DIPLOMARBEIT

Development of a method for the assessment of parts' reusability

A contribution towards increased resource efficiency

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Towards what ultimate point is society
tending by its industrial progress?
When the progress ceases, in what condition
are we to expect that it will leave mankind?

John Stuart Mill, 1857

Acknowledgement

I want to thank all who actively supported me during my studies and while writing this thesis.

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Abstract

In recent decades, a general topic has continuously raised general public's awareness and has grown in importance for all stakeholders in society: careful handling and protection of our environment. Over the majority of past years the functions our planet provides have been considered as matter of course. But, step by step, mankind becomes aware that those services are not abundantly at our disposal. At the moment, fossil primary minerals and fossil energy is the main fuel for our economic, and, in consequence, of our societal life. In the last years, several scientists have already pointed to the fact that, at finite resources and definite annual consumption, in future we will have to face an inconvenient truth when mankind will run out of resources – this forecast is neither excessive pessimism nor conscious fallacy but a simple assessment of the situation. Some effects of scarcity are already partially perceptible now, and some individuals are already eagerly trying to mitigate those phenomenons. The majority, however, is not aware of the seriousness of the situation although the only conclusion to draw now, is to change our today's pattern of economical behaviour, start handling fossil resources more carefully and increase material efficiency throughout the entire economic world.

So, the order of the day reads as promoting and establishing a circular economy – or in other words – recycling. The term recycling refers to the use of waste inherent energy or material. The ultimate form of recycling is 'product recycling' which intends to reclaim both inherent material and energy, and to work up used products and parts so as an anew use is enabled. The current thesis deals with the big topic of product recycling and tries to contribute towards the big aim of a sustainable society. This paper's purpose is the development of a method which supports design engineers in evaluating a product's eligibility for product recycling, also called reusing.

In the first part, the theoretical framework of recycling is discussed, terms are defined and general (preconditions of) assessment methodologies are introduced. After a discussion about the economic chances and limitations of recycling and a brief overview about existing assessment tools for determining reusability of parts / products, the real methodology is introduced. Subsequent to a short explanation of the method's structure, this thesis takes a dive in the detailed description of the underlying assumptions and thorough scrutiny of the methodology. In the chapter next to last, the developed assessment method is applied to a practical example in order to prove its usability and to verify the assumptions. In the last chapter the results are discussed and desiderata for future research are articulated.

Contents

List of Tables

List of Figures

Nomenclature

AD	Acidification
AGS	Alliance for Global Sustainability
aka	also known as
approx.	approximately
ARD	Abiotic resource depletion
asm	assembly
Avg.	average
B2B	Business to business
bbl	barrel
BOM	Bill of materials
BRIC	Brasil, Russia, India and China
Cd	(chemical abbreviation for) Cadmium
CFC	Chlorofluorocarbon
DIN	Deutsche Institut für Normung, (engl.: German Institute for Standardisation)
e.g.	exempli gratia
EoL	End of Life
et seq.	et sequentes, (engl.: and the following ones)
etc.	et cetera
ETH	Eidgenössische Technische Hochschule, (engl.: Federal Institute of Technology)
EU	European Union
EU	eutrophication
GHG	Green house gas
GW	Global warming
Hg	(chemical abbreviation for) mercury
i.e.	id est
Inc.	Incorporated
km	kilometre
LCA	Life cycle assessment
misc.	miscellaneous
N	(chemical abbreviation for) nitrogen
NO_x	(chemical abbreviation for) nitrogen oxide
No.	Number
OD	Ozone layer depletion
P	(chemical abbreviation for) phosphorus
Pb	(chemical abbreviation for) lead
PBB	(chemical abbreviation for) poly**b**rominated **b**iphenyls
PBDE	(chemical abbreviation for) poly**b**rominated **d**iphenyl **e**thers
pc.	piece (Plural: pieces – pcs.)

POC . . . . photochemical oxidant creation
PR . . . . Public relations
RoHS . . . . Restriction of the use of certain Hazardous Substances in electrical and electronic equipment
SO_x . . . . (chemical abbreviation for) sulphur oxide
U.S. . . . . United States (of America)
UN . . . . United Nations
UV . . . . Ultraviolet rays
VDI . . . . Verein deutscher Ingenieure, Association of German Engineers
vs. . . . . versus
WCED . . . . World Commission on Environment and Development
WEEE . . . . waste electrical and electronic equipment
WRI . . . . World Resource Institute

1 Introduction

1.1 Motivation

My inspiration for the present thesis I found while attending a summer school, organised by the AGS, an organisation at the ETH Zurich, in Braunwald, Switzerland, in summer 2007 where we dealt with the topic of sustainability in many respects. Under the presupposition of and the commitment to dignified living conditions for our children and descendents in a sound environment, there is doubtlessly no other way than the sustainable one.

According to Gro Harlem Brundlandt, chair of the Brundtland-Commission, formally known as WCED, sustainability and sustainable development, respectively, is defined as follows:

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*[1]

I personally deeply believe that we are indebted to our descendents to care as much as possible about our unique planet in order to ensure better or, at least, the same preconditions for living for the upcoming generations. An old proverb literally depicts our responsibility:

> *We do not inherit the earth from our ancestors; we borrow it from our children.*[2]

For me as a student with technical as well as economical background, the only way to contribute towards meeting mankind's superior objective of sustainable development is trying to find solutions in this field of study where I am interested and specialised in.

Today's economic and ecological situation, historically grown over years and being used to mankind, can be described as follows:

At the moment the consumption and deterioration of natural resources is focused on in numerous discussions. People who live in developed countries, countries mainly on the northern hemisphere and representing only a small part of world's population, deplete the most part of natural resources; the bigger part of world's population, the so called 'south', mainly domiciled in developing countries, is lacking resources, as the WRI states.[3] Also, the 1992 UN summit in Rio de Janeiro revealed that 80 % of world's resources are consumed by only 20 % of population.[4,5]

Barring the ethical tenability of these circumstances, this inequality will lead to massive problems in the future. People in developing countries, living partly in poverty, have – as much as people

1 see Brundland (1987), S.46.

2 source unknown and disputed, respectively; either Ancient Indian proverb or attributed to de Saint Exupéry, A., to Emerson, R.W. or to Bower, D.

3 see WRI (1995), p.11.

4 see Stahel (2006), p.40.

5 see Liedtke/Kaiser (2006), p.47.

in developed countries do – the human right to live in dignity, and, thus, strive for better living conditions, wealth and prosperity. This future increase in wealth is (according to the today's definition of wealth[6]) tightly connected with the use and consumption of resources. However, since the world is a restricted system, also our natural resources are limited,[7] and, seemingly, the growth of wealth is capped, too.

The ecological footprint, a measure of human demand on Earth's ecosystem, is approx. 1,3[8] at the moment. This number strikingly depicts the fact that world's population, especially the minority, namely mainly the developed countries, already consume as much resources as 1,3 planets of the size of the earth could provide – this under consideration of the inequalities between the developed and the developing countries. Under the presumption of harmonising living standards, the world will definitely run out of resources.

Already Dennis L. MEADOWS ET. AL., members of in the broad public maybe well renown '*Club of Rome*', advised against the limitation and scarcity of natural resources in their book '*The Limits to Growth*'.[9] MEADOWS ET. AL. tried to forecast the time until mankind runs out of the most important industrial raw materials (see Table 1.1, column 4).

Table (1.1): *Non-renewable natural resources* according to MEADOWS ET. AL. (1972)*, pp. 60, subselection*

1	2	3	4	5
RESOURCE	KNOWN GLOBAL RESERVES	AVG. GROWTH RATE	EXPONENTIAL INDEX (YEARS)	EXPONENTIAL INDEX CALC. USING 5 X KNOWN RESERVES (YEARS)
Aluminium	1.17 x 10^9 tons	6,4 %	31	55
Coal	5 x 10^{12} tons	4,1 %	111	150
Copper	308 x 10^6 tons	4,6 %	21	48
Iron	1 x 10^{11} tons	1,8 %	93	173
Petroleum	455 x 10^9 bbl	3,9 %	20	50
Zinc	123 x 10^6 tons	2,9 %	18	50

These numbers in Table 1.1 were figured out almost 40 years ago and were quite shocking to the broad public which gradually had become aware that economic growth of the post-war era was not unlimited. Of course, the numbers issued by MEADOWS ET. AL. can be totally questioned, especially under consideration of the example of aluminium, copper, petroleum and zinc. Today, manhood should – according to the Club of Rome – theoretically already lack of aluminium, for instance, because the 1972 forecast, basing on average growth rates, was only for approx. 31 years (see Table 1.1, column 4). But we all know that primary aluminium is still available. However, in general the conclusion has neither suffered from loss of topicality nor in truth. In order to anticipate criticism Meadows et. al additionally calculated how long world's resources will reach

6 Wealth is a positive state which is individually perceived. Wealth consists of immaterial and material wealth. An equal term for the latter one is ‚living standard'
7 Up until now scientist have not found ways to commercially use possible resources of the space e.g. the moon, hence it is taken for granted that natural resources are limited
8 see GLOBAL FOOTPRINT NETWORK (2008).
9 see MEADOWS ET. AL. (1972), pp.54.

assuming that 5 times known reserves are available (see Table 1.1, column 5). This rather theoretical experiment was intended to weaken the critique that not all sources of natural resources have been discovered up until then. But even taking this rather unrealistic supposition as granted, the numbers did not significantly change because of the underlying assumption's characteristics of exponential growth – the Club of Rome's conclusion seems to be valid.

Another scientist who actively dealt with scarce resources is M. King Hubbert. In the middle of the 20^{th} century, he introduced his theory, known under the headline *'Hubbert's peak'* or *'peak oil'*. Using the example of conventional crude oil and presupposing finite supply, he stated that the curve of annual production rate follows a bell-shape-like function – be it for conventional crude oil depleted in a particular geographical area or be it for the entire global reserve. In the early part of resource's mining history (pre-peak), the annual depletion rate increases because of discovery rate as well as additional infrastructure. Later in time, when peak production is passed (post-peak), the curve declines because of resource depletion.[10] For U.S. oil production Hubbert quite precisely forecasted the time of peak oil in the early 1970 ths; for world production 'post-Hubbert' scientists are still disputing whether peak oil is still to come or already passed. Anyway, the consequences of decreasing oil supply on our oil-dependent economy are pretty severe.

In the light of this imminent scarcity of resources, many scientists proposed the introduction of increased resource efficiency in production and sufficiency in consumption. In the field of *sufficiency*,[11] scientists deal with the important topic of necessary and needless consumption, respectively. In these days, the approach of sufficiency is doubtlessly a question we have to deal with. But it is mainly a concern of social science, hence, we don't want to deal with in the subsequent thesis.

A rather technical approach is the further increase of resource efficiency, as mentioned before. Both energy and resources have always been scarce and relatively expensive in relation to the available income.[12] Especially before Industrial age, unessential consumption of resources was the privilege of only a few. The successive Industrial economy was eager for improving its efficiency in respect to resources and energy consumption so as cost could be lowered. Up until the middle of the 20^{th} century, increased resource productivity has resulted from technical progress. For instance, the amount of coal to produce 1 ton of iron declined permanently. Inventions allowing improvements of efficiency by the factor of 2, 5 or up to 10, quickly penetrated the market and extended the set of techniques available to companies. A positive side effect was the enhancement of competitiveness.

Despite of progress in efficiency by means of technological development, the urgent need of saving resources still exists. Bearing the unequal consumption pattern of world's resources in mind, as pointed out on page 1, and anticipating the hunger for resources of the emerging countries like e.g. Brasil, Russia, India and China (also called the BRIC countries), the effort for finding new solutions to the '*resource dilemma*' must be strengthened. Rising prices for e.g. steel and oil, as seen in the last years,[13] are only one aspect of the fast economic catch-up of developing countries and, thus, a significant (monetary) incentive for finding alternatives to the today's way of producing and consuming.

