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RESEARCH ARTICLE

Dynamic buy-back for product recovery in end-of-life spare parts procurement

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The efficient supply of spare parts is of prime concern for OEM's. While manufacturing the parent product, spare parts can be sourced efficiently by using existing manufacturing facilities. This situation completely changes once the OEM ceases production of the parent product. Next to traditional spare parts sources in form of final order and remanufacturing, the option to buy back parts or products provides a viable alternative in the end-of-life phase. This can prevent the OEM from fulfilling his spare parts availability obligation or increase his ability to remanufacture. Current practice in industry is on the one hand to offer trade-in campaigns to acquire functional products from customers by giving substantial discounts on a new generation product. On the other hand, trade-in rebates are given when customers return their broken parts in exchange for spare parts. We propose consideration of a third option, i.e. to buy back broken products in order to improve control demand for spare parts and supply of recoverable parts. This contribution seeks to assess the potential benefit of buy-back strategies in contrast to both traditional sourcing and trade-in campaigns for different settings regarding information availability and buy-back flexibility. For each situation, a MILP formulation is presented, and in a numerical study we analyze circumstances under which buy-back of broken products is especially beneficial for the OEM.

Keywords: Inventory Management, Spare Parts Management, Reverse Logistics, Buy-back, Trade-in

1. Introduction

In recent years, original equipment manufacturers (OEMs) of durable goods identified the after-sales market as one of their key business segments. For instance, a 1999 AMR Research report states that on average aftermarket business activities generate about 45% of their gross profits (see Cohen *et al.* 2006). Furthermore, a competitive advantage can be established if the OEM provides superior service to his customers, e.g. by guaranteeing

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the availability of spare parts during a comparably long service period. Thus, the length of this period becomes an important strategic parameter for management. The service period is subdivided into two distinct phases, the normal phase during which the primary product is manufactured and sold as well as the final phase. This phase starts when serial production ceases and can be considerably longer than the production period. In the automotive sector, for instance, the final phase lasts for 10-15 years. Yet, several OEMs promise a significantly longer availability of spare parts for premium products as the example of a 30 years service period for Mercedes-Benz cars indicates.

In a recent contribution, Kim and Park (2008) propose a model that allows to determine the optimal length of the final phase. They argue that the marketing department seeks to stimulate demand by offering a long service period as this signals a high quality of the product (see, e.g., Spence 1977, Gal-Or 1989). From an operations point of view, however, the final phase would be chosen considerably shorter when only accounting for the costs and revenues of providing spare parts. This contribution focuses on situations in which both perspectives (marketing and operations) yield large differences in the length of the service period.

Inventory management for spare parts differs considerably from inventory management applied to manufacturing processes, mainly because demand for spare parts is less predictable and highly dynamic on a comparably low level (see, e.g., Kennedy *et al.* 2002, Huiskonen 2001). In addition, options for re-supply become increasingly rare during the final phase. While in the normal phase production facilities of the primary product can be used, this efficient sourcing option is often no longer available since manufacturing facilities are used for new generation products. Thus, a frequently adopted strategy is to place a final order at the time when regular production comes to an end. However, this is connected with high stock levels resulting in large holding cost and a high obsolescence risk as all demands occurring in the final phase need to be estimated beforehand. Extra production represents an additional option which is under certain circumstances prohibitively expensive or technically infeasible (see Hesselbach *et al.* 2002, for a comprehensive overview on this issue).

There is a one-to-one correspondence between a spare part and the defective (or 'broken') component. This creates the opportunity to recover the defective part for later use as a spare part. An overview on different recovery processing options is provided by Thierry *et al.* (1995) including repair, refurbishing, and remanufacturing. Although all of these options could be applied to satisfy the demand for spare parts, remanufacturing is of special interest for the OEMs since remanufactured parts are considered to be as-good-as-new and therefore likely to be accepted by the customers. Remanufacturing can complement other sourcing options if a sufficient supply of recoverables is assured. For this purpose, a common method in practice is to buy back defective parts by giving a rebate on remanufactured spare parts only if the defective parts are returned to the OEM. Compared to extra production, remanufacturing is relatively cheap, but since not all broken parts might be remanufacturable it should be accompanied by other options to avoid shortages (see, e.g., Inderfurth and Mukherjee 2008, Inderfurth and Kleber 2009). A strategy including remanufacturing complemented by a final order is used as a benchmark in this work.

In case of not being able to fulfill all spare part demands towards the end of the final phase and in order to avoid a penalty or a goodwill loss, OEMs can offer further options including swapping and trade-in of the whole product. Swapping refers to a replacement of the dysfunctional product with a new generation product free of charge for the customer (as has been reported by Pourakbar *et al.* 2009). This option is favorable

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 5 for high-tech products experiencing a considerable price deterioration between successive
 6 product generations but is less beneficial for durables. Trade-in of products is typically
 7 performed in the form of broadly advertised, time-limited campaigns. These campaigns
 8 intend to increase the sales of new products and, thus, also functional products are
 9 accepted. Although there are many examples from industry (see, e.g., Ray *et al.* 2005),
 10 an acquisition of products for satisfying spare part demands is (at best) seen as a side
 11 effect and is not explicitly stated as motivation for such a campaign.

