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Product life-cycle implications for remanufacturing strategies

Johan Östlin*, Erik Sundin, Mats Björkman

Division of Assembly Technology, Department of Management and Engineering, Linköping University, 581 83 Linkoping, Sweden

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ABSTRACT

For remanufacturing to be successful, there is a need to gain information on future market needs of remanufactured products, and match this to information on the magnitude of return flows. One of the major issues impacting remanufacturing is in the difficulty of obtaining used products (cores) that are suitable for remanufacturing. The timing and quantity of product returns is dependent on the type of product. Factors such as the mean product lifetime, rate of technical innovation, and failure rate of components all influence the return rate of products from end-of-use and end-of-life. The balance between product returns and demand for remanufactured products is a function of many variables, where the rate of technological innovation and the expected life of a product are the major influencing characteristics. The main contribution of this paper is the support that is provided in different supply and demand situations. By using a product life-cycle perspective, the supply and demand situations can be foreseen, and support given regarding possible strategies in these situations.

1. Introduction

Remanufacturing is an industrial process whereby used/broken-down products (or components) – referred to as “cores” – are restored to useful life. Remanufacturing means that a product is reprocessed or upgraded in an industrial process. During this process, the core passes through a number of remanufacturing operations, e.g., inspection, disassembly, part reprocessing, reassembly, and testing, to ensure it meets the desired product standards [19]. The business concept of remanufacturing is based on the idea that resources that were used in the manufacturing of the product are reused, thereby making remanufacturing advantageous. The reused resources consist of the material in the product, energy, machine time, labour and other costs that have been accumulated in the new production process [1]. Remanufacturing can, in many cases, offer superior material recovery due to additional reused resources [12,15,17]. From an environmental perspective, it is still important to consider the impact of prolonging the life of products with obsolete or polluting technologies. Remanufacturing products with less environmentally sound technology can have a negative impact, especially if the major environmental impact is concentrated in the use-phase [1].

The driving forces for using product remanufacturing in product recovery are many (see e.g. [28]), just as the barriers against remanufacturing are. These motives and barriers can be both economic and technical. Several researchers have tried to characterise under which conditions remanufacturing is advantageous (see Seitz [14] for an overview). A main conclusion from these studies is that the motives for remanufacturing a product are very case-dependent [14]. For remanufacturing to be successful [21], Thierry et al. highlight the need to gain information on future market needs for remanufactured products, and match this to information on the magnitude of return flows. Toffel [23] also concludes that one of the major issues impacting the possibility to perform remanufacturing is the difficulty in obtaining used products (cores) that are suitable for remanufacturing. The timing and quantity of return of a product is dependent on the type of the product. Factors such as the mean product lifetime, rate of technical innovation, and failure rate of components all influence the return rate of products from end-of-use and end-of-life [24]. End-of-use returns refer to those situations where the user has a return opportunity at a certain life stage of the product. This refers to leasing cases and returnable containers like bottles, or returns to second-hand markets. Although end-of-use products are not new, they are often in a good or reasonable state. With respect to end-of-use returns, end-of-life returns refer to those returns where the products are at the end of their economic or physical lives. They are either returned to the OEM because of legal product-take-back obligations, or “returned” to another company for value-added recovery. Customers can be more or less active concerning the returns, as illustrated respectively by returning bottles to the supermarket or by sending back toner cartridges via

* Corresponding author. Tel.: +46 13281000.
E-mail address: johan.ostlin@liu.se (J. Östlin).

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mail [4]. The balance between product returns and demand for remanufactured products is clearly a function of many variables, where the rate of technological innovation and the expected life of a product are the major influencing characteristics [7]. One conclusion that can clearly be drawn regarding this balance is that when a product is new on the market, the return of cores from end-of-use is generally lower than the potential demand for remanufactured products. Vice versa, after a point when the product has been on the market for a long time, the returns of end-of-use products are generally higher than the demand for remanufactured products [24].

The purpose of this paper is to further investigate how companies can balance the demand for remanufacturing products with the rate of product returns. The aim is to develop strategies for companies that can aid them in balancing supply and demand, as well as providing insights for possible remanufacturing strategies in different supply and demand situations. To analyse the problem of balancing the supply and demand, the theory of the product life-cycle (see definition in the forthcoming section) will be used as an analytical framework.

2. Previous research

The concept of the "product life-cycle" has been discussed widely in research (see the overview by [10]). In the theory, at least two conflicting definitions about the product life-cycle can be found. The first refers to the progress of a product from raw material, through production and use, to its final disposal as illustrated in Fig. 1.

The second definition of the product life-cycle, which will be used in this paper, describes the evolution of a product, measured by its sales over time, as seen in Fig. 2. Every product passes through a series of phases in the course of its life, referred to as the product life-cycle. The phases that a product goes through during it life-cycle are the introduction, growth, maturity and decline stages [3]. The product life-cycle can be analysed on different levels, from the main product type (product class) down to different product models, as illustrated in Fig. 2 [22]. The characteristics of the life-cycle and its effects on the reversed supply chain have been discussed by Tibben-Lembke [22], although this author fails to discuss its effects on remanufacturing operations.

When the historical sales data (product distribution) is known, this data can be used as a basis for forecasting when these products are likely to be returned (product disposal distributions). Umeda et al. [24] present a model based on empirical data from return rates for remanufacturing of a single-use camera and the remanufacturing of a photocopier. In this model, a simple normal distribution function has shown sufficient results in predicting returns when using average life as an indicator for timing of

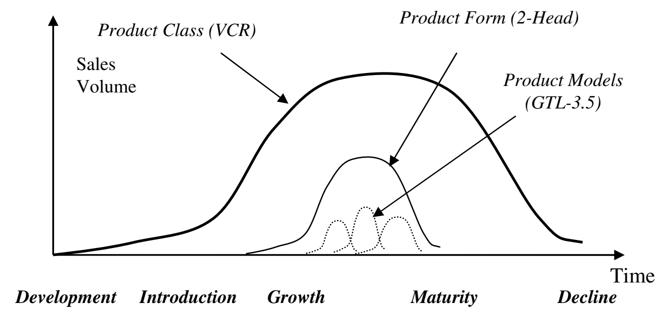

Fig. 2. The product life-cycle for a VCR [22].

returns. In the study by Umeda et al. [24], the distribution of disposed products S(t) is calculated as the historical sales data D(t) over a limited timeframe D(τ)Δτ, distributed as a normal distribution function (NDist) with a standard derivation (σ) after an average usage time (μ). This is illustrated in Fig. 3 [24]:

