Substitution in a hybrid remanufacturing system

Sarah Marshall [1] and Tom Archibald [2]

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

[2]University 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

What is product recovery?

Used products are:

- returned to producer or specialised facility
- recovered (eg repaired, recycled, remanufactured)
- reused / resold

Introduction - Product Recovery

What is product recovery?

Used products are:

- returned to producer or specialised facility
- recovered (eg repaired, recycled, remanufactured)
- reused / resold

Why is it important?

- economic benefits
- legislation
- green image
- shortage of new materials

Introduction - Product Recovery

What is product recovery?

Used products are:

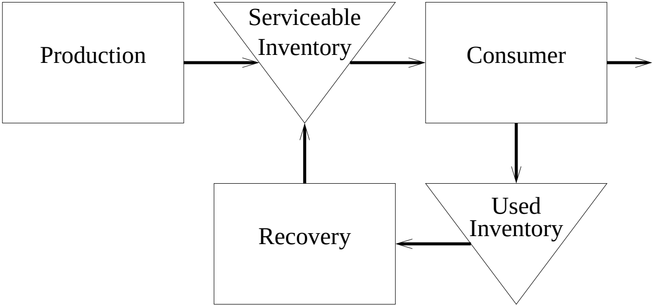
- returned to producer or specialised facility
- recovered (eg repaired, recycled, remanufactured)
- reused / resold

Why is it important?

- economic benefits
- legislation
- green image
- shortage of new materials

Industries

A product recovery system



Key papers:
Schrady (1967); Teunter (2004); Simpson (1978); Inderfurth (1997)

Remanufacturing

- 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

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

Operational issues in hybrid remanufacturing

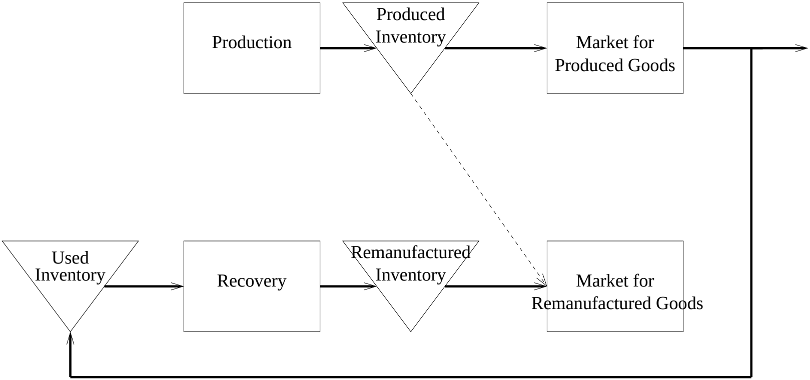
Different from production system

- 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

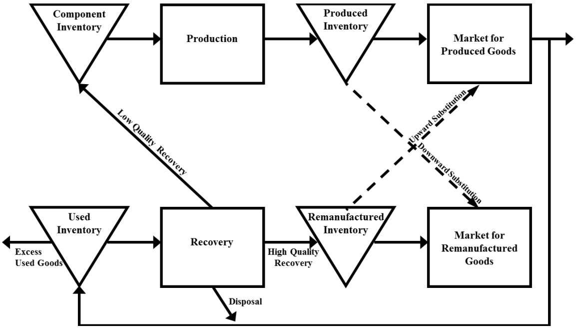


Key papers: Federgruen et al. (1984); Inderfurth (2004); Bayindir et al. (2007); Kaya (2010); Li et al. (2006); Jaber and El Saadany (2009); Piñeyro and Viera (2010)

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

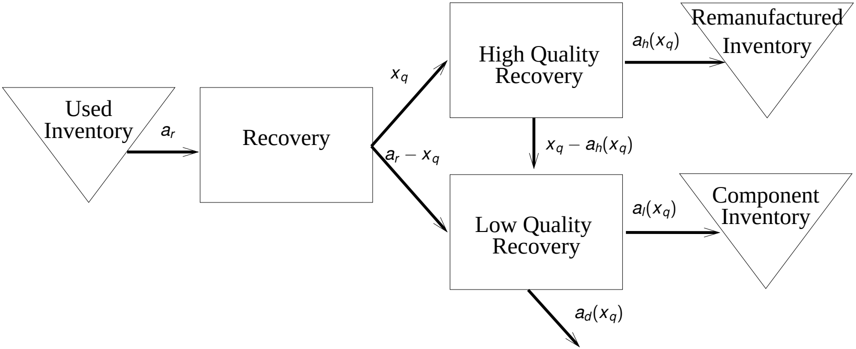


- Stochastic demand, returns, quality of returns
- High quality returns $\rightarrow$ recovered "in full"
- Low quality returns $\rightarrow$ recovered for components
- Two-way substitution, consumer acceptance is uncertain
- Substitution decisions: strategic and operational

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



Semi-Markov Decision Process

Elements	*Product recovery with substitution*
Decision Epochs	when system is reviewed and a decision made (time between is stochastic)
States	inventory levels: i_p, i_r, i_u, i_c outstanding orders: i_{op}, i_{or}
Rewards/Costs	production, recovery, ordering, and substitution costs; holding costs; lost-sales costs; sales revenue
Transition Probabilities	demand, returns, quality of returns, acceptance of substitution
Actions	production, recovery and buying: a_p, a_r, a_b substitution: a_U, a_D

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 μ_p
  - Completion of a recovery order μ_r
  - Demand for produced goods λ_p
  - Demand for recovered goods λ_r
  - Arrival of a batch of returns (size of batch is a random variable) λ_u
- Expected time till next decision epoch $\tau_i(a) = \frac{1}{\lambda(i,a)}$, where $\lambda(i,a) = \lambda_r + \lambda_p + \lambda_p + \delta(i_{op} + a_p)\mu_p + \delta(i_{or} + a_r)\mu_r$
- State will be updated depending on type of decision epoch
- If substitution is offered, accepted with probability α_U, α_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:

$$\begin{array}{ll} (i_u, i_p, i_r - d, i_c, j_{op}, j_{or}) & i_r \geq d \\ (i_u, i_p, i_r, i_c, j_{op}, j_{or}) & i_r < d, a_D = 0 \\ (i_u, i_p, i_r, i_c, j_{op}, j_{or}) & i_r < d, a_D = 1 \text{ and substitution is rejected} \\ (i_u, i_p - d, i_r, i_c, j_{op}, j_{or}) & i_r < d, a_D = 1 \text{ and substitution is accepted} \end{array}$$

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 π_n if: $0 \le M_n - m_n \le \epsilon$

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

Solution Methodology

Optimal policy π

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.
  e.g. $\overline{R}(i, a) = \frac{R(i,a)}{\tau_i(a)}$

Computational Experiements

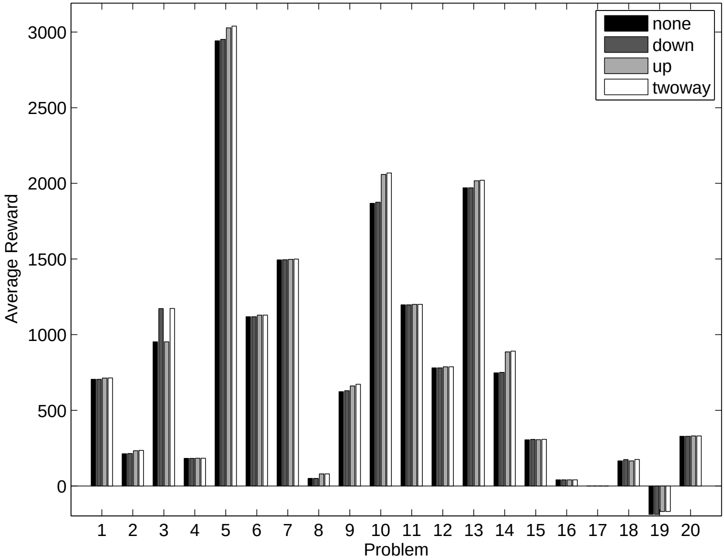
Computational Burden

- 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

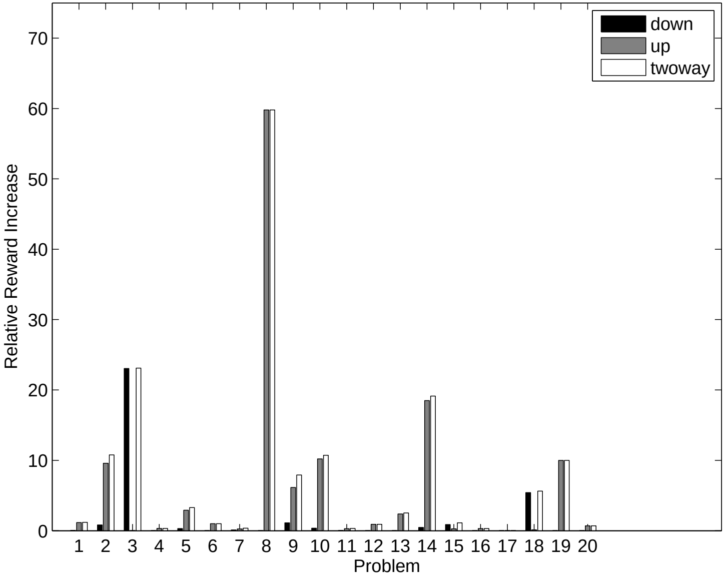
Test problems

- 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



Relative reward increase from substitution



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 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

Bayindir, Z. P., Erkip, N., Güllü, R., 2007. Assessing the benefits of remanufacturing option under one-way substitution and capacity constraint. Computers & Operations Research 34 (2), 487–514.

Federgruen, A., Groenevelt, H., Tijms, H. C., 1984. Coordinated replenishments in a multi-item inventory system with compound poisson demands. Management Science 30 (3), 344–357.

Fleischmann, M., Kuik, R., 2003. On optimal inventory control with independent stochastic item returns. European Journal of Operational Research 151 (1), 25–37.

Fleischmann, M., van Nunen, J. A. E. E., Gräve, B., 2003. Integrating closed-loop supply chains and spare-parts management at ibm. Interfaces 33 (6), 44–56.

Inderfurth, K., 1997. Simple optimal replenishment and disposal policies for a product recovery system with leadtimes. OR Spektrum 19 (2), 111–122.

Inderfurth, K., 2004. Optimal policies in hybrid manufacturing/remanufacturing systems with product substitution. International Journal of Production Economics 90 (3), 325–343.

Inderfurth, K., van der Laan, E., 2001. Leadtime effects and policy improvement for stochastic inventory control with remanufacturing. International Journal of Production Economics 71 (1-3), 381–390.

Jaber, M. Y., El Saadany, A. M. A., 2009. The production, remanufacture and waste disposal model with lost sales. International Journal of Production Economics 120 (1), 115–124.

Kaya, O., 2010. Incentive and production decisions for remanufacturing operations. European Journal of Operational Research 201 (2), 442–453.

Kiesmüller, G. P., Scherer, C. W., 2003. Computational issues in a stochastic finite horizon one product recovery inventory model. European Journal of Operational Research 146 (3), 553–579.

Kiesmüller, G. P., van der Laan, E. A., 2001. An inventory model with dependent product demands and returns. International Journal of Production Economics 72 (1), 73–87.

Konstantaras, I., Papachristos, S., 2008. A note on: Developing an exact solution for an inventory system with product recovery. International Journal of Production Economics 111 (2), 707–712.

Li, Y. J., Chen, J., Cai, X. Q., 2006. Uncapacitated production planning with multiple product types, returned product remanufacturing, and demand substitution. OR Spectrum 28 (1), 101–125.

Nakashima, K., Arimitsu, H., Nose, T., Kuriyama, S., 2002. Analysis of a product recovery system. International Journal of Production Research 40 (15), 3849–3856.

Nakashima, K., Arimitsu, H., Nose, T., Kuriyama, S., 2004. Optimal control of a remanufacturing system. International Journal of Production Research 42 (17), 3619–3625.

Piñeyro, P., Viera, O., 2010. The economic lot-sizing problem with remanufacturing and one-way substitution. International Journal of Production Economics 124 (2), 482–488.

Schrady, D. A., 1967. A deterministic inventory model for reparable items. Naval Research Logistics Quarterly 14 (3), 391–398.

Simpson, V. P., 1978. Optimum solution structure for a repairable inventory problem. Operations Research 26 (2), 270–281.