[10] see DEFFEYES (2009), pp.133.
[11] see SCHUMACHER (1976), pp.10.
[12] see STAHEL (2006), p.39.
[13] see SCHNEEBERGER (2008), p.4.

In 1994 scientists around Friedrich Schmidt-Bleek founded the '*factor 10 institute*', an organisation which is heavily concerned by the '*unchartered role of human-induced global material flows, and the ecological ramifications of [...] unchecked growth*'.[14] As its name already indirectly hints at, the endeavours for higher resource efficiency are casted in a mathematical goal for the very first time – to cut resource consumption, especially in developed countries, by the factor 10. Unfortunately, in the last couple of years all efforts emphasised the role of production in this struggle which, of course, is necessary but not sufficient. After years of intensive discussions, in only a few cases this factor 10 goal was reached by e.g. betterment of material specification, better controlled processes or process innovations. But on the whole, no fundamental breakthrough has been achieved. It seems that the roots of the prevailing dilemma are originated somewhere else. Without doubt, production is inextricably linked with consumption and vice versa. But apparently, our longtime way of consuming is the main contributor of the problems we face now. Our pattern of consumption is described with three simple steps of action: buying — using — disposing. And the last step is the very essential one. Already mankind in the Stone Age buried its waste which it wanted to get rid of. Besides the positive fact that this dumps give us information about their way of living, this human behaviour has come up to an alarming dimension. Since population was only a fraction of today's one at this age, the overall impact was manageable. Today, existing landfills are full and new ones '*must not*' be built.

A promising and today's most dominant strategy to cope with this problem and to save resources is to recycle waste. For instance, since the seventies of the last century, when environmental awareness among population started to grow, a dense network for recycling valuable materials has been established in Austria. Today, residential waste like paper, glass, metal, plastic and organic waste, as well as industrial waste are separately collected in order to recycle the material. But also legislation of national states as well as of the EU tries to regulate the waste treatment. An often cited example is e.g. the directive on recycling of end-of-life vehicles.[15] All these examples are only targeted on harnessing waste's intrinsic material. Since changes in human behaviour oftentimes needs decades, and shaping men's mind towards increased environmental consciousness is such a change, the introduction of these recycling networks was an essential step forward. But, focusing on only the material aspects of recycling would not go far enough. The ultimative and at the moment not very popular way of recycling would be *reusing*.

Reusing means using a product, of course, after proper treatment, again – a theoretically utterly well known, but not practised and, nevertheless, fascinating idea. Thus, the subsequent paper will deal with this rather scientifically new topic.

1.2 Research question and definition of aims

The main objectives of the current thesis are

- Identifying impacts influencing the reusability of products
- Development of a method to assess product's reusability
- Providing hints in order to increase the reusability of products

[14] see Factor 10 Institute (2009).
[15] see European Parliament and European Council (2000).

1.3 Course of action

Due to the main aims given above, the thesis is structured as follows:

1. In the first part, the theoretical background is explained. I.e. the terminology used is defined and the conceptual delimitation to other related forms of recycling and the waste hierarchy, respectively, is done in order to prevent confusion.
2. The next chapter deals with reusing and its according implications. Hence, we go into detail – first on the rather theoretical economic level and, then, we focus on those main processes incurred by the strategic decision of reusing.
3. The next chapter focuses on assessment methodologies already available. A sample of important approaches regarding *reusing* is presented and their strengths and weaknesses are briefly discussed.
4. The next chapter deals with the self-developed assessment methodology. The preconditions and assumptions are explained and the method is described in detail.
5. The penultimate chapter applies the methodology developed in the previous chapter to a practical example.
6. The last chapter will give a conclusion and summarise the findings.

2 Theoretical background

The following chapter shall provide insights about the theoretical background of product recycling and reusing, respectively. This aim is comprehensively accomplished by using a top – down approach and firstly drawing a picture where society should head for. Determing the inherent motivation of action helps answering the question of 'Why?'. In a next step, we will briefly introduce the main concept how this overall target and ultimate point can be met in future, and show the links between this theoretical method and real world. After defining the terminology of recycling as whole, where product recycling and reusing, respectively, definitely belongs to and especially delimiting them to other related activities, we will cast a glance on the legal framework in which product recycling and reusing, respectively, acts in.

As regards content, this chapter terminates with a section about assessment in general, and with a particular emphasis on life cycle assessment, since the overall aim of the present paper is the development of an assessment method.

2.1 Nature – an example worthy of imitation

Taking nature as inspiring example, we can observe that all flows of materials are closed loops, meaning that there is neither a defined source nor explicit sink. Roughly divided, living nature consists of the two main players *flora* and *fauna*. Choosing an example in the category *flora* and assuming no anthropological influence, we see that every plant, irrelevant whether we focus on agricultural crops, trees or algae and moss, extracts nutrients and water from the surrounding environment which it needs for flourishing and building seeds. After reaching its intended purpose – namely reproducing itself – the plant dies off and is mechanically and chemically decomposed and metabolised into its base elements or other intermediate catabolic products by means of e.g. beetle and worms or other mostly simple organisms like fungi or microbes. Those elements are available for new plants to nourish, and, so, the loop closes, or in other words, can start again. Same here with an animal example building on the above example – the zebra is fed upon savannah's grass, the lion gets wind of the zebra and hunts it, and after a long life and hunting numerous prey animals, the lion dies, too. After lion's decomposition, supported by scavengers, the loop starts from the very first beginning again.

Even one recent bone of contention, the unregulated use of oil, which is inter alia supposed to cause climate change, can somehow be quoted as an example. Crude oil is, in a simplified way, nothing else than under heat and pressure transformed organic matter. Unfortunately, this process takes millions of years, but it can be described as cycle. Of course, those examples are pretty much simplified and won't necessarily bear up any scientific examination, but they clearly depict the circular material flows in nature. Only by input of energy, e.g. sun, those loops can permanently revolve and material flows are recycled again.

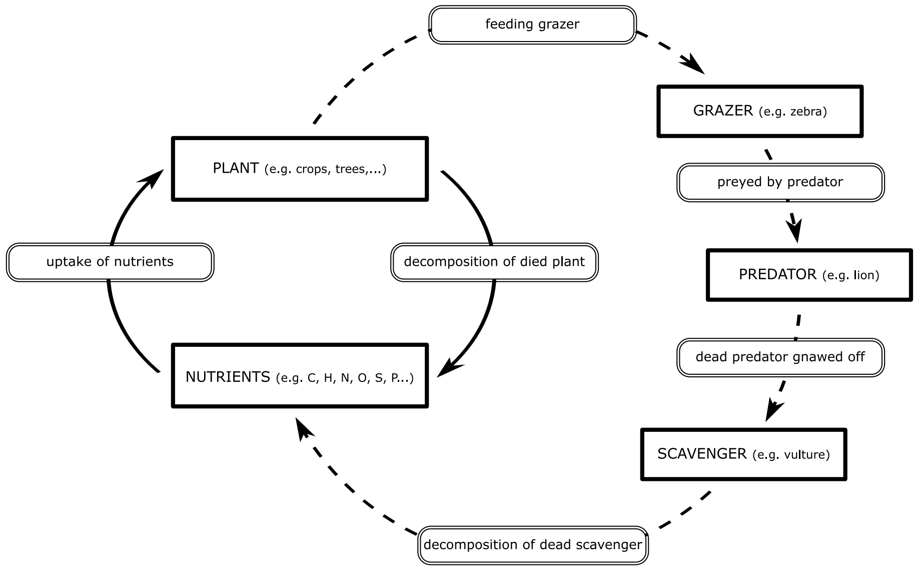

Figure (2.1): *Loops in nature (flora and fauna)*

Since manhood has recognised that only those material loops and thinking in cycles will lead to sustainable living, man has tried to imitate nature, and to leave the track of a so called *source - and - sink - economy*. This means that all companies producing goods can be labelled as *sources*. After the phase of use, the beneficiary – in our case the consumer – gets rid of the used products. An often used pattern is the disposal at landfills, so called *sinks*. So, those valuable materials bound in these discarded products are lost for further utilisation in the immediate and intermediate future. Maybe there are natural decaying processes which will transform the dumped waste into a useful source, but this will definitely exceed the time horizon manhood is usually thinking and planning in.

Glancing at nature and imitating its acting in loops is the ultimate state which we should (but hardly will) reach in our every day processes in the next years. Hence, manhood can only try to partly adopt nature's strategies and mitigate the impacts caused by men's acting. That's why in recent years the ECODESIGN approach has become more and more popular and important among scientists and experts involved in company's designing of new physical products and services. This approach will be introduced in the next chapter.

2.2 Life Cycle Thinking and ECODESIGN

Since the overall aim of companies is to succeed in the long term, it is necessary to anticipate the needs and desires of the market (i.e. consumers), transform them into real products and services, and provide those products and services in the most efficient way. However, it is not that easy as it is described here. In today's multipolar world, the interests of different stakes have to be considered and satisfied. As already identified above, the customer is one of the most important stakeholders. Nonetheless, during the last couple of years, environmental issues have gradually become more important and the legislative body and society in general are interested in environmentally sound products, as well. The target to hit is the designing of environmentally sound products[16] – this course of action is called *ECODESIGN*. The most essential questions arising during developing environmentally sound products are listed below[17]:

- ... how to logically proceed in product design?
- ... how to purposefully recognise ecological and economic weaknesses of products?
- ... how to systematically improve products regarding ECODESIGN?
- ... how to properly incorporate ECODESIGN in product development?
- ... how to successfully implement ECODESIGN in companies?
- ... what are the key factors for successful ECODESIGN projects?

The insight, which is most important for the purpose of this paper, is the holistic approach of *ECODESIGN*. This means that all phases of product life are considered and, inter alia, all significant economic and ecological impacts caused by producing and using this specific product are identified. In the upcoming paragraphs those disjunct phases in product life, depicted in Figure 2.2, are shortly described.

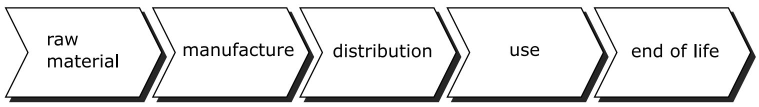

Figure (2.2): *Overview of life phases in product life,* according to WIMMER/ZÜST (2001)*, p.21* and OSTAD (2006)*, p.3*

2.2.1 Raw material

In order to provide customers with both physical products and services, companies need physical input. In the case of mechanical engineering like e.g. producing an internal combustion engine, these inputs are, for example, different types of steel, aluminium, different kinds of plastics or rubbers and many more. Due to the holistic approach of ECODESIGN, even all those impacts caused by exploring and processing the natural resources so as to gain the material input specified by the design department and required in production, have to be taken into account in the evaluation. In fact, regarding the economic dimension this claim for incorporating all impacts connected with the production of a certain raw material is obvious and becomes more clear. The price of a commodity like e.g. 1 kg steel consists (at least) of the costs incurred by the foregoing processes. Stressing the previous example, such processes can be, to name only a few, the exploring of iron ore, the separating from worthless by-material and concentrating of pure iron as well as the processing into transportable and marketable shape and goods. It is obvious that the considerations have to start at the very first point of the value chain and must not forget to bear energy consumption in mind. The same is valid for environmental impacts caused by processing natural resources into raw materials for production.

[16] see WIMMER/ZÜST (2001), p.12.
[17] see ibid.

2.2.2 Manufacture

In *production*, all input flows like directly needed material (e.g. sheet steel, aluminium as chill-mould and plastics granules) as well as auxiliary input (e.g. lubricants, coolants, energy) are processed and transformed into single parts and components. These processes are e.g. machining and chipless forming as well as surface treating, etc.

However, a set of loose parts and components constitute no product at all. Only the assembling process converts loose parts into a marketable product. Hence, assembling and all related joining techniques are an important step in production, as well.