Another source of items suitable for remanufacturing is the components of a product. Here, the end product (e.g. a car) is not at its end-of-use but requires the exchange of a component to continue working properly (e.g. exchange of the brake caliper). This disposal distribution of components (CD) is therefore a function of how many products there are in the market (the installed base (IB)) and the failure rate of the individual components λ(t). This is shown in Equations (1 and 2) [24]:

$$IB(t) = \int_0^t D(\tau) - S(\tau)\mathrm{d}\tau \quad (1)$$

$$CD(t) = IB(t) \times \lambda(t) \quad (2)$$

The relations between the different distributions are illustrated in Fig. 4. In this figure, the upper line is the total number of products on the market (the installed base). The installed base is the sum of the produced products for a given time subtracted by the sum of the disposed products during the given time (see Equation (1)). Linked to the formulations of these distributions Umeda et al. [24], present a framework for product reuse based on three possible reuse scenarios: (1) product installation reuse, (2) spare part reuse from maintenance, and (3) spare part reuse from disposed products.

The disposal distributions in the Umeda et al. [24] study are made with regard to end-of-use, end-of-life and reusable components, but there are also additional sources of cores that can be good sources for remanufacturing. Krikke et al. [11] present commercial returns as another category, i.e., ones that are linked to the sales process. These products can be returns from customers

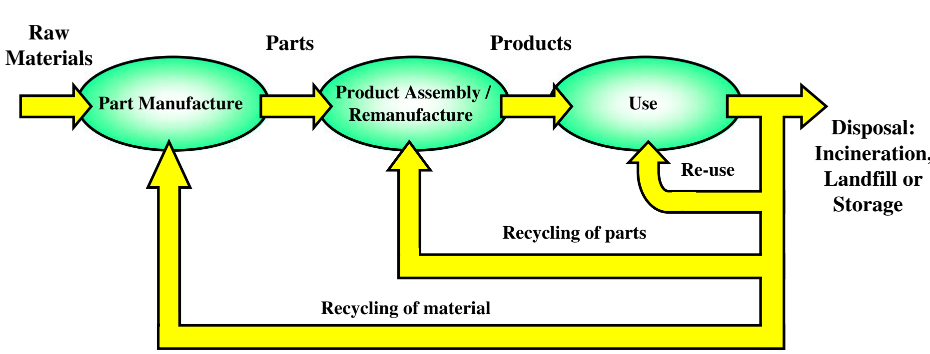

Fig. 1. The physical product life-cycle often referred to in environmental research, modified from Sundin and Bras [18].

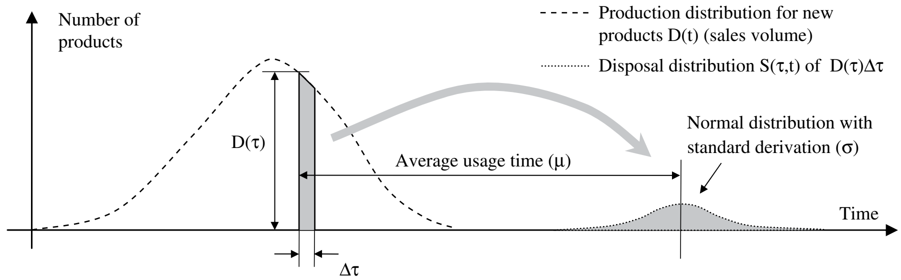

Fig. 3. Model of the linkage between the product distribution and the disposal distribution [24].

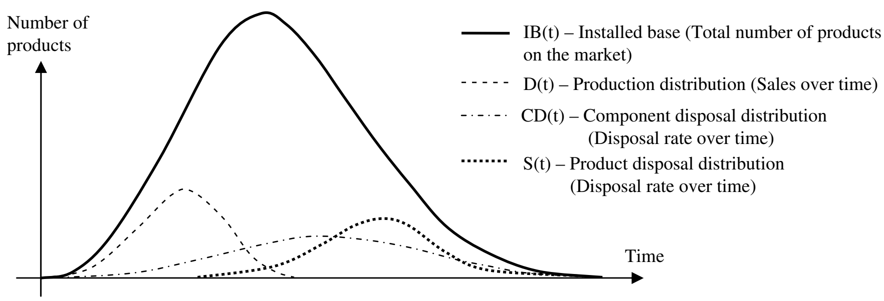

Fig. 4. Illustration of the relations between the different distributions [24].

that return products shortly after purchase. Other reasons for the returns include problems with products under warranty or a product recall. The different sources of core supply are illustrated in Fig. 5 below. Further, Guide and Jayaraman [6] also report "seed stock" as a possible solution for core acquisition. Seed stock is composed of products that failed OEM specifications at the manufacturing plant. However, the possibility for independent remanufacturing companies to acquire seed stock is limited due to their frequent competition with OEMs [8].

This previous research shows that the product life-cycle and the technical and economic issues linked to the life-cycle have a major impact on the ability to balance the returns and demand for remanufactured products. The characteristic of the life-cycle provides a theoretical foundation regarding the possibilities of acquiring used products suitable for remanufacturing. Different companies in different industries will apply different relations with the suppliers of the cores to get a sufficient number of cores for their remanufacturing operations. In a study, Östlin *et al.* [29] presents seven different kinds of relationships with suppliers/end-users that have different characteristics for the ability to control the rate and timing of the returns of used products/components. These take-back relationships are ownership-based (e.g. leasing and rental), service-contracts, direct-order, deposit-based, credit-based, buy-back, and voluntary-based relationships [29]. Guide and Jayaraman [6] present a number of management propositions on what to focus on when trying to balance the supply and demand for remanufacturing. Regarding core (used products or components) acquisition, one of the most important issues is to focus on identifying different sources of cores and rating them according to their characteristics. Forecasting core availability is critical in order to balance supply and demand. This reduces the need to purge the system of excess cores and reduces stock-outs of unavailable units. Managers should also try to synchronise return rates with demand rates, since doing so will lower the overall uncertainties in the system and lead to lower overall operating costs.

3. Methodology

The purpose of the design of a research methodology is to support the purpose and the research questions of a study [26]. The research made for this study is based on empirical data linked to several case studies of different remanufacturing companies, as well as previously documented research in the area of remanufacturing. The research has its foundation in empirical data, and links are made to the existing theoretical base. Case studies are particularly feasible in situations where the issues that are under investigation cannot be easily separated from their context or environment [26]. By using case studies, one can gain a complex and holistic view of a specific issue or problem. A case study can be described as "*problem-focused, small-scale and entrepreneurial*" [13]. Some specific abilities can be linked to case studies. According to Merriam [13], case studies can do several things. First, they can give guidance to the reader regarding what could be done, and what should not be done, in a similar situation; second, they help the reader to regard specific situations and still conclude to a general problem; and finally, they illustrate the complexity of a situation, e.g., the fact that not a single but a multiple of variables affect a given situation.