12 In our study, we propose the use of more focused buy-back campaigns that specifically
 13 target on dysfunctional products requiring repair. Since the customers need to contact
 14 the OEM's service network in case of repair, this option could be implemented along with
 15 the buy-back of defective parts. In particular, we are interested in those conditions under
 16 which buying back broken products for obtaining spare parts profitably complements the
 17 traditional sourcing options final order and remanufacturing. An active integration of
 18 buying back used products into a generic product recovery system has been examined by
 19 Minner and Kiesmüller (2010) in a deterministic setting with a stationary price-response
 20 function. There, the effects of the acquisition decision on current and future demands are
 21 neglected. In our case, however, buying back would on the one hand decrease current and
 22 future demands for spare parts since there will be no future spare part demand generated
 23 from a bought back product. On the other hand, customers with a dysfunctional product
 24 might accept a comparably low compensation yielding a cheap supply of recoverable parts
 25 towards the end of the final phase. Therefore, the trade-off between cannibalizing current
 26 and future demands to release oneself from the obligation to provide spare parts and
 27 creating an additional source of supply for satisfying the remaining demand represents
 28 the main focus of this work.

29 The remainder is organized as follows. In Section 2 we introduce a basic model that
 30 integrates the buy-back of broken products in the decision-making process. Afterwards,
 31 in Section 3 a numerical example is used to demonstrate the possible benefit of buying
 32 back broken products in contrast to both a strategy where a final order is complemented
 33 only by the buy-back of broken parts and another where additionally trade-in campaigns
 34 are conducted. In doing so, we abstract from the above mentioned sales promoting effects
 35 for other products and isolate the sole effect of buying back broken products on spare
 36 parts management. In the fourth section we discuss the impact of additional buy-back
 37 related constraints. Furthermore, a sensitivity analysis is performed. Finally, Section 5
 38 summarizes the main conclusions and gives some directions for future research.

41
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 43
 44
 45 **2. A basic model with buy-back**

46 We consider a single product for which the OEM guarantees the availability of spare
 47 parts during the final phase of service. The planning horizon of length T starts at the
 48 end of regular production, i.e. at the time when no further products are manufactured
 49 and thus, the number of products with the customers (called install base) no longer
 50 increases. For the sake of simplicity, the considered product includes only one vital part or
 51 component that can fail and needs to be replaced by a spare part to restore the products
 52 functionality. Otherwise, the product's value would reduce considerably. Failures occur
 53 deterministically with rate $\lambda \in (0, 1)$, i.e. each period a fraction of the install base requires
 54 spare parts to replace broken components. This is accomplished by the existing service
 55 network operated by the OEM which is also used to return broken components to a
 56 remanufacturing facility. The spare parts supply system is depicted in Figure 1.
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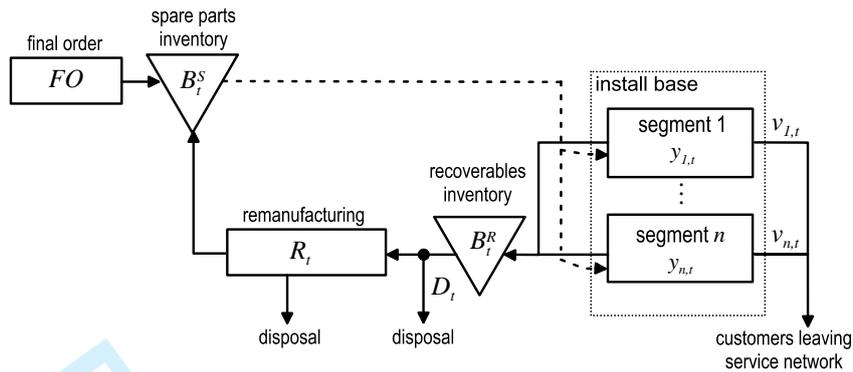


Figure 1. Spare parts supply system

Demand for spare parts is satisfied from a central stock-keeping point. Let B_t^S denote the OEM's spare parts stock at the end of period t that can be replenished using two different options. At the beginning of the planning period, the OEM places a final order FO at unit cost c_f . Afterwards, regular production ceases and remanufacturing broken components becomes the only sourcing option. The stock of recoverables B_t^R is efficiently filled from broken parts in exchange for spare parts sold at a (net) price p_s . The parameters h^R and h^S represent the unit holding cost for broken parts and spare parts per period, respectively.

In each period t , the OEM must decide on the amount of broken components to remanufacture R_t at unit cost c_r , on the quantity of broken components to dispose of D_t , and on the buy-back quantities. As is commonly presumed for practical applications, we suppose that revenues and costs for the material recovered are about the same size, i.e. disposal costs are negligible. Due to an imperfect remanufacturing process only a fraction $q \in (0, 1]$ of the remanufactured products fulfill the designated quality standards to be sold as spare parts.

If the OEM decides to buy back the entire broken product, he loses the revenue for selling a spare part but he also increases the recoverables stock by one unit. The compensation paid to the customer depends on her valuation of the product, which might differ within the install base. Depending on the OEM's buy-back decisions the size and composition of the install base changes over time. This results in complicated dynamic relationships between current and future decisions. An appropriate method to incorporate decision dynamics would be to segment the install base into groups $i = 1, \dots, n$ in which all customers value their product similarly. The initial size of each segment \bar{y}_i is known in advance and the number of functioning products in each customer segment i at the end of period t is denoted by $y_{i,t}$. Independent of the OEM's decisions a fraction $\nu_{i,t}$ of all products in customer segment i leaves the service network. Let p_i denote the reservation price of all customers in segment i representing their valuation of a defective product. Without loss of generality, the customer segments are arranged such that inequality $p_1 < \dots < p_n$ is satisfied, providing the OEM with a set of candidates for buy-back prices. All costs and revenues are discounted by using the interest rate r . The notation is summarized in Table 1.