2.2.3 Distribution

In the traditional perception of businesses, *distribution* is the 'last important' step in the value chain. Only when the products reaches its intended final target, namely the customer, the company succeeds with its business model. Depending on the point of view, packing belongs to the current or the former life phase. According to the distribution strategy and network, different modes of transportation are involved in the allocation of products. The most important ones are transport by truck, by train, by freight ship and by freight plane.

2.2.4 Use

As already the term 'use' indicates, in this lifecycle phase the product serves its intended purpose and fulfils the customer's special need(s). This time of customer satisfaction is usually restricted. Depending on the type of product, the consumption of additional input flows (e.g. auxiliary materials like lubricants, coolants, or energy in form of electricity, fuel, or natural gas) heavily depends on the interaction patterns and utilisation patterns, respectively, of the socio-technical system. The utilisation pattern, also called user behaviour, directly determines the extent of product induced external impact. Illustrating this with the practical example *'lighting of a room'*, one can easily recognise that the function of the bulb is lighting the room in case of darkness. It is obvious that the switched-on lamp consumes electrical energy. But the customer can only derive advantage from the shining lamp (equal to serving the customer's need) if the surrounding brightness is lower than the local bulb-produced one, and only if the customer is present. Another easily understandable example is the following one: Roughly speaking, a car's purpose is the transportation of persons and goods from A to B. It is well known, that the fuel consumption is directly dependent on the way of driving. Anticipatory driving will always be superior to aggressively driving, a style with frequently alternating phases of acceleration and braking, in terms of fuel consumption. Although the car is the same, the fuel consumption may considerably differ.

2.2.5 End of Life

The life cycle phase immediately following the use phase is *end of life*. In this in traditional considerations rather neglected phase, the customer gets rid of his/her product to be disposed of. There are several reasons why a used product is retired. These cases are pictured in Figure 2.3.

The first cause in the list of reasons initiating product's end of life is product's malfunction or, simply called, product defect (equal to future inability of function provision). This lack of function is either caused by accidental damage or by consumption of the entire functional capacity. For the latter, there are again multiple causes. While undesired but technically inevitable phenomenons like e.g. wear and fatigue can limit this capacity, also consciously designed restrictions of functional capacity might occur. For instance, in case of a so called single use cameras when the number of pictures taken equals the capacity indicated in the product specifications, there is no further potential for taking pictures left anymore. These reasons resulting in exhaustion functional capacity wouldn't necessarily cause the end of product's useful life. The logical next step to make, if faced with a defect product, is to repair it in order to regain a certain extent of residual functional potential. But the trade-off between functional potential regained in connection with its reliability and effort to be invested has to be carefully analysed. If repairing seems inefficient, the product is discarded.

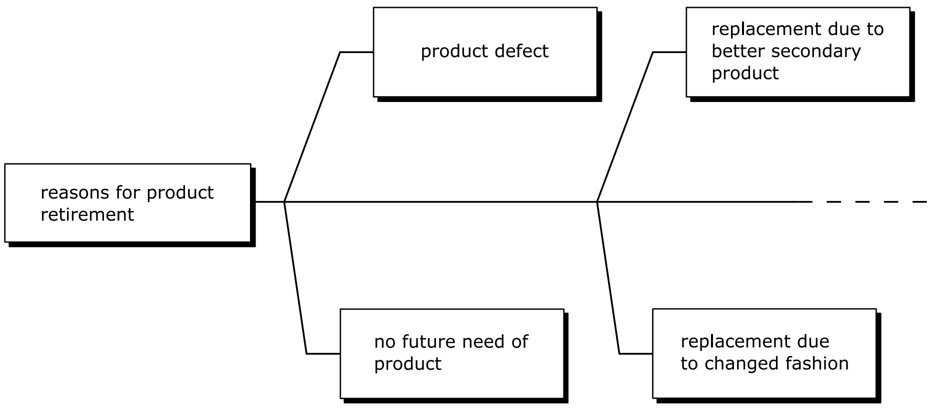

Figure (2.3): *Reasons for retiring a products*

In the event of loosing the purpose of use (see Figure 2.3, *no future need of product*), the product leaves its benefit generating phase and enters the phase *End of Life*, as well. Looking more into detail, this may happen either if the customer's need, which has been satisfied by utilising the product, ceases to exist (change in user behaviour / shift of user interests) or the external support needed for operating the product stops. An example for the latter reason are, for instance, cell phones which base e.g. on the out-dated C- or D-net. Of course, in this case the implied precondition is that the product is not able to achieve a reasonably high price at the second-hand market anymore and, thus, is retired.

The third cause for disposing a product is the replacement by a qualitatively better one. There are two main parameters in which product's quality[18] can be improved. On the one hand, there are the functions of a product which provide satisfaction of customer's needs. If a secondary product aggregates more functions than the preceding one, it may offer a higher benefit for its user. Meaning that one product is now able to satisfy several needs which could only be accomplished by two or more products before. On the other hand, a new product may run more efficiently which causes decreased consumption of energy or other auxiliary materials during use.

[18] Without providing a scientific explanation, for the subsequent purposes the 'quality of a product' is defined as the subjective perception of product's value

The last causation for retiring a product in use is a possible change in fashion. If the utilisation of a product is closely connected to current fashion and the parts responsible for appearance and compliance with fashion, most times parts of the outer shape, cannot be changed or adapted during use, the end of life is determinded by customer's decision and may result in the replacement of the entire product.

Regardless of the final pivotal reason for initiating the 'end-of-life', there are different post-use treatment processes available. The following list itemises a set of different intentions how products can be treated at the end of their use phase and, in the case of the first 3 entries, can be used again for business purposes.

- reusing of product constituting parts
- recycling of product's inherent material
- recovering of product's inherent energy
- dumping in landfills

The previous list bases on VDI 2243 (2002) and RUDOLPH (1999). Strictly speaking, the classification according VDI 2243 (2002) is, unfortunately, a kind of inconsistent. That is why an adopted classification is necessary (as shown above in the itemisation).[19]

In the following chapter, the term 'recycling' will be classified and explained more in detail. So do the first three items of the above list. Solely *dumping in landfills*, a way to dispose of waste, won't be mentioned later – thus, it is detailed here.

The main aim of disposing a used product with no intrinsic value left (= waste in the habitual language use) is simply getting rid of it. One option is the all over the world well known dumping of waste in landfills. In contrast to disposal at landfills, thermal disposal changes the chemical state of used products / waste. Beside the first goal of getting rid, the second goal met by incinerating waste (= thermal disposal) is the reduction of space used for final storage, and in certain cases accompanied by, the intention to achieve compliance with current law.[20] Depending on the material to be burnt, it is an endothermic or exothermic process. However, in the latter case, the energy released is wasted. The criticism which automatically pops up is responded with 'Energy recovery'. If waste burns under exothermic conditions, this process can be harnessed for anthropogenic purposes like e.g. district heating or generating electric current.

[19] Note: Firstly, VDI 2243 (2002) also counts *repairing* as an end-of-life activity. Usually, repairing is only applied to defect products; hence, products retired because of changed fashion, better secondary product or ceased future need can't get repaired by definition. In addition, we assumed the inefficiency of repairing as precondition for retiring a defect product. Hence, repairing is excluded as end-of-life treatment; secondly, VDI 2243 (2002) is issued in both German and English. Since VDI is a German association it is presumed that the original text is in German. Comparing both languages, it is peculiar that 'Instandsetzung' is translated with 'maintenance'. However, maintenance is rather a periodical process preventing early wear, fatigue or other causes for break-down. The correct translation for 'Instandsetzung' would be 'repair', an event-driven process. Additionally, maintenance is rather a task accomplished during an ongoing use phase. But according to the headline of the enumeration it deals with processes '*...at the end of the use phase*'.

[20] see THE COUNCIL OF THE EUROPEAN UNION (1999), Art.5

2.3 Terminology of Recycling

As figured out above, this thesis deals with '*reusing*', a topic having gradually gained importance and societal awareness. For the last couple of decades, the societal and scientific headline has been '*recycling*'. Unfortunately, in comparison to the German language, this English term is more kind of fuzzy, and in the sense of everyday's application not clearly specified. However, there are several different meanings of the term '*recycling*' which only becomes clear when used in a specific context. So, it is necessary to define some terms in the following paragraphs so as to do justice to all the different facets existent. In addition, the explanation of post-use treatment methods (see subsection 2.2.5) is completed. The former rather economical approach will be subsequently followed by a rather technical, production-related one.

Basically, recycling is the reclaiming of natural resources (i.e material and energy) already invested into a product by closing resource flows. It can be distinguished in fractional recycling and total recycling. As it is clearly perceptible, total recycling is only a theoretical construct.[21] Oftentimes, for instance, a by-product of economic process fuelled by e.g. fossil resources is heat – and there are strict limitations for recovering this form of energy. Another example is abrasive wear. It is totally impossible to collect all particles sourced from wear effects in order to enable total recycling. It is apparent that some resource flows are lost for future anthropogenic use – hence, only fractional / partial recycling is realistically feasible and empirically observable.

In everyday's linguistic usage, recycling always refers mainly to the physical fraction of a product to be recycled and only to a certain extent to the energy necessary for production, distribution and use. In this context, recycling means recovering all natural resources already invested during product life and still inherently existent in the product at its end-of-life.

In literature, there are several ways of categorising recycling. Subsequently, a selection of often cited approaches is provided.

A first way to classify is according to its 'places of occurrence' combined with its institutions involved. Hence, the following list is resulting:[22]

- in-house recycling – which is the closing of material flows / resource loops on production process level involving only one single company; resource backflow originates at the end of the production process (output side) and terminates at process' input side (e.g. cast iron scrap in production of cast iron)
- industrial recycling – is similar to in-house recycling, as defined above but comprises more process steps of different, succeeding business entities within a particular value creation chain (e.g. cullet / breakage of glass in glass melt)
- recycling of consumer's residue – residue after consumer's use is redirected to production processes (e.g. yellow bin recycling of plastics)

The former two categories are aggregated to 'recycling of process waste'.

In contrary to the paragraphs above, a rather technical, production-related point of view, partly similar to the one already described, follows. However, there are severals ways to subcategorise

[21] see Kaufmann (2002), pp.145.
[22] see ibid., p.146.

recycling in this manner. We will follow the approach of STEINHILPER (1988) who bases his findings on the drafts and previous versions of VDI 2243, as shown below.

During the entire life cycle of products, there are, inter alia, the phases *production*, *use* and *end-of-life* (as already mentioned above). On basis of this temporal distinction, the subsequent categorisation is derived from:[23]

- recycling during production (recycling of process-related waste)
- recycling during use phases (product recycling)
- recycling after disposal (recycling of valuable material)

For better understanding, this categorisation is depicted in Figure 2.4.