3.1. Empirical investigations

The empirical data for this study is linked to an ongoing research project called "REKO[1]" which employs an explanatory multiple-case study concerning multiple types of products. The main source of data collection was semi-structured interviews. The questions formulated for this type of study are normally open and give the respondents a chance to go into detail regarding the answers, i.e., the questions were prepared without specific

[1] The REKO project ran during 2003–2006 and was sponsored by the Swedish Governmental Agency for Innovation Systems (VINNOVA) – see www.vinnova.se.

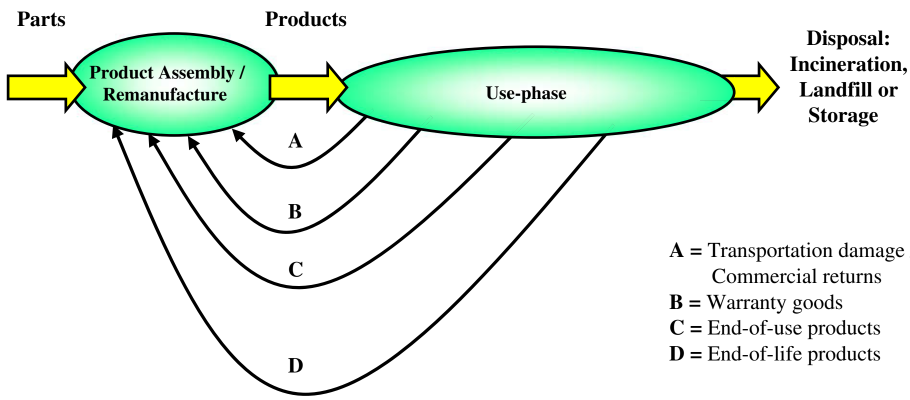

Fig. 5. The different sources of cores for the remanufacturing process retrieved from different stages within the use-phase.

sequence or answering options [9]. Prior to the interviews, a theoretical literature review was performed; this review was the basis for the formulation of the interview questions. The formulation of the interview questions was reviewed and feedback provided by the research group linked to the REKO project. After the questions were formulated, a pilot study was made to verify their validity. The main source of data for the case studies was interviews, all of which were recorded and varied in length from 1 to 4 h, depending on how much information the respondents had to contribute. Typically, those interviewed were facility managers, production managers, controllers and technicians. Other sources of data were direct observations made during the study visits to the companies, as well as documentation in the form of photographs, brochures and information from the Internet (independent as well as issued from the case companies). These sources were mainly used for data triangulation.

The case company selection was made from companies that were found in the study of the remanufacturing industry in Sweden [19]. In this study, a multitude of potential companies was found. The choice of case companies was made based on variables concerning their annual remanufacturing volumes, as well as product complexity and remanufacturing process.

According to Eisenhardt [5] there is no ideal number of cases, though a number between 6 and 10 is good for theory building. Empirical data was gathered primarily from different Swedish remanufacturing companies. The companies selected for the case studies were:

Case company	Remanufactured products	Company size	Relation to OEM
BT Industries	Forklift trucks	Large	OEM
Scandi-Toner	Toner cartridges	Small	Independent
Swepac International AB	Soil compactors	Medium	OEM
Tetra Pak	Filling machines	Large	OEM
Volvo Parts	Engines	Large	OEM
UBD Cleantech AB	Automotive components	Medium	Contracted and independent

To validate the findings of the case study, further (interview) studies were performed at the following companies:

Company	Remanufactured products	Company size	Relation to OEM
Alfa Laval	Heat exchangers	Large	OEM
Bättre Kontor	Office furniture	Small	Independent
Greenman Toners	Toner cartridges	Small	Independent
Inrego	Computers	Medium	OEM
Scania	Diesel Engines	Large	OEM
Turbo Tech	Turbo chargers	Small	Independent

These case companies were found to be sufficient for this study, since they provided good in-depth knowledge to fulfil its purpose. It was determined that additional cases would take too much time to investigate; according to Voss et al. [25] this is an important skill in theory building for case studies – to know when to stop.

4. Life-cycle implications for the remanufacturing system

In the remanufacturing environment, the life-cycle of a product and the disposal rate for both products and components has a great impact on the possibility to perform profitable remanufacturing. Previous research has shown that issues such as the age of the generation of the product, the expected life (reliability), the rate of technological development and the willingness to return products for remanufacturing will influence these distributions [6]. This section will focus on shedding light on these issues, as well proposing strategies that have the potential to make the overall remanufacturing system more efficient. In the following section, the stages of the life-cycle will be addressed according to three different remanufacturing scenarios (adapted from Umeda et al. [24]).

- Product remanufacturing – Used products are remanufactured to "as-new" or upgraded status; an example of this category is the remanufacturing and upgrading of Tetra Pak filling machines.
- Component remanufacturing – Used components are remanufactured to "as-new" or upgraded status; an example of this category is the remanufacturing of automotive components (UBD case) and toner cartridges (Scandi-Toner case).
- Component cannibalization – Used products are cannibalized for components, and the components are then remanufactured to an "as-new" or upgraded status. An example of this category is the cannibalization of components from heavy trucks (Scania) and forklift trucks (BT Industries); in these cases, the component cannibalization option is mainly a supporting activity for the product and component remanufacturing scenarios.

4.1. Product remanufacturing

4.1.1. Demand for remanufacturing

The shape of the product distribution of newly produced products has a major impact on the demand for remanufactured products. A theoretical illustration of the linkage between demand for new and remanufactured products can be seen in Fig. 6.

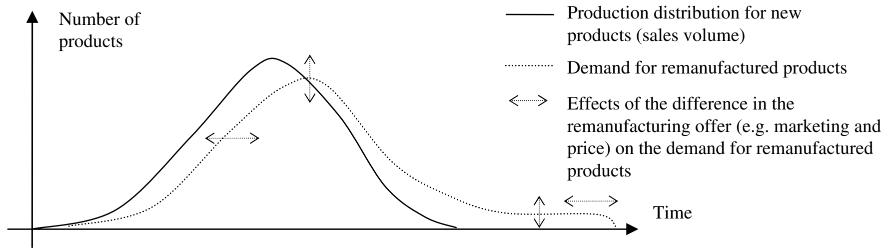

Fig. 6. Linkage between new product sales and demand for manufactured products.

Just as for new manufacturing, there is a possibility to affect the shape of the demand for remanufactured products by different remanufacturing offers; this is illustrated by the dotted lines in Fig. 6. For example, if no marketing of the remanufacturing product is possible, then the demand of remanufactured products often tends to be lower, due to customers' poor knowledge of the availability of remanufactured products. In addition, the pricing strategy of remanufactured products has a major effect on the shape of the demand for remanufactured products. For example, in traditional manufacturing a major reason for the drop in sales is that once new products with better performance are introduced, the price for the older version of the products cannot compete with the price of the newer product. In the case of remanufacturing, some products can still be attractive for a longer period of time due to the traditionally lower price for remanufactured products. This is especially true for products with low technological development, or within customer segments that are not sensitive to new technology. One factor that limits the demand for remanufactured products is other types of product recovery options; reuse is one example. In the secondary market, resale can be a more viable solution in the eye of the customer if the product at hand is in working order and the expected lifetime of the product is sufficient (the quality of the used product). In practice, this is largely a matter of the cost of the reuse and the remanufacturing options, as illustrated in Fig. 7. For example, when the quality of a forklift truck is high, there is no motivation to remanufacture. This is because the value of the forklift on a secondary market is sufficient, and the cost for remanufacturing this high-quality product is greater than the increase in market price for the remanufactured product. Later, when the product is worn and has been on the market for a longer time, the cost for remanufacturing is less than the additional value of a product when it is remanufactured in respect to the resale price. For cores with low quality, the cost for remanufacturing can become so great that it cannot match the possible value on a secondary market; in this situation, it can be motivated to sell the used product to a segment with lower quality demands. Examples of these customers are those having very limited needs of "lifting capacity", and who might need a forklift just a couple of times each week. For this customer, a reusable forklift of lower quality is "good enough" because the usage is so low that the remaining lifetime of the forklift will be sufficient. Hence, the competition from other recovery options limits the demand for remanufacturing volumes over the life-cycle.

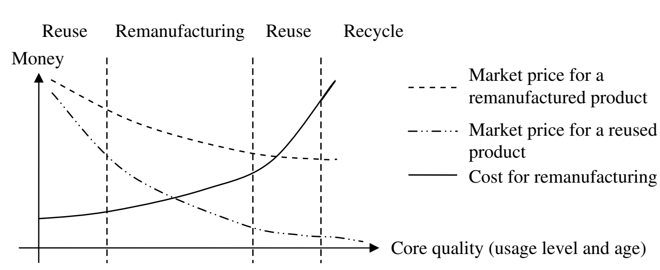

Fig. 7. Illustration of the economically preferred product recovery option as a function of core quality (from the forklift truck case).

Another interesting factor in respect to the demand for remanufactured products over time is that there is sometimes a local peak of remanufacturing sales right after that the product is no longer manufactured. This can be especially apparent for independent remanufacturers competing with OEMs that do not perform remanufacturing. One practical example of this can be taken from the furniture industry in Sweden, where Bättre Kontor (independent remanufacturer) remanufactures IKEA (furniture retailer) furniture that is no longer in production. In this case, the customer is normally interested in complementing a set of furniture with additional examples of the same furniture.

4.1.2. Supply for remanufacturing

To match the demand for remanufactured products there is a need to forecast the future supply of cores suitable for remanufacturing. The potential supply of cores from end-of-use and end-of-life can be forecasted according to historical OEM production data as explained in the theoretical framework [24]. One problem with this is that the forecast is made for the total disposal distributions of all products, regardless of the quality level of the product. The disposed products are also subject to reuse/repair (if the quality level is high enough) and recycling/waste treatment (if the quality is too low), as illustrated in Fig. 7. As a result and as seen in Fig. 8, the supply of cores suitable for remanufacturing will always be lower than the disposal distribution. In addition, the supply of cores will fluctuate according to the quality level of the disposed products over time, due to the logic of the economically preferred product recovery option as a function of core quality as illustrated in Fig. 7.

4.1.3. Life-cycle aspects for balancing supply and demand

The possible remanufacturing volumes for a product are dependent on the relation between the supply and demand curves, as seen in Fig. 9. In the growth phase, the potential volumes are limited to the supply of cores suitable for remanufacturing. After the growth phase comes a maturity phase, where underlying supply and demand are more or less balanced. After a while, when supply increases and the demand starts to decrease, more cores are available than needed. In this decline phase, the limiting factor for remanufacturing volumes is the demand for remanufactured products. The case when remanufacturing is generated from end-of-use returns is illustrated in Fig. 9. The shape of the potential remanufacturing volumes is dependent on the shape of supply and demand distributions. The exact shape of the distributions differs between different types of products, for example, and the potential remanufacturing volumes of single-use cameras are high due to the short average usage period that "pushes" the supply distribution to

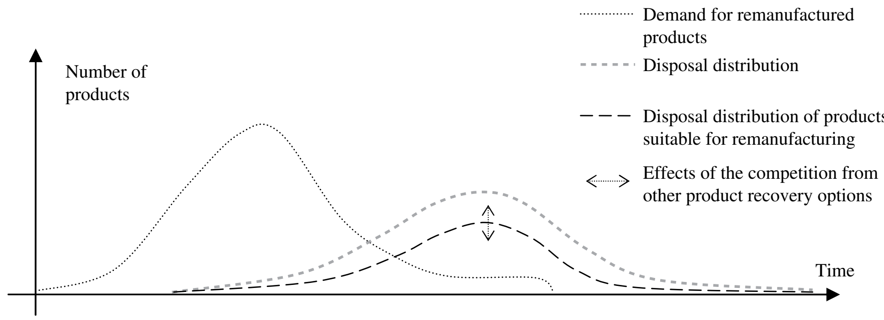

Fig. 8. Linkage between the disposal distribution and the distribution of products suitable for remanufacturing.

the left in Fig. 9. An opposite example is the remanufacturing of filling machines to "as when produced status"; in this case, the machines are returned after a long period of time and the supply distribution is pushed to the right.

In product remanufacturing, there is one special case where this reasoning does not apply: when the supplier of the core is also the customer of the remanufactured product as in a direct-order customer relationship, as for example in remanufacturing as a service. In this case, the customer supplies the core directly according to a make-to-order principle, and there is potentially a perfect match between supply and demand. A practical example of this is the remanufacturing service provided for soil compactors (Swepac case), where the customer (often a rental company) supplies the compactor and gets it back within two weeks. The logic regarding this case is very similar to the make-to-order case of component remanufacturing; a discussion of this is referred to in the forthcoming section.

