Chapter 1

Introduction

The practice of reusing products is a very old one. Since old times materials of used objects are recovered and reused for similar or completely different purposes. For example, metal objects can be remelted to serve as raw material in other metal objects, or wooden objects can be recycled after use as burning material. Although this type of reusing products is still common practice today, more typical examples for this century are the reuse of for instance paper, milk bottles, car parts, and toner cartridges.

While the classical reason to reuse materials and product parts often was the scarcity of resources, the introduction of cheap materials and more efficient technologies to discover and obtain resources, gave rise to a society of mass consumption in the sixties, where reuse was often not economically justified. This 'throw-away age' was characterized by cheap, disposable products with a relatively short life-cycle. As a direct result, our society today faces a considerable waste problem caused by a huge amount of discarded products and materials. For instance, in the Netherlands 33,000 tons of electronics were discarded in 1992, while it is expected that this figure will increase to 57,000 tons in 2005 (see De Ron [44]). Moreover, high production rates have nearly depleted natural resources.

One of the first reactions against this development came in the early seventies, when a major oil-crisis lead to significant price increases throughout the complete product chain. However, foreign political problems (for instance the cold war) and economic recession removed the focus from the environmental problem. A number of environmental disasters in the late eighties (Chernobyl, Exxon Valdez) and a growing concern towards the ozone layer and the greenhouse-effect started to convince legislators, producers and consumers that something had to be done. Since then products are shifting from disposable towards reusable. A new management research area has emerged: Product recovery management.

1.1 Product recovery management

We will call the process that tries to control the recovery of products 'product recovery management'. A formal description is given in Thierry [55]:

> "Product recovery management (PRM) encompasses the management of all used and discarded products for which a manufacturing company is responsible. The objective of PRM is to recover as much of their economic (and ecological) value as reasonably possible, thereby reducing the ultimate quantities of waste."

The above description suggests that it is clear for which used and discarded products a company is responsible. In practice this does not seem so straightforward. Legislation on product and material reuse is not yet fully developed and changes rather quickly. In Europe for instance there is still little consensus about the issue (see e.g. Aardoom [1], and Bitter and van Zomeren [6]). Also, legislation need not to be the only motive for product recovery. In situations in which companies are not legally responsible, they may *feel* responsible for their sold products, or they may even have direct economical motivations. Certainly, 'the ultimate reduction of waste' is not necessarily the main goal of a business firm that is engaged with product recovery.

Another objection to the above description results from the last phrase: 'The objective of PRM is to recover *as much* of their economic (and ecological) value as reasonably possible,...'. This suggests that firms (should) in principle recover as much as possible. Legislation however typically speaks in terms of minimum recovery *percentages* and companies are not necessarily obliged or motivated otherwise to recover as much as possible. Total recovery need not be the optimal strategy in an ecological sense (see e.g. Bloemhof [7]), nor in an economical sense (this thesis).

Considering the above, a slightly more appropriate definition could be the following:

> "Product recovery management (PRM) is the management of all used and discarded products for which a manufacturing company takes responsibility. The objective of PRM is to recover

that amount of products that is economically and ecologically justifiable, while satisfying the legal constraints."

Product recovery is not an easy solution to the problem of waste reduction. PRM poses many difficult, but interesting questions in various areas. Some of these areas are:

- **Product design**; In order to be able to recover products or product components in an efficient way products need to be specially designed for quick disassembly and testing, while materials and product parts need to be of sufficient quality to make them reusable. To give an example, BMW engineers use the following directives in their product designs for easy disassembly and recycling (see Vandermerwe and Oliff [64]): reducing the number of materials used, avoiding composite components, marking parts and components to show their composition of materials.

- **Logistics**; Materials and product parts need to be collected, possibly sorted, and transported. In doing so several options should be considered: *(i)* are used products handled by the manufacturer itself or by an external actor, *(ii)* are the used products processed by the manufacturer, and if so are they incorporated in the existing production line, or is it done by an external actor, *(iii)* are distribution and collection completely separated or is there a level of integration, (iv) should testing occur immediately after collection (decentralized, which saves transportation costs of non-reusable products) or after transportation (centralized, which saves testing equipment). Similarly, if sorting occurs early in the reverse logistics chain, this may save (future) handling costs.