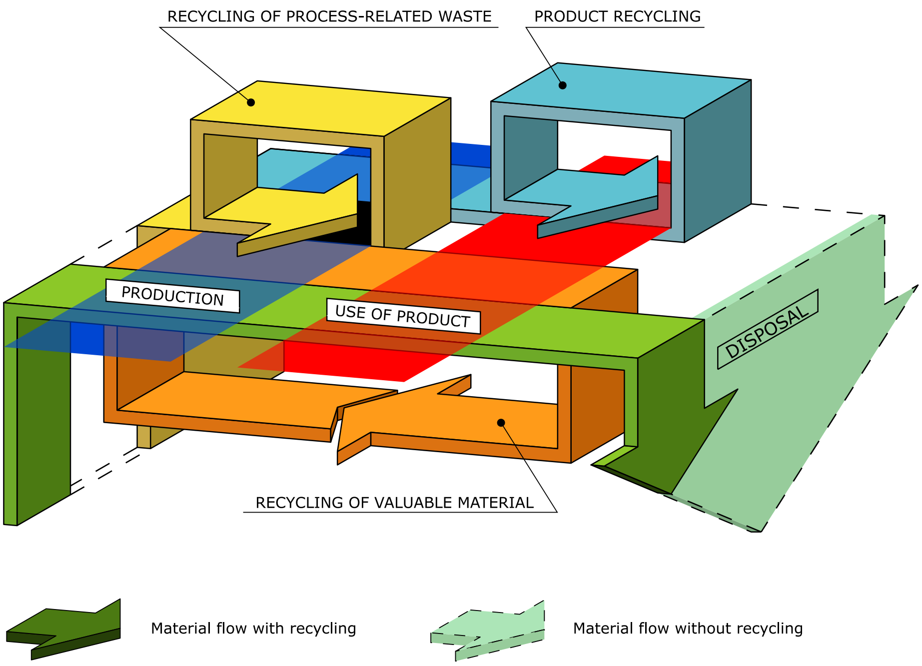

Figure (2.4): *Categorisation of recycling according temporal distinction*, adapted from STEINHILPER (1988), *p.25*

Another similar classification is according to processes needed for treating the products to be recycled. Those processes differ in terms of intention and focus; hence, the following list results:[24]

- treatment for reclaiming the whole part/product (aka product recycling)
- treatment for reclaiming the intrinsic material (aka material recycling)
- treatment for reclaiming the intrinsic energy (aka energy recovering)

[23] see STEINHILPER (1988), p.24.
[24] adopted from STEINHILPER (1988), p.40

A last way of distinguishing the umbrella term *recycling* is on basis of intended resource type to be recovered (material & energy, only material or only energy) in combination with a subcategorisation according to future assignment of the recovered resource:

- product recycling (aka direct recycling)
  - reusing (aka direct primary recycling)
  - continued using (aka direct secondary recycling)
- material recycling (aka indirect recycling)
  - material recycling for the same purpose (aka indirect primary recycling)
  - material recycling for a hierarchically lower purpose (aka indirect secondary recycling)
- energy recovery

Since this paper deals with the development of a method in order to assess product's reusability, the most interesting items, obviously, are *recycling during use phase*, *treatment for reclaiming the whole part* and, of course, *product recycling* and *reusing*, respectively. Since the last classification is the most pictorial one, it is chosen for further in-depth explanation.

2.3.1 Product recycling

The main core of *product recycling* is recovering both part's intrinsic material and energy. Consequently, part's outer shape is sustained and, thus, in addition to the inherent material, the intrinsic energy and information required for original production is saved. The added value already invested into this particular part during production is used again for an additional use phase. Hence, this approach is recycling at its highest stage.[25]

There are many names describing one and the same thing. Inter alia, this main process or treatment step, respectively, is also called *refurbishing*, *remanufacturing* as well as *rebuilding* or *overhauling*. However, *product recycling*, and *remanufacturing* are the terms which has become commonly used standard, so they will be the terms we will use in this thesis, too.

In Figure 2.5, a finer classification according to the final assignment and extent of remanufactured parts is shown. In opposite to the above classification, namely a retrospect dealing with different names of industrial processes, the following depicted categorisation has the prospective perspective in the centre of focus.

2.3.1.1 Reusing

Reusing is defined as the de novo use of used parts in an additional use phase in the way as it was intended during designing this particular part. This means that, after a more or less sophisticated treatment process, the used part is reused once more again for an entire use phase. The output of this treatment is an 'as good as new' and flawless part from an already used one.

[25] see Bollmann (2001), p.6.

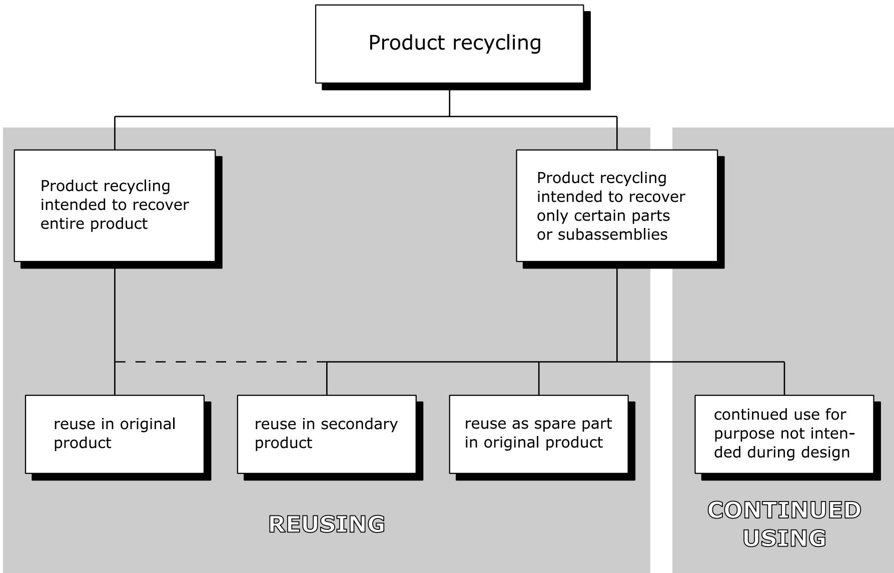

Figure (2.5): *Categorisation of product recycling according final assignment*

In global economy, there are already some examples which prove the idea of *reusing* as capable. *Reusing* is not a certain branch's phenomenon but is scantily spread in a number of different companies. E.g. in automotive industry, *reusing* is successfully applied yet. E.g. clutches, alternators, truck engines, cardan shafts/power trains are reused. But as mentioned above, *reusing* is not only restricted to the automotive sector. Xerox Inc., an office equipment producer, particularly of copying and fax machines, is an often quoted example, too, followed by industrial robots, office furniture or vending machines for beverages, snacks or cigarettes.

2.3.1.2 Continued using

Consequently, *continued using* is defined as the de novo use of used parts in an additional use phase. In comparison to the above definition of *reusing*, there has been no difference up until now. Even the need for treatment processes might remain and part's outer shape stays unchanged. But in contrast to *reusing*, the intended purpose of a 'continued used part' is a hierarchically lower or during design stage not intended one. Thus, e.g. the continued used part is not assembled to the original product or an at least related one anymore but is installed in another product and used for a completely other purpose. Examples, for instance, are clothes washer's porthole (vision panel in front of the the washing machine) as salad bowls, washing drums as waste paper baskets, electrical resistance as bling jewellery or worn out tyres as ballast in agriculture or shock absorber along piers for preventing ships getting damaged.

2.3.2 Material recycling

2.3.2.1 Material recycling for the same purpose

Material recycling for the same purpose is, not surprisingly, a way of recycling which only focuses on the recovery of the intrinsic material intended for the same purpose as in its previous use phase. This means that the process therefore needed dissolves the outer shape of the part. Popular processes are cracking, shredding, chipping or other cutting techniques as well as the subsequently oftentimes following melting of the materials (particularly for metals). Materials eligible for such a recycling technique, which is often called *reprocessing*, too, are e.g. glass, metals in general as well as plastics which do not belong to thermosetting plastics or paper and cardboard. As the name already indicates, the material recycled in this way meets the same quality specification as the original material and, hence, can be input in the same production cycle again. *Material recycling for the same purpose* often occurs directly in production or after use phase. In some cases, an important fact is the mono-fractioned separation of the materials in order to ensure a high-quality recycling material. Examples for *material recycling for the same purpose* are e.g. recycling of chippings / turnings, cut-outs of metal sheets or the cut-off sprue and riser from foundry (recycling during production) as well as several materials from the public collection system like e.g. waste glass, scrap metal and recovered paper (recycling after use phase).

2.3.2.2 Material recycling for a hierarchically lower purpose

Material recycling for a hierarchically lower purpose resembles the former mentioned *material recycling for the same purpose*. As the expression is already revealing, the only difference is made up of the distinction of the subsequent use scenario. Since not all materials can be reprocessed with the same genuine quality (e.g. due to lack of recycling techniques, or simply because of too high expenses incurred by a theoretically possible recycling process) some materials are used in a different way than in their first use phase. For instance, rubbers or thermosetting plastics can hardly be reprocessed in order to gain high-quality material. Hence, those materials are oftentimes shredded and grinded, and used as filler material e.g. in road constructions or in building materials industry. E.g. shredded demolition rubble is used for this purposes, as well.

2.3.3 Energy recovery

Energy recovery is the last way of treatment left in the set of recycling techniques. Hereby, the energy stored in the particular part is in the centre of interest. As already hint at, it might be possible that for certain materials or combination of materials no one of the above mentioned recycling techniques is applicable due to limiting general conditions. Besides dumping, the only alternative left is burning the particular part. If and only if the intrinsic material reacts exothermicly, energy recovery is possible. The released energy might be harnessed for anthropogenic purposes. It is popular to burn waste in order to use the inherent energy for warming water of district heating systems, or in combination with a combined heat and power cycle to use the high temperature energy for generating electric current and to use the low temperature energy for heating the just mentioned district heating systems. Since district heating is demanded by the market mainly only in winter when it's cold outside, in summer this excessive low-temperature heat can be used for generating cold.[26]

2.4 Conceptual delimitation to *'repair'* and *'maintain'*

Since this work deals with *product recycling* in general and *reusing* in special, it is also important to define what *reusing* is not about. Imaging all recycling processes as continuum along one dimension, ordered according their impacts on environment, the subgroup of product recycling is restricted on one side by the subgroup of material recycling (as previously categorised). On the other side there is the subgroup of maintenance. As it can be seen in Figure 2.6, maintenance is the umbrella term for all efforts ensuring product's operational reliability during use. This effort can be subdivided according their frequency in time and impact on the product in:[27]

- **servicing** belongs to the subgroup *preventive maintenance* and is a set of timely regular measurements intended for delaying the decrease of operational reliability; → little cost and idle time incurred
- **inspecting** are all measurements intended to evaluate and assess a particular product's individual current state which enables the holder to derive from the proper action needed; → higher cost and idle time than servicing
- **repairing** is the (event-driven) restoring of operational reliability (after e.g. breakdown caused by a damage and by means of e.g. changing the flawed part(s)); → usually relatively high costs due to unexpected idle time and consequential damages

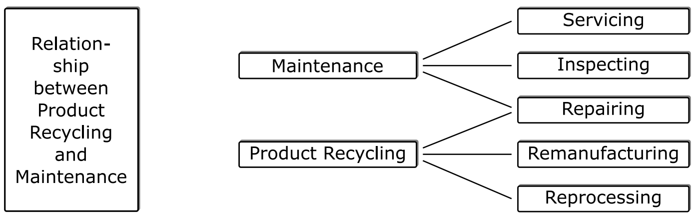

Figure (2.6): *Comparison of product recycling and maintenance*, according to Steinhilper (1988)*, p.42*

Unfortunately, the border between maintenance and product recycling is kind of blurred (see Figure 2.6). Oversimplified, *product recycling* with its imposed processes can be also described as an thorough repairing of all product's parts and, hence, theoretically belong to *maintenance*. But since *repairing* leaves the product in its original use phase and – in distinction to *product recycling* – is restoring only a part of the overall usefull life, *product recycling* is regarded as not being a part of product's *maintenance* in the context of the present work.

This fact is also shown in Figure 2.7. There, the difference between *repairing* and *product recycling* in terms of residual utility potential is depicted. Since product's provision of functionality is the interaction of numerous parts, the result after the repairing process – i.e. the repaired product

[26] see Angerer (2008), p.8.
[27] see DIN EN 31051 (2003), pp.3.