In the case when remanufactured products are being upgraded to the latest specifications from cores based on a previous version (illustrated as A + 1 in Fig. 10), the situation can become advantageous from a potential remanufacturing volume perspective, as illustrated in Fig. 10. Examples of this include filling machines that are upgraded to the newest development steps (Tetra Pak) or upgraded copying machines (Xerox). Upgrading products to the latest technical solution is a viable option when expanding the lifetime of a product. The possibilities to do so are limited according to the upgrading cost it generates, but also according to the level of technology of the core to be upgraded. If the fundamental technology of a product is changed completely in the new product (product class level), the possibilities to remanufacture are low. If instead the changes in technology are minor and concentrated only to specific modules/components (product model level) in the product, the potential for upgrading is greater. (For a detailed discussion about design solutions that can ease upgrading in a remanufacturing case, see e.g., Zwolinski et al. [27] and Bras and Hammond [2].) To summarize, upgrading products can be a very effective strategy for matching supply and demand and increasing remanufacturing volumes.

4.1.4. The introduction phase

Before remanufacturing can be undertaken, there can be difficulty in identifying the potential products for which remanufacturing is profitable and technically feasible [27]. One important competitive mean for remanufacturing companies in this phase is to quickly develop and present remanufactured products to the market once a new type of product has been introduced (i.e., shorten the time-to-market for remanufactured products). To do this, it is important to quickly identify and secure the access of used products suitable for remanufacturing. One of the independent remanufacturers puts it like this: *"If we can work in different ways with the customer to identify products earlier, we can stand prepared when the need for a remanufactured product arises"*. Closer cooperation between the remanufacturing stakeholders, new manufacturing and potential customers can result in these advantages:

- Better identification of potential remanufactured products can stimulate increased remanufacturing of products.
- A faster time-to-market for remanufactured products, gaining a first-movers' advantage in respect of competitors.
- An earlier start of remanufacturing has the potential to better match underlying demand for remanufactured products, and hence increase remanufacturing volumes.
- Demands regarding quality and technical specifications of cores/components can be distributed from the OEMs to the remanufacturing industry.

In this phase, the possibility to identify potential products and shorten the time-to-market is largely dependent on the ability to act in a network of actors such as OEMs, component suppliers and customers. Hence, relationships between partners become important. Previous research reports that competition between OEM

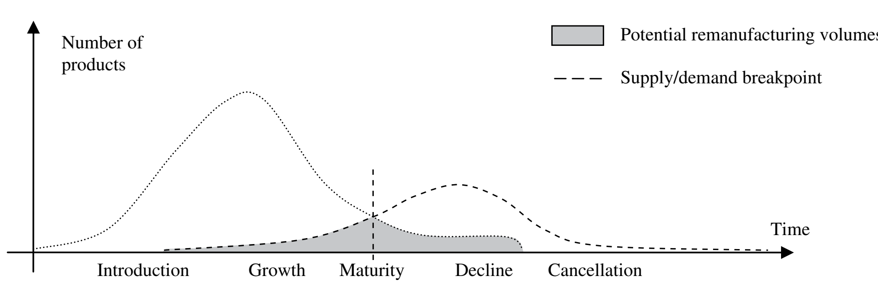

Fig. 9. Potential remanufacturing volumes.

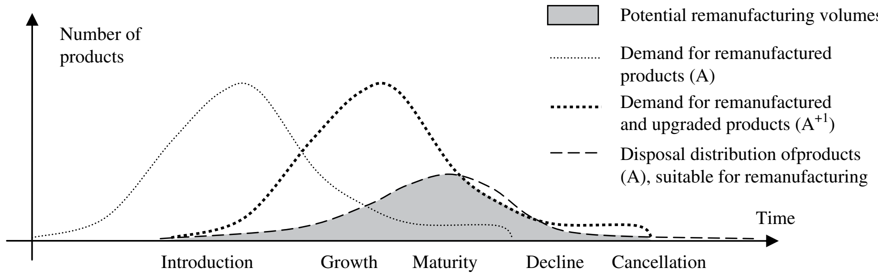

Fig. 10. Potential remanufacturing volumes when upgrading to latest technology is a viable option.

remanufacturers and independent remanufacturers can be a major limitation for collaboration, although this is not always the case [8]. In this study, there have been examples of fruitful collaboration between OEMs and independent/contracted remanufacturers. In the UBD case, the remanufacturer is contracted by the OEM, but it also competes with the OEMs as they also provide remanufactured products to the independent market. Additionally, if the products have been designed for remanufacturing in the first place, the possibilities to identify and motivate remanufacturing will be greater.

4.1.5. *Growth phase*

This is the phase when remanufacturing volumes emerge and increase over time. Here, the core returns from end-of-use are limited, and the potential demand for products is high. In this phase, the possibilities for generating good profit margins are high, mainly due to the high demand for remanufactured products with respect to the lower supply of products suitable for remanufacturing. The companies that have a better ability to acquire cores in this phase will have a major competitive advantage. As the end-of-use and end-of-life disposal rates are limited to failure rates and average usage periods, the possibility to manage the returns is low. In this phase, the greatest potential for acquiring cores is from other sources such as seed stock, commercial returns and other Secondary Channel Goods, as for example warranty claims and transportation damage (see Fig. 5). A practical example of this is the remanufacturing of warranty claims and transport-damaged household appliances at Electrolux. These sources of cores are especially fruitful because they appear early in the life-cycle. A source for competitive advantage is the ability to find new and creative ways to acquire cores needed for remanufacturing. One example is automotive companies (e.g. Scania), which are beginning to work closely with insurance companies, creating contracts for the supply of products being damaged linked to insurance activities (e.g. traffic accidents).

The growth phase also has a great impact on the inventory control of remanufacturing companies. The supply and demand situation makes it important to remanufacture the incoming cores and prepare them for delivery as soon as possible (see more about the importance in lead-time reduction in Section 4.2). Hence, in order to decrease lead-times there is a need to minimise the number of products listed as work-in-process in the supply chain. An example of causes that can generate high work-in-process are infrequent transports between retailer and the remanufacturing facility, the need to batch products together, and a lack of new replacement components.

In this phase, there is a need to secure that the remanufacturing system is able to accept these new products. To secure the acceptance of these products, a justified degree of flexibility is needed at the same time as a stable process is being created. Flexibility in the remanufacturing process is an important factor in its efficiency due to the complexity and uncertainties in the process. In some cases, there is also a need for large investments in machining, test equipment and process equipment.

4.1.6. *Maturity phase*

In this phase, the return rates from end-of-use increase more and more, to the extent that they start to meet and extend the demand for remanufactured products. As volumes increase and a more stable remanufacturing process is developed, efficiency and cost-consciousness become important issues. Important in this phase is to manage the inventory levels of returned products in relation to the demand for remanufactured products. Another important issue is how make the processes become even more efficient, e.g., through lean production principles (see e.g. [20]).

As illustrated in Fig. 9, there is a breakpoint between supply and demand. This breakpoint also has a significant impact on the competitive advantage for remanufacturing companies. Before the breakpoint, competitive advantage is based on, e.g., identifying potential products and the ability to acquire cores. After the breakpoint, this becomes less important, while efficiency in the remanufacturing process increases in importance. As the supply of end-of-use and end-of-life products increases, an important issue is to limit and acquire only the cores that are most suitable for remanufacturing. Another characteristic in the latter stages of this phase, as well as in the decline phase, is that the quality of the cores can become lower; this in turn can cause a demand for new types of reprocessing operations.

4.1.7. *Decline phase*

In this phase, the need for remanufacturing decreases, and there is normally an abundance of cores available on the market. The main danger in this phase is having excessively high inventory levels of cores and remanufactured products when demand for remanufactured products decreases. This can result in high obsolescence costs, both for end products as well as for components that are kept in inventory as spare parts. This is especially important for complex, low-volume products with many product-specific components, as for example diesel engines (as in the Volvo case). Knowing when this drop is about to happen is critical in reducing the risk and cost of obsolescence.

4.2. *Component remanufacturing*

The cases of component remanufacturing and product remanufacturing are quite different. In the case of component remanufacturing, the demand for remanufacturing activities is primarily linked to the characteristics of the installed base and the failure rate of individual components. One example of this is that the need for brake caliper remanufacturing is dependent on the number of installed cars (UBD case). Just as in the case of product remanufacturing, the component remanufacturing volumes are not directly correlated to the disposal distribution of components from a product.

Competition from other after-market options such as component replacement by new components (spare parts) influences the remanufacturing volumes. One additional problem in assessing the failure rate for components is that different components also have different characteristics, e.g., mechanical components tend to fail in respect to how the product has been used, whereas electronic components display a more random failure pattern [16].

Just as for product remanufacturing, component remanufacturing volumes are sensitive to new component pricing (spare parts pricing). As a result, automotive companies (Volvo case) report that when the end products are still in production, the prices for new replacement components generally tend to be lower, and increase when the end product goes out of new production. This logic is derived from the fact that when end products are no longer produced, the manufacturing volumes of components become limited to spare parts production, and the produced volumes of new components decrease. As a result, the higher costs for new components (spare parts) can further stimulate remanufacturing volumes later on, when demand already has started to decrease. A negative impact reported to affect the remanufacturing companies is that some of the prices for replacement parts (sub-components) used in the remanufacturing process also have a tendency to increase according to the same logic. This increase in remanufacturing volumes late in the life-cycle is a result of component replacement options being reduced to buying a remanufactured or a reused one, as shown in Fig. 11.

As a general conclusion, the competition arising from replacement volumes by new components is generally higher in the early life-cycle; vice versa, completion from component cannibalization/reuse occurs later in the life-cycle (see reasoning in the forthcoming component cannibalization section).

4.2.1. Balancing supply and demand

In a perspective of matching supply and demand, component remanufacturing is a lot different from product remanufacturing. In component remanufacturing, the supply of a core is linked to the demand for remanufacturing. Simply put, when a customer needs a replacement component they supply a component, and in return receive a remanufactured component. In this perspective, the need to balance supply and demand is not as prevalent as in the product remanufacturing case. Still, in the introduction phase there is a shortage of cores to be remanufactured, as not every core is reusable. Another issue to consider is that the number of available cores from remanufacturing can also be decreased by losses of cores in the supply chain. One example of these losses can be the failure to collect used cores when selling a remanufactured product to a customer. Later in the life-cycle, when the rate of product disposal

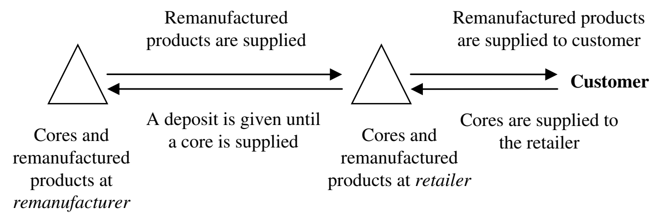

Fig. 12. Illustration of core/deposit flow in a deposit-based relationship.

is increased, there is also an increase in available used components through component cannibalization of disposed products. This is illustrated in Fig. 11, along with the potential for remanufacturing volumes.

Fig. 11 is typical for direct-order relationships (make-to-order). Here, the components are sent to the remanufacturer, remanufactured and returned to the customer. In this situation, there is a direct link between supply of the core and demand for the remanufacturing service, just as in the case of soil compactor remanufacturing as a service to rental companies (Swepac case). The situation with a deposit or a credit-based relationship (make-to-stock) is different, as it is a previously supplied (and remanufactured) component that is sold to the customer. In this situation, there is a lag between the supply of a component and the delivery of a remanufactured product, as illustrated in Fig. 12. In this situation, the customer returns the used component and receives a different remanufactured component immediately. This system is common in the automotive industry, where the remanufacturer normally supplies a product to a sort of "middle man"; an automotive part retailer (as in the UBD example) is one such intermediary. The retailer pays a price and a deposit for the remanufactured product. When the retailers sell the product, they collect the used core from the customers; later, they return the core to the remanufacturer and their deposit is refunded, resulting in the one-for-one (1:1) take-back relationship shown in Fig. 12.

The problem with this system is the existence of a lead-time between the supplying of cores until the product is remanufactured and put in inventory, ready for sale. As seen in Fig. 13, this lead-time will push the supply curve forward in time and reduce the possible remanufacturing volumes. A detailed discussion of the effects of lead-time is given in the following discussion about the life-cycle phases.

4.2.2. Introduction and growth phases

Just as for product remanufacturing, there is a need to find potential components for remanufacturing; here, the same type of reasoning used for product remanufacturing is valid. Once new products have been introduced into the market, there is a specific

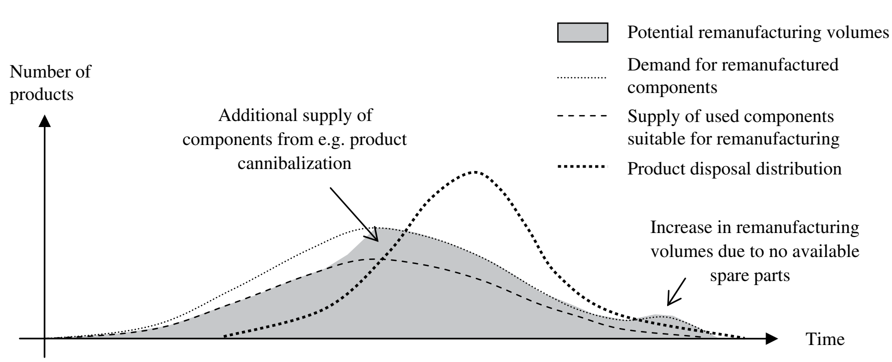

Fig. 11. Potential remanufacturing volumes for component remanufacturing.

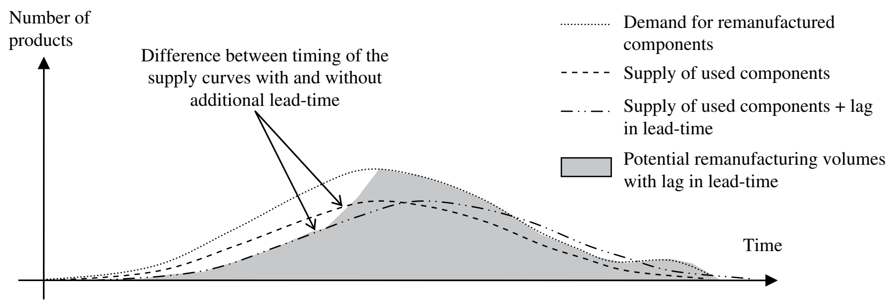

Fig. 13. Potential remanufacturing volumes for component remanufacturing with additional lag in lead-time for the supply of cores.

problem for companies using deposit-based relationships (make-to-stock). Before being able to sell remanufactured products, there is a need to acquire cores; with no sale of remanufactured products, however, there is no incoming flow of used cores. In this phase, the producers will have to make an investment in cores before they can begin to sell remanufactured products. This need for investment can be quite large if, e.g., a remanufacturer is to put an inventory of remanufactured products at each retailer (as for example in the UBD case). One way of minimizing the number of components to be used as an investment is to try to minimize the lead-times between when products are returned from the customer and when they are available for sale.

The possibilities to acquire cores suitable for remanufacturing are limited in the growth phase. Cannibalization of components from end-of-use and end-of-life is a potential source of cores, but it appears much later in the life-cycle (see discussion about component cannibalization). Cores coming from seed stock and commercial returns can be a much more fruitful option in line with the case of product remanufacturing. In the automotive industry, auto repair shops are a major source for cores (UBD case). In the early life-cycle, the broken components are replaced with new components, while the used cores are sold to core dealers or directly to remanufacturers. Another frequent solution used in automotive practice is to supply new components instead of remanufactured products. Minimising lead-times from the supply of cores to the delivery of remanufactured products in the earlier phases of the life-cycle is an important issue, since the costs for acquiring cores are generally higher during the later phases of the life-cycle, when cores are more abundant. In the case of toner cartridges, the use of voluntary take-back is more widely used. This system is based on new components purchased early in the life-cycle, and used cores given back voluntarily to the remanufacturer. The drawback with this system is that there is no way of competing early in the life-cycle; it also entails the major risk that competition will gain a first-mover advantage.

4.2.3. Maturity phase

In this phase, the product returns from end-of-use and end-of-life start to increase. Acquiring component cores that have been cannibalized from end products begins to be a viable source. In the automotive industry, scrap yards are a frequent source of component cores for remanufacture.

4.2.4. Decline and cancellation

As previously discussed, in the case of component remanufacturing there can be a local peak of remanufacturing volumes in the latter phases of the life-cycle. This is a result of OEMs stopping manufacturing of new components (spare parts). Simply put, these components need to be replaced by remanufactured ones, or possibly reused products. Just as with product remanufacturing, the risks of obsolescence are great in this phase, especially for companies with make-to-stock polices. One solution to become less sensitive towards obsolescence is to apply a make-to-order policy on some parts of the offered products, thereby reducing the need to keep a finished product inventory. The disadvantage with the make-to-order policy is that the customer has to wait while the product is being remanufactured. As a result, this option is only viable when (1) the product can be sent off for a longer period of time, (2) when no cores are available, and (3) when the customers want the same product back as they sent in (e.g. customized products).

4.3. Component cannibalization

This last category is based on the idea that products are cannibalized for components that are later remanufactured. Cannibalization of components for reuse, in e.g., scrap yards, is a frequent activity in the automotive industry. Cannibalized components are also a source of components for both component remanufacturing and product remanufacturing.

4.3.1. Balancing supply and demand

The supply of used products suitable for component cannibalization is dependent on what other options are available. Fig. 7 presented a framework regarding options about reuse and remanufacturing; a similar approach can be taken for the case of component cannibalization. For cannibalization to be economically motivated, the earnings must be higher than the earnings from other product recovery options such as remanufacturing, recycling, and reuse. The earnings from component cannibalization can be calculated as Equation (3) (example taken from component cannibalization of forklift trucks).

$$Earnings = \sum_{0}^{x} p(x) + \sum_{0}^{y} r(y) - \sum_{0}^{x} ic(x) - DC - MP \quad (3)$$

x = number of components that can be reused
y = number of components that cannot be reused
p = market price of disassembled components
r = gain/cost for recycling/waste treatment of disassembled components
ic = inventory carrying cost for cannibalized components
DC = total disassembly cost
MP = market price or cost for lost sales for the core in an "as is" status

There are two main variables that change according to the quality of the core and which determine the outcome of Equation (3): the number of reusable components and the cost for acquiring the core or cost for the lost sales. For cannibalization to be a viable option, the market price of the core should not be too great, and secondly the number and value of the reusable components should be sufficient. As a result, cannibalization has the greatest potential

