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FEMM Working Paper No. 30, September 2009

F E M M

Faculty of Economics and Management Magdeburg

Working Paper Series

On how the acquisition of recoverable parts influences the profitability of spare parts management for durables

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Abstract

In the management of spare parts for durables OEMs often face a sharp decline in sales of spare parts when the warranty period of their products ends. One reason for this effect is given by the high profitability of the after sales market which attracts competitors. If the competitors' main sourcing option consists of repairing used or broken parts, an acquisition of those parts by the OEM might lower competition and increase sales. The purpose of this paper is to provide a case-based framework to offer insights on the opportunity of recovering parts. We consider a two-stage supply chain, where independent repair shops are responsible for handling the repair process. There are two options to meet spare parts demand: repair shops may replace the part with a new one (ordered from the OEM) or they may use a part that they repaired before. While repair shops achieve a larger profit by repairing parts, the OEM would prefer the use of new parts. However, he has no control on demand which might be obtained through buyback of broken parts. Furthermore, the OEM could recover these parts on a higher level, thus reducing production/procurement of new parts. The main contribution of this paper is to elaborate the important effects of recoverable items acquisition on spare parts demand by using a simple deterministic framework thus outlining the impact of different parameters on the profitability of spare parts management.

Key words: Closed-Loop Supply Chains, Spare Parts, Competition in Product Recovery, Case Study

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1. Introduction

An efficient spare parts management is of strategic importance for Original Equipment Manufacturers (OEM) producing durable goods. In fact, OEMs must assure the availability of an after sales service enabling the replacement of broken parts during the entire product life cycle (PLC) and also for a given period in the post PLC. By regulation in many countries, the provision of spare parts must be guaranteed not only during the warranty period, but also over the average usage period. The main features of spare parts management and its implication on related inventories have been discussed in a recent literature review by Kennedy et al. (2002) and may be subsumed as follows:

- **Dynamic and uncertain demand.** According to Hesselbach et al. (2002), the time-variability of spare parts demand follows a different pattern along PLC and along post PLC. As a complicating issue, information on reliability is usually not available at the beginning of the PLC. Moreover, according to Kalchschmidt et al. (2003), spare parts management is often organized in supply chains with a various number of echelons including multi-modal operations where the highly variable (and often lumpy) demand is lacking visibility over the whole distribution channel.
- **Multi item.** Spare parts management has to support all the goods that a company sold in the past, as well as those it currently produces. Each generation has different parts, so the service network often has to cope with 20 times the number of SKUs that the manufacturing function deals with (Cohen et al., 2006). Sherbrooke (1968) firstly proposed a system approach instead of an item approach for simplifying the recoverable item control, and Thonemann et al. (2002) present analytical models to easily approximate the improvements.
- **Obsolescence.** According to Hesselbach et al. (2002), the levels of spare part inventory are determined by balancing the risk/cost of extended downtime of a critical part, because of delay in obtaining a spare part, against the cost of holding the inventory and the risk that the stored spare parts become obsolete

before use. Obsolescence is a severe problem for those parts which are rarely needed.

An additional complexity of the spare parts management activities originates from the possibility of satisfying spare parts demands from different sources. These sources may be grouped into two main sets:

- Production or procurement of new parts
- Recovery of returned parts, e.g. through repair or remanufacturing

In the case of part recovery, the flow of parts becomes complicated and additional effects cannot be neglected, such as the presence of uncertainty in the recovery process itself in terms of timing, quantity and quality (see, e.g., Inderfurth and Mukherjee, 2008). Moreover, enabling part recovery implies that recovery activities in principle can be performed both by the manufacturer of the original parts (or by the supplier of the OEM) but also by others.

According to Toffel (2003), different product recovery strategies may involve several independent actors (Parts Manufacturer, OEM, Repair Center) that may cooperate or compete each other, therefore involving a wide set of after sales service control alternatives. In some cases OEMs (e.g. Lexmark printer and toner cartridge manufacturer) tried to prevent the possibility of local remanufacturing by independent third parties by introducing legal restrictions or technology constraints (e.g. an encrypted chip in the cartridge that can be reset only by the OEM). However, in many industries (of which the automotive sector is the most significant) a parallel grey market already exists for spare part supply. As underlined by Majumder and Groenevelt (2001), a key issue in the competition is given by the capability of the procurement of recoverable used parts. Moreover, the possibility of independent recovery made by smaller firms (i.e. local remanufacturers or Repair Shops) may lead to recovery processes using different systems and technologies, thus causing a spread recovery process in terms of quality and reliability of spare parts.

This paper presents an analytical model which aims at capturing the main economic trade-offs in spare parts management considering two main actors of the service supply chain: an OEM of durable goods and a network of independent repair shops. Both

actors are engaged in product recovery but only the repair shops have direct access to broken parts. This supply chain structure differs from the existing literature and allows us not only to focus on the competition between recovered and new parts in the supply of spare parts but also to show that both actors could be better off when cooperating. From this perspective our analysis contributes to a deeper understanding of the inherent characteristics of spare parts management for durables and the effects of part recovery along a closed-loop supply chain. The real-life application that motivates this research is taken from the after sales service provided by an Italian manufacturer of heaters and boilers.

The paper is organized as follows: Section 2 describes the case study that inspired the current work while Section 3 presents a focused literature review. Section 4 introduces the model assumptions and the notation. Section 5 describes a basic two period deterministic model, and Section 6 presents a numerical example to show the applicability of the model. Section 7 outlines the main conclusions and managerial insights that can be drawn from this research.

2. Case Study

The company that inspired the current study is located in Northern Italy and manufactures gas heating systems and boilers. It has been active in the sector for more than forty years, reaching a recognized reputation of specialization and reliability. In 2005, the company reached a turnover of 200 Million Euro employing more than 700 people. The product range encompasses more than 60 boilers differing in the heating purpose (hot water or combined hot water for the heating system and domestic use), power capacity, and installation capabilities (outdoor or indoor). Products are continuously under development implying that the average selling life of a product is about 5 years.