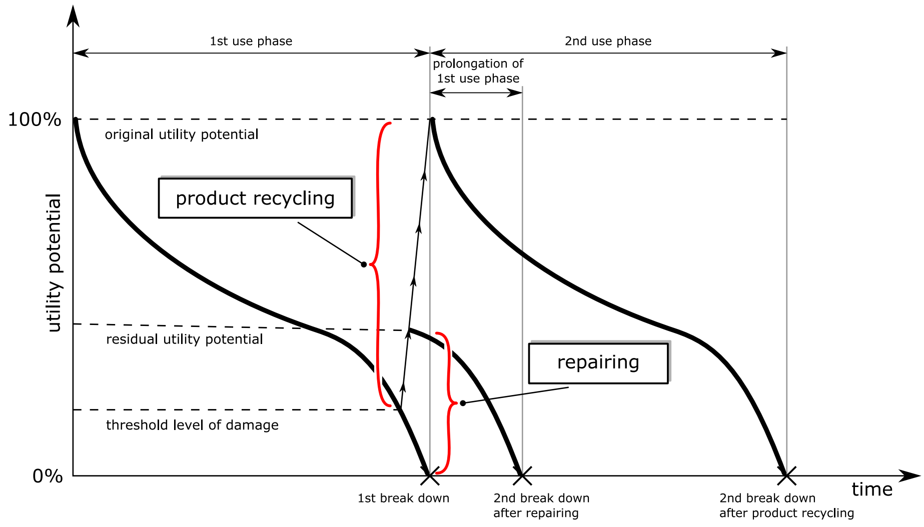

Figure (2.7): *Difference between repairing and product recycling in terms of residual utility potential*, adapted from STEINHILPER (1988), *p.45*

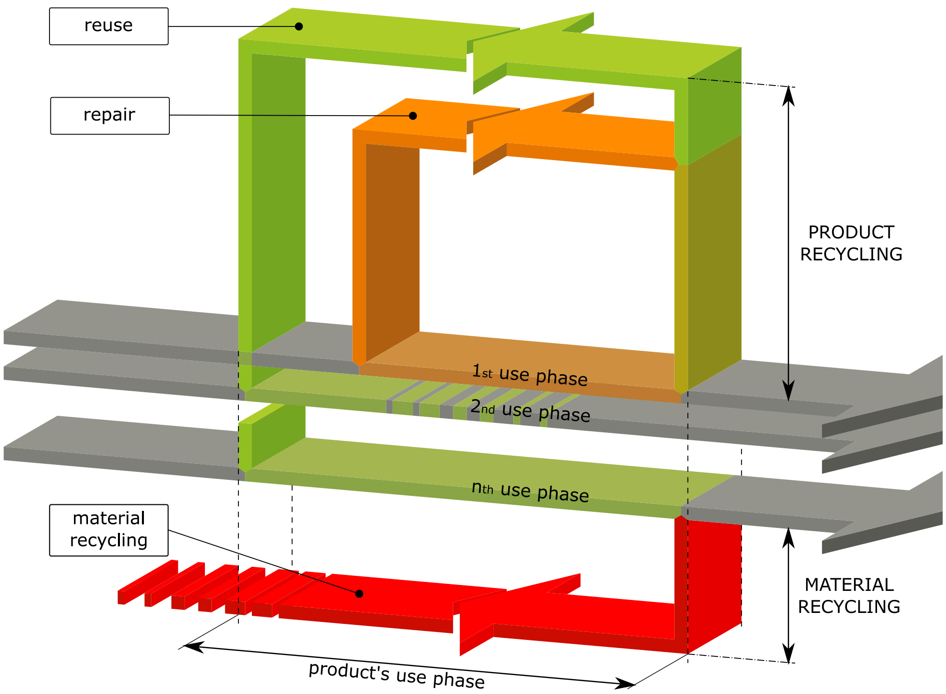

Figure (2.8): *Overview of post-use treatment recycling processes*, adapted from STEINHILPER (1988), *p.39*

– metaphorically speaking, can only be as good as its weakest chain link. Because repairing focuses only on those single parts already or almost flawed, the residual utility potential of the other parts is not improved. However, defect parts are replaced by new ones or at least by parts with significantly higher residual utility potential left. This disparity in part's life time and part's operational reliability will lead soon to another break down caused by another part which has been the weakest link up until now. By contrast, *product recycling* considers the refreshment of all part's utility potential to an as good as new standard.

Figure 2.8 depicts the same finding but with a rather material-flow related approach. In this figure the corresponding loops can be seen along product's life time. The orange arrow (also labelled with 'repair') displays the repairing loop which is, of course, not capable of increasing product's residual utility potential as much as the product recycling (or reusing) loop (labelled with 'reuse'), illustrated by the light green arrow. Since nothing lasts supposedly forever, the number of repetitions of subsequent reusing loops is finite. Hence, after the last entire use phase the whole product is treated in order to reclaim the intrinsic material – the red arrow in the bottom of the figure (labelled with 'material recycling').

2.5 Waste hierarchy

It is obvious, as mentioned above, that *reusing* is part of the big field of post-use treatment or waste treatment, respectively. Legislation of the European Union savours waste and the corresponding treatment a high value. Hence, it issued already in 1975 the first waste framework directive. Due to changes in science and technology, this directive on waste was adapted and released again as Directive 2006/12/EC in 2006. The most important article for the topic of *reusing* and *product recycling*, respectively, is Article 3[28] which is quoted in part below:

> Article 3
>
> 1. Member States shall take appropriate measures to encourage:
>   a) first, the prevention or reduction of waste production and its harmfulness, in particular by:
>   i. the development of clean technologies more sparing in their use of natural resources;
>   ii. the technical development and marketing of products designed so as to make no contribution or to make the smallest possible contribution, by the nature of their manufacture, use or disposal, to increasing the amount or harmfulness of waste and pollution hazards;
>   iii. the development of appropriate techniques for the final disposal of dangerous substances contained in waste destined for recovery;
>   b) second:
>   i. the recovery of waste by means of recycling, reuse or reclamation or any other process with a view to extracting secondary raw materials; or
>   ii. the use of waste as a source of energy.
> 2. [...]

[28] see European Parliament and European Council (2006a).

As the article clearly states, the prevention of waste is the more desirable aim in respect to the waste dilemma. Increase in resource efficiency in production and use phase is, inter alia, the first aim economy should strive for. Secondly, as equally weighing measure to prevention the recovery of waste is proposed. Under the term of recovery the directive summarises recycling, reusing and reclaiming. Unfortunately, this directive neither deals with a clear definition of the terms used – the directive is really misleading – nor with a ranking of them. It is proven as evident that the intrinsic potential of value creation of reusing is significantly higher than e.g. reclaiming part's material; hence, reusing should be recommended as the method to be preferred. Sadly, this 2006 directive pays no effort on classifying these waste treatment techniques in order to give a reference in which sequence they should be used.

Already in 2002 the Verein deutscher Ingenieure (see VDI 2243 (2002)) released a so called recycling cascade. On the premise of the maximum ecological and economical creation of value, respectively, this cascade is depicted in Figure 2.9. The ecological premises therefor are:

- efficient use of resources, that is to say of raw materials and energy ('resource efficiency')
- avoidance, reduction and recycling of residual materials
- avoidance and reduction of emissions

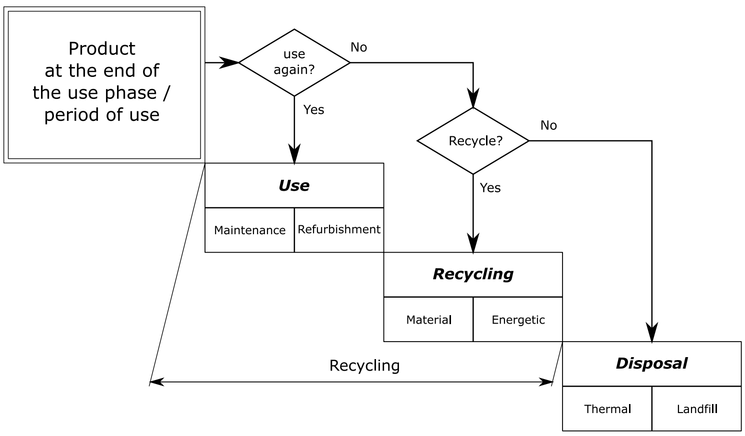

Figure (2.9): *Recycling cascade* , according to VDI 2243 (2002)*, p.10*

This recycling cascade[29] and waste hierarchy, respectively, generally recommends a priority order of what constitutes the best overall environmental option in waste treatment.

European legislation followed the VDI approach in November 2008 and issued the Directive 2008/98/EC of the European Parliament and of the Council on waste and repealing certain directives. Herein in Article 4,[30] legislation forges the priority order in common law and lists as:

(a) prevention;

(b) preparing for re-use;

[29] In order to avoid confusion in respect to some terms used in Figure 2.9 but defined not yet: VDI uses 'Energetic recycling' as synonym for 'energy recovery' and 'Thermal disposal' for 'Incineration'.

[30] see European Parliament and European Council (2008a).

(c) recycling;

(d) other recovery, e.g. energy recovery; and

(e) disposal

In order to move towards a European recycling society with a high level of resource efficiency, incentives for the acting subjects to apply this priority order must be created. In connection with the extended producer responsibility (as stated in Article 8 of Directive 2008/98/EC) this goal should be reached. Extended producer responsibility herein intends to strengthen the application of prevention and reuse. Moreover, it aims for appropriate measures which force producers (these are all natural or legal persons who professionally develop, manufacture, process, treat, sell or import products) to e.g. accept returned products and their corresponding waste or to design products with reduced environmental impact and waste generation in the course of production and subsequent use. This incentives might culminate in the development, production and marketing of products which are suitable for multiple use, technically durable and – after becoming waste and not eligible for further product recycling – suitable for proper and safe material recovery and environmentally compatible disposal.

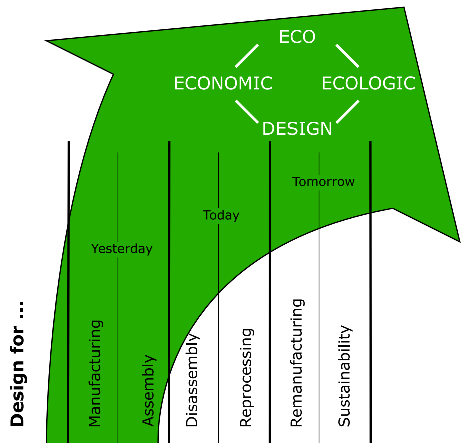

Figure (2.10): *Transition in Design for X*, according to STEINHILPER (1998)*, p.86*

However, since there is still a long way to go, especially science has to contribute enormously in order to achieve this plan. As can be seen in Figure 2.10[31], in the last couple of decades in the fields of e.g. production, design and automation, science has mainly dealt with issues like manufacturing itself and assembling, as well. In the last years *Design for Disassembly* developed so as the partial self commitment to material recycling is met. In the upcoming years, the effort put into research has to be multiplied to meet the goals set by the European Union. Hence, the present thesis is on good track to contribute to this ambitious aim of a more sustainable economy.

[31] In order to avoid confusion in respect to some terms used in Figure 2.10 but defined not yet: STEINHILPER (1998) uses 'Reprocessing' as synonym for 'material recycling' and 'Remanufacturing', as already mentioned in chapter 2.3.1, for 'Product recycling' [see STEINHILPER (1998), p.94].

2.6 Life Cycle Assessment

Since the overall aim of this thesis is the development of an assessment method, we will briefly summarise requirements for assessment methods in general, and then introduce one of the most important assessment method in the context of product recycling in the subsequent paragraph.

2.6.1 General requirements for assessment methodologies

In general, assessment methods have the common aim to cumulate a set of complex and different aspects so as an overall evaluation of an object to be assessed is enabled. Most time such evaluation is done when an assessment of decisions already passed is required or a future decision should choose the optimal alternative among a set of possibilities.

The majority of assessment methodologies consist of a triple of subsequent stages, namely

1. definition of the aims and the object to be assessed, and delimitation to its environment
2. identification and quantification of sources of impact
3. assessment of the consequences caused by these impacts

In particular for the assessment of product's reusability, we have – according to the course of action mentioned above – to lay our focus on the product and its life cycle which reusability we intend to evaluate. Furthermore, it is of prime importance to define exactly the borders of what has to be assessed and what not. The next step is characterised by the identification of all factors impacting the object. As impacts those factors are regarded which cause influence on the dimension(s) in which the achievement of targets defined in the previous stage is measured. As we will see later on, the main dimensions for the method to be developed are the economic, the environmental and the strategical dimension. Factors with high impact are, inter alia, e.g. flows of material, consumption of energy (and their according economic value), as well as design and market issues. These two preceding steps of mainly collecting data and information are followed by the assessment of the findings. In this last step, it is tried to cumulate and aggregate the information collected according to the applied, underlying value system so as a clear statement can be made.