In an idealized setting (denoted by M1), the OEM decides for each segment separately which quantities to buy back for which price. This requires the OEM to assign each customer to her segment, i.e. individual customer information is available. Buy-back

Table 1. Notation used

Parameters	
n	Number of customer segments
T	Planning horizon
c_r	Unit cost of remanufacturing
c_f	Final order unit cost
h^S	Spare parts holding costs per unit and period
h^R	Returned products holding costs per unit and period
p_i	Reservation price in customer segment i
p_s	Revenue per spare part sold
q	Remanufacturing yield rate
λ	Components failure rate
r	Interest rate
\bar{y}_i	Initial product stock in customer segment i
\bar{B}_0^R	Initial stock of broken products
$\nu_{i,t}$	Percentage of products leaving the OEM's access of segment i in period t
Decision and state variables	
B_t^S	Spare parts inventory at the end of period t
B_t^R	Recoverables inventory at the end of period t
FO	Size of the final order
R_t	Number of remanufactured parts in period t
D_t	Number of broken products disposed of in period t
E_t	Fulfilled spare part demand in period t
$x_{i,j,t}$	Number of broken products bought back from segment i at price p_j in period t
$y_{i,t}$	Number of customers in segment i in period t

quantities are denoted by $x_{i,j,t}$ representing the number of broken products bought back from customer segment i at price p_j in period t . Consequently, each broken product bought back in period t reduces the number of spare parts sold (denoted by E_t). **Model M1** can be formulated as follows:

$$\max \Pi_1 = -c_f \cdot FO + \sum_{t=1}^T (1+r)^{-t} \left[p_s \cdot E_t - c_r \cdot R_t - h^R \cdot B_t^R - h^S \cdot B_t^S - \sum_{i=1}^n \sum_{j=1}^n x_{i,j,t} \cdot p_j \right] \quad (1)$$

s.t.

$$E_t = \lambda \sum_{i=1}^n y_{i,t-1} - \sum_{i=1}^n \sum_{j=1}^n x_{i,j,t} \quad t = 1, \dots, T \quad (2)$$

$$B_0^S = FO \quad B_t^S = B_{t-1}^S - E_t + q \cdot R_t \quad t = 1, \dots, T \quad (3)$$

$$B_0^R = \bar{B}_0^R \quad B_t^R = B_{t-1}^R - R_t - D_t + \lambda \cdot \sum_{i=1}^n y_{i,t-1} \quad t = 1, \dots, T \quad (4)$$

$$y_{i,0} = \bar{y}_i \quad i = 1, \dots, n \quad (5)$$

$$y_{i,t} = y_{i,t-1} \cdot (1 - \nu_{i,t}) - \sum_{j=1}^n x_{i,j,t} \quad i = 1, \dots, n \quad t = 1, \dots, T \quad (6)$$

$$\sum_{j=1}^n x_{i,j,t} \leq \lambda \cdot y_{i,t-1} \quad i = 1, \dots, n \quad t = 1, \dots, T \quad (7)$$

$$x_{i,j,t} = 0 \quad i, j = 1, \dots, n \quad j < i \quad (8)$$

$$B_t^S, B_t^R, E_t, R_t, x_{i,j,t}, y_{i,t} \geq 0 \quad i, j = 1, \dots, n \quad t = 1, \dots, T \quad (9)$$

The OEM's objective (1) is to maximize his discounted profit Π_1 . This includes expenses for the final order, each period's revenue of selling E_t spare parts, and out-of-pocket cost incurred for remanufacturing, stock-keeping, and buy-back. In restriction (2), the number of spare parts sold E_t is determined by the amount of products requiring repair in t reduced by the buy-back quantity. Constraints (3) and (4) are inventory balance equations for the spare parts and recoverables inventory with given initial levels. The initial spare parts stock equals the size of the final order. The stock of spare parts at the end of period t B_t^S is calculated by reducing the stock at the end of the previous period B_{t-1}^S by E_t plus the yield from the remanufacturing process $q \cdot R_t$. Starting from an initial value \bar{B}_0^R , the stock of recoverables reduces by the number of remanufactured R_t and disposed of parts D_t . It increases by the number of broken products returning to the OEM.

The number of products in each customer segment develops according to balance equation (6) while (5) represents their initial sizes. It reduces by the exogenous drain of leaving customers and the total number of bought-back products from the corresponding segment. Constraint (7) ensures that only products can be bought back which fail in the respective period. Logical constraint (8) guarantees that no buy-back occurs for a lower price than the segment specific reservation price. Non-negativity restrictions (9) assure validity of decisions.

The proposed model M1 is solved efficiently by using a standard package for linear optimization. It can be easily seen that the optimal solution of M1 will always show $x_{i,j,t} = 0$ for $i \neq j$. Since the OEM can approach each customer individually, he offers her the corresponding reservation price.

3. The value of buy-back

In this section, a numerical example illustrates the potential benefit of buying back broken products compared to two other strategies. The first one is a benchmark situation (BM) without actively controlling spare parts demand, which only uses the final order and the buy-back of broken parts for remanufacturing. A second strategy additionally includes the trade-in of non-defective products (TI). After introducing the required changes to model M1 a base case scenario with a single customer segment is introduced and evaluated. Afterwards, we elaborate potential gains of a more detailed modeling of the install base by varying the number of customer segments.

3.1. Modeling of alternative strategies

While a solution for the benchmark situation (BM) could easily be obtained by forcing all buy-back quantities $x_{i,j,t}$ to zero in model M1, the option to trade in products currently in use by the customers (TI) requires several changes to the model. An additional binary decision variable $\Theta_{i,t}$ is introduced which represents the OEM's decision to offer a trade-

in at price \hat{p}_i in period t . In the objective (1), the buy-back price p_i (at which the customer would sell the defective product) is substituted by a corresponding trade-in price $\hat{p}_i = p_i + p_s$, representing the price at which the customer is willing to sell the functional product. This assumption can be imposed since any defective product can be transformed into a functional one at a price p_s . Restrictions (2) and (7) have to be replaced by

$$E_t = \lambda \sum_{i=1}^n y_{i,t-1} \quad t = 1, \dots, T \tag{10}$$

$$x_{i,j,t} \leq M \cdot \Theta_{j,t} \quad i = 1, \dots, n \quad t = 1, \dots, T \tag{11}$$

$$y_{i,t-1} \cdot (1 - \nu_{i,t}) - x_{i,j,t} \leq M \cdot (1 - \Theta_{j,t}) \quad i, j = 1, \dots, n \quad t = 1, \dots, T \tag{12}$$

$$\sum_{i=1}^n \Theta_{i,t} \leq 1 \quad t = 1, \dots, T \tag{13}$$

$$\Theta_{i,t} \in \{0, 1\} \quad i = 1, \dots, n \quad t = 1, \dots, T \tag{14}$$