  Since the collection and transportation of used products and materials seems like a reversed image of distribution, this is sometimes called 'reverse logistics' or 'reverse distribution'. In the literature many authors have proposed modifications of the traditional facility location models (see Mirchandani and Francis [35]) to adapt to reverse distribution networks. Convergent network structures have been studied for instance by Batta and Chu [5], Erkut [13], and Ginter and Starling [18]. Other location models are by Barros et al. [4] who design a network for the recycling of sand from construction waste, Caruso and al. [9] who describe a solid waste management system, which includes collection, transportation, recycling, and disposal, and Kroon and Vrijens [33] who develop a reverse logistics system for returnable containers.

- **Production planning and inventory control**; The flow of used products and used materials is usually more variable and uncertain than flows of ordinary raw materials and half-fabricates. Also, the combination of manufacturing and product recovery tends to make planning and control more complex (this issue will be covered in section 1.4.2).

- **Information systems**; Quality and timing of returned products and materials often have to be monitored. This may require information systems like electronic data interchange (EDI), and other (new) technologies to trace individual products while they are still in the market.

- **Finance**; Intriguing is the problem of valuing reusable products and materials. Since materials and product components can be reused (sometimes more than once), it is far from trivial to assess their share in the total production costs.

- **Marketing**; Considering the above, product recovery seems to pose many threats towards manufacturers, for instance large investments for business process redesign, uncertainty regarding legislation, and uncertainty regarding product quality and recovery rates. On the other hand, reusable products may be positioned as 'environmental-friendly' to attract new or to commit already existing customers.

The above may suggest that the advantages of product recovery, i.e., cheap resources of materials and a competitive advantage, may not outweigh the disadvantage of more difficult control of processes and the extra costs associated with reverse logistics. The deciding factor that may push manufacturers towards product recovery may well be the issue of legislation. Since legislation regarding waste flows is increasing rapidly in the developed countries throughout the world, manufacturers are more and more forced to take responsibility for there products throughout the complete product life-cycle, i.e., from production onto disposal. Also international stock markets may insist on a green image of big firms (see Vandermerwe and Oliff [64]).

1.2 Product recovery options

The nature of the collected products after use (the 'return' flow), influences the nature and configuration of the product recovery processes. In this light Thierry et al. in [54] consider the following types of product recovery:

- *Repair.* Products are brought to working order. This implies that typically the quality standards of repaired products is less than those for new products. Usually repair requires minor (dis)assembly, since only the non-working parts need to be repaired or replaced.

- *Refurbishing.* Products are upgraded to some prespecified quality standards. Typically these standards are less than those for new products but higher than those for repaired products.

- *Remanufacturing.* Products are upgraded in such a way that exactly the same quality standards are satisfied as for new products. This means that remanufactured products can be resold at the market of new products.

- *Cannibalization.* This involves selective disassembly of used products and inspection of potentially reusable parts. Parts obtained from cannibalization can be reused in the repair, refurbishing or remanufacturing process.

- *Recycling.* Materials rather than products are recovered. These materials are reused in the manufacturing of new products.

It is evident that the degree of testing, disassembly, and rework depends largely on the quality of the return flow. In the literature several models are proposed to determine the optimal disassembly sequence (see Johnson and Wang [27], Penev and De Ron [39], and Krikke et al. [32]). Krikke et al. also take the quality of the returned products into account. The number of returned products that can actually be reused depends of course heavily on the quality of the return flow. For some accounts of the difficulties that are encountered to obtain sufficient quality of reusable products we refer to Flapper and De Ron [16]. The issue of forecasting the number of returns is considered by Kelle and Silver [29] for reusable containers.

To illustrate the importance of the quality aspect, recycling seems typically attractive for products of relatively low quality, for which the materials are relatively easy to separate, while for example remanufacturing is typically attractive for high quality products, that are easily disassembled into modules. It is the latter option that we will focus on in the remainder of this thesis.

1.3 Examples of remanufacturing in practice

Recent research in the area of production planning and inventory control for *hybrid manufacturing/remanufacturing* systems (from now on denoted by HMR systems) was initiated by a research project which was carried out in the Netherlands for a large U.S. manufacturer of copiers (see Thierry et al. [54]). The manufacturer had developed a prototype of a new generation of copiers, which differed from older generations in that some components stemming from used copiers could be reused in new copiers.

As mentioned before, one of the motivations for the manufacturer to develop copiers with remanufacturable components was the anticipation on environmental laws that eventually will apply in many European and other countries. These laws make product manufacturers responsible for the collection and further handling of their products and packaging materials after customer usage. Furthermore, in the near future it is expected that environmental laws will even be tightened in many countries, forcing manufacturers to design products and production processes such that waste is limited and a significant percentage of product components can be reused.

A second incentive to remanufacture products was the development of new technologies, which enabled manufacturers to design products and production processes such that remanufacturing of used components becomes *cost-effective*, i.e., such that it reduces the total production costs during a product life-cycle.