Each quantitative assessment methodology bases on 3 main modules. Figure 2.11 shows the acting-together of those modules.

A common dilemma of the practical implementation of all those assessment methodologies is the discrepancy between accuracy and usability. This means in detail that all impacts of the object evaluated should be best possibly comprised. In contrast, the practical usability requests the limitation on only substantial impacts and quantify them with only sufficient accuracy. So, the trade-off between precision and practicability is inevitable.

Another restriction of the assessment method in respect to completeness occurs when aspects must be assessed which haven't comprehensively been researched up until now. Necessarily, only those impacts and interactions can be taken into account which are well renown. Thus, the current state of research can be a limiting factor; especially the assessment of environmetal impacts incorporates such difficulties.

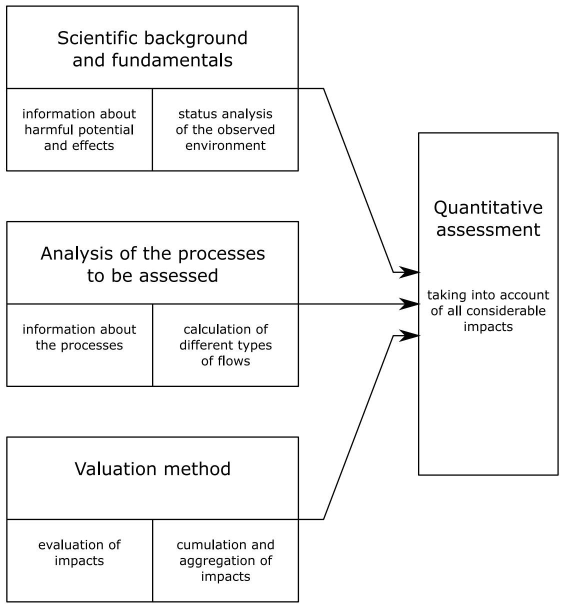

Figure (2.11): *Three fundamental modules in assessment modules*, adapted from AHBE (1995)*, p.13*

Assessment methodologies have the highest benefit if they are applied on questions impacting upcoming decisions.

From the perspective of businesses, assessment methods should fulfil the following preconditions and requirements[32]:

- the method should deliver clear results helping to bring alternatives in order and lead to a priorisation providing a profound basement for deciding upon
- the method assigns each object to be assessed a value so as those objects can be compared; this is only valid if the objects to be compared serve the same purpose
- in order to provide support for future decisions, the assessment method should highlight the most important impacts of an object to be assessed
- the findings should be usable for and dedicated to internal and external use, as well
- the introduction of an assessment method should fit into the operational workflow of decision finding and be capable of being integrated and implemented
- the method has to be traceable and provide sufficient transparency (even in respect to information and data used in)

These general requirements from company's point of view are extended by special ones which deal with the practical implementation and perception of the user[33]:

- independence of user – the findings resulting from the assessment methodology must not be dependent on the user applying the approach;

[32] adopted from AHBE (1995), pp.15.
[33] see ibid., pp16.

- possibility of aggregating data – to a certain extent, the aggregation of data is necessary so as different objects can be compared; ideally, there is only one single value to be compared; if there is more than one value to be compared, a ranking and therefore a clear statement about which object is superior might be exacerbated
- transparency – all parameters which may influence the outcome and which are capable of being influenced by the user of the assessment methodology must be clearly perceptible; only because of this transparency and clearness, the user is provided with possibilities to adjust if the outcome of the assessment is not satisfactory
- usability – the most sophisticated tool has no value-adding character if the application of this tool is too cumbersome and non-practical; particularly, the effort to be invested in terms of time is crucial for the general decision whether to apply a certain tool or not

A special assessment method which is useful for the purposes of the present work is the so called *Life cycle assessment*. This important method is explained below.

2.6.2 Life cycle assessment

Inter alia, ECODESIGN is targeted on minimising the total environmental impact of a product. In order to comprehensively assess all impacts caused by a particular product, like e.g. impacts during producing, using and disposing, and to quantify them, all life cycle phase and all corresponding processes must be thoroughly analysed by means of the so called *Life cycle assessment (LCA)*. A LCA is defined as the *'compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle'*.[34]

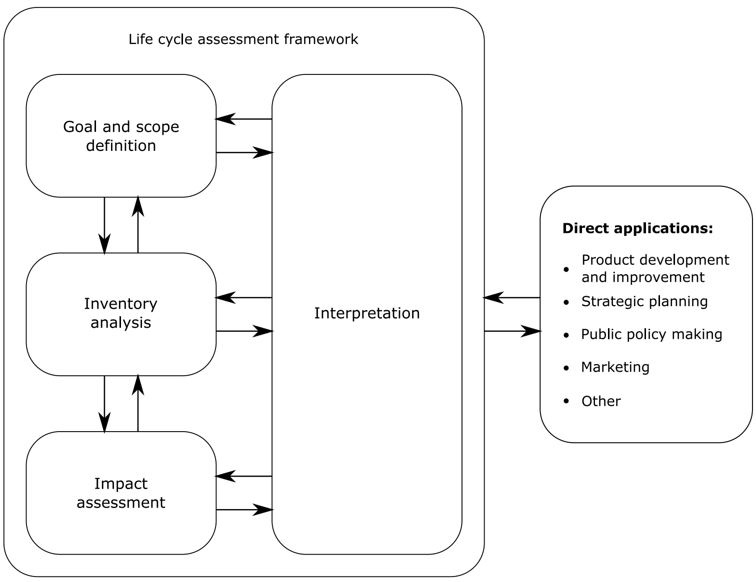

Figure (2.12): *Framework of LCA according* according to DIN EN ISO 14040 (2006), *p.17*

[34] DIN EN ISO 14040 (2006), p.11.

DIN EN ISO 14040 (2006) standardises a LCA's course of action. The four main phases, depicted in Figure 2.12, which *enable to systematically analyze [sic!] complicated product systems*, are:[35]

- Definition of goal and scope
- Life cycle inventory analysis
- Life cycle impact assessment and
- Life cycle interpretation

The first step to take – **definition of the goal(s)** – defines the purpose which the subsequently accomplished LCA must serve. This seemingly rather easy task tries to ensure the target-oriented approaching of the entire LCA. The **definition of scope** must clearly describe the product system and its borders / boundaries, specify the function and functional unit and predefine requirements of data quality.

As AHBE (1995) put it, not the product itself causes environmental impacts but the processes linked to it.[36] Consequently, deploying a LCA on a given product, means that not the product itself is observed but its connected processes. A process in its simplest way of illustration is pictured in Figure 2.13.

Figure (2.13): *Simple illustration of a process*

Simply speaking, each process consists of input, a transformation stage and output. Basically, output is distinguished in two separate categories, viz., namely the intended output and the not desired but unavoidable output. The intended output is the reason why a process is performed and subject of the value creation chain, the not desired output is a by-product and/or emissions, a – so to say – ‚necessary evil'. A general illustration of a process more in detail is provided in Figure 2.14.

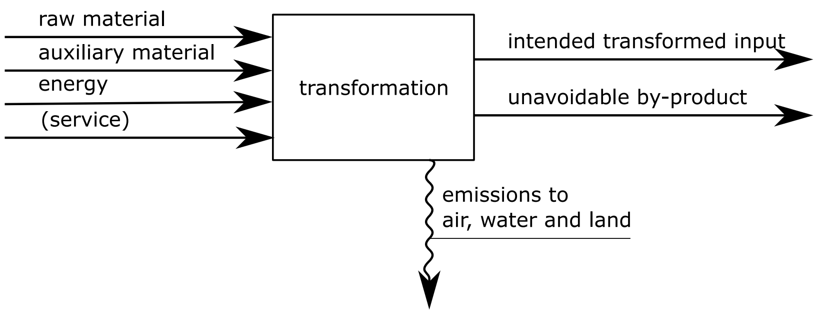

Figure (2.14): *Illustration of an exemplary life cycle process with input and output flows*

[35] see DIN EN ISO 14040 (2006), p.15.
[36] see AHBE (1995), p.13.

As illustrated, there are four arrows pointing towards the transformation stage. These arrows indicate the input. Raw material and auxiliary material (e.g. lubricant, coolant, catalyser,...) are self-explaining. Furthermore, each transformation needs energy, more or less. The last input in Figure 2.14 is called 'service'. This term summarises all other inputs necessary in order to run the transformation stage. E.g. information is an indispensable essential.

Regarding a product from the viewpoint of processes, an entire product life consists of interaction and succession of numerous processes. All processes together are called product system. Depending on the complexity of a product, figuratively speaking, a product system resembles a chain or net where the nodes are the processes and the input or output are connecting lines between. As processes occur throughout the entire life cycle, so do the connected environmental impacts. Thus, each process is analysed and the environmental impacts quantified. The keyword '*from cradle to grave*', often used in the context of LCAs, points directly to the holistic thinking applied to the assessment of the entire product system.

Because of the huge number of processes engaged in a product system, only those processes are included in the further assessment which contribute relatively more to the total environmental impact. So, workload to be undertaken during the next stage is reduced. In addition, the argument of work efficiency enforces this way of proceeding. As the evaluation of a LCA provides the basis for minimising total environmental impact, logically consistent, the highest marginal benefit in improving an existing product is obtained if focus lies on impacts with the highest leverage. In this context, leverage is the mathematical product of the two parameters 'quantity' and 'potential'. Usually, environmental impact correlates well with the flow of input resources (quantity). So, also for the sake of usability, an cut-off rule which obviously simplifies the data collection, is set in the course of a LCA. An in literature often used rule bases on input flows like e.g. mass of raw materials or energy. Exemplary, only those parts (and hence the processes linked with) are included where the single input flow exceeds a certain percentage of total input. This rule fails if the bigger part of input flows is similar in magnitude and below the decision rule's limit. Alternatively, an exclusion rule basing on cumulated input flows might be applied as well. Here, parts (and in consequence the corresponding processes, again) are ranked according their input flows (e.g. mass) in descending order and the input flow is cumulated. Only those parts are considered where the cumulated input flow is beneath a chosen threshold. In respect to impact's quantity, this kind of PARETO-analysis ensures that all important contributors are taken into account. Nevertheless, a critical review is certainly advisable. Since these kind of decision rules only address only one single quantitative aspect, it is absolutely necessary to quickly search the excluded parts and according process for significant environmental impacts. This might be e.g a part of little mass but incorporating materials of high toxicity like mercury (Hg) or lead (Pb) (high potential → second parameter influencing environmental impact)

Specifying product's function and the functional unit is required so as 'effort' (environmental impact) can be juxtaposed in opposite to 'utility' (satisfaction of costumers needs). Clearly determining product's function is necessary, if two (or more) products should be compared in respect to their environmental impacts. A comparison of environmental impact caused by these products can deliver a meaningful result then and only then, if the function of products to be compared is the same. If product function is the same, the total environmental impact must be relativised by means of the functional unit. Only this ensures a fair comparison.

The second step to perform is **Life cycle inventory analysis**. The main tasks in this stage are the collecting and processing of data. As already addressed before, this step is the most time-consuming one. Each significant process of the product system, from the very first step of raw material to the very last of end-of-life treatment, must be analysed and quantified regarding its input(s) and output(s). Before starting the data collection, the inventory parameter(s) must be predefined. For processes which are outside of the sphere of influence, the corresponding data is gained from data bases. Data of processes which are accomplished at the manufacturing site must be collected on-site. Only so an as accurate as possible result is achieved. Collecting environmental data is similar to calculations in costing. In case of facing uncertainties (e.g. user behaviour dependent input flows), estimations / assumptions, as realistic as possible, must be made. If possible, the collected data should be verified by help of miscellaneous balances (e.g. mass, energy,...).