On the average, a boiler life-time is about 10 years: during this period a number of components might fail because of wearing out. The failure behavior of the product is almost unpredictable due to usage (e.g. heating load) and environmental conditions (e.g. water alkalinity). Gas heating boilers consist of about 15 different modules out of three categories: non failing (e.g. casing), repairable, and non-repairable (e.g. burner).

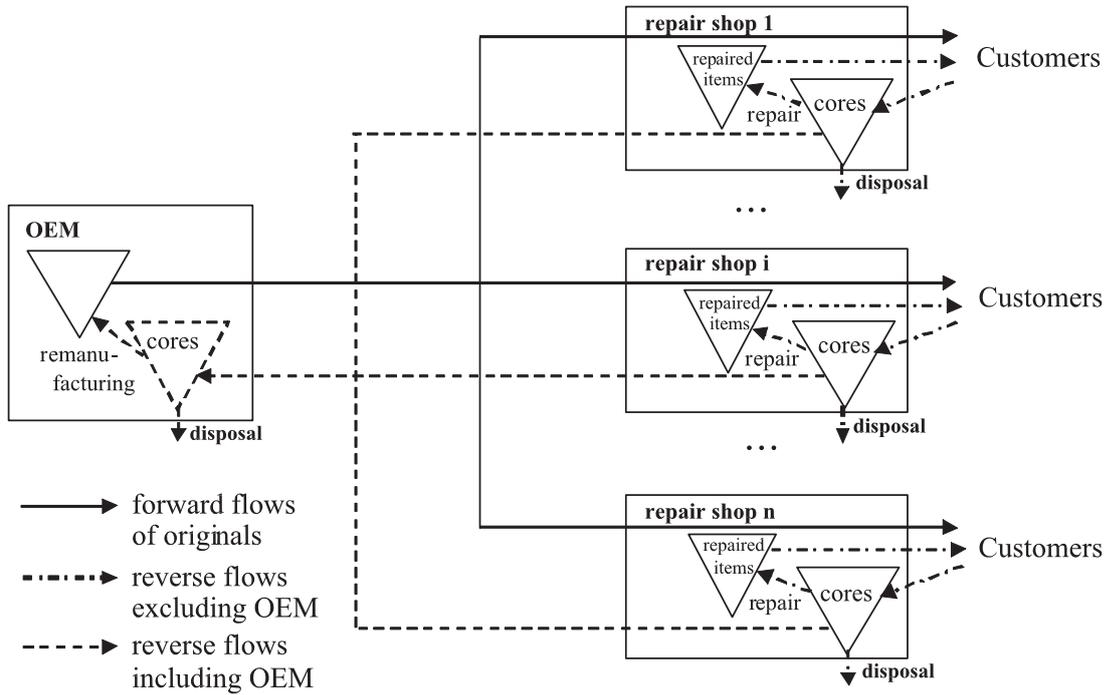


Figure 1: OEM and repair shops forward and reverse flows

Out of the repairable class, the most expensive (about 6 percent of product value) is the gas valve. In several countries legal obligations require the OEM to provide spare parts during the normal life span of their products (e.g. referring to the Italian case study, 10 years for boilers). Thus, within this period, the OEM is obliged to satisfy any customer demand with spare parts when product components fail.

After sales service is performed by a network of independent repair shops (about 500 all over Italy). All relevant forward and reverse flows between the different actors are depicted in Figure 1. Repair shops are responsible for the installation of new boilers and they also take care of the repairing process during the entire life cycle. For several parts (e.g. gas valve), two alternatives to service exist: repair shops may replace the component by a new one ordered from the OEM (replacement part) or, if a formerly broken and restored part is available, they can use such a recovered component (repair part). Both service options lead to an inflow of broken parts at the repair shop. All broken parts can be repaired using so-called “repair kits”.

Currently, the OEM does not control the after sales service channel, thus repair shops freely choose their sourcing option. In general, repair shops earn a larger profit

by selling repaired parts rather than using new parts and customers usually prefer (due to cheaper price) repaired parts to new ones. Thus, only when repaired parts are out of stock, repair shops order parts at the OEM. Such a behavior yields sudden and unexpected disruption of the demand streams the OEM faces. The present work investigates the profitability of an acquisition of broken parts from the repair shop, therewith trying to prevent uncontrolled repair, too. Furthermore, the results provide insights on how buyback prices should be set under different conditions.

3. Literature Review

This paper focuses on the competition between different suppliers including at least one supplier performing product recovery. A number of papers addresses related issues by dealing with the primary product. Similarly to our model Majumder and Groenevelt (2001) propose a two-period model to examine the effects of competition in remanufacturing. In the first period, only the OEM manufactures and sells new items. In the second period, a fraction of these items are returned for remanufacturing. However, the OEM does not get all returned items, as some are used up by the local remanufacturer. The model's results show how the presence of competition causes the OEM to manufacture less in the first period intending to increase the local remanufacturers costs. In addition, a recent contribution by Ferguson and Toktay (2006) analyzes the competition between new and remanufactured products a monopolistic manufacturer sells with the objective of identifying conditions under which the firm would choose to remanufacture its own products. Moreover, the potential profit loss due to external remanufacturing competition is considered.

The durable goods literature is relevant because it allows to appreciate the effect of endogenous competition determined by used items. Ferrer and Swaminathan (2006) investigate market segmentation in situations where a manufacturer sells both original and remanufactured goods. They study a company that makes new products in the first period and uses returned cores to offer remanufactured products, along with new ones, in several future periods. They consider a monopoly environment both in two-period and multi-period scenarios to identify the thresholds in remanufacturing operations. In addition, they focus on the duopoly environment where a third party may recover

cores of products made by the OEM.

In Ray et al. (2005), the optimal pricing/trade-in rebate strategies for durable remanufacturable products is analyzed to catch the main drivers that encourage customers to give back products. In particular, the aim of the model is to determine the optimal price for new customers and the optimal trade-in rebate for replacement customers. Heese et al. (2005) propose a model to investigate profitability of the take-back strategy adopted by an OEM that resells refurbished products. They show that a refurbishing manufacturer not only increases its unit margin, but also its market share to the detriment of a non-interfering competitor.

A case study related to the spare parts management for durable goods is discussed in Deneijer and Flapper (2005). The authors analyze business drivers that push the OEM to take back the parts resulting from repair activities. In particular, they identify three main reasons:

- to accommodate users who ask the repair shop to dispose of broken parts,
- to avoid accidents due to inappropriate repair or overhaul of parts, and
- to collect data on the quality state of used parts so as to gain insight into the time-phased failure behavior of these parts.

Beside this, they concentrate their analysis on organizational aspects concerned with the logistic and planning activities of the recovery process. As a relevant difference with respect to our case Deneijer and Flapper (2005) assume a network which is under full control of the OEM whereas here independent actors are considered.

4. Assumptions and Notation

We develop a two-period model where the competition on spare parts demand comes into effect in the second period only, since broken parts returning in the first period are supposed to be recovered by repair shops or the OEM for use in the second period. Thus, a two period model (with period index $t = 1, 2$) captures all relevant relationships and effects, still guaranteeing a sufficient analytical tractability of the model itself.

There are n repair shops servicing customer demand in distinct areas. Each repair shop $i = 1, \dots, n$ faces a deterministic demand in period $t = 1, 2$, which is denoted by $d_{i,t}$ and known to all players. Customers are homogeneous regarding their willingness to pay for repair service: they only accept a repaired spare part when a discount is offered. Thus, the prices that customers pay for spare parts are set to the customers' maximum willingness to pay for the respective service, and are given by p_x for new (OEM) replacement and by p_r for repaired parts ($p_r < p_x$). We only consider the non-warranty service, since warranty demand for spare parts must be satisfied using new replacement parts.

The main source for spare parts is the OEM, which delivers new parts to repair shops at a price p_s . Another option consists of repairing broken parts. In our case, broken parts are property of the customer, but for convenience reasons most customers leave broken parts to the repair shop: therefore, we assume that all customers will behave like this. Although being authorized by the OEM, repair shops can not be forced to return broken parts to the OEM. Thus, they are completely free to repair these parts for later service at cost c_r^r . This parameter already includes cost of holding the item until the next period. If the item is not needed it can be disposed of yielding a non-negative salvage revenue $s \geq 0$. Otherwise, repair shops would not take back broken parts. We assume that the salvage revenue does not differ between broken and repaired/remanufactured parts.

The OEM is assumed not to keep any inventory of new parts but to produce/procure spare parts as needed at cost c_p^o . So as to encourage an abundant repairable part flow from repair shops to the OEM, a buyback price $p_b > 0$ is considered. In contrast to repair shops, the OEM is able to remanufacture broken parts such that they are as good as a new part to be sold at the same price. Remanufacturing unit cost is given by c_r^o . Furthermore, the OEM is responsible for all transportation. Forward transportation unit cost for spare parts is given by c_t^s and transportation cost of parts returned from repair shops is c_t^b . Transportation costs linearly depend on the number ordered because, in practice, replacement parts are only ordered when needed for service. A similar procedure is assumed to be applied for broken parts returned. In order to assure a meaningful solution, providing spare parts should be profitable to the OEM, i.e. the

price that repair shops pay for spare parts should exceed the cost of providing a new spare part (including transportation cost, $c_p^o + c_t^s < p_s$).

We consider a simplified framework with complete information on costs and demand at each repair shop. Further modeling assumptions, mainly related to the two-period model considered, are:

- There is neither an initial stock of repaired components at repair shops or remanufactured components at the OEM nor a stock of produced items. The buyback price p_b is set by the OEM.
- In the first period, repair shops face a demand and consequently, they order a number of replacement parts $x_{i,1}^s$ at the OEM. A decision is to be made by the repair shop on the number of broken parts that are kept and repaired y_i^r , returned to the OEM x_i^b , or disposed of x_i^d . Then, the OEM will decide about the remanufacturing quantity y^o .
- In the second period, repair shops use their inventory to meet demand and, if necessary, they order further $x_{i,2}^s$ units from the OEM. The OEM first fills demand using remanufactured items and, as a second choice, it produces to satisfy the remaining demand.
- At the end, all remaining items need to be disposed of.
- We restrict the analysis to the case of the same time dependent demand structure faced by each repair shop, i.e. a commonly rising ($d_{i,1} \leq d_{i,2} \forall i$) or falling demand ($d_{i,1} \geq d_{i,2} \forall i$). This assumption is justified when considering identical product life cycle patterns at each repair shop.

The notation is summarized in Table 1.

5. The Model

In this section, a multistage decision process is modeled to determine whether the OEM offers buyback, which buyback price p_b the OEM pays for each returned core and all subsequent operational decisions made by OEM and repair shops. Afterward, the model is solved in reverse order of decisions made.

Table 1: Notation used

Parameters and data	
t	period index with $t = 1, \dots, 2$
n	number of repair shops
i	repair shops index with $i = 1, \dots, n$
$d_{i,t}$	deterministic demand in period t at repair shop i
p_x	price paid by customer for installation of replacement parts
p_s	price paid by repair shops for buying replacement parts from the OEM
c_t^s	forward transportation cost for spare parts (paid by the OEM)
c_p^o	cost of producing replacement parts by the OEM
p_r	price paid by customer for installation of repaired parts
c_r^r	cost of repairing a part at the repair shop
s	salvage revenue for unused items
c_t^b	buyback transportation cost for broken parts (paid by the OEM)
c_r^o	remanufacturing cost at the OEM
Decisions and states	
y_i^r	parts repaired to stock at a repair shop i in the first period
x_i^b	parts sent back by repair shop i to the OEM in the first period
x_i^d	parts disposed of by repair shop i in the first period
$x_{i,t}^s$	parts procured by repair shop i from the OEM in period t
y^o	parts remanufactured to stock by the OEM in the first period
p_b	buyback price the OEM pays for broken parts sent back from repair shops

5.1. Decisions and period specific cash flows

Initially, the OEM decides whether buyback is offered and, if it is, upon the buyback price p_b at which broken parts are bought back in the first period.