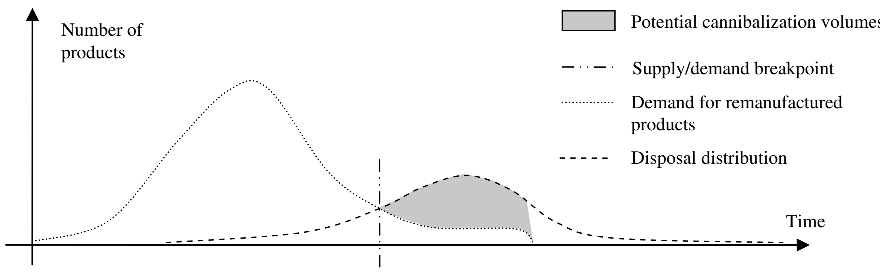

Fig. 14. Potential component cannibalization volumes to be reused in product remanufacturing.

late in the life-cycle, when the supply of cores is higher then the demand for remanufacturing and reuse of the product, resulting in a generally lower market price for used products. Fig. 14 illustrates the potential area for product cannibalization in respect to the remanufacturing option. The timeframe in which the possibilities to cannibalize components can be quite limited, something which increases the risks of obsolescence in reused components. A technical hindrance linked to cannibalization is that components that are usually demanded for remanufacturing operations are also in such bad shape in the object for cannibalization that they cannot be reused in remanufactured products. As a result, there might be a need to dissemble several cores to find one component that can be remanufactured or reused in a satisfying manner. The possibility to reuse and remanufacture cannibalized components is also a question of compatibility between different versions of a product. If the components can be reused between the different versions, the window in which cannibalization is possible is expanded, and the chance that the components will be reused is greater.

Component cannibalization can also be motivated even though the potential earnings are low or negative. For the OEMs, the option to recycle/cannibalize a product instead of selling the product to a secondary market (e.g. an independent retailer) can be more advantageous. If the quality of the object is too low, or if the product causes an accident, the product still carries the brand and can bring bad will to the company. As far as brand image, there can be legitimate reasons for keeping the end-of-use and end-of-life products off the market; in this case, cannibalization can be a solution for restoring some value. Other motivation factors for taking a product off the market are that the resale option is competing with other, more profitable solutions, such as new sales and remanufacturing.

5. Discussion and conclusions

This paper addresses the effects of balancing supply and demand in the remanufacturing industry. This analysis is in its essence focused on how to provide remanufactured products in an effective way during the product's life-cycle. The life-cycle theory can be effective when trying to forecast the general trends of remanufacturing volumes. When going into further detail, the problem becomes more difficult and addresses the problem of uncertainty in timing and quantity. The difficulty in applying a life-cycle perspective with more detailed forecasting is that the variables used to calculate future returns are insecure. The average use and life of a product/component can be forecasted beforehand, but this factor is also dependent on complex factors, for example to what extent the product has been used and in which environment (to mention some variables). Another factor is the willingness to return old products for reuse. An example of this can be taken from the mobile phone industry, where customers are reluctant to return their old mobile phones even after purchasing a new one, rationalizing *"my old phone can come in handy if my new one breaks"*. In addition, the demand for remanufactured products can be said to follow new production demands, but are also sensitive to prices of substitute products as brand new products and reused second-hand products (if available). The rate of technical development also has a major impact on the demand for remanufactured products, in some cases resulting in a sudden drop of sales for remanufactured products. In all, these insecurities make it difficult to accurately forecast the supply and demand for calculating exact return quantities and timing.

The major advantage of using the life-cycle as a foundation for balancing supply and demand is the insights it brings on a general/strategic level. In this paper, a number of insights have been presented that can be used in the different phases of the life-cycle. At a general level, some additional conclusions can also be made. The OEMs are generally in a more favourable position to perform remanufacturing with respect to independent remanufacturers, especially in the earlier phases of the life-cycle when access to commercial returns and seed stock are a competitive advantage.

In the remanufacturing product life-cycle, there is a breakpoint where the supply of cores becomes greater than the demand for remanufactured products as shown in Fig. 9. This breakpoint has a significant impact on the competitive advantage for remanufacturing companies. Before the breakpoint, competitive advantage is based on, e.g., identifying potential products and the ability to acquire cores. After the breakpoint, this becomes less important while efficiency in the remanufacturing process increases in importance. As the supply of end-of-use and end-of-life products increases, an important issue is to limit and acquire only the cores that are most suitable for remanufacturing. These conflicting ways of looking at cores may introduce difficulties for companies. Normally remanufacturers handle a vast amount of products that are in different life-cycle phases, but they have to be coordinated in the same supply chain; the coordination and administration of different take-back systems is an important aspect in managing this. The mix of different marketing channels for product returns is also an important aspect for matching the different needs over the life-cycle.

Upgrading products to the latest standard is one possible solution for increasing the potential remanufacturing volumes for the product remanufacturing case, using for example modular design strategies. For component cannibalization, this is not an as important issue; for this category to expand further, component remanufacturing has to become a more attractive option with respect to the new component alternative. Also, a more standardized and modularized use of components could increase the possibilities to cannibalize components for remanufacturing and reuse.

Furthermore, remanufacturers should focus on the development of methods that can make returns predictable. In remanufacturing, the source of cores is the current users of the desired cores. Each of these users is a potential supplier, but with a limited supply capacity and usually very long lead-times for core production. To identify and communicate continuously with all of these potential suppliers is simply perceived as impossible. The result of this lack of communication is that the user comes to the remanufacturer with the core only "when they think if it" (if they come back at all), thus displaying a stochastic return rate. The problem of sourcing cores becomes a question of which of these potential suppliers can supply a core at the right time, at the right quality and at the right price. To be able to find the right cores, different marketing channels and business concepts provide communication solutions with potential suppliers. For example, off-lease products have been rated more predictable than other types of returns due to the additional information that is available to the remanufacturing company [19,21]. The off-lease product provides some degree of security that the product be returned at the right time and at a known price (and hopefully the right price). Using different contracts that result in the take-back of cores can be one solution for securing that products are returned at the right time and for the right price, although the quality of the returned product cannot be contracted that easily.

The problem of balancing supply and demand can also be limited or aided depending on the business solution. Remanufacturing of single-use cameras with fast exchange cycles are, for example, aided by the policy of returning the entire camera for development, resulting in faster returns. Coordination of leasing and rental contracts according to average usage age, as in the Xerox and Tetra Pak cases, can also aid a balance between supply and demand. As a result, the more thought about the business solution and how it can aid in balancing returns with demand, the greater the possibilities for successful remanufacturing.

6. Future research

The topic of this research has many branches which could be expanded in research. For example, not only the pricing of the cores coming into the remanufacturing process but also how to set the price of the remanufactured products depending on in which phase the product is in its life-cycle. Furthermore, the product data management during the product life-cycle is important to study further since it has much influence of the remanufacturing operation performance.

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