The step of inventory analysis is followed by the stage of **Life cycle impact assessment**. For each process, the inventory parameters are now available. These inventory parameters must be assigned to different categories of environmental impact, so called impact categories. Another term for this task is classification.

Basically, environmental impacts are distinguished according their subject of impact, which are air, land and water. The impact categories most cited in literature are listed and briefly explained below:[37]

- Global warming (GW) – this term summarizes the effects responsible for an increase of average temperature in the atmosphere. Contributors to GW, also called greenhous gases, are carbon dioxide (CO_2) and methane (CH_4), amongst others. Due to this anthropogenically increased concentration of GHG, the reflected heat of the planet's surface is trapped within the atmosphere.
- Ozone layer depletion (OD) – in the stratosphere, an atmospheric layer in 8 - 10 km altitude, an increased concentration of ozone prevents the immission of harmful radiotion like e.g. ultraviolet rays (UV). The depletion of this layer, caused by man-released substances like e.g. chlorofluorocarbons (CFC), decreases the natural protective effect.
- Acidification (AD) – mainly the burning of fossil resources releases air pollutants like e.g. sulphur oxide (SO_x) or nitrogen oxide (NO_x). In connection with precipitation as rain or fog, these gases chemically react to acids. Flora as well as Fauna suffer because of this development.
- Eutrophication (EU) – this term subsumes the effects of ascending concentration of nutrients like e.g. phosphorus (P) or nitrogen (N) in water. This increase is fed by sewage/faecal matter and washing-away/elution of agricultural fertilizers used excessively for growing crop. These watersoluble substances most likely concentrate in stagnant water where they first facilitate growth of water organisms. Then, after their lives, they die off and bind the existing oxygen while decomposing. Dependent on the extent of decreasing water's oxygen freely available, the consequences may lead up to total imbalance and dying-off of all aquatic life.
- Photochemical oxidant creation (POC) – POC means a rise in ozone concentration in immediate proximity to ground. In broad public, this phenomenon is renown as 'smog'. First of all, highly reactive ozone harms the respiratory systems of children or elder people and hinders vegetation.
- Abiotic resource depletion (ARD) – resources like e.g. crude oil, iron ore or bauxite belong to the category of non-renewable resources. Due to the irreversible character of depletion of

[37] see WIMMER/ZÜST/LEE (2004), p.22.

non-renewable resources, each process using this sources influence the ‚upcoming courses of life‘ and transforms the basis for future living on earth. These consequences, caused by the consumption of non-renewable resources, are aggregated in the category 'ARD'.

After classification follows characterisation. Since not all inventory parameters equally contribute to a specific impact category, the characterised impact is calculated. Only if all inventory parameters of an impact category are standardised to one characteristic factor and converted, the total environmental impact in a specific impact category may be computed. This task is called 'characterisation'. A brief overview of in literature often used impact categories and their corresponding characterised factors is shown below (see Table 2.1).

Table (2.1): *Name and unit of characterization factors of typical impact categories,* according to WIMMER/ZÜST/LEE (2004)*, p. 50*

Impact category	Characterisation factor name	Characterisation factor unit
Global warming	Global warming potential (GWP)	g $CO_2 - eq/g$
Ozone layer depletion	Ozone depletion potential (ODP)	g $CFC11 - eq/g$
Acidification	Acidification potential (AD)	g $SO_2 - eq/g$
Eutrophication	Eutrophication potential (EP)	g $PO_4^{3-} - eq/g$
Photochemical oxidant	Photochemical oxidant creation potential (POCP)	g $C_2H_4 - eq/g$
Abiotic resource depletion	Abiotic resource depletion potential (ADP)	1/yr

The aggregation of all environmental impacts provides the final environmental profile which is the starting point for interpretation and possible (design) improvement.

The last step according DIN EN ISO 14040 is the **life cylce interpretation**. Outcome of this pragmatic analysis is the identification of weak points of a product or environmental key issues[38] and possible recommendations. In addition, the LCA result is tested regarding its reliability.

As it becomes clear, the LCA is a comprehensive and powerfull tool for supporting decision making. However, the huge time consumption (and in consequence the economic effort to invest) might impose a drawback in respect to its usability. To lower the barrier for application, computer support is integrated so as to increase this method's convenience of usage. Another approach for enhancing its acceptance is to employ abbreviated and simplified LCAs so that effort to be undertaken is significantly decreased while informative value remains similarly high. Also the use of generic data results in a simplification.[39]

[38] see WIMMER/ZÜST/LEE (2004), p.20.
[39] see MÖLTNER (2009), p.62.

Comprehensive LCAs always include a detailed view on all input and output flows. In contrary, the abbreviated methods neglect parts of the inventory analysis which reduces the complexity and effort for data collecting. Trimming the product system and excluding certain parts (and the connected input and output flows) of the product system causes simplification. Focusing on only a specific set of environmental impact categories results in the same. Of course, both approches may be combined, as well. Use of generic data is an option, too. Substituting the data collection in the life cycle inventory analysis saves much time. Usually, this data is accessed either by internet databases or literature. Step by step, support by means of computer-aided software, which is the last item in the above listing, finds its way into the field of application.

2.7 Insight gained

Acting upon the maxim of equal and fair living conditions for following mankind's generations, there is doubtlessly no other way to go than the sustainable one. Out of it, especially when it comes to utilisation of non-renewable resources, the only option at hand, in order to fulfil above maxim, is to recycle.

While studying German and English literature, it had been observed that the term 'recycling' is often used in a different manner with changing conotation. Especially the linguistic use of the foreign language term 'recycling' in German poses a source for confusion. That's why an intuitive and consistent, on different sources of literature basing categorisation is explicitely put into writing.

Since product recycling and reusing, respectively, saves both inherent material and inherent energy, it is, apart from prevention, also the option preferred by legislation.

The conclusio out of the second part (assessment method in general and LCA in particular) is the claim for holistical and objective assessing while reducing work load to a minimum. The output of the assessment must be a clear response to the question asked at the very beginning before starting the evaluation.

3 Implications of product recycling

The implementation of recycling in the business model is influenced by numerous parameters. Identifying those influencing variables, especially for the case 'product recycling', is the task of following chapter's first part. This macro-economic view is subsequently extended by the rather technical examination of the business process 'product recycling' in a second part. In subchapters, the key steps required for successful product recycling will be explained.

3.1 Between the poles of newly manufacturing and recycling – structural chances and limits for product recycling

The following chapter aims to describe the environment which recycling activities act in. It summarises the ideas of KAUFMANN (2002) and uses his findings as starting point for discussion. Wherever necessary, his statements are complemented by other literature, mainly by newer legislative sources, and also own annotations. Purposefully, as stated above, mainly the activity 'product recycling' will be in the centre of interest.

Firstly, it is useful to approach the concept of 'product recycling' from a process perspective with its basic transition stage and, then, to analyse, step by step, the claims in respect to its input (waste), output (products and parts intended for reuse) and the also the encircling general framework.

The process of recycling in general and product recycling as subordinate category of recycling can be regarded as a process innovation, particularly from the perspective of business strategy. Hence, the adoption of the principle of reusing in the global economic system faces the same reluctance as innovations, like unwillingness and inability[40] – this resistance has to be overcome. If individuals should be convinced of the implementation of reusing / acceptance of remanufactured products, among stake holders the generally positive perception must be induced that the application of this principle is reasonable. Among others, the relative advantage is critical. The incentive derived from reusing has to be perceptible on both sides, for companies and for customers. Only then, the adoption of innovations, in this case it is *reusing / product recycling*, succeeds.

Regarding product recycling more in detail, it makes sense to define the term 'product' more precisely. A product in the economic context can either be a service, an immaterial or a material / physical commodity. As precondition mentioned later on, waste emerges mainly only in the post-use stage of physical commodities. Consequently, only physical commodities are subject of product recycling.[41] Besides efforts for retrodistribution, product recycling demands activities like disassembling, cleaning, testing, reconditioning and reassembling. These activities will be explained later (see chapter 3.2).

[40] see KAUFMANN (2002), p.119.
[41] see ibid., p.187.

In this economic context, recycling is defined as the anthropogenic creation of closed loops for energy and / or material flows. Actually, it is a closing of resource flows which are started because of anthropogenic and economically motivated acting. Recycling in general and product recycling / reusing in particular cause a reduction of input flows in (i.e. reduction of resource depletion) and reduction of output flows (i.e. reduction of waste to be disposed of) out of the economic system. Material as well as energy flow through the economic system and, after intermediately satisfying men's needs, are transformed into waste. In general, recycling does not avoid the backflow of material or energy in form of waste out of the economic system at all; it only postpones the flow back into the ecological system[42] and guarantees a more intensified utilisation. Mainly, the ecological system provides manhood and the economic system with two fundamental services – supply of material and energy and support in terms of absorption of man-made waste.[43,44] The supply function is the initial point for resource provision. Those natural resources are transformed by means of economic processes and harnessed for men's purposes. Depletion of resources, transformation and utilisation of these materials and energies has characterised the classical value chain up until now. In the post-use phase, those formerly useful input flows turn into physical waste and / or anthropogenically not anymore usefull energies, and return into the ecological system where they are absorbed (see Figure 3.1). It is easy to see that the ecological system is encircling the economic one.

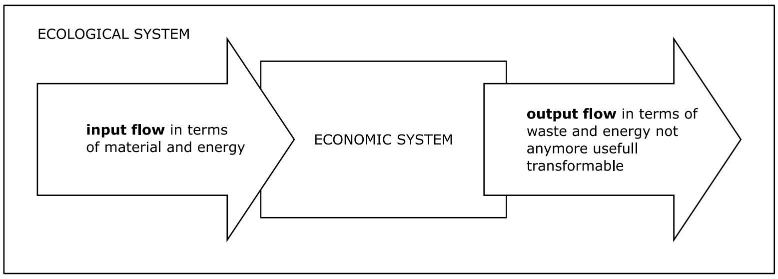

Figure (3.1): *Illustration of the classical economic system with its input and output flows*

Due to its economically motivated acting, manhood influences the natural material and energy household. This can be beneficial to a certain extent. In former times, the reclaiming and cultivation of land, respectively, contributed to the enhancement of environment's support and supply potential. In turn, the development of recent times opposes the former mentioned trend. The massive expansion of economic activity due to increasing wealth and growth of population stresses the support and supply function of the ecosystem. It seems that the natural limits are reached soon.[45]

Although it would be desirable, a permanent absolute recycling economy, where all input flows are recycled, is only a theoretical construct. But, if materials and energy remain as useful resources as long as possible within the economic system, the strain for ecosystem's supply and support function is lowered sustainably.

[42] see KAUFMANN (2002), p.131.
[43] see RUDOLPH (1999), p.5.
[44] General services like e.g. provision of oxygen or water are also essential, but are connected with the existence of mankind, and not the existence of the economic system; thus these essential services are neglected here.
[45] see KAUFMANN (2002), p.131.