Another important motivation to apply remanufacturing was the potential for a *competitive advantage* resulting from the 'environmental friendly' image of remanufacturing companies.

The above led to the management's decision to further develop the remanufacturable prototype to a commercial product-line of copiers. During the development phase the manufacturer got confronted with many technical and organizational problems, concerning e.g product design and logistics. An important logistics problem was for instance the development of a new distribution network, in which both the supply of new copiers to the market and the collection of used copiers from the market could be handled efficiently.

Company name	*Product*	*Reference*
De Vlieg-Bullard	Machine tools	Sprow (1992)
Abbott Laboratories	Medical diagnostic instruments	Sivinski (1993)
Volkswagen Canada	Automotive engines	Brayman (1992)
Grumman	F-14 aircraft	Kandebo (1990)
BMW	Engines, starting motors, alternators	Vandermerwe & Oliff (1991)

Table 1.1. *Some companies active in remanufacturing.*

Initiated by the arguments just listed, a growing number of industries is now becoming interested in remanufacturing. In some 'high-tech' industries, like in the aircraft industry, the automobile industry, the computer industry, and the medical instrument industry, remanufacturing has already been implemented. Table 1 lists some large companies within these industries that currently apply product remanufacturing to some degree.

1.4 Problem structure and complexity

The research project mentioned in the foregoing section was regarding another category of logistics problems, i.e., *production planning* and *inventory control* problems. The project finally resulted in an advice on how to reorganize the production/inventory system for the specific situation at the manufacturer. Motivated by this and other consulting projects (Thierry et al. [54]), we decided to set up a research project to investigate the effects of product remanufacturing on production planning and inventory control from a more theoretical perspective.

To structure the discussion on production planning and control in HMR systems Section 1.4.1 presents a model which depicts the processes and goods flows of a remanufacturer, as observed in practice (see Thierry et al. [54]). Using this model, Section 1.4.2. shows how planning and control in HMR systems tends to be more complex than planning and control in traditional manufacturing systems.

1.4.1 Relevant processes and goods-flows

As observed in practice, the following processes and goods-flows play an important role in HMR systems:

- The *manufacturing* process. The activities in this process are outside procurement orderings to obtain raw-materials and sub-assemblies, and production/assembly operations to obtain *serviceables*, which are end-products and/or components that are sold in the *first-hand* market. This process differs from the manufacturing process in systems without remanufacturing in that serviceables may be a assembled from a composite of *new* components and *remanufactured* components. Consequently, the material flows that are input of this process are raw materials and sub-assemblies, and (re)manufactured components. Output of this process are serviceables.

- The *disassembly and testing* process. Returned products first enter the disassembly and testing process. During disassembly returned products are decomposed into modules and components, while during testing it is determined whether the modules and components satisfy the quality requirements for remanufacturing. The module and component level to which returned products are disassembled is usually predetermined by technical constraints set by *product design* and by *production process design.* Based on the testing outcome, *remanufacturables* are separated from *non-remanufacturables.* Remanufacturables enter the remanufacturing process, whereas non-remanufacturables may be handled according to alternative options, such as recycling, cannibalization, refurbishing, or disposal (Thierry et al., [54]). Summarizing, input of this process are material flows of used products that are returned from the market. Output of this process are two different material flows, i.e., the flow of non-remanufacturables and the flow of remanufacturables.

- The *remanufacturing and testing* process. Purpose of this process is to transform remanufacturables into serviceables. The process usually consists of repair, replacement, and cleaning operations. Furthermore, after remanufacturing the remanufactured components are usually tested. Components that satisfy the quality requirements of serviceables may be sold directly in the first-hand market, or may serve as input of the manufacturing process. The *non-serviceable* components, i.e., the components that do not satisfy these quality requirements, may be handled according to alternative options. Summarizing, input of this process are remanufacturables. Output of this process are serviceable and non-serviceable components.

- The *disposal* process. There are two types of product disposal: *(i)* unplanned disposal, i.e., product disposals because the returned products do not satisfy the required quality standards for reuse, and *(ii)* planned disposal, i.e., product disposals because disposal of returned products is more cost efficient then remanufacturing. The latter does not imply that all products should be disposed off. Disposals may occur only if the inventory of remanufacturables has reached a certain prespecified level. Of course, the above classification also extends to product components.