Restriction (10) ensures that only functioning products are bought back (after repair if required). Constraint (12) ensures that all customers return their products to the OEM when $\Theta_{i,t}$ is set to one. In this case, all products remaining in segment i after the drain are procured by the OEM. If, otherwise, $\Theta_{i,t}$ is set to 0, restriction (11) forces the buy-back quantity to 0. Finally, restriction (13) guarantees that only one buy-back price is set by the OEM in period t .

3.2. The value of buy-back without segmentation

We start our analysis with a base case considering a single customer segment ($n = 1$) for which all spare part demands must be satisfied for the next $T = 80$ periods. A period is hereby defined to be a quarter of a year which means the OEM faces a 20 year planning horizon. The OEM estimates the initial number of products in the install base to be $\bar{y}_1=400$ out of which a fraction of $\nu_1 = 1.5\%$ are leaving the service network each period. The main component fails at a rate $\lambda = 10\%$, i.e. each product has to be repaired on average once in two and a half years yielding a revenue of $p_s=10$. The OEM estimates that a broken product can be acquired at a price of $p_1 = 20$ being twice the revenue from selling a spare part. Hence, the trade-in price for a functional product is given by $\hat{p}_1 = 30$.

Spare parts are procured by placing a final order at unit cost $c_f=3$ yielding an initial profit margin of 70%. Broken parts returning to the OEM can be remanufactured at unit cost $c_r = 1.5$. Remanufacturing is successful in $q = 50\%$ of the cases, i.e. one of two broken parts can be used further. Thus, there is no direct cost advantage for neither parts procured in the final order nor for parts successfully remanufactured. The discount rate is set to $r = 2.5\%$ per quarter or about 10% per year. Out of pocket holding cost are $h^S = 0.2$ and $h^R = 0.1$ per unit and period for spare parts and recoverable parts, respectively. Taking both discounting and holding cost into account, it would be economically beneficial to satisfy demand from parts procured in the final order for at most 20 periods (5 years) and to switch to remanufacturing afterwards, given a sufficient supply of recoverables.

The main results are presented in Table 3. The benchmark situation (BM) shows a

Table 2. Base case parameter values

n	T	\bar{y}_1	ν_1	λ	p_s	c_f	c_r	q	r	h^S	h^R	p_1	\hat{p}_1
1	80	400	1.5%	10%	10	3	1.5	50%	2.5%	0.2	0.1	20	30

Table 3. Optimal final order FO , discounted profit Π , relative profit surplus Δ and first period in which buy-back takes place z in the benchmark, the trade-in solution, and for M1

Benchmark		Optimal Trade-in			Optimal buy-back in M1			
FO_{BM}	Π_{BM}	FO_{TI}	Π_{TI}	Δ_{TI}	FO_1	z_1	Π_1	Δ_1
935	2390	935	2390	0%	658	46	3127	+30.8%

solution structure in which (as has been examined in a related approach by Kleber and Inderfurth 2007) two phases to be distinguished. In a first phase (periods 1 to 29) the demand for spare parts is satisfied from the final order of size $FO_{BM} = 935$. All broken parts that return are held in the recoverables inventory and none is disposed of. In a second phase (periods 30 to 80) the strategic stock of returned parts built up in the first phase is remanufactured to serve demand. Since the first phase lasts for more than 20 periods, the base case parameters (summarized in Table 2) depict a situation in which the operations manager is confronted with a much longer final phase than he would choose individually. The benchmark solution yields a total discounted profit of 2390.

In the single segment case, running a trade-in campaign (TI) would instantly deplete the whole install base. This provides a control on the length of the service period by balancing trade-in cost and future losses when having to satisfy demands. Since selling spare parts remains a profitable business opportunity for the OEM over the entire planning horizon, the solution does not deviate from the benchmark solution.

When including the option to buy back broken products using model M1, the final order reduces to 658 implying a substantial reduction in holding cost. Although considerably shorter (the first phase ends in period 19), both of the above phases are present. In an adjacent third phase (starting in period $z_1 = 46$), the OEM buys back the amount of broken products that just compensates the yield loss from remanufacturing broken parts. Due to the increased flexibility in controlling the install base the discounted profit rises by about 31% to 3127.

3.3. The value of customer segmentation

Segmenting the install base w.r.t. differences in the customers' valuation of the product increases the flexibility for both trade-in and buy-back strategies. In order to assess the value of this flexibility, customer segments are created based on the trade-in or buy-back price, respectively. All other parameters remain the same as in the base case.

For determining the segment specific prices, the customers' valuation of the broken product is assumed to be uniformly distributed among the 400 customers in an interval

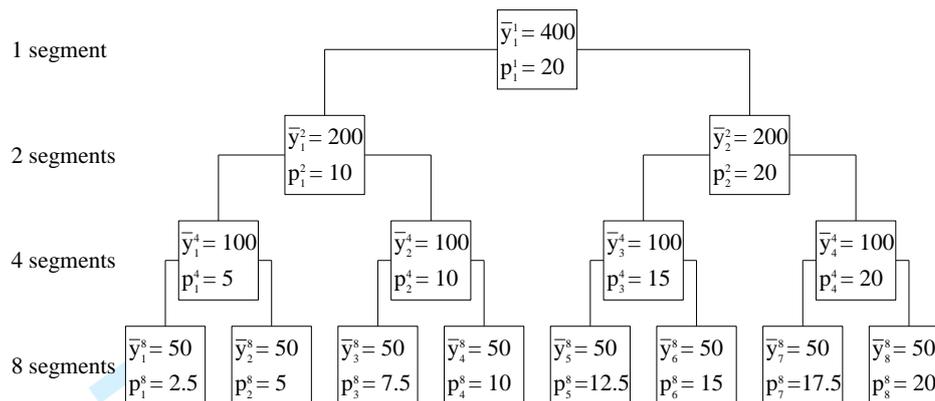


Figure 2. Initial segment sizes \bar{y}_i^n and corresponding buy-back prices p_i^n for different numbers of segments n

Table 4. Influence of the number of segments n on the final order and discounted profit

n	Optimal Trade-in				Optimal buy-back in M1			
	FO_{TI}	z_{TI}	Π_{TI}	Δ_{TI}	FO_1	z_1	Π_1	Δ_1
1	935	/	2390	0%	658	46	3127	+30.8%
2	848	56	2416	+1.1%	621	41	3383	+41.5%
4	840	52	2474	+3.5%	592	38	3514	+47.0%
8	834	49	2505	+4.8%	582	36	3578	+49.7%
16	831	48	2520	+5.4%	576	35	3610	+51.0%
32	832	45	2526	+5.7%	573	35	3626	+51.7%

between 0 and 20. Given n segments, $400/n$ customers with the lowest reservation price $p_1^n = 20/n$ are assigned to the first segment, the next $400/n$ customers to segment 2, and so on. Each buy-back price, thus, indicates the value for which all customers of a respective segment would sell their broken products. The segmentation of customers is sketched in Figure 2. The corresponding trade-in prices \hat{p}_i are determined by adding p_s to the respective segments' buy-back prices.

Table 4 depicts the results of the experiments which can be interpreted as follows. For both strategies (optimal trade-in and buy-back), a more detailed segmentation increases the total profit $\Pi_{TI/1}$, since take back occurs in smaller batch sizes allowing for a more focused control of the install base. However, a repeated doubling of the number of customer segments has a decreasing impact on profit. The final order $FO_{TI/1}$ decreases as less spare parts are sold compared to the benchmark case. This observation corresponds to an earlier start of the trade-in/buy-back activities ($z_{TI/1}$).

Comparing the optimal strategies, one finds a substantial difference in the percentage gains. This is attributed to a more direct control of spare parts demand when buying back broken products. In contrast to trade-in each unit bought back immediately decreases demand for spare parts by one in addition to the common reduction of future demands by lowering the install base. The trade-in strategy additionally bears the burden of having

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to take back a whole segment at once. Buy-back, on the other hand, only applies to the fraction of the considered segment that actually induces demand for spare parts and thus, in general total profit cannot be smaller than when applying a trade-in strategy.

For instance, in the case of 32 segments the total trade-in quantity equals to 91 (in TI) while 165 broken products are bought back (in M1). This reduces the total spare parts sales from 1870 in the benchmark solution by 206 (11%) in TI but by 559 (30%) in M1. Since the buy-back strategy reduces the final order by 39% in contrast to only 11% with trade-in, the decrease in sales is overcompensated by a larger reduction in final order related production and stock-keeping cost.

4. Robustness with respect to exogenous constraints and parameters

In this section, we focus on elaborating the impact of several assumptions that might limit the practical applicability of buy-back strategies. Furthermore, we isolate parameters that play an important role on the profitability of buying back broken products.

4.1. Buy-back related exogenous constraints

In industry problems arise due to possibly existing exogenous constraints, such as communication, information, and pricing related constraints. In the basic model M1, the OEM is able to offer each customer individually a buy-back and has therefore the flexibility to decide on the quantity he buys back in each planning period. *Quantity flexibility* can be limited if (like in the trade-in case) the buy-back is proposed to all customers simultaneously via a mass-media marketing campaign. As the OEM cannot withdraw his offer, he has to accept all broken products the customers wish to sell.

The OEM can face *information constraints* if he cannot assign a customer to her corresponding segment and does hence not know from which segment a broken product originates. In the marketing literature, a number of market-segmentation approaches distinguish between observable and unobservable characteristics (see, e.g., Kotler and Keller 2008, Wedel and Kamakura 2000). Observable criteria are mostly geographic or demographic data. Additionally, the type of relationship like B2B (car rental enterprise) or B2C (private customer) could be used. Unobservable criteria typically contain psychographic or behavioral characteristics that cannot be used to discriminate between customers.

Finally, the OEM can face limited *pricing flexibility*. Pricing constraints describe the OEM's restriction to address each segment individually. Therefore, the OEM might be limited to set only one price per period. In this case, he is not able to buy back products from different segments for different prices in a given period. Bernstein *et al.* (2006) give an overview on reasons why an OEM is restricted in his pricing format.

These three dimensions, namely pricing and quantity flexibility as well as individual information availability result in eight subclasses of problems (see Table 5). However, it can be shown that several subclasses are redundant (shaded cells). First, the OEM is not able to exploit pricing flexibility if he cannot assign his customers to the respective segments, as every customer will apparently claim to have a high reservation price (this excludes A and C). Second, if the OEM communicates segment specific buy-back prices via mass-media marketing campaigns, this is usually done by proposing an 'up-to' price. If (as is the case in B) individual information is available, actual prices offered to the customers can be used to regain quantity flexibility. This could be done by proposing

Table 5. Three dimensions of flexibility and information availability

		quantity flexibility			
		yes		no	
individual information		available	not avail.	available	not avail.
pricing flexibility	yes	full pricing and quantity flexibility, full information availability (M1)	A	B	C
	no	limited pricing and full quantity flexibility, full information availability (M2)	limited pricing and full quantity flexibility, limited information availability (M3)	limited pricing and quantity flexibility, limited information availability (M4)	

too low prices as soon as the designated buy-back quantity is reached. Then, a setting results which is comparable to M1. Finally, individual information is not useful if there is neither pricing nor quantity flexibility (M4).

There are three relevant subclasses of problems (M2-M4) when deviating from the idealized setting M1. Subsequently, the economic impact of these assumptions is assessed. For this, model M1 needs to be adapted which is described in the next subsection.

4.2. The economic impact of exogenous constraints

Setting **M2** is characterized by a restricted pricing flexibility, i.e. only a single buy-back price can be set in each period. However, this setting allows to assign each customer to her segment and to choose which quantity to buy from which customer segment. The OEM's pricing decision is described, as in Section 3, by a binary decision variable $\Theta_{i,t}$ that determines the OEM's buy-back price in period t . In order to implement setting M2, constraints (11), (13), and (14) have to be added to the original setting M1. Obviously, due to the additional restrictions imposed the optimal profit for M2 (denoted by Π_2) cannot exceed the optimal profit for M1.

In setting **M3**, the absence of available information regarding each customer's assignment results in the problem that it cannot be easily determined how many items were bought back from which customer segment. Further assumptions are required to keep track of the number of customers in each segment. However, the profit must lie between the profits of the less restricted setting M2 and the even more restricted setting M4. A more detailed analysis of this setting will be left for future research.

Setting **M4** provides us with the least flexible buy-back environment that still allows for customer segmentation. Due to its limited pricing flexibility only a single price can be selected per period. All customers with a reservation price smaller than the offered price return their dysfunctional product to the OEM. Constraint (12) is replaced by

$$\lambda \cdot y_{i,t-1} - x_{i,j,t} \leq M \cdot (1 - \Theta_{j,t}) \quad i, j = 1, \dots, n \quad i \leq j \quad t = 1, \dots, T. \quad (15)$$

Constraint (15) captures the fact that for a given buy-back price p_j (i.e. $\Theta_{j,t} = 1$) all customers from segments $i = 1, \dots, j - 1$ are going to sell their broken products.

By solving the respective optimization problems M2 and M4 for $n=2$ segments, the economic impact of the limitations regarding pricing and quantity flexibility as well as

Table 6. Total discounted profit, relative deviation from M1 and corresponding final order sizes.

	Benchmark	M1	M2	M4
Final order size FO	935	621	622	626
First buy-back period z	-	42	41	41
Total discounted profit Π	2390	3383	3358	3343
Relative deviation from Benchmark Δ	-	+41.6%	+40.5%	+39.9%

information availability can be evaluated. In Table 6, the total discounted profits and the final order sizes are presented for all settings. Interestingly, while showing in general the same solution structure with three phases as M1, the third (buy-back) phase of both settings M2 and M4 is characterized by switching price decisions. While in most periods the low price p_1 is set and defective products from the first customer segment are bought back only, sporadically the larger price p_2 is set. In those 'campaign' periods a stock of broken products is build up, i.e. more broken products are bought back than are actually needed to satisfy the current period's demand. For a detailed description of the policy structure see Kleber *et al.* (2009).

The comparably small gap between M1, M2, and M4 can be explained by the similarity of the optimal solution structures. First, it can be observed that the different limitations do not influence the final order size substantially. Second, changes in the solution structure occur quite late in the planning horizon as indicated in Table 6 by the first buy-back period z . As all cash flows are discounted, a deviation in one of the later periods only has a limited effect on the total discounted profit.

It seems that the OEM can significantly enhance his performance by including buy-backs into the decision making process. This result also holds when comparing M4 with the trade-in solution described in Section 3.3. Although both model settings are comparable, the impact of a focused buy-back and (to a smaller extent) of price differences is substantial. The following subsection aims to provide insights into the robustness of these findings.

4.3. Sensitivity to changing parameters

Taking the base case from Section 3 with two segments as starting point, a sensitivity analysis is performed that focuses on elaborating which parameters especially affect the buy-back profitability. To achieve this, all relevant parameters are modified to a considerably higher and lower value while keeping all other parameters constant. We start our discussion with a comparison of M1 and the benchmark solution before presenting the specific characteristics of settings M2 and M4. All results can be found in the Appendix. Table 7 presents the parameters that seem to have a substantial impact on the profitability of the buy-back option, i.e. the remanufacturing yield rate q , the interest rate r , the final lot unit cost c_f , the length of the planning horizon T as well as both holding cost parameters h^R and h^S .

The findings can be interpreted as follows. In the benchmark setting, both spare parts demand and recoverables supply are not actively controlled by the OEM. As serving customers close to the end of the planning horizon becomes more and more expensive, profitability gains of buying back broken products (in M1) increase since (in contrast

Table 7. Optimal final order FO , discounted profit Π , first buy-back period z and relative profit change Δ in the benchmark solution and M1 for parameters with significant impact.

		Benchmark		Optimal buy-back in M1			
		FO_{BM}	Π_{BM}	FO_1	z_1	Π_1	Δ_1
base case		935	2390	621	42	3383	+41.6%
q	40%	1122	836	689	36	2415	+188.7%
	50%	935	2390	621	42	3383	+41.6%
	60%	748	3821	541	47	4396	+15.1%
r	1.25%	935	4142	758	55	4513	+8.9%
	2.5%	935	2390	621	42	3383	+41.6%
	5%	935	567	462	29	2287	+303%
c_f	1.5	935	3793	724	48	4369	+15.2%
	3	935	2390	621	42	3383	+41.6%
	4.5	935	986	553	36	2510	+154.4%
T	60	795	3156	628	42	3454	+9.4%
	80	935	2390	621	42	3383	+41.6%
	100	1039	1644	610	41	3371	+105%
h^S	0.15	935	2868	652	45	3604	+25.7%
	0.2	935	2390	621	42	3383	+41.6%
	0.25	935	1912	587	39	3185	+66.6%
h^R	0.05	935	3210	674	47	3816	+18.9%
	0.1	935	2390	621	42	3383	+41.6%
	0.15	935	1789	576	38	3108	+73.7%

to the benchmark) it can react properly to changing parameters. This is the case if the remanufacturing yield rate q decreases or if the interest rate r , the final order unit cost c_f or one of both holding cost parameters become larger. A larger h^S , for instance, creates the incentive to start buying back earlier which reduces the number of spare parts procured in the final order. Regarding the length of the planning horizon T , a longer planning horizon reduces the profits substantially if the buy-back option is neglected. When incorporating the buy-back option into the spare parts fulfillment strategy, however, even longer service periods can be offered while keeping the costs for this additional service at a moderate level.

All other parameters affect the advantageousness of the buy-back option only slightly. Increasing one of the outflow rates (ν_1, ν_2) or one of the the buy-back prices (p_1, p_2) decreases the performance gain of M1. In the first case, total demand for spare parts decreases and in the second, an active demand control becomes more expensive. Changing the composition of the install base by altering the initial segment sizes (\bar{y}_1, \bar{y}_2) results in similar effects as buy-back price modifications, i.e. increasing the number of customers in segment two augments the average price of a buy-back. Interestingly, the relative deviation Δ_1 remains constant if the number of customers in both segments is multiplied by the same factor. A change in the failure rate λ , on the other hand, does not have a large impact as all decisions are increased or decreased approximately proportionally. Furthermore, the cost of remanufacturing broken products c_r has no substantial influence.

Regarding model settings M2 and M4 it is to be said that the profit loss from re-

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stricted information availability and/or quantity and pricing flexibility is quite robust with respect to parameter changes. The largest loss in total profit observed when comparing settings M4 and M1 is 2.7% in a situation with a large remanufacturing yield rate $q=60\%$.

5. Conclusions

Due to its high profitability, after-sales management has received an ever increasing attention in the recent past. This study was particularly motivated by the automotive industry which guarantees to supply spare parts for their cars over a long period. These guarantees are an attractive instrument for the marketing and sales department while they impose a challenge for spare parts management. A favorable sourcing option is provided by remanufacturing broken parts obtained in exchange for spare parts. In the case of considerable yield losses, however, it should be complemented by other sources like a final order placed at the end of regular production. This option bears the burden of large holding cost over a long planning horizon, making demand satisfaction expensive especially during late periods of the final phase. To avoid this problem, options like trade-in or buy-back of the whole product are considered that release the OEM from his obligation to deliver spare parts.

For evaluating both strategies basic MILP models have been developed. A numerical example was used to compare the potential gains of both strategies. It revealed that both strategies can be beneficial for the OEM while the buy-back strategy outperforms a trade-in strategy as it specifically focuses on taking back broken products. In a sensitivity analysis, parameters have been identified that especially influence the profitability of the buy-back option. It seems that there is a rather limited impact of buy-back related parameters whereas those parameters determining the profit impact of the final order size (like unit production cost and holding cost) appear to be of highest importance. In case of a high remanufacturing yield rate, the system can be handled like a repair system (see, e.g., Sherbrooke 2004) where the buy-back option is less favorable. If the planning horizon is extended, stock-keeping of final order produced parts becomes more costly and thus, the OEM benefits to a larger extent from compensating the customers for not fulfilling the spare parts availability guarantee.

To our knowledge, this study is the first attempt to investigate the value of buying back broken products for spare parts management. There are certainly some limitations to this study which can be overcome by further research. The model could be extended into several directions. Several parameters (like e.g. the failure rate) are likely to change over time or can differ between customer segments. Segment specific quality levels of recoverables would impact remanufacturing cost and yield rates. Another extension would be that multiple parts are included in a product and thus, a product bought back would yield inflows of several remanufacturable parts. Furthermore, segmenting the install base could also be used to price discriminate between consumers when selling spare parts. This would entail a shift towards buying back from segments showing lower spare parts prices.

In contrast to the MILP approach, general structural properties of optimal solutions could be obtained by using optimal control methods, as have been successfully applied in product recovery systems (see Kiesmüller *et al.* 2004, Kleber 2006). Finally, complementing our deterministic approach, a stochastic simulation could be used to evaluate more realistic models involving uncertainty. Here, due to the high flexibility, buying back

broken products becomes an even more attractive option.

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17 **Appendix**
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Table 9. Impact of selected parameters.