Period 1. During the first period, the final customer demand for spare parts is $d_{i,1}$ at each repair shop i . Since there is no initial stock of repaired items on hand, all demand is satisfied by buying new spare parts from the OEM yielding a net cash inflow of $(p_x - p_s) \cdot d_{i,1}$. At the end of the period, repair shops decide upon further use of the returned cores according to three available options:

- repair and stock-keeping of a number of cores $y_i^r \leq d_{i,1}$ at cost $c_r^r \cdot y_i^r$,
- dispose of the remaining cores x_i^b
- return the remaining cores to the OEM

The salvage revenue allows the determination of which one of the last two options should be chosen, i.e.

$$(x_i^b, x_i^d) = \begin{cases} (d_{i,1} - y_i^r, 0) & \text{if } p_b > s \\ (0, d_{i,1} - y_i^r) & \text{if } p_b \leq s \end{cases}. \quad (1)$$

This choice yields a revenue of $\max\{p_b, s\} \cdot (d_{i,1} - y_i^r)$. Cash flows of repair shops in the first period $CF_{i,1}^r$ depend on repair, disposal and return decisions, i.e.

$$CF_{i,1}^r(y_i^r, x_i^d, x_i^b; p_b) = (p_x - p_s) \cdot d_{i,1} + \max\{p_b, s\} \cdot (d_{i,1} - y_i^r) - c_r^r \cdot y_i^r \quad (2)$$

$$\text{where } y_i^r \leq d_{i,1}$$

The OEM faces a total demand for spare parts $D_1 = \sum_{i=1}^n d_{i,1}$, which are supplied by procuring/producing new items at unit costs c_p^o and sending them to the respective repair shops at cost c_i^s , thus yielding a net cash inflow of $(p_s - c_p^o - c_i^s) \cdot D_1$. A total number of returned cores $X^b = \sum_{i=1}^n x_i^b$ causes a cash outflow of $(p_b + c_i^b) \cdot X^b$ which takes into account both transfer price and transportation cost. Now, the OEM decides upon remanufacturing and stock-keeping cores $y^o \leq X^b$, leading to a cash outflow $c_r^o \cdot y^o$ for the remanufactured ones and an inflow $s \cdot (X^b - y^o)$ for those items which

are disposed of. Once total return quantities are given, the cash flow of the OEM only depends on his remanufacturing decision y^o , i.e.

$$\begin{aligned} \text{CF}_1^o(y^o; X^b, p_b) &= (p_s - c_p^o - c_t^s) \cdot D_1 - (p_b + c_t^b) \cdot X^b - c_r^o \cdot y^o + s \cdot (X^b - y^o) \\ \text{where } y^o &\leq X^b. \end{aligned} \quad (3)$$

Period 2. During the second period, the final customer demand for spare parts is $d_{i,2}$ at each repair shop i . Let D_2 be the total demand, i.e. $D_2 = \sum_{i=1}^n d_{i,2}$. At the end of the second period all obligations for supplying spare parts end, therefore no decisions are to be taken on repair/remanufacturing. Repair shops use their stock of repaired parts y_i^r to fill demand for spare parts $d_{i,2}$ as far as possible. This fact leads to a cash inflow $p_r \cdot \min\{y_i^r, d_{i,2}\}$. Excess demand is filled by procuring new parts from the OEM. Both the remaining stock (if any) and the returned cores are disposed of. Therefore repair shop i orders a quantity $x_{i,2}^s = (d_{i,2} - y_i^r)^+$ from the OEM (where $(x)^+$ denotes $\max\{x, 0\}$). The net cash flow of repair shop i in the second period $\text{CF}_{i,2}^r$ is given by

$$\text{CF}_{i,2}^r(y_i^r) = p_r \cdot \min\{y_i^r, d_{i,2}\} + (p_x - p_s) \cdot (d_{i,2} - y_i^r)^+ + s \cdot (y_i^r - d_{i,2})^+. \quad (4)$$

Given the OEM's initial stock of remanufactured spare parts y^o and the total demand of all repair shops in the second period $X_2^s = \sum_{i=1}^n x_{i,2}^s$, the net cash flow of the OEM in this period CF_2^o becomes:

$$\text{CF}_2^o(y^o, X_2^s) = (p_s - c_t^s) \cdot X_2^s - c_p^o \cdot (X_2^s - y^o)^+ + s \cdot (y^o - X_2^s)^+. \quad (5)$$

Our aim is to find the buyback price that maximizes the total profit of the OEM. As the repair shop strategies, with the exception of the buyback price, are not influenced by the OEM and the OEM's decisions depend on the repair shop choices, we further proceed as follows. First, optimal strategies of the repair shops are derived for a given buyback price and the results are used to find optimal responses of the OEM and finally, a buyback price is selected.

5.2. Optimal strategies for repair shops

The objective of a repair shop is to select a repair quantity y_i^r given a buyback price p_b in order to maximize the total profit consisting of both periods' cash flows.

Subsuming (2) and (4) and rearranging the expression obtained yields the following optimization problem

$$\begin{aligned} \max \Pi_i^r(y_i^r; p_b) &= (p_x - p_s) (d_{i,1} + (d_{i,2} - y_i^r)^+) + \max\{p_b, s\} (d_{i,1} - y_i^r) \\ &\quad - c_r^r y_i^r + p_r \min\{d_{i,2}, y_i^r\} + s(y_i^r - d_{i,2})^+ \\ \text{s.t. } &0 \leq y_i^r \leq d_{i,1}. \end{aligned} \quad (6)$$

It is easy to see that, in the case of deterministic demand, the repair quantity should not exceed the second period's demand, i.e. $d_{i,2} \geq y_i^r$. Thus, objective (6) reduces to

$$\Pi_i^r(y_i^r; p_b) = (p_x - p_s) (d_{i,1} + d_{i,2} - y_i^r) + \max\{p_b, s\} (d_{i,1} - y_i^r) - c_r^r y_i^r + p_r y_i^r.$$

Resorting terms and introducing the *additional unit profit earned by the repair shops through repairing* of used parts $\pi_r = (p_r - c_r^r) - (p_x - p_s)$ leads to the following formulation:

$$\begin{aligned} \Pi_i^r(y_i^r; p_b) &= [\pi_r - \max\{p_b, s\}] y_i^r + (p_x - p_s) (d_{i,1} + d_{i,2}) + \max\{p_b, s\} d_{i,1} \\ \text{s.t. } &0 \leq y_i^r \leq \min\{d_{i,1}, d_{i,2}\}. \end{aligned} \quad (7)$$

Total profit linearly depends on the repair decision y_i^r . If the square brackets term in (7) is positive, repair takes place at the highest possible level, otherwise it does not take place at all, i.e.

$$y_i^r = \begin{cases} \min\{d_{i,1}, d_{i,2}\} & \text{if } \pi_r > \max\{p_b, s\} \\ 0 & \text{otherwise} \end{cases}. \quad (8)$$

In conclusion, all decisions on returning cores to the OEM x_i^b , disposal of cores x_i^d , repairing cores y_i^r , together with the consequential demand for new spare parts in the second period $x_{i,2}^s$ depend on the relationship between salvage revenue, buyback price, and additional profit for repair shops through repair, as provided by (1) and (8). In other terms, four cases with a different policy structure are obtained, as stated in Table 2.

In **Case 1 (disposal only)** salvage revenue s exceeds both buyback price p_b as well as additional unit repair profit π_r . All returned cores are disposed of and demand of the second period is completely filled by using new spare parts. **Case 2 (repair and**

Table 2: Optimal repair shop strategies.

Cases and conditions	Policy structure			
	x_i^b	x_i^d	y_i^r	$x_{i,2}^s$
Case 1				
$\max\{\pi_r, p_b\} \leq s$	0	$d_{i,1}$	0	$d_{i,2}$
Case 2				
$p_b \leq s < \pi_r$	0	$(d_{i,1} - d_{i,2})^+$	$\min\{d_{i,2}, d_{i,1}\}$	$(d_{i,2} - d_{i,1})^+$
Case 3				
$s < p_b < \pi_r$	$(d_{i,1} - d_{i,2})^+$	0	$\min\{d_{i,2}, d_{i,1}\}$	$(d_{i,2} - d_{i,1})^+$
Case 4				
$p_b > \max\{s, \pi_r\}$	$d_{i,1}$	0	0	$d_{i,2}$

where $\pi_r = (p_r - c_r^r) - (p_x - p_s)$ is the additional profit for repair shops through repair

disposal) is characterized by a buyback price lower than the salvage revenue which, in turn, is exceeded by the additional unit repair profit. Repairing takes place at its highest possible level. In the second period, excess demand is filled by new spare parts. If the number of used cores available in the first period is larger than actually needed, exceeding cores are disposed of. **Case 3 (repair and take back)** differs from the previous case because buyback price is higher than salvage revenue. Therefore, those cores which would have been disposed of in Case 2 are now returned to the OEM. In **Case 4 (full take back)**, returning used cores to the OEM shows the highest profitability. Thus all cores are returned and second period's demand is filled by new parts.

5.3. Optimal OEM responses

Two decisions made at the repair shops particularly affect the OEM. Second period's demands $x_{i,2}^s$ influence the quantity of new spare parts sold and return quantities x_i^b determine transfer payments and remanufacturing opportunities. Of course, both decisions depend on the relationship between salvage revenue at repair shops and the additional unit repair profit. However, they also depend on the buyback price. We first examine these decisions from the OEM point of view and subsequently elaborate their impact on his profit Π^o for a given buyback price. Later, findings will be used to

determine the buyback decision that maximizes the profit.

Second period's orders for new spare parts $x_{i,2}^s$ equal customer demand in two cases, either if the repair option is dominated by disposal of cores or by the buyback option. If the additional unit repair profit encompasses the benefits of all other options, the OEM faces a demand only when the second period's demand is larger than the number of cores becoming available in the first period, i.e. first periods demand. Thus,

$$x_{i,2}^s = \begin{cases} d_{i,2} & \text{if } \pi_r \leq \max\{p_b, s\} \\ (d_{i,2} - d_{i,1})^+ & \text{otherwise} \end{cases}. \quad (9)$$

If the buyback price is sufficiently high and it further exceeds the salvage revenue, all returns are sent back to the OEM. Otherwise, the OEM will not receive anything when the buyback price is smaller than salvage revenue and demand is expected to fall, or when repair shops do not return needed items which can only be disposed of, i.e.

$$x_i^b = \begin{cases} d_{i,1} & \text{if } p_b > \pi_r \text{ and } p_b > s \\ (d_{i,1} - d_{i,2})^+ & \text{if } p_b \leq \pi_r \text{ and } p_b > s \\ 0 & \text{otherwise} \end{cases}. \quad (10)$$

Given an identical cost structure for all repair shops, also the cumulative return quantities as well as second period's orders the OEM faces show the just derived structure and we could proceed with aggregate numbers $X^b = \sum_{i=1}^n x_i^b$, and $X_2^s = \sum_{i=1}^n x_{i,2}^s$. Once a buyback price is set, the objective of the OEM is to select a remanufacturing quantity y^o that maximizes total profit:

$$\begin{aligned} \max \Pi^o(y^o; X^b, X_2^s, p_b) &= (p_s - c_p^o - c_t^s)D_1 - (p_b + c_t^b - s)X^b - (c_r^o + s)y^o \\ &\quad + (p_s - c_t^s)X_2^s - c_p^o(X_2^s - y^o)^+ + s(y^o - X_2^s)^+ \\ \text{s.t.} \quad &0 \leq y^o \leq X^b \end{aligned} \quad (11)$$

From (9) it can be observed that $x_{i,2}^s \leq d_{i,2}$ and therefore $X_2^s \leq D_2$. Since demand is known to him, the OEM never would remanufacture more than needed, i.e. $y^o \leq X_2^s$, thus $y^o \leq D_2$. After some resorting of terms, the following optimization problem results

$$\begin{aligned} \max \Pi^o(y^o; X^b, X_2^s, p_b) &= (p_s - c_p^o - c_t^s)(D_1 + X_2^s) - (p_b + c_t^b - s)X^b + \\ &\quad + [c_p^o - c_r^o - s]y^o \\ \text{s.t.} \quad &0 \leq y^o \leq \min\{X^b, X_2^s\} \end{aligned} \quad (12)$$

An optimal solution to optimization problem (12) is easily obtained by evaluating the term in square brackets which we further define as the direct remanufacturing cost advantage (DRCA). In case of a positive DRCA ($c_p^o - c_r^o - s > 0$), returns are remanufactured at the highest possible level. Otherwise, remanufacturing does not take place, i.e.

$$y^o = \begin{cases} \min\{X^b, X_2^s\} & \text{if } c_p^o - c_r^o - s > 0 \\ 0 & \text{otherwise} \end{cases}. \quad (13)$$

As observed before, return and order quantities (and thus profit, too) depend on repair shop decisions as given in (9) and (10). In order to be able to subsequently select a buyback price by comparing the corresponding profit functions, four different cases are identified.

Case 1 ($\max\{\pi_r, p_b\} \leq s$). In this case the most profitable option for repair shops is to dispose of all used parts, thus $X^b = 0$ and the second period's orders equal total demand $X_2^s = D_2$. Due to the lack of returns, the remanufacturing quantity at the OEM is zero ($y^o = 0$), and total profit (12) simplifies to

$$\Pi_1^o = (p_s - c_p^o - c_t^s)(D_1 + D_2) \quad (14)$$

Case 2 ($p_b \leq s < \pi_r$). In this case no used products are returned to the OEM ($X^b = 0$), thus remanufacturing is not possible at all ($y^o = 0$). Second period's demand is positive only, if it is larger than the number of repaired items which is limited by first period's demand for spare parts, i.e. $X_2^s = \max\{D_2 - D_1, 0\}$. Total profit is given by

$$\Pi_2^o = (p_s - c_p^o - c_t^s) \max\{D_1, D_2\} \quad (15)$$

Case 3 ($s < p_b < \pi_r$). In Case 3, for each repair shop a positive send back quantity $x_i^b = (d_{i,1} - d_{i,2})^+$ and positive order quantity in the second period $x_{i,2}^s = (d_{i,2} - d_{i,1})^+$ exclude each other option. Therefore, if a simultaneously falling (i.e. $d_{i,1} \geq d_{i,2}$) or rising (i.e. $d_{i,1} \leq d_{i,2}$) demand occurs at each of the repair shops, remanufacturing would not make sense for the OEM. Therefore, $y^o = 0$ and the total profit is

$$\max \Pi_3^o = (p_s - c_p^o - c_t^s) \max\{D_1, D_2\} - (p_b + c_t^b - s)(D_1 - D_2)^+. \quad (16)$$

However, if demand expectations would differ among repair shops, i.e. for some demand decreases from period to period and it increases for others, both in Case 2 and

3 *pooling effects* emerge, since e.g. in the latter case there might be both returns of broken parts from repair shops for which demand decreases as well as second period's orders from those facing an increase in demand.

Case 4 ($p_b > \max\{s, \pi_r\}$). In this case, the buyback price is such high that repairing is no longer a profitable alternative for the repair shops. Thus, all broken parts are returned to the OEM $X^b = D_1$ and second period's orders equal full demand $X_2^s = D_2$. Now the OEM's problem becomes to select a remanufacturing quantity $y^o \leq \min\{D_1, D_2\}$ that maximizes total profit Π_4^o

$$\begin{aligned} \Pi_4^o(y^o) &= (p_s - c_p^o - c_t^s)(D_1 + D_2) - (p_b + c_t^b - s)D_1 + [c_p^o - c_r^o - s]y^o \\ \text{s.t.} \quad &0 \leq y^o \leq \min\{D_1, D_2\} \end{aligned} \quad (17)$$

In case of a negative DRCA, remanufacturing does not take place and profit is:

$$\Pi_{4a}^o = (p_s - c_p^o - c_t^s)(D_1 + D_2) - (p_b + c_t^b - s)D_1 \quad (18)$$

Total profit consists of net profit due to spare parts sold (revenue decreased by transportation and production costs), reduced by the cost of getting back broken parts and their disposal.

Given a positive DRCA, two cases are to be distinguished. If the OEM faces a constant or rising total demand, all returns are remanufactured and sold in the second period ($y^o = D_1$), as spare parts must be produced to meet the second period's demand. Thus,

$$\Pi_{4b}^o = (p_s - c_t^s - p_b - c_t^b - c_r^o) D_1 + (p_s - c_p^o - c_t^s) D_2 \quad (19)$$

In the case of a falling demand, not all returned parts are remanufactured but some are disposed of ($y^o = D_2$). No production will occur in the second period, i.e.

$$\Pi_{4b}^o = (p_s - c_p^o - c_t^s - p_b - c_t^b + s) D_1 + (p_s - c_t^s - c_r^o - s) D_2 \quad (20)$$

Table 3 summarizes the main findings of all four cases.

5.4. Total profit comparison to find conditions for setting price p_b

In order to set the optimal buyback price p_b , it is necessary to identify conditions which make it reasonable to enter in one of the above determined Cases 1 to 4. This objective is accomplished by comparing OEM profits in the respective cases. We identify

Table 3: Optimal OEM strategies.

Cases and conditions	y^o	Π^o
Case 1:		
$\max\{\pi_r, p_b\} \leq s$	0	$(p_s - c_p^o - c_t^s)(D_1 + D_2)$
Case 2:		
$p_b \leq s < \pi_r$	0	$(p_s - c_p^o - c_t^s) \max\{D_1, D_2\}$
Case 3:		
$s < p_b < \pi_r$	0	$(p_s - c_p^o - c_t^s) \max\{D_1, D_2\} - (p_b + c_t^b - s)(D_1 - D_2)^+$
Case 4a:(no reman.)		
$p_b > \max\{\pi_r, s\}$ and $c_p^o - c_r^o - s \leq 0$	0	$(p_s - c_p^o - c_t^s)(D_1 + D_2) - (p_b + c_t^b - s)D_1$
Case 4b:(reman.)		
$p_b > \max\{\pi_r, s\}$ and $c_p^o - c_r^o - s > 0$	$D_1 (\leq D_2)$ $D_2 (< D_1)$	$(p_s - c_t^s - p_b - c_t^b - c_r^o)D_1 + (p_s - c_p^o - c_t^s)D_2$ $(p_s - c_p^o - c_t^s - p_b - c_t^b + s)D_1 + (p_s - c_t^s - c_r^o - s)D_2$

two drivers which influence product recovery at the repair shop level, i.e. the relationship between additional profit earned by repair shops when repairing broken parts π_r and the salvage revenue they obtain when disposing of broken parts s .

Setting A: $\pi_r \leq s$. In Setting A, repair shops would not repair and thus, independently of his buyback price decision the OEM would face full demand in both of the periods. Under this setting Cases 2 and 3 by definition cannot occur, and therefore (depending on the buyback price) either Case 1 or 4 is present. If there is no DRCA, and remanufacturing is therefore not profitable for the OEM, Table 3 shows that Case 1 always dominates Case 4a. This means that from a strategic point of view there is no motivation to buy back broken parts if these neither can be used for remanufacturing nor influence spare parts demand faced by the OEM.

In case of a positive DRCA, i.e. $c_p^o - c_r^o - s > 0$, Case 4b is preferable to Case 1 if there is a price p_b for which the difference

$$\Pi_{4b}^o - \Pi_1^o = \begin{cases} (c_p^o - c_r^o - p_b - c_t^b)D_1 & \text{for } D_1 \leq D_2 \\ (c_p^o - c_r^o - p_b - c_t^b)D_2 + (s - p_b - c_t^b)(D_1 - D_2) & \text{for } D_1 > D_2 \end{cases} \quad (21)$$

is positive. In order to favor Case 4b, this comparison requires at least

$$s < p_b < c_p^o - c_r^o - c_t^b, \quad (22)$$

i.e. the price p_b must be large enough to encourage repair shops to return broken parts and, at the same time, it must be such small that remanufacturing can compensate cost of buyback as well as transportation. Consequently, the DRCA should be larger than transportation cost c_t^b . This necessary condition is also sufficient in the case of increasing demand. However, since in the case of falling demand some of the returned parts must be disposed of, the actual profit difference must be evaluated in order to decide. In Case 4b the optimal buyback price would be slightly larger than disposal revenue, i.e. $p_b = s + \epsilon$, and in Case 1 buyback would not take place.

Setting B: $\pi_r > s$. Under this setting, no buying back of broken parts would mean a loss in demand faced by the OEM in the second period. For this setting, all cases apply, exception given for Case 1. Case 2 applies for p_b values with $p_b < s$, Case 3 is present if $s \leq p_b < \pi_r$, and Case 4 requires $p_b \geq \pi_r$. When comparing Cases 3 and Case 2 the profit difference becomes:

$$\Pi_3^o - \Pi_2^o = -(p_b + c_t^b - s)(D_1 - D_2)^+. \quad (23)$$

Case 3 would be preferable to Case 2 when $s < p_b < \pi_r$ for which $p_b < s - c_t^b$ and $D_1 > D_2$ hold. By definition of Case 3 ($p_b > s$), no such price can exist. Thus, Case 3 always is dominated by Case 2. It is not reasonable for the OEM to select a buyback price p_b out of the interval (s, π_r) , otherwise repair shops would return only parts which can not further be used. This fact requires to identify circumstances under which it makes sense to have a buyback price smaller than salvage revenue s or larger than the additional repair profit π_r . This is accomplished by comparing Cases 2 and 4.

If the DRCA is negative ($c_p^o - c_r^o - s \leq 0$), Case 4a is preferable to Case 2 if there is price $p_b > \pi_r$, for which

$$\Pi_{4a}^o - \Pi_2^o = (p_s - c_p^o - c_t^s) \min\{D_1, D_2\} + (s - p_b - c_t^b)D_1 \quad (24)$$

is larger than zero. The first term in (24) denotes the additional profit from selling more spare parts to repair shops and it is always positive. The second term gives the

cost of taking back broken parts and disposing of them and it is negative by definition of Setting B. Thus, Case 4a is preferable to Case 2 if the additional profit more than compensates additional cost.

In case of a positive DRCA ($c_p^o - c_r^o - s > 0$), Case 4b is chosen if the difference

$$\Pi_{4b}^o - \Pi_2^o = \begin{cases} (p_s - c_t^s - p_b - c_t^b - c_r^o)D_1 & \text{for } D_1 \leq D_2 \\ (p_s - c_t^s - p_b - c_t^b - c_r^o)D_2 + (s - p_b - c_t^b)(D_1 - D_2) & \text{for } D_1 > D_2 \end{cases} \quad (25)$$

is positive. In order to receive broken parts from repair shops, the buyback price must at least surmount salvage revenue ($p_b > s$), thus requiring a price p_b for which it holds

$$\pi_r < p_b < p_s - c_t^s - c_t^b - c_r^o, \quad (26)$$

which in turn requires that the price of a spare parts should be less than the transportation cost and the remanufacturing cost should exceed the additional repair shop profit. Thus, Case 4b is preferable to Case 2 if equation (25) is positive. In Case 4b, the buyback price would be set at a level enabling it to exceed additional repair profit, i.e. $p_b = \pi_r + \epsilon$, and in Case 2 buyback would not take place.

Main insights. Table 4 provides a complete guideline on how to decide whether to perform buyback at all and which buyback price p_b to choose. The additional profit generated through buyback (given it takes place) can be determined from equation (21) in Situations where $\pi_r \leq s$ and otherwise from equations (24) or (25), depending on whether the direct recovery advantage (DRCA) is positive or not. With respect to the buyback price it can be stated that it should be set to $\max\{s, \pi_r\} + \epsilon$. Generalizing the results it can be stated that buyback is more likely to be profitable if the demand for spare parts increases, and therefore it should be implemented early in the service life cycle of a product.

6. Numerical Example

In this section we show the applicability of the results found in the previous section. We will use as reference two different boilers produced by the case company. All prices and cost data given in Table 5 originate from that company but they have been disguised in order to protect confidentiality. Customer demands for spare parts

Table 4: Guideline on decision about performing buyback at all and which buyback price p_b to choose.

	Setting A: $\pi_r \leq s$	Setting B: $\pi_r > s$
DRCA ≤ 0	no buyback	compare profit: $\Pi_{4a}^o - \Pi_2^o \leq 0 \Rightarrow$ no buyback $\Pi_{4a}^o - \Pi_2^o > 0 \Rightarrow p_b = \pi_r + \epsilon$
DRCA > 0	if $DRCA \leq c_t^b \Rightarrow$ no buyback if $DRCA > c_t^b$ and demand is – rising $\Rightarrow p_b = s + \epsilon$ – falling \Rightarrow compare profit: $\Pi_{4b}^o - \Pi_1^o \leq 0 \Rightarrow$ no buyback $\Pi_{4b}^o - \Pi_1^o > 0 \Rightarrow p_b = s + \epsilon$	if $\pi_r \geq p_s - c_t^s - c_t^b - c_r^o \Rightarrow$ no buyback if $\pi_r < p_s - c_t^s - c_t^b - c_r^o$ and demand is – rising $\Rightarrow p_b = \pi_r + \epsilon$ – falling \Rightarrow compare profit: $\Pi_{4b}^o - \Pi_2^o \leq 0 \Rightarrow$ no buyback $\Pi_{4b}^o - \Pi_2^o > 0 \Rightarrow p_b = \pi_r + \epsilon$

are estimated. There are about 500 repair shops the company must deal with. The two considered products are characterized by different settings: one product has been recently introduced into the market (therefore its spare parts demand is increasing) while the second product is going to be eliminated from the product range and demand for spare parts will be decreasing in the next years. All parameter values are reported in Table 5 where cost are in €. Since remanufacturing is not performed at the moment, there are no cost data available. We will therefore use our approach to select a buyback price for each of the two products (1) for the case where remanufacturing cost are very high and (2) we will determine maximum unit cost for which remanufacturing will be applied by the OEM.

In the case of high remanufacturing cost, the direct recovery cost advantage (DRCA) is negative. Since for both of the products the additional profit when repairing π_r exceeds disposal cost s (see Table 5) we have to deal with the top right box of Table 4. Evaluating the additional profit when performing buyback (i.e. the profit difference

Table 5: Data in illustrating examples.

Data	$d_{i,1}$	$d_{i,2}$	p_x	p_s	p_r	c_r^r	π_r	s	c_p^o	c_t^s	c_t^b
Model 1	5	10	80	65	40	15	10	2	36	15	3
Model 2	45	30	90	75	50	15	20	3	39	15	3

between Cases 4a and 2) yields for Model 1: $\Pi_{4a}^o - \Pi_2^o = 77\,500\text{€} - 70\,000\text{€} = 7\,500\text{€}$ and for Model 2: $-135\,000\text{€}$. Thus, for the first model the buyback would pay off ($p_b^{Model\ 1} = 10 + \epsilon$), because of the additional units sold by the OEM. For Model 2 buyback does not take place.

When introducing remanufacturing, it emerges that remanufacturing cost should be small enough to have a positive direct remanufacturing cost advantage, i.e. $c_p^o - c_r^o - s > 0$. Thus, remanufacturing cost for Model 1 must not exceed 34€ and for the second 36€ . Next we must assure that remanufacturing costs are small enough that the inequality in the bottom right box of Table 4 is satisfied, i.e. $c_r^o < p_s - c_t^s - c_t^b - \pi_r$. For both of the models this yields 37€ which is larger than the upper bounds. Since for Model 1 demand is rising, remanufacturing is profitable for any unit cost lower than 34€ and the buyback price is $p_b^{Model\ 1} = 10 + \epsilon$. Since demand for Model 2 is falling, we have to find a remanufacturing unit cost rate at which the profit difference (i.e. $\Pi_{4b}^o - \Pi_2^o$) is zero. This happens at $c_r^o = 27\text{€}$. Therefore, for Model 2 remanufacturing would take place at unit cost below 27€ with a buyback price equal to $p_b^{Model\ 2} = 20 + \epsilon$.

7. Conclusions

In this work an analytical model was presented, which aims at capturing the economic trade-offs in service supply chains where two main actors are considered: an OEM and a network of independent repair shops. The industrial case that inspired this work mainly concerns the investigation of the opportunity for an OEM to take back damaged, though recoverable, components and sub-assemblies to start itself a remanufacturing activity. This opportunity may lead to a threefold objective: the first one is to prevent uncontrolled part recovery activities (being already performed by some repair shops) from third parties. The second objective is represented by the opportunity to collect more information and data about the on-field performance of the components installed (e.g., failure behavior and frequency), thus offering the opportunity for design improvement and preventive maintenance adoption. Of course, the last but not least objective is the opportunity to increase profit because of the higher demand and the remanufacturing activity.

The adopted optimization approach is directly related to the industrial case: op-

timal strategies for repair shops are derived for a given buyback price, and these are further used to find optimal responses of the OEM. By comparing total profit of the OEM, a buyback price is selected and consequently the remanufacturing cost capable of guaranteeing a profit to the OEM is calculated. Results have been applied to the real case settings considering two different products. A numerical example shows that each product requires a different buyback strategy and it reveals upper bounds for the OEM's remanufacturing costs so as to optimize the service chain.

There are certainly some limitations to this study which can be overcome by further research and model refinements. In order to keep the analysis simple we assumed identical costs for all repair shops and known to the OEM. Demand has been considered to be deterministic, although in reality the demand for spare parts is uncertain. When operating within a stochastic environment, varying demand situations at different repair shops might yield an opportunity for the OEM to exploit risk pooling effects from centralized product recovery. The length of the planning horizon is limited to two periods after which the remaining inventory becomes obsolete. A longer horizon would make it possible to collect broken parts for later use. Another interesting question that we would like to address in future consists of a simultaneous setting of the buyback price and the price repair shops pay for new parts.

Acknowledgments

This research was financially supported by the Italian Ministry of Education, University and Research (MIUR) as part of the Interlink project on Supply Chain Sustainability.

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