Substitution in a hybrid remanufacturing system

Sarah Marshall ¹ and Tom Archibald ²

¹School of Computer and Mathematical Sciences
Auckland University of Technology
Auckland, New Zealand
sarah.marshall@aut.ac.nz

²University of Edinburgh Business School, University of Edinburgh
Edinburgh
United Kingdom
t.archibald@ed.ac.uk

12th Global Conference on Sustainable Manufacturing
September 2014
Outline

Introduction - Product Recovery & Remanufacturing

Previous Literature

Modelling approach

Computational Experiments & Challenges

Conclusion & Future Directions
What is product recovery?

Used products are:

- returned to producer or specialised facility
- recovered (e.g., repaired, recycled, remanufactured)
- reused/ resold
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Why is it important?

- economic benefits
- legislation
- green image
- shortage of new materials
Introduction - Product Recovery

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A product recovery system

Key papers:
Schrady (1967); Teunter (2004); Simpson (1978); Inderfurth (1997)
Remanufacturing returns products to an “as-new” condition.

Remanufactured products are typically cheaper than new products.

Remanufactured products are typically sold with the same warranty as the equivalent new product.

A hybrid remanufacturing system produces new goods and remanufactures used goods.
Markets for Remanufactured Products

Single Market
Remanufactured products are:
- as good as new
- sold alongside newly produced products

Separate Markets
Remanufactured products are:
- functionally similar to newly produced products
- sold on a separate market
- perceived to be inferior to newly produced products
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Operational issues in hybrid remanufacturing

Different from production system

- additional inventories to manage
- coordinating returns and recovery
- option to offer substitution between markets

Uncertainties

- quality, quantity and timing of returns
- demand for new and recovered goods
- willingness of customers to accept substitution
Previous Literature
A hybrid remanufacturing system with separate markets

Key papers: Federgruen et al. (1984); Inderfurth (2004); Bayindir et al. (2007); Kaya (2010); Li et al. (2006); Jaber and El Saadany (2009); Piñeyro and Viera (2010)
Previous literature – Summary

- Most assumes recovered goods are as good as new
- Only a few papers consider quality of returns
- Two types of substitution
  - downward substitution - superior product fulfils demand for inferior product
  - upward substitution - inferior product fulfils demand for superior product
- Most assumes one-way, downward substitution only
- Assumes acceptance of substitution is known
Hybrid remanufacturing with two-way substitution

- Stochastic demand, returns, quality of returns
- High quality returns $\rightarrow$ recovered “in full”
- Low quality returns $\rightarrow$ recovered for components
- Two-way substitution, consumer acceptance is uncertain
- Substitution decisions: strategic and operational
Hybrid remanufacturing with two-way substitution

When should production and recovery be performed and when should substitution be offered in order to maximise the total reward?
Remanufacturing Process

- **Used Inventory**

- **Recovery**
  - \( a_r \)
  - \( a_r - x_q \)
  - \( x_q \)

- **High Quality Recovery**
  - \( x_q - a_h(x_q) \)
  - \( a_h(x_q) \)

- **Low Quality Recovery**
  - \( a_l(x_q) \)
  - \( a_d(x_q) \)

- **Component Inventory**

- **Remanufactured Inventory**
Semi-Markov Decision Process

<table>
<thead>
<tr>
<th>Elements</th>
<th>Product recovery with substitution</th>
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<tbody>
<tr>
<td><strong>Decision Epochs</strong></td>
<td>when system is reviewed and a decision made (time between is stochastic)</td>
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<tr>
<td><strong>States</strong></td>
<td>inventory levels: $i_p, i_r, i_u, i_c$ outstanding orders: $i_{op}, i_{or}$</td>
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<tr>
<td><strong>Rewards/Costs</strong></td>
<td>production, recovery, ordering, and substitution costs; holding costs; lost-sales costs; sales revenue</td>
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<td><strong>Transition Probabilities</strong></td>
<td>demand, returns, quality of returns, acceptance of substitution</td>
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<tr>
<td><strong>Actions</strong></td>
<td>production, recovery and buying: $a_p, a_r, a_b$ substitution: $a_U, a_D$</td>
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We want to find an optimal (reward-maximising) policy which specifies the action for a given state. Strategic level substitution decision - none, down, up, two-way.
Model Formulation

Let $\delta(x) = 1$ if $x > 0$ and 0 otherwise.