HMR systems may further consist of a number of decoupling points (buffers or inventories) to store returned products, remanufacturables, non-remanufacturables, serviceables and non-serviceables. The actual existence and location of each of these stocking points differs however from situation to situation, and depends for instance on the existence of specific goods-flows and on the policy that is followed to plan and control the goods-flows.

As an example, Figure 1.1 depicts a simple HMR system for one product that consists of components A and B.

1.4.2 Complexity of planning and control in HMR systems

In studying HMR systems, it is important to know which characteristics of hybrid systems actually make planning and control more complex than planning and control in traditional manufacturing systems. Naturally, in traditional manufacturing systems solely the manufacturing process and related goods-flows need to be managed, whereas in hybrid systems also the disassembly and remanufacturing related processes and goods-flows need to be controlled. Thus, HMR systems typically have

- *more stocking points* to balance the inputs and outputs of the involved processes, to protect against various sources of uncertainty, and to reduce the required level of coordination in process control, i.e., to keep planning and control manageable,

- *more uncertainties*, since in addition to the uncertainties that are present in traditional manufacturing systems, such as the timing and

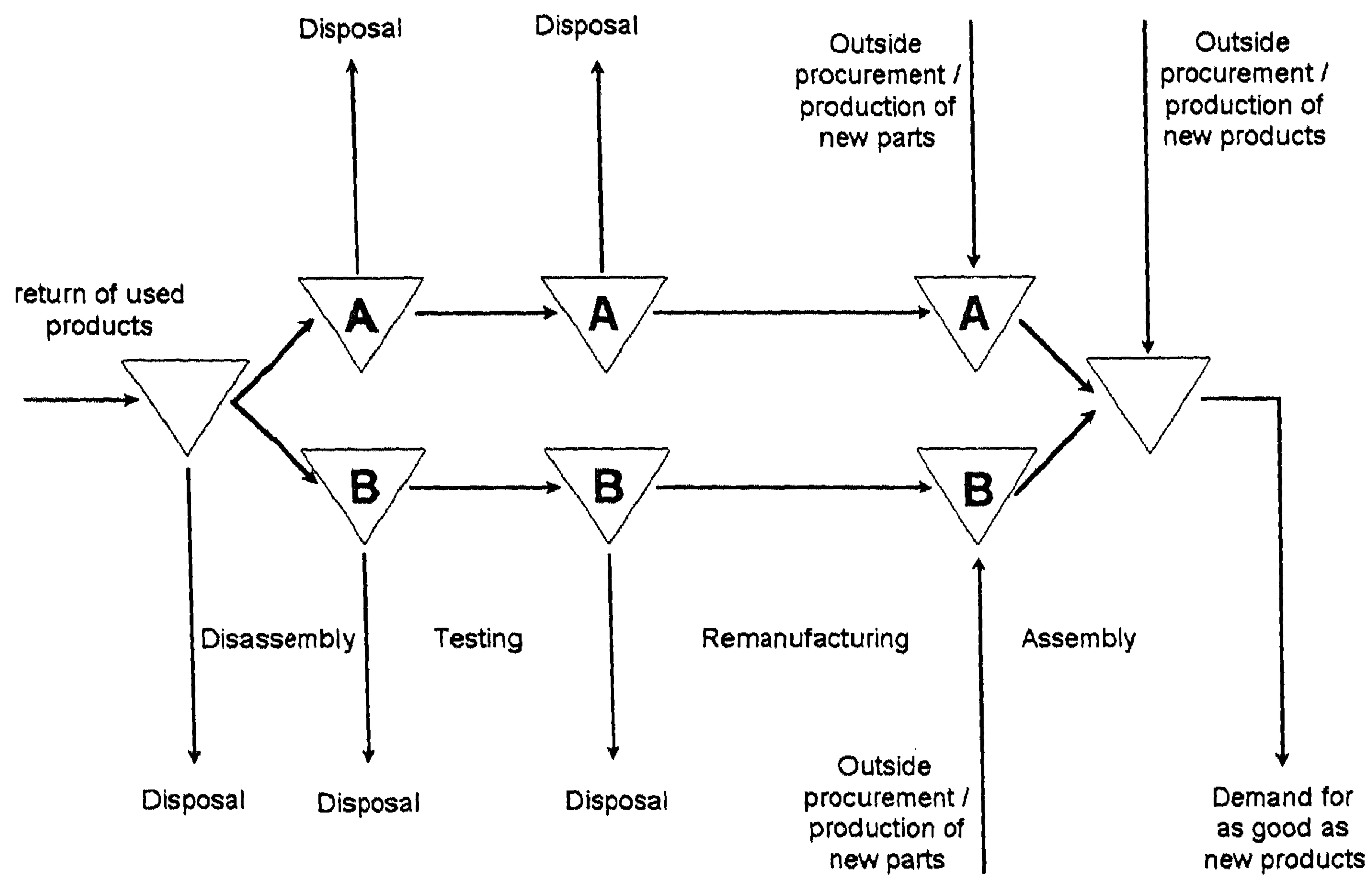

Figure 1.1. *A schematic representation of the relevant processes and goods-flows in an HMR system for one product consisting of two components* A *and* B.

sizing of demand occurrences, the yield of the manufacturing process, and manufacturing and procurement lead-times, there are in hybrid systems also uncertainties concerning the timing and sizing of product returns, the quality of returned products, the yield of the remanufacturing process, and the lead-times in the disassembly and remanufacturing processes,

- *more complex cost-structures*, since an increase in the number of processes, goods-flows and stocking points results in an increase in the number of different cost components that have to be taken into account at planning and control in hybrid systems. It should be noted that the assignment of suitable costs to the cost components that appear in hybrid systems is far more complicated than the assignment of costs in traditional manufacturing systems, since the costs and benefits related to (multiple) reuse of products and/or components have to be taken into account.

Moreover, the processes and goods-flows are often inter-related, due to the following system interactions:

- *Interactions between the timing of demands and returns.* These interactions occur due to two different types of correlations, i.e, *demand-return* correlation, and the *return-demand correlation.* The first type of correlation occurs since customers demand a new product which may be returned after a certain unknown period of usage in case of a regular purchase contract, or after a known period of usage in case of a lease contract. The second type of correlation occurs due to product replacements: after use a customers may demand a new product while returning the old one.

- *Process/goods-flow interactions.* This interaction occurs since some goods-flows that are output of a particular process serve as input to other processes. In this way, the disassembly/testing process is linked with the remanufacturing process and the manufacturing process is linked with the remanufacturing process. Particularly in the latter case, when during manufacturing the goods-flows of manufactured/outside procured components must be *integrated* with the goods-flows of remanufactured components, complex timing problems may arise.

- *Capacity interactions between manufacturing and remanufacturing operations.* Scarce resources, such as labor and/or machinery may be shared by multiple processes. For example, the same machinery may be used both for carrying out remanufacturing and manufacturing operations.

Concluding, HMR systems consist of more process-components, are subject to more uncertainties, and contain complex interaction mechanisms that are typical for hybrid systems. All these aspects ask for more sophisticated planning and control methods than those for traditional manufacturing systems.

In the literature only few articles have appeared to integrate remanufacturing activities into (existing) planning systems. Scheduling for disassembly operations within the concept of Material Requirements Planning (MRP) is considered by Gupta and Taleb [22], Flapper [14], [15], and Taleb and Gupta [53]. Shop floor control in a remanufacturing environment has been addressed by Guide [19] and Guide et al. [20], [21] in a number of simulation studies.

1.5 Research questions

Considering the various complexities and interactions that play an important role in HMR systems, this thesis will address the following questions:

1. *Which policies are currently available to coordinate manufacturing and remanufacturing operations simultaneously?*

To answer this question, we review in Chapter 2 the relevant literature on planning and control policies, and we discuss the specific system assumptions under which these policies apply.

2. *What are the effects of typical process variables and process characteristics on overall system costs?*

To investigate these effects, we introduce in Chapter 3 a relatively simple, single-product single-component system. For this system we analyze two statistical reorder point strategies, which mainly differ in the way in which the timing of remanufacturing operations is controlled. In Chapter 4 we empirically evaluate the system behaviour in general. Moreover, the sensitivity of the reorder point strategies for different assumptions regarding process characteristics is studied. In Chapter 5 we focus on the effects of (re)manufacturing lead times.

3. *Which actions can be taken by a remanufacturer to improve the cost-efficiency in hybrid manufacturing/remanufacturing systems?*

Based on the outcomes of the numerical study we suggest in Chapter 4 some actions that may be taken by a remanufacturer to improve the cost-efficiency. One of these actions may be to implement a disposal strategy (Chapter 6).

4. *Which heuristics may be used to find (near)-optimal values for the decision variables within a reasonable time?*

A drawback from the exact analysis and optimization procedures that are used in Chapters 3–6 is that they are very time consuming and therefore not very suitable in practice. In Chapter 7 some heuristical procedures are proposed to resolve this.

5. *How do the theoretical findings relate to practice?*

To investigate this issue a case study is carried out in Chapter 8. Real life data were provided by Volkswagen AG Kassel, which is a remanufacturer of car parts.