\sigma}$.

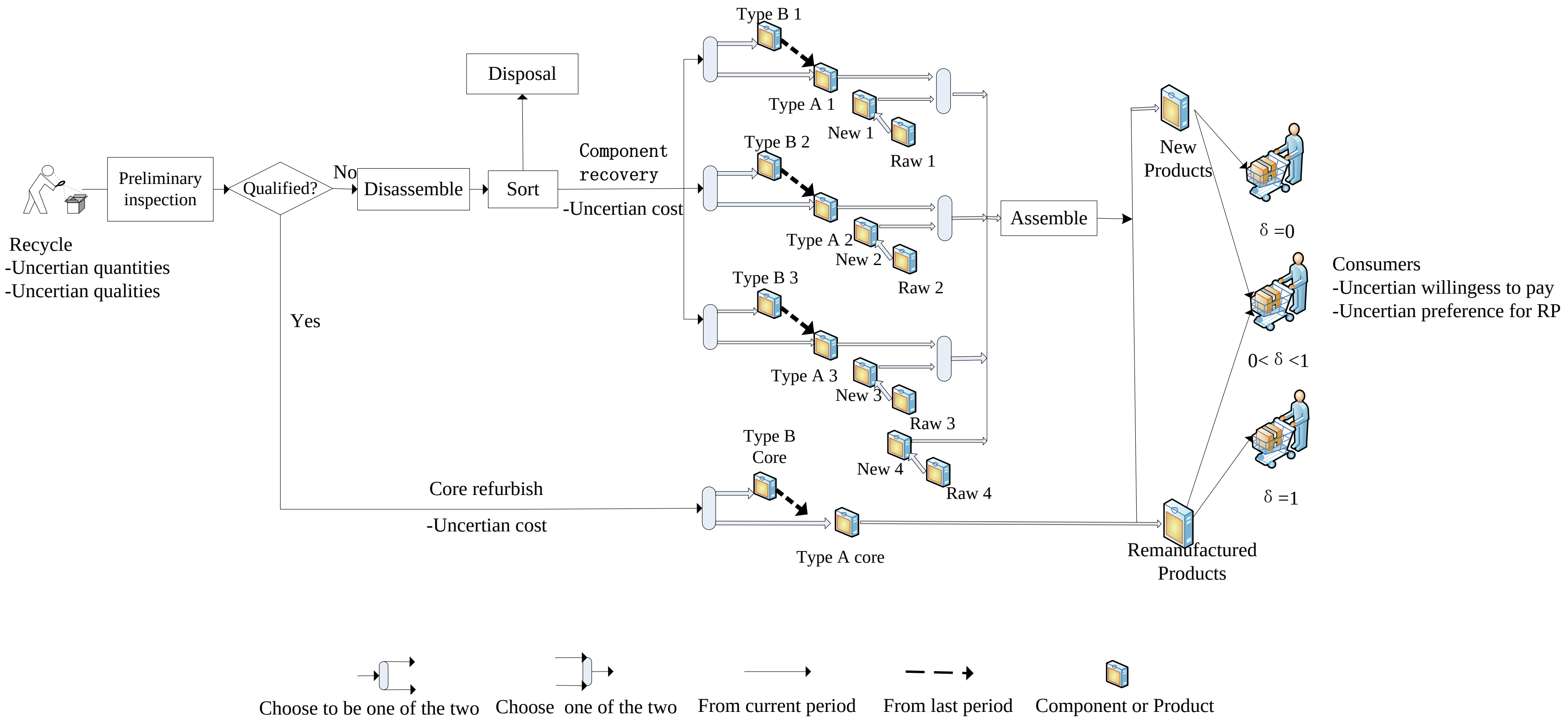


Figure 1 Manufacturing/remanufacturing hybrid system model

Some key assumptions should be made when modelling the hybrid RMS. Firstly, this research considered only the multi-period production of a single product, which is under capacity constraints. The remanufacturing operation will not affect the manufacturing operation. The quality and quantity of returned products are uncertain. The cores and components can be recovered to the same quality level but the recovery time varies. Secondly, the production processes of new components and new products are simplified. This research assumed that the supply of raw materials is always sufficient and the production of new components and products can be well scheduled, thus the inventory of raw materials and new components is not considered in the model. Finally, backorders are not considered in the hybrid RMS.

4.2 Mathematical model

Based on the conceptual model above, a robust optimization model for the production planning in hybrid RMS is formulated. Three scenarios, *good*, *fair*, and *poor*, are specified and incorporated the quantity and quality uncertainties of the returned products, the correspondingly different recovery cost, and the stochastic market demand considering the consumers' preference for remanufactured products. In order to maximize the profit, the OEM needs to determine the quantity of both new and remanufactured products over each period to respond to any realization of different scenarios.

Indices

t	Planning horizon, and $t = 1, \cdots, T$
m	The number of components in RCG
n	The number of components in UCG

i	Code of all components. When the component belongs to the cores, $i \in \{0\}$; when it belongs to the RCG, $i \in \{1,2,\dots,m\}$; when it belongs to UCG, $i \in \{m+1, m+2, \dots, m+n\}$

Parameters

p^n	Price of new products, constant every period
p^r	Price of remanufactured products, constant every period
p_i^c	Price of recovered component (or core) $i \in \{0,1,\dots,m\}$ resold to other manufacturers
CA_t	Unit assembly cost in period t
CPX_t^i	Cost of producing a new component $i \in \{1,\dots,m+n\}$ in period t
$CRC_t^{i,s}$	Cost of recovering a remanufacturable component i $\in \{1,\dots,m+n\}$ in period t under scenario s
CHP_t	Cost of holding a new or remanufactured product in period t
CHC_t^i	Cost of holding a new or recovered component (or core) $i \in \{0,\dots,m\}$ in period t
$\mathrm{CIP_t}$	Cost of inspecting a returned product in period t
$\mathrm{CDP_t}$	Cost of discarding a returned product in period t
$\mathrm{CDC_t^i}$	Cost of discarding a unusable componenti $\in \{1,\dots,m\}$ in period t
NC^i	The number of the component $i \in \{1,\dots,m+n\}$ make up each product
MI	The maximum inventory of new and remanufactured products
MC	The maximum inventory of recovered components
LNC_t^i	Average labour hours required to produce a new component $i \in \{1,2,\dots,m,m+n\}$ in period t
LRC_t^i	Average labour hours required to recover a component (or core) $i \in \{0,1,2,\dots,m\}$ in period t
LAC_t	Average labour hours required to assemble a new or remanufactured product in

	period t
MNC_t^i	Average machine hours required to produce a new component $i \in \{1,2,\dots,m,m+n\}$ in period t
MRC_t^i	Average machine hours required to recover a component (or core) $i \in \{0,1,2,\dots,m\}$ in period t
MAC_t	Average machine hours required to assemble a new or remanufactured product in period t
ML_t	Maximum available labour hours in period t
MM_t	Maximum available machine hours in period t

Control Variables

Q_t^s	Size of the potential market in period t under scenario s
σ^s	Potential customers' tolerance for the remanufactured product under scenario s
$\alpha A_t^{i,s}$	Rate of yield on component recovery by component $i \in \{1,2,\dots,m\}$ of Type A in period t under scenario s
$\alpha B_t^{i,s}$	Rate of yield on component recovery by component $i \in \{1,2,\dots,m\}$ of Type B in period t under scenario s
αC_t^s	Rate of yield on component recovery by core in period t under scenario s
TD_0^s	The initial total quantity of new and remanufactured products at the start of the planning horizon under scenario s (units)
NGI_0^s	The initial inventory level of new products at the start of the planning horizon under scenario s (units)
RGI_0^s	The initial inventory level of remanufactured products at the start of the planning horizon under scenario s (units)
$RPI_0^{i,s}$	The initial inventory level of recovered component (or core) $i \in \{0,1,2,\dots,m\}$ at the

start of the planning horizon under scenario s (units)

Decision Variables

X_t	Number of new products produced from all new components in period t
CY_t	Number of remanufactured products recovered from some new and recovered components in period t
RYU_t	Number of remanufactured products recovered from the cores in period t
RYS_t	Number of the remanufacturable cores stored in period t
RYR_t	Number of the remanufacturable cores resold in period t
PXN_t^i	Number of new component i produced and used for new products at period t, $i \in \{1,2,\ldots,m+n\}$
PXR_t^i	Number of new component i produced and used for remanufactured at period t, $i \in \{1,2,\ldots,m+n\}$
PYU_t^i	Number of recovered component i used in period t,$i \in \{1,2,\ldots,m\}$
PYR_t^i	Number of recovered component $i$resold in period t, $i \in \{1,2,\ldots,m\}$
$PYAS_t^i$	Number of recovered component i of Type A stored in period t, $i \in \{1,2,\ldots,m\}$
$PYBS_t^i$	Number of recovered component i of Type B stored in period t, $i \in \{1,2,\ldots,m\}$
TD_t^s	Total quantity of new and remanufactured products in the market in period t under scenario s (units)
RDI_t^s	Total quantity of returned products to be inspected in the hybrid RMS in period t under scenario s (units)
RDD_t^s	Total quantity of returned products to be disposed in the hybrid RMS in period t under scenario s (units)
NGI_t^s	The inventory level of new products at the end of period t under scenario s (units)
RGI_t^s	The inventory level of remanufactured products at the end of period t under scenario

s (units)

$RPI_t^{i,s}$ The inventory level of recovered component (or core) $i \in \{0,1,2,\dots,m\}$at the end of period t under scenario s (units)

4.2.1 Objective function

(a) Revenue

$$TR_s = \sum_{t=1}^{T} p^n (X_t - NGI_T^s + NGI_0^s) + \sum_{t=1}^{T} p^r (CY_t + RYU_t - RGI_T^s + RGI_0^s) + \sum_{t=1}^{T} p_0^c RYR_t + \sum_{t=1}^{T}\sum_{i=1}^{m} p_i^c PYR_t^i \tag{6}$$

Expression (6) is the revenue function. The first term is the total revenue of new products, the second term is the total revenue of remanufactured products, the third term is the total revenue of reselling remanufacturable cores, and the fourth term is the total revenue of reselling the recovered components.

(b) Assembly cost

$$TAC = \sum_{t=1}^{T} CA_t X_t + \sum_{t=1}^{T} CA_t CY_t \tag{7}$$

As for the assembly costs function, depicted as Expression (7), the first term is the assemble costs of new products and the second term is the assembly costs of remanufactured products.

(c) Production cost

$$TPC = \sum_{t=1}^{T}\sum_{i=1}^{m} CPX_t^i \left(PXN_t^i + PXR_t^i\right) \tag{8}$$

The production cost of new components in Expression (8), which includes the procurement, labour and manufacturing cost, equals to the numbers of production multiplied by the unit cost of production.

(d) Recovery cost

$$TRC_s = \sum_{t=1}^{T} CRC_t^{0,s}(RYU_t + RYR_t) + \sum_{t=1}^{T}\sum_{i=1}^{m} CRC_t^{i,s}\left(PYU_t^i + PYR_t^i\right) \tag{9}$$

Expression (9) is the recovery cost function, in which the first term is the total recovery cost of remanufacturable cores under scenario$s$, and the second term is the total recovery cost of remanufacturable components under scenario s.

(e) Inventory cost

$$THC_s = \sum_{t=1}^{T} CHP_t(NGI_t^s + RGI_t^s) + \sum_{t=1}^{T}\sum_{i=0}^{m} CHC_t^i RPI_t^{i,s} \tag{10}$$

In Expression (10), the first term is the total inventory cost of new and remanufactured products under scenario s, and the second term the total inventory cost of recovered components under scenario s.

(f) Inspection and disposal cost

$$\begin{gathered} TIDS_s = \sum_{t=1}^{T} CIP_t RDI_t^s + \sum_{t=1}^{T} CDP_t RDD_t^s + \sum_{t=1}^{T} CDC_t^0(1 - \alpha C_t^s)RDI_t^s \\ + \sum_{t=1}^{T}\sum_{i=1}^{m} CDC_t^i\left(1 - \alpha A_t^{i,s} - \alpha B_t^{i,s}\right) NC^i RDI_t^s \end{gathered} \tag{11}$$

In the inspection and disposal cost function, the first term is the total inspection cost of returned products to be recovered, the second term is the disposal cost of unused returned products, and the last two terms are the disposal cost of unused cores and components. For the reason that a component cannot be Type A and Type B at the same time, $\alpha A_t^{i,s} + \alpha B_t^{i,s} \leq 1$ must be set up for each component.

According to the framework of robust optimization, the objective function for production planning of hybrid RMS under the uncertainties of market demand and remanufacturing is formulated as follows:

$$\begin{aligned}\max \sum_{s=1}^{S} \boldsymbol{p}_s[TR_s - (TAC + TPC + TRC_s + THC_s + TIDS_s)] \\ - \lambda \sum_{s=1}^{S} \boldsymbol{p}_s \left\{ [TR_s - (TAC + TPC + TRC_s + THC_s + TIDS_s)] \right. \\ \left. - \sum_{s=1}^{S} \boldsymbol{p}_s [TR_s - (TAC + TPC + TRC_s + THC_s + TIDS_s)] + 2\theta_s \right\} \\ - \omega \sum_{s=1}^{S} \sum_{t=1}^{T} \boldsymbol{p}_s (\delta_{Nt}^s + \delta_{Rt}^s)\end{aligned} \quad (12)$$

The first and second terms are the mean and variance of total profit respectively, which denote solution robustness. The third term is the measurement of infeasibility associated with control Constraints (24) to (25) under scenario s, which denotes model robustness.

4.2.2. Structure constraints

(a) Market demand constraints

$$TD_t^s = NGI_{t-1}^s + X_t - NGI_t^s + RGI_{t-1}^s + CY_t + RYU_t - RGI_t^s, \quad \forall\, t \in T, s \in S \quad (13)$$

Constraint (13) represents the total quantity of new and remanufactured products in the market in period t equals to the total quantity of new and remanufactured products produced and recovered from the hybrid RMS plus the inventory change of new and remanufactured products during period t.

(b) Production constraints

$$NC^i X_t = PXN_t^i, \quad \forall\, i \in \{1,2,\dots,m+n\}, t \in T \quad (14)$$

$$NC^i CY_t = PYU_t^i + PXR_t^i, \quad \forall\, i \in \{1,2,\dots,m\}, t \in T, s \in S \quad (15)$$

$$NC^i CY_t = PXR_t^i, \quad \forall\, i \in \{m+1, m+2, \dots, m+n\}, t \in T, s \in S \quad (16)$$

$$\sum_{i=1}^{m} PYU_t^i \geq CY_t, \quad \forall\, t \in T \quad (17)$$

Constraint (14) represents the new products that are assembled by the corresponding number of new components. Remanufactured products are assembled by the components in RCG and UCG. Constraint (15) represents the RCG of remanufactured products that can either use new or recovered components, while Constraint (16) represents the UCG of remanufactured products that can use new components only. Constraint (17) determines the total amount of recovered components to be more than the amount of production of remanufactured products, which ensures that at least one recovered component can be used for assembling a remanufactured product.

(c) Inventory constraints

$$RPI_t^{0,s} = RYS_t, \qquad \forall\, t \in T, s \in S \tag{18}$$

$$RPI_t^{i,s} = PYAS_t^i + PYBS_t^i, \qquad \forall\, i \in \{1,2,\dots,m\}, t \in T, s \in S \tag{19}$$

$$X_t + CY_t + RYU_t \le MI, \quad \forall\, t \in T \tag{20}$$

$$RPI_t^{i,s} \le MC, \quad \forall\, i \in \{0,1,\dots,m\}, t \in T, s \in S \tag{21}$$

Constraints (18) and (19) determine the inventory level of recovered cores and components. Constraint (20) ensures the inventory level of new and remanufactured products must not be greater than the maximum inventory level at the end of each period. Constraint (21) determines the inventory capacity limit of recovered components at the end of each period.

(d) Labour and machining constraints

$$\begin{aligned} LAC_t X_t + \sum_{i=1}^{m+n} LNC_t^i\left(PXN_t^i + PXR_t^i\right) + \sum_{t=1}^{T} LRC_t^0 (RYU_t + RYR_t) \\ + \sum_{t=1}^{T}\sum_{i=1}^{m} LRC_t^i\left(PYU_t^i + PYR_t^i\right) \le ML_t, \quad \forall\, t \in T \end{aligned} \tag{22}$$

$$\begin{aligned} &MAC_tX_t + \sum_{i=1}^{m+n} MNC_t^i\left(PXN_t^i + PXR_t^i\right) + \sum_{t=1}^{T} MRC_t^0(RYU_t + RYR_t) \\ &+ \sum_{t=1}^{T}\sum_{i=1}^{m} MRC_t^i\left(PYU_t^i + PYR_t^i\right) \le MM_t, \quad \forall\, t \in T \end{aligned} \tag{23}$$

Constraint (22) ensures the labour hours required for manufacturing and remanufacturing cannot exceed maximum available labour hours, while Constraint (23) determines the machining time required for manufacturing and remanufacturing does not exceed the available machining time.

4.2.3. Control constraints

Market allocation constraints

$$NGI_{t-1}^s + X_t - NGI_t^s + \delta_{Nt}^s = Q_t - \frac{p^n - p^r}{1-\sigma^s}, \qquad \forall\, t \in T, s \in S \tag{24}$$

$$RGI_{t-1}^s + CY_t + RYU_t - RGI_t^s + \delta_{Rt}^s = \frac{p^n - p^r}{1-\sigma^s} - \frac{p^r}{\sigma^s}, \qquad \forall\, t \in T, s \in S \tag{25}$$

Constraints (24) and (25) determine whether the amounts of new and remanufactured products available in the hybrid RMS satisfy the market demand, i.e. stocks or shortages. If the total quantity of new (or remanufactured) products produced (or recovered) from the hybrid RMS during period t plus previous stock of new (or remanufactured) products is greater than market demand, the stock of new (or remanufactured) products at period t will be equal to $NGI_t^s = NGI_{t-1}^s + X_t - Q_t + \frac{p^n-p^r}{1-\sigma}$ ($RGI_t^s = RGI_{t-1}^s + CY_t + RYU_t - \frac{p^n-p^r}{1-\sigma} + \frac{p^r}{\sigma}$) and the deviation will be $\delta_{Nt}^s = 0$ ($\delta_{Rt}^s = 0$); otherwise, if the market demand is not satisfied, $NGI_t^s = 0$ ($RGI_t^s = 0$) and $\delta_{Nt}^s = Q_t - \frac{p^n-p^r}{1-\sigma} - NGI_{t-1}^s - X_t$ ($\delta_{Rt}^s = \frac{p^n-p^r}{1-\sigma} - \frac{p^r}{\sigma} - RGI_{t-1}^s - CY_t - RYU_t$). Thus, the obtained solution becomes infeasible. Note that no backorders are considered in the model, so both δ_{Nt}^s and δ_{Rt}^s are not carried over as extra demand to the next period.

4.2.4. Other constraints

(a) Robust optimization constraints

$$\begin{aligned} & TR_s - (TAC + TPC + TRC_s + THC_s) \\ & \qquad - \sum_{s=1}^{S} \boldsymbol{\rho}_s [TR_s - (TAC + TPC + TRC_s + THC_s)] + \theta_s \geq 0, \quad \forall\, s \in S \end{aligned} \tag{26}$$

Constraint (26) is converted into a robust control constraint based on Constraint (12).

(b) Non-negative integer constraints

$$\begin{aligned} & X_t,\ CY_t,\ RYU_t,\ RYS_t,\ RYR_t, PXN_t^i, PXR_t^i, PYU_t^i, PYR_t^i, PYAS_t^i, PYBS_t^i, \\ & RDI_t^s, RDD_t^s, TD_t^s, NGI_t^s, RGI_t^s, RPI_t^{i,s} \geq 0, \quad \forall\, i, t \in T, s \in S \end{aligned} \tag{27}$$

Constraint (27) ensures all the dependent variables are non-negative integers.

5. Computational Result

The data from an OEM of a mobile phone in Southern China was collected to study the performance of the proposed robust optimization model, and to explore the OEM’s optimal profits and production plan considering the possible scenarios. Three scenarios were specified, which are “*good*”, “*fair*”, and “*poor*”, with a probability of 0.4, 0.3, 0.3 respectively. Note that Hause and Lund (2003) reported customers’ willingness-to-pay for remanufactured products were an average of 35-55% discount to new products, it is assumed that the customers’ tolerance for remanufactured products is 0.42, 0.47, 0.55 accordingly. Different scenarios also incorporate the uncertainties that were previously mentioned, including quantity and quality uncertainties of the returned products, and the corresponding recovery costs, and the stochastic market demand taking into account consumers’ preference for remanufactured products.

The following is the description of decision making in the production planning process.

(1) A product composed of four components was considered: Component 1, Component 2, Component 3 and Component 4. Components 1, 2 and 3 belong to RCG and Component 4 belongs to UCG.

(2) Six periods of production cycle are considered.

(3) The price of the new product is 1500 and that of remanufactured product is 700. The available labour time is 2000h.

(4) The OEM adopts a safety stock policy on products, components and raw materials. The initial inventory, including products, components and raw materials is zero.

(5) It is assumed that the returned product quantity and the total market demand scales are all in normal distributions: $RDI_t^s \sim normal(300,50)$, $Q_t^1 \sim normal(2500,100)$, $Q_t^2 \sim normal(3500,100)$ and $Q_t^3 \sim normal(4500,100)$. The value for each period is generated by a normal distribution generator, as listed in Table 1.

Table 1. Total market scale and returned product quantity

Scenario		*Period*					
		1	*2*	*3*	*4*	*5*	*6*
Total market scale	*Good*	4458	4421	4576	4527	4343	4434
	Fair	3423	3531	3640	3498	3438	3648
	Poor	2449	2554	2563	2424	2805	2584
Returned products quantity		318	281	346	261	306	249

(6) Since type B needs more time to recover than type A, the recovery cost of type B component was set higher than that of type A. Assume that component remanufacturing costs are subject to normal distribution, the costs under Scenario 2 are 1.4 times more than Scenario 1, while under Scenario 3 are 1.4 times more than Scenario 2. The distribution of remanufacturing costs of Type A and type B are as

follows:

$$\Omega(cost\ of\ Type\ A) = \{N(\mu,\sigma) * 1.4n, [(0,1),(1,2),(2,3)]\}\ n = 0,1,2;$$

$$\Omega(cost\ of\ Type\ B) = \{N(\mu,\sigma) * 1.4n, [(3,4),(4,5),(5,6)]\}\ n = 0,1,2;$$

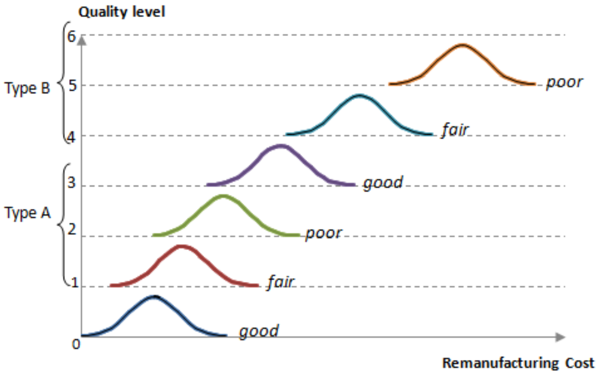


Figure 2. Remanufacturing cost under different scenarios

5.1 The Influence of uncertainties on the system

To examine the influence of endogenous uncertainty (remanufacturing cost) and exogenous uncertainty (market demand) with respect to scenarios separately, this research firstly fixed both the remanufacturing cost and total market demand scale in a fair status and obtained the optimal solution (Experiment I). Then, the volatility of recovery cost for different scenarios was introduced to explore the way it influences the OEM's profit and the production plan's robustness (Experiment II). Next, the recovery cost in the fair status was fixed and the market demand variation's influence on those indexes was examined (Experiment III). Finally, the system with mixed scenarios of uncertainties of both recovery cost uncertainty and total market demand scale was examined (Experiment IV). The profit and under-fulfilment of each experiment is shown in Table 2.

It can be seen that the introduction of the market demand volatility brings a significant increase in the under-fulfilment and a reduction of profit in the OEM if comparing

Experiments III and IV with Experiments I and II, which exclude the uncertainty of market demand. However, if comparing Experiments III with IV, their difference in both profit and under-fulfilment is not significant. This result addresses the problems OEM faced to manage market demand uncertainties, which cause the manufacturing cost to rise in order to handle the satisfaction of customers under good, fair or poor scenarios. Therefore, the OEM should pay more attention to exogenous market demand variations and adjust production planning strategy accordingly. The details about OEM's optimal solution obtained for such a hybrid RMS with uncertainties are discussed in the next section.

Table 2. Experiments for introducing uncertainties into the system ($\omega = 500$)

	Market demand	*Recovery cost*	*Expected Under-fulfilment*	*Expected Profit*
Experiment I	Fixed	Fixed	3213	6174268
Experiment II	Fixed	Volatile	3212	6174858
Experiment III	Volatile	Fixed	5635.8	4061702
Experiment IV	Volatile	Volatile	5613.6	4059998

5.2 OEM's optimal solution

Based on the mixed scenario which OEM most often faces in reality, this research further validated the obtained optimal solution of the system. The total cost and total profit under different scenarios are given in Table 3. Table 4 shows the under-fulfilment for each scenario.

Table 3. Revenue, costs and profits under different scenarios

Scenario	*Good*	*fair*	*poor*
Total revenue	9601000	9601000	9562500
Total costs	5520728	5524197	5530312
Total profits	4080272	4076803	4032188
Expected profits		4059998	
Expected Under-fulfillment		5613.6	

Table 4. Expected under-fulfilment for different scenarios

	Scenario	*Period*							Expected under-fulfilment
		1	2	3	4	5	6	Total	
Shortage for New products	*Good*	1731	1599	1745	1834	1270	1582	9771	4449.6
	Fair	851	854	954	951	510	941	5061	
	Poor	0	0	0	0	0	0	0	
Shortage for Remanufactured products	*Good*	480	483	478	**485**	**453**	**296**	**2675**	**1164**
	Fair	235	238	233	**240**	**208**	**51**	**1205**	
	Poor	0	0	0	0	0	0	0	
Total Expected under-fulfilment									5613.6

Based on Table 3, the good scenario yields the highest revenue and lowest manufacturing cost, and the most net profit. For both new and remanufactured products, the demand under poor scenario will be totally satisfied, while under fair and good scenarios there would be a certain amount of shortage.

If further examine the production plan in Table 5, it shows that for new products, the poor scenario would be just satisfied, and for remanufactured products, the production would surpass the poor scenario demand and most of them come from core recovery. The reason is that new products incur higher costs. If the new products could not be sold, the corresponding procurement, inventory, assemble cost may badly affect the OEM’s expected profit. For component manufacturing and recovery plan, take Component 1 for example, the new Component 1 will just meet the production plan plus the safety stock, and a total of 180 recovered Component 1 are used for remanufactured products.

Table 5. Production plan (Component 1 as an example)

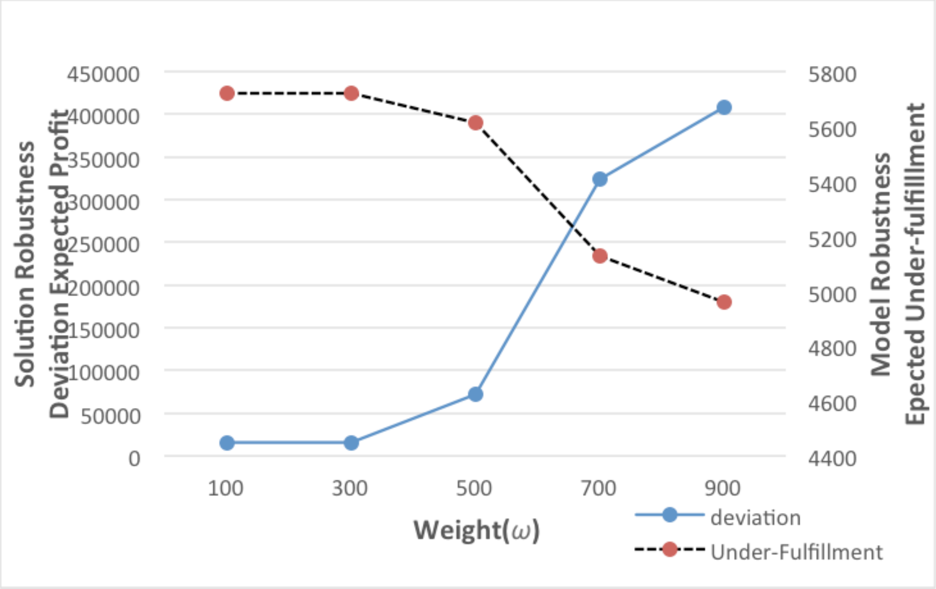
Production type	*Period*					
	1	*2*	*3*	*4*	*5*	*6*
New products	939	1044	1053	914	1295	1074
Remanufactured products	25	22	27	**20**	**90**	**171**
Recovered Core type A	25	22	27	20	24	19
Recovered Core type B	0	0	0	0	38	0
New component 1 produced	1039	1044	1053	914	1295	1074
New used for remanufactured products	0	0	0	0	0	0
Recovered component 1 used for remanufactured products	0	0	0	**0**	**28**	**152**

Besides uncertain manufacturing and market conditions, the optimal production plan and the corresponding profit the OEM can make are also closely related to the OEM’s aversion to out-of-stock, which is represented by the penalty weight ω in the robust model. The following section would cover the influence of the out-of-stock penalty weight.

5.3 The influence of the penalty weight on the system

Robust optimization allows infeasibility in the control constraints. In the proposed model, the infeasibility goes to the under-fulfilment of the market demand representing the out-of-stock aversion of the decision maker. The penalty weight plays a role in finding a trade-off between solution robustness (close to an optimal solution) and model robustness (close to a feasible solution). When ω increases, the solutions of the model are more feasible, but get further away from optimal.

Figure 3 shows the results of the trade-off between the robust solutions and the model robustness under the change of ω. A profit standard deviation is a measure of profit solutions for robustness; the greater the profit standard deviation is, the more deviation it would be from the optimal solutions. An unsatisfied demand expectation is used to measure the model robustness; the smaller the expectation value is, the less quantity of unsatisfied demand would be, and hence, the model of solutions is more viable.



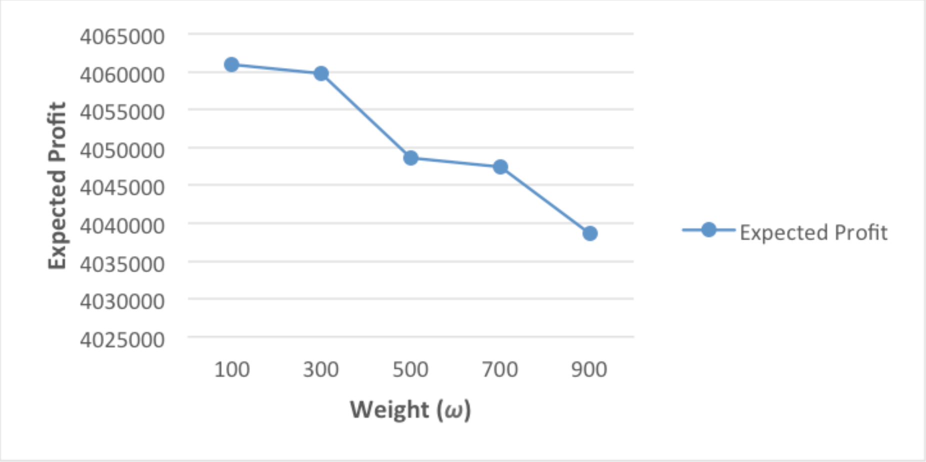


Figure 3. Trade-off between robust solution and model robustness

With the increase of ω, the profit standard deviation becomes larger, and the unsatisfied demand expectation reduced and corporate profits declined. A further analysis was conducted to the results as follow. Robust optimization allows the control constraints to be viable. If the constraints are not a viable option, the acts should be penalized. If ω=0, there is no punishment for the viable acts, and the unsatisfied demand is maximum. At this point, the customer demand is totally satisfied under poor scenario, while the demands under general and good scenarios are not completely satisfied, and the unsatisfied demand will be at the highest. Increasing ω means stock penalties increased. If the punishing costs exceed the scope of OEM can bear, the OEM is bound to increase production to reduce the volume of unsatisfied customer demand. As production increased further, the customer demands are also met under fair scenario. Continue to increase ω, the production volume will continue to expand, and the poor and the fair scenarios will face the problem of oversupply. On one hand, under the poor and fair scenarios, the product revenue will be at maximum and will not continue to increase. On the other hand, the expansion of production makes the production cost and inventory cost increased under poor and fair scenarios. While the production under good scenario revenue is increased, yet it is less than the amount of the cost of sales have increased, therefore the total profits will decline.

This is a different result from Mulvey and Ruszczynski (1995). In the hybrid RMS, unsatisfied demand expectation will not end with 0. Because the hybrid system has restrictions on the production capacity and the returns' quantity, so the production volume is limited. Even if the penalty costs increased, enterprises have no more conditions to expand the production volume. Therefore, the OEM's estimation of the loss of out-of-stock should be made meticulously in order to obtain a satisfactory solution.

6. Sensitivity Analysis

In previous sections, the uncertainties were analyzed with respect to different scenarios in the hybrid RMS that lead to difficulty for the OEM to manage production, and have a significant impact on their performance regarding to revenues, costs, profits and under-fulfilment. In this section, it is further investigated into how the range of these uncertainties affects the OEM's optimal solution.

6.1 Sensitivity analysis of the recovery cost

Since remanufacturing cost constitutes a major part of the total production cost, the rise and fall of the recovery cost level may also have an influence on the optimal solution for the OEM. Therefore, the effect of the variation of recovery cost is also worth investigating.

In the fourth period the OEM improves their remanufacturing technology and the recovery cost for the subsequent three periods was reduced by 20%. Table 6 shows the corresponding optimal revenues, costs and profits. Table 7 is the data of customer satisfaction, and Table 8 listed the updated production plan, with Component 1 as a representative for components. To highlight, the data that change comparing to when there is no cost savings was also listed (relative data in Tables 4 and 5 are in bold).

With lower recovery cost in the latter three periods, production costs and total revenues have increased, leading to a higher profit. The explanation is that since remanufacturing becomes more profitable, from the fourth period, the OEM will naturally choose to assemble more remanufactured products to better meet the market demands. As shown in Table 7, the expected under-fulfilment for remanufactured products is reduced from 1164 units (see Table 4) to 983.4, the extra supply mainly contributing to the good and fair scenarios.

Similarly, if comparing Table 8 from Table 5, the production plan would be to assemble 301 more remanufactured products with recovered components in the latter three periods. The amount of recovered Component 1 is also increased by 301 units.

Meanwhile, the amount of the un-remanufacturable component (i.e. Component 4), should be increased accordingly.

So, if the OEM is able to predict technological improvement, preparations for production change can be made in advance, say procuring more un-remanufacturable components, so that the OEM can respond more rapidly.

Table 6. Revenue, costs and profits with recovery cost savings under different scenarios

Scenario	*Good*	*Fair*	*Poor*
Total revenue	9937700	9937700	9562500
Total costs	5693949	5706092	5734137
Total profits	4243751	4231608	3828363
Expected profits	4115492		
Expected Under-fulfillment	5433		

Table 7. Expected under-fulfilment with recovery cost savings for different scenarios

	Scenario	*Period*			*Expected under-fulfilment*
		4	*5*	*6*	
Shortage for Remanufactured products	Good	**331**	**306**	**296**	
	Fair	**86**	**61**	**51**	
	Poor	0	0	0	983.4

Table 8. Production plan with recovery cost savings (Component 1 as an example)

Period	*4*	*5*	*6*
Production quantity of remanufactured products	**174**	**237**	**171**
Recovered component 1 used for remanufactured products	**154**	**175**	**152**

6.2 Sensitivity analysis of product price

The pricing strategy plays an important role as part of the OEM's decision. According to the customers' utility and preference for remanufactured products, the actual demand for new or remanufactured products would vary for different prices. At the same time, the pricing also influences the sales revenues. So, this is how the range of prices affecting the system's performance was investigated.

Firstly, the new product price $p^n = 1500$ was fixed to examine the effect of the remanufactured product price ranging. Figure 4 shows the sales revenue, total cost will increase as the price of remanufactured products increases. The reason is that when the price of remanufactured products goes up, the demand for them will shrink and the demand for new ones will grow. Thus, the OEM would produce more new products, which leads to higher production cost, sales revenue and higher profit.

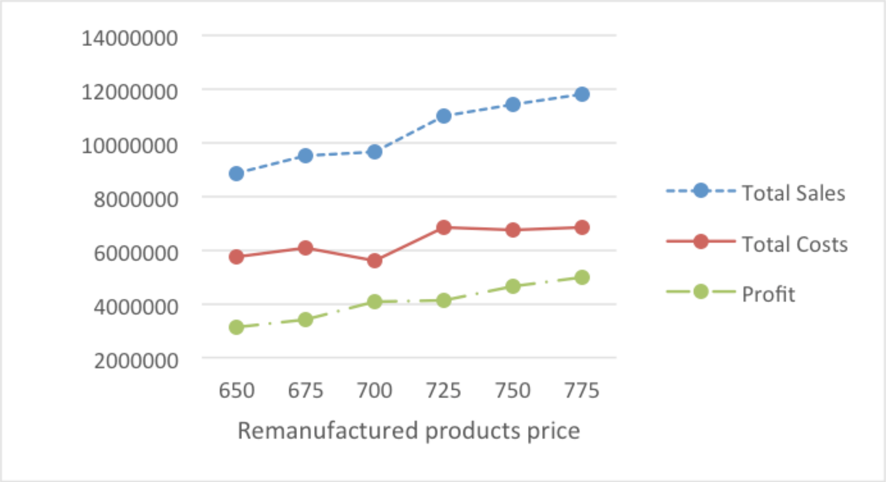


Figure 4. Total sales, costs and profits with different remanufacturing product price

Secondly, the price of the new products was changed while fixing the price of the remanufactured products $p^r = 700$. It is noticed from Figure 5 that when p^n is smaller than 1600 and as the price of the new products goes up, the total revenue and total manufacturing costs will decrease, resulting in a lower profit. That is because the demand of new products shrinks for higher new product price while that of the remanufactured product would goes up, given the total market demand scale.

Consequently, the OEM would produce more remanufactured products and the net profit drops. If the price is high enough, say above 1600 in this study, the higher price can make up for sales revenue, and reverse slightly the decreasing trend of the net profit. To conclude, in this study, the OEM risks more profit loss if they raise the price of new products. However, they will gain more profit if the price of the remanufactured products grows.

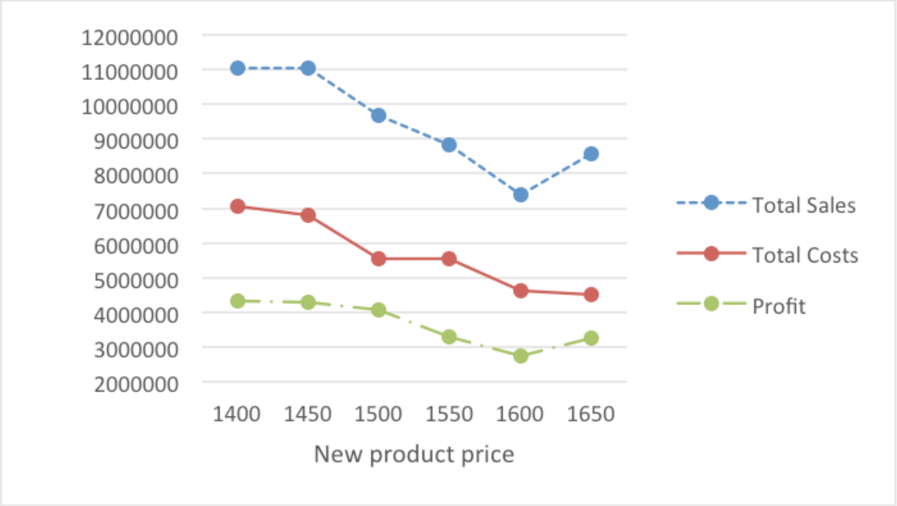


Figure 5. Total sales, costs and profits with different new product price

7. Conclusions and Future Works

In this paper, a production planning model was proposed for hybrid remanufacturing and manufacturing systems (RMS) with component recovery where the product returns have different quality levels and uncertain market demands. An extensive numerical study was conducted to illustrate the performance of the proposed model with respect to business indexes and response to exogenous and endogenous condition variations.

Some managerial implications are as follows. Firstly, the market demand volatility brings a significant increase in the under-fulfilment and a drop in the OEM’s profit. To deal with the scenario-based optimization problem, the general method is, for new products, to fill only the demand under the worst scenario, since new product manufacturing cost is high and pursuing low under-fulfilment will dramatically hurdle the net profit. On the other hand, remanufactured products can surpass the worst scenario's demand to ensure market demand increase in better scenarios for the remanufacturing cost is lower.

Secondly, the penalty weight ω represents the OEM's attitude towards out-of-stock aversions. With the increase of ω, the production volume will expand, and the profit standard deviations became larger and unsatisfied demand expectations reduced. When ω is large enough, oversupply will occur in worse scenarios, under which the sales revenue will be at the maximum while the costs increase. If the market favour under good scenario cannot make up for the loss brought by more production, the total profit will decline. Therefore, the OEM's estimation of the aversion of out-of-stock and their own cost structure should be made meticulously to obtain a satisfactory optimal solution.

Endogenous cost savings, like recovery cost reduction, would encourage the OEM to produce more remanufactured products, contributing to making up the demand of better scenarios. Therefore, if a technological improvement is under process, the OEM can prepare more materials for un-remanufacturable components for production planning.

As for the pricing strategy, in this study, the OEM risks greater profit loss if they raise the price of new products. This is due to the fact that there would be a certain drop in the new product market demand under which the reduction of the profit from the new products cannot be offset by the slight increase in the remanufactured product market. However, the OEM can gain more profit if they raise the price of the remanufactured products, under which case the profit gain from the increased new product market surpass the loss from the remanufactured products.

There are several potential future works beyond the current research. For instance, this paper considers only one type of product to be remanufactured, so a mixture of multiple products manufacturing/remanufacturing production planning can be made on the basis of this model extension. Furthermore, this proposed model was from the OEM's standpoint and assumed that the price of remanufactured products and new products had little impact on the purchasing behaviour of customers, which in itself is a space for exploratory. Lastly, this study considers only robust optimization model under the condition of uncertain demand and fixed returned amount; production planning under uncertain demand and returns scenarios still remains a problem to be solved.

Acknowledgment

This research was supported by the National Natural Science Foundation of China under Grant 70971112.