- Exponential inter-arrival time between decision epochs, independent Poisson processes with rates:
  - Completion of a production order $\mu_p$
  - Completion of a recovery order $\mu_r$
  - Demand for produced goods $\lambda_p$
  - Demand for recovered goods $\lambda_r$
  - Arrival of a batch of returns (size of batch is a random variable) $\lambda_u$

- Expected time till next decision epoch $\tau_i(a) = \frac{1}{\lambda(i,a)}$, where $\lambda(i,a) = \lambda_r + \lambda_p + \delta(i_{op} + a_p)\mu_p + \delta(i_{or} + a_r)\mu_r$

- State will be updated depending on type of decision epoch
  - If substitution is offered, accepted with probability $\alpha_U$, $\alpha_D$
Next State

The state of the system is:
(used, produced, remanufactured, components, outstanding production, outstanding recovery)

Examples of state transitions:
If there is an outstanding production order (of size $j_{op}$) and the next event is the **arrival of a production order** then the next state is:

$$(i_u, i_p + j_{op}, i_r, i_c + a_b - j_{op}, 0, j_{or})$$

If there is **demand $d$ for a recovered item**, the next state is:

$$(i_u, i_p, i_r - d, i_c, j_{op}, j_{or}) \quad i_r \geq d$$

$$(i_u, i_p, i_r, i_c, j_{op}, j_{or}) \quad i_r < d, a_D = 0$$

$$(i_u, i_p, i_r, i_c, j_{op}, j_{or}) \quad i_r < d, a_D = 1 \text{ and substitution is rejected}$$

$$(i_u, i_p - d, i_r, i_c, j_{op}, j_{or}) \quad i_r < d, a_D = 1 \text{ and substitution is accepted}$$
Value Iteration Algorithm

Value Iteration Algorithm for MDP

Step 0  Initialise $v_0(s) = 0$ for $s \in S$, $n = 0$.  

Step 1  For all states $s \in S$, compute $V_n(s)$

$$V_n(s) = \max_{a \in A(s)} \left\{ R(s, a) + \sum_{s' \in S} p(s'|s, a)V_{n-1}(s') \right\}$$

and determine the policy $\pi_n(s)$ for all $s \in S$, where

$$\pi_n(s) = \arg \max_{a \in A(s)} \left\{ R(s, a) + \sum_{s' \in S} p(s'|s, a)V_{n-1}(s') \right\}$$

Step 2  Compute the bounds $m_n = \min_{s \in S}\{V_n(s) - V_{n-1}(s)\}$ and $M_n = \max_{s \in S}\{V_n(s) - V_{n-1}(s)\}$

Step 3  Stop the algorithm with policy $\pi_n$ if: $0 \leq M_n - m_n \leq \epsilon$

Otherwise, set $n := n + 1$ and return to Step 1.
Solution Methodology

Optimal policy $\pi$
Specifies an action $a = (a_p, a_r, a_b, a_U, a_D)$ that maximizes the long run average reward for each state $s \in S$.

Finding an optimal policy

- Can use the well-established **value iteration algorithm** adjusted to “convert” to a discrete time model.

  \[ \bar{R}(i, a) = \frac{R(i,a)}{\tau_i(a)} \]
Computational Experiments

Computational Burden

- State space and action space are very large
- e.g. max inventory= 20, then $21^6 > 85$ million states.
- Limited number of problem scenarios investigated
- Value iteration algorithm is computationally intensive

Test problems

- 60 problems to address a range of situations - some adapted from Konstantaras and Papachristos (2008)
- Simplifications:
  - Fixed order size based on expected demand (20 problems x 3 order sizes)
  - Components only bought when needed
  - Customers arrive individually and demand a single good
- Most taking 10-15 min, some taking over 20 min
Rewards across substitution strategies

![Graph showing average rewards for different substitution strategies across various problems. The x-axis represents problem numbers from 1 to 20, and the y-axis represents average rewards. The graph compares four substitution strategies: none, down, up, and twoway.]
Relative reward increase from substitution

![Graph showing relative reward increase for different problems with 'down', 'up', and 'twoway' categories.]
Findings

Substitution:

- upward substitution was almost always offered, whereas downward substitution was sometimes offered
- can allow firms to increase their profit
- can sometimes lead to an increase in their fill-rates
- impacts the optimal policy:
  - downward sub $\rightarrow$ recovery frequency $\downarrow$
  - upward sub $\rightarrow$ production frequency $\downarrow$

Value of substitution: Offering substitution can improve system performance, (reward $\uparrow$), but impacts the nature of the optimal policy.
Limitations & Opportunities for Future Research

- Number and size of problems is small - a larger systematic computational study is required.
- Optimal policy structure is complicated so impractical to implement - heuristic policies?
- Limited insight into structure of policy
- Computational Burden – alternative solution methods?
Thank you for your attention

Questions?
References