altered parameter	Benchmark		M4		M2		M1					
	FO_{BM}	Π_{EM}	FO_4	Π_4	FO_2	Π_2	FO_1	Π_1				
base case	935	2390	626	3343	622	41	3358	621	42	3383	Δ_1	+41.6%
q	1122	836	689	2352	685	35	2366	689	36	2415		+188.7%
	935	2390	626	3343	622	41	3358	621	42	3383		+41.6%
	748	3821	545	4372	541	47	4383	541	47	4396		+15.1%
r	935	4142	781	4493	777	55	4496	758	55	4513		+8.9%
	935	2390	626	3343	622	41	3358	621	42	3383		+41.6%
	935	567	471	2249	461	28	2263	462	29	2287		+303%
c_f	935	3793	700	4332	694	48	4341	724	48	4369		+15.2%
	935	2390	626	3343	622	41	3358	621	42	3383		+41.6%
	935	986	559	2457	552	35	2478	553	36	2510		+154.4%
T	795	3156	644	3436	639	42	3437	628	42	3454		+9.4%
	935	2390	626	3343	622	41	3358	621	42	3383		+41.6%
	1039	1644	626	3327	620	41	3346	610	41	3371		+105%
(h^R/h^S)	935	2868	657	3569	654	44	3581	652	45	3604		+25.7%
	935	2390	626	3343	622	41	3358	621	42	3383		+41.6%
	935	1912	604	3138	590	38	3157	587	39	3185		+66.6%
	935	3210	677	3789	677	46	3798	674	47	3816		+18.9%
	935	2390	626	3343	622	41	3358	621	42	3383		+41.6%
	935	1789	582	3056	586	38	3076	576	38	3108		+73.7%
	935	3688	725	4061	718	50	4067	715	51	4082		+10.7%
	935	2390	626	3343	622	41	3358	621	42	3383		+41.6%
	935	1091	555	2785	549	35	2809	539	35	2846		+160.8%

Table 10. Impact of selected parameters (contd.)

altered parameter	Benchmark		FO ₄	z ₄	M4		Δ ₄	FO ₂	z ₂	M2		Δ ₂	FO ₁	z ₁	M1		Δ ₁
	FO _{BM}	Π _{BM}			Π ₄	Π ₂				Π ₁	Π ₁						
(1.5%/1%) (1.5%/1.5%) (1.5%/2%) (1%/1.5%) (1.5%/1.5%)	1020	2222	664	41	3335	3356	+50.1%	649	40	3356	3356	+51.1%	645	41	3385	3385	+52.4%
	935	2390	626	41	3343	3358	+39.9%	622	41	3358	3358	+40.5%	621	42	3383	3383	+41.6%
	868	2492	593	41	3335	3346	+33.8%	589	41	3346	3346	+34.3%	590	42	3368	3368	+35.1%
	1020	2222	651	41	3422	3438	+54%	643	41	3438	3438	+54.7%	643	41	3467	3467	+56.1%
	935	2390	626	41	3343	3358	+39.9%	622	41	3358	3358	+40.5%	621	42	3383	3383	+41.6%
(2%/1.5%) (1%/1%) (1.5%/1.5%) (1.5%/1.5%) (2%/2%)	868	2492	604	41	3269	3283	+31.2%	601	41	3283	3283	+31.8%	598	42	3305	3305	+32.6%
	1105	2051	671	40	3412	3434	+66.3%	680	41	3434	3434	+67.4%	668	41	3468	3468	+69.1%
	935	2390	626	41	3343	3358	+39.9%	622	41	3358	3358	+40.5%	621	42	3383	3383	+41.6%
	801	2592	571	41	3259	3269	+25.8%	568	41	3269	3269	+26.1%	567	42	3289	3289	+26.9%
	935	2390	626	41	3343	3358	+39.9%	622	41	3358	3358	+40.5%	621	42	3383	3383	+41.6%
(10/15) (10/20) (10/25) (5/20) (10/20)	935	2390	614	41	3423	3437	+43.2%	603	40	3437	3437	+43.8%	605	41	3456	3456	+44.6%
	935	2390	626	41	3343	3358	+39.9%	622	41	3358	3358	+40.5%	621	42	3383	3383	+41.6%
	935	2390	640	41	3276	3291	+37.1%	635	41	3291	3291	+37.7%	628	42	3317	3317	+38.8%
	935	2390	597	37	3488	3505	+46%	600	38	3505	3505	+46.7%	595	39	3534	3534	+47.9%
	935	2390	626	41	3343	3358	+39.9%	622	41	3358	3358	+40.5%	621	42	3383	3383	+41.6%
(5/15) (10/20) (15/20) (5/15) (10/20)	935	2390	646	44	3220	3232	+34.7%	644	44	3232	3232	+35.2%	638	44	3249	3249	+36%
	935	2390	582	37	3567	3584	+49.3%	578	37	3584	3584	+50%	576	38	3612	3612	+51.1%
	935	2390	626	41	3343	3358	+39.9%	622	41	3358	3358	+40.5%	621	42	3383	3383	+41.6%
	935	2390	657	44	3151	3164	+31.9%	661	45	3164	3164	+32.4%	652	45	3187	3187	+33.4%
	935	2390	626	41	3343	3358	+39.9%	622	41	3358	3358	+40.5%	621	42	3383	3383	+41.6%
(300/100) (200/200) (100/300)	935	2390	605	41	3473	3484	+45.3%	595	40	3484	3484	+45.8%	594	40	3495	3495	+46.2%
	935	2390	626	41	3343	3358	+39.9%	622	41	3358	3358	+40.5%	621	42	3383	3383	+41.6%
(\bar{y}_1/\bar{y}_2)	935	2390	638	39	3217	3235	+34.6%	642	40	3235	3235	+35.4%	635	41	3256	3256	+36.2%
c _r	0.75	2808	612	40	3859	3877	+37.4%	620	41	3877	3877	+38%	610	41	3905	3905	+39.1%
	1.5	2390	626	41	3343	3358	+39.9%	622	41	3358	3358	+40.5%	621	42	3383	3383	+41.6%
	2.25	1971	629	41	2827	2840	+43.5%	626	41	2840	2840	+44.1%	623	42	2863	2863	+45.3%
λ	5%	468	1195	316	42	1652	+38.3%	318	42	1656	1656	+38.6%	316	43	1679	1679	+40.5%
	10%	935	2390	626	41	3343	+39.9%	622	41	3358	3358	+40.5%	621	42	3383	3383	+41.6%
	15%	1403	3584	916	40	5087	+41.9%	910	40	5112	5112	+42.6%	911	41	5134	5134	+43.2%