Reference

[1]. Bakal, I. S., & Akcali, E. (2009). Effects of Random Yield in Remanufacturing with Price-Sensitive Supply and Demand. Production and Operations Management, 15, 407–420.
[2]. Bertsimas D, Sim M. The price of robustness. Operations Research 2004; 52 (1):35–53.
[3]. Cai, X., Lai, M., Li, X., Li, Y., & Wu, X. (2013). Optimal acquisition and production policy in a hybrid manufacturing/remanufacturing system with core acquisition at different quality levels. European Journal of Operational Research, 233(2), 374-382.
[4]. Çapraz, O., Polat, O., Gungor, A. (2015) Planning of Waste Electrical and Electronic Equipment (WEEE) Recycling Facilities: MILP Modelling and Case Study Investigation, Flexible Services and Manufacturing Journal, (Articles in Press).
[5]. DeCroix, G. A., & Zipkin, P. H. (2005). Inventory Management for an Assembly System with Product or Component Returns. Management Science, 51(8), 1250-1265.
[6]. Dekker, R., Fleischmann, M., Inderfurth, K., & Van Wassenhove, L. N. (2004). Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains. Interfaces , 35, 103–104.
[7]. Denizel, M., Ferguson, M., & Souza, G. (2010). Multiperiod Remanufacturing Planning With Uncertain Quality of Inputs. IEEE Transactions on Engineering Management,57(3), 394-404.
[8]. DePuy, G. W., Usher, J. S., Walker, R. L., & Taylor, G. D. (2007). Production planning for remanufactured products. Production Planning and Control, 18(7), 573–583.
[9]. Dong, M., Lu, S., & Han, S. (2011). Production planning for hybrid remanufacturing and manufacturing system with component recovery. In Advances in Electrical Engineering and Electrical Machines (pp. 511-518). Springer Berlin Heidelberg.
[10]. Ferguson, M., Guide, V. D., Koca, E., & Souza, G. C. (2009). The Value of Quality Grading in Remanufacturing. Production and Operations Management, 18, 300–314.
[11]. Ferrer, G., & Swaminathan, J. M. (2006). Managing New and Remanufactured Products. Management Science, 52(1), 15-26.
[12]. Ferrer, G., & Swaminathan, J. M. (2010). Managing new and differentiated remanufactured products. European Journal of Operational Research, 203, 370–379.
[13]. Flapper, S. D., Gayon, J.-P., & Lim, L. L. (2014). On the optimal control of manufacturing and remanufacturing activities with a single shared server. European Journal of Operational Research, 234, 86–98.
[14]. Fleischmann, M., Bloemhof-Ruwaard, J. M., Dekker, R., van der Laan, E., van Nunen, J. A. E. E., & Van Wassenhove, L. N. (1997). Quantitative models for reverse logistics: A review. European Journal of Operational Research, 103(1), 1-17.

[15]. Franke, C., Basdere, B., Ciupek, M., & Seliger, S. (2006). Remanufacturing of mobile phones-capacity, program and facility adaptation planning. Omega, 34, 562–570.

[16]. Geyer, R., Van Wassenhove, L. N., & Atasu, A. (2007). The Economics of Remanufacturing Under Limited Component Durability and Finite Product Life Cycles. Management Science, 53(1), 88-100.

[17]. Guide, V. (2000). Production planning and control for remanufacturing: industry practice and research needs. Journal of Operations Management, 18, 467–483.

[18]. Gungor, A., & Gupta, S. M. (1999). Issues in environmentally conscious manufacturing and product recovery: a survey. Computers & Industrial Engineering, 36(4), 811-853.

[19]. Guo, S., Aydin, G., & Souza, G. C. (2014). Dismantle or remanufacture? European Journal of Operational Research, 233(3), 580–583.

[20]. Han, S. H., Dong, M. Y., Lu, S. X., Leung, S. C. H., & Lim, M. K. (2013). Production planning for hybrid remanufacturing and manufacturing system with component recovery. Journal of the Operational Research Society. 64(10): 1447-1460.

[21]. Hauser W, Lund R. The remanufacturing industry: anatomy of a giant. Boston, MA: Boston University, 2003.

[22]. Ilgin, M. A., & Gupta, S. M. (2011). Performance improvement potential of sensor embedded products in environmental supply chains. Resources, Conservation and Recycling, 55, 580–592.

[23]. Iyengar G. N. Robust dynamic programming. Mathematics of Operations Research 2005; 30(2): 257–280.

[24]. Jin, X., Ni, J., & Koren, Y. (2011). Optimal control of reassembly with variable quality returns in a product remanufacturing system. CIRP Annals-Manufacturing Technology, 60(1), 25-28..

[25]. Lund, R. T. (1983). Remanufacturing, United States experience and implications for developing nations. Center for Policy Alternatives, Massachusetts Institute of Technology, (Vol. 31).

[26]. Leung, S. C., Tsang, S. O., Ng, W. L., & Wu, Y. (2007). A robust optimization model for multi-site production planning problem in an uncertain environment. European Journal of Operational Research, 181(1), 224-238.

[27]. Mula, J., Poler, R., Garcia-Sabater, J. P., & Lario, F. C. (2006). Models for production planning under uncertainty: A review. International journal of production economics, 103(1), 271–285.

[28]. Mulvey, J. M., Vanderbei, R. J., & Zenios, S. A. (1995). Robust Optimization of Large-Scale Systems. Operations Research, 43(2), 264-281.

[29]. Nenes, G., Panagiotidou, S., & Dekker, R. (2010). Inventory control policies for inspection and remanufacturing of returns: A case study. International Journal of Production Economics, 125, 300–312.

[30]. Reveliotis S.A. (2007). Uncertainty management in optimal disassembly planning through learning-based strategies. IIE Transactions39(6): 645 – 658.

[31]. Soyster A.L. Convex programming with set-inclusive constraints andapplications to inexact linear programming.Operations Research 1973; 21 (5): 1154–1157.

[32]. Tang, O., & Grubbström, R. W. (2005). Considering stochastic lead times in a manufacturing/remanufacturing system with deterministic demands and returns. In International Journal of Production Economics (Vol. 93–94, pp. 285–300).

[33]. Wei, C., Li, Y., & Cai, X. (2011). Robust optimal policies of production and inventory with uncertain returns and demand. International Journal of Production Economics, 134(2), 357-367.

[34]. Whybark, D. C., & Hill, C. (2001). Material planning for a remanufacturing facility. Production and Operations Mangement, 10, 112–124.

[35]. Yu, C. S., & Li, H.L. (2000). A robust optimization model for stochastic logistic problems. International Journal of Production Economics, 64(1), 385-397.