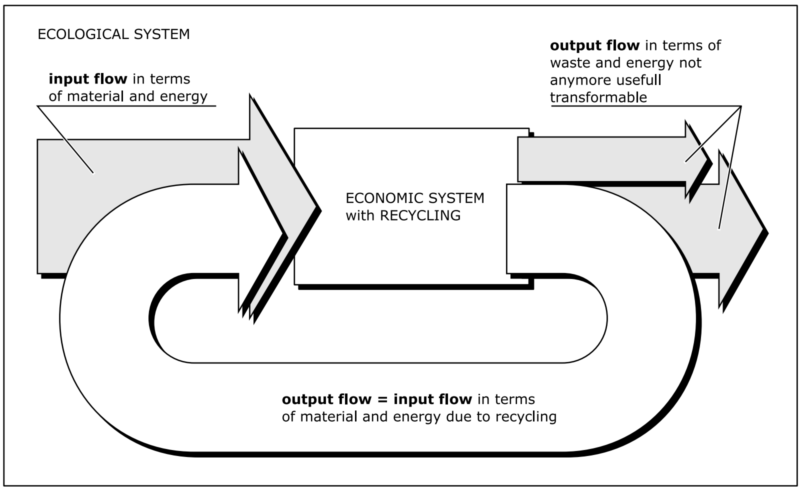

Figure (3.2): *Illustration of the economic system with recycling of its output flows*

As recycling is an anthropogenic activity aiming for a reduction of laying claims to the supply and support function, exactly this represents the difference between natural recycling and today's comprehension of 'economic' recycling. Natural recycling necessarily occurs in closed system because material and energy can't get lost.[46] But the time horizon for those processes engaged usually exceeds our horizon of planning. This means that time needed for e.g. converting organically trapped CO_2, which originates from burning fossil fuel, into crude oil or coal again, doesn't comply with the time horizon of human expectation.[47]

Although intended to lower the environmental burden for the ecosystem, detrimentally, the implementation of recycling generally leads to augmented spatial allocation of products' life cycle stages from the perspective of the value creation chain because of the distributed emergence of waste as input factor. Therefore, increased logistic activities are necessary which, in turn, are afflicted with material and energy flows as input factors, burdening again the supply and support function of the ecosystem. From this, it follows that the inevitable precondition for recycling is a higher benefit than effort to be invested – the process must be 'efficient'.[48] Since benefit is defined as difference of output and input, it is reasonable to qualitatively describe them here.

Usually, residues of consumer processes accrue decentralised and contaminated in relatively small amounts in heterogeneous mixture at different points in time. In opposite, the economic system necessitates exact amounts of homogeneous commodities in certain quality at dedicated locations as input. In contrast to residues of consumer processes, production waste occurring as (undesired) output of manufacturing processes accrues relatively concentrated in forecastable homogeneous quantities at given points in time.[49] It becomes easily perceptible how difficult it is to do the split of connecting the output side of the economic system with the input side, especially in the case of product recycling. Material recycling seems to be more advantageous. In order to overcome this hurdle and to establish this economic connection, investment of resources

[46] Conservation of mass and energy must always be valid in closed systems; see first law of thermodynamics
[47] see Kaufmann (2002), p.134.
[48] see ibid., p.133.
[49] see ibid., p.136.

is required. That means that recycling is not necessarily reasonable at any cost. Putting effort in recycling activities only pays off if and only if the benefit of these activities is positive (higher effort saved / gained than effort invested).

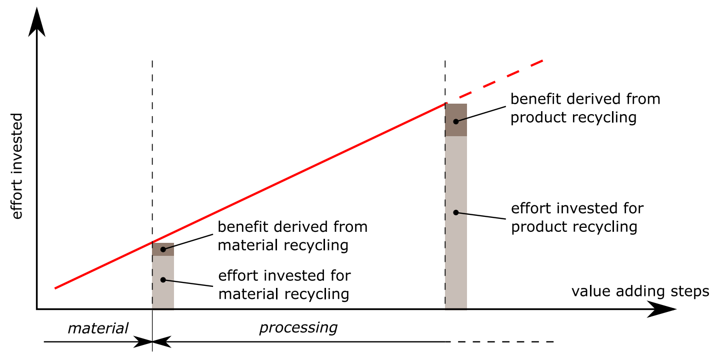

Figure (3.3): *Schematical illustration of a simple value creation chain with its potential starting points for recycling*

If it's possible to generate a higher benefit from product recycling than from material recycling (see Figure 3.3), then this final result is realised while consuming less resources in total, although the same need is satisfied. Since product recycling comprises numerous process steps, the potential for incremental improvement and effort saving is higher by trend than in the case of material recycling.

The call for efficiency of recycling activities heavily depends on economic system's level of development (i.e. disposability of production techniques, product requirements and degree of vertical differentiation in the value creation chain). A trend observed in recent decades is the increase in complexity of products on the market (for instance, type writer in the middle of the 20^{th} century in comparison to a personal computer and printer at its end) The more specialised and sophisticated products and processes become, the less likely it seems to successfully combine used components and the corresponding processes and reuse them in order to substitute a newly manufactured product / part. It appears that future higher technological development leads to higher entropy because of elevated product's complexity[50], and in consequence to a higher likeliness of inefficiency of future product recycling endeavours.[51] Product recycling appears to be economically and ecologically futile. However, this conclusion bases on the assumption of extrapolating past trends. If product recycling as EoL-treatment is already considered a priori in design of new products, an approach which has been done only for a neglecting share of products yet, the above mentioned tendency or futility of reusing might be avoided.

As already listed in section 2.3, recycling is distinguished according its place of occurrence. Taking the above argumentation into account, residues for in-house recycling and industrial recycling

[50] The second law of thermodynamics declares that if in closed systems irreversible processes take place, system's entropy will increase. This means that such systems tend on their own to fade from systems of high order (low entropy) in systems of low order (high entropy). Entropy is regarded as measure of probability for a system's state of order. Low entropy equals to low probability of system's high order; in opposite, high entropy implies a system of low order at high probability. Utilisation of natural resources, and in particular burning of fossil fuel, transforms a state of high order/low entropy (e.g. regular arrangement of carbon in the crystal lattice of coal) in one of low order/high entropy (e.g. chaotic allocation of carbondioxide in the atmosphere)

[51] see Kaufmann (2002), p.143.

primarily arise – contrary to recycling of consumer residues – spatially concentrated in homogeneous composition and relatively big amounts. Thus, the effort to be invested, especially for retrodistribution and processing, is low, rather manageable and determined. In case of in-house recycling, mainly material recycling is the structural recycling option at disposal and, hence, equates with. Of course, product recycling can also be applied for those products which fail in the final quality check after assembling (defective products, not compliant with quality requirements), but usually businesses apply total quality management methods and strive for lowering this number as much as possible. So, necessary quantities for successful process implementation are missing. For recycling consumer residues, both material recycling and product recycling are viable options.

In order to determine the benefit yielded from a particular recycling option, one must identify the 'primary effort' and the 'secondary (recycling) effort' needed for the satisfaction of a special 'business need'. The difference between the former and the latter forms the total benefit of the recycling process, which will only be applied if this difference is positive (see Figure 3.3). In case of material recycling, only the economic cost and environmental impact caused by primary material provision can be substituted by secondary material. Since material is rather at the beginning of the value creation chain, this effort surrogated is rather low. But fortunately, also the effort to be invested for material recycling is rather low, which leads to a certain benefit. In case of product recycling a certain part or component may be replaced by a remanufactured one. Because of its later position within the value chain, a higher 'primary effort' can be substituted. But, in turn, product recycling also needs higher effort to run all the process steps needed, which also leads to a certain benefit.

Up until now, out of the recent argumentation, no recycling option can be preferred in general. Due to the higher quality requirements towards parts, product recycling seems to be the more difficult one and, hence, the option with lower probability of success. But, in contrast to material recycling, product recycling has a lot of potential for optimisation (increasing probability of method's success and also lowering effort to be invested both due to technological development). In combination with future technological progress, product recycling seems to be the more powerful option. This statement gets enforced, when benefit resulting from product recycling aligns with its counterpart of material recycling. Comparing both options from the microeconomic perspective, usually the basis for company's decisions, the option with the higher benefit will be preferred. But from a macroeconomic perspective the best choice might look different. While a value chain, basing on material recycling, still needs primary input in order to reach a higher point within this chain, product recycling enters it directly on a high level. As consequence, in this gedanken experiment, product recycling does not burden the ecological system as much as material recycling does, if a particular product is headed for. Contrarily, as a matter of fact, the output of material recycling is more flexibly deployable.

A specific characteristic of product recycling is part's integrity. This does not compulsorily mean that the outer surface of the whole product stays the same but at least of its components and parts. The treatment processes don't destroy the shape but focus on reusing the product / part in a subsequent, additional use phase. Reclaiming product's utility, which, easily speaking, consists of inherent material, inherent energy and inherent information required for newly manufacturing this product / part, is in the centre of efforts. Contrarywise, material recycling accentuates only the reclaiming of the inherent material and does not sustain part's shape.

Along with enhanced wealth and, consequentially, rising amount of waste, the attitude in society changed. Not the historically prevailing economic scarcity of natural resources but their conservation, not averting of waste related danger but the environmentally sound removal of waste is explicitly underlined in current law.[52] Even the priority order concerning waste is defined for the first time and forged into law: avoidance — utilisation (in terms of recycling) — removal.

This change in attitude was also responsible that legislation, particularly the European Parliament as 'forerunner', has issued several directives in the last years. Amongst others, the most important legal sources directly or indirectly influencing recycling activities are:

- Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives
- Directive 2002/95/EC of the European Parliament and of the Council on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS)
- Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles (ELV)
- Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE)
- Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EC
- Directive 2005/32/EC of the European Parliament and of the Council of 6 July 2005 establishing a framework for the setting of ecodesign requirements for energy-using products and amending Council Directive 92/42/EC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council (EuP)

Waste, which availability is a precondition of recycling, is legally regulated in the first source of above list. The longer part in history of manhood, waste had consisted mainly of residues resulting from food production and consumption. Commodities in every day life like e.g. clothing, tools, furniture, crockery and table ware were too valuable to dispose. Moreover, people tried to repair them and bequeath it to the next generation. Only due to emergence of mass production commodities turned into waste at their end-of-life.[53] According to European legislation, *waste means any substance or object which the holder discards or intends or is required to discard*.[54] Waste is a byproduct of production or consumption processes which involuntarily, but inevitably emit material and energy flows (see Figure 2.14). Legislation honours and appreciates recycling because, in contrast, disposal of waste deprives society of sustainable future utilisation of waste's inherent value. In the centre of recycling in general and product recycling in particular, rather the aspect of (future) utilisation than of disposal is prevailing.

A for recycling not less important directive is the *Directive 2002/95/EC of the European Parliament and of the Council on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS)* which regulates the use of certain hazardous substances in electrical and electronic equipment and defines corresponding threshold values. The set of hazardous substances momentarily defined are lead (Pb), mercury (Hg), cadmium (Cd), hexavalent chromium (Cr^{6+}), polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE). In other words, if containing one of these substances, products put on the market must not exceed the

[52] see, for instance, Kaufmann (2002), p.156; Directive 2000/53/EC, preamble (3) – (4) or Directive 2002/96/EC, preamble (1) – (2)
[53] see Kaufmann (2002), p.161.
[54] European Parliament and European Council (2008b), Article 3 (1).

defined limits. Regardless of its final end-of-life treatment, all products on which this directive is applicable have to comply with since its commencement. Hence, it can be assumed that all products marketed after the directive's commencement fulfil the criteria. At a first glance, the directive's influence on recycling activities is not immediately perceptible. Only products which are marketed before and perhaps do not comply with the limits form a matter of concern. If material recycling of such not compliant products is aimed for, the strict obedience must be ensured by changing the material formulation while processing. If this requirement can't be fulfilled, the particular part made of this very material is excluded from putting on market and alternative end-of-life treatments must be selected. If product recycling of a currently not compliant product is considered, there is no obstacle since in Article 2 exceptions for this very case are defined.[55]

The only difficulty in respect to the RoHS directive emerges if those threshold values defined in the directive are changed because of e.g. new scientific insight or new substances are added, and no exceptions for older products already marketed before commencement are defined. Then, if there is no possibility for legally changing part's extent of toxicity, product recycling is hampered. Material recycling might still have a chance for succeeding, but must also be refrained if those new limits are reneged on. The problems connected with material recycling of parts containing those substances listed are not dealt with in this paper, since it would exceed the scope of the current paper.

Besides those 'general' directives, there are a number of directives especially dedicated to deal with certain products and product groups. For example, for batteries and accumulators[56], cars at their end-of-life[57] or electrical and electronic equipment[58] there is own European law which, in respect to recycling activities mainly important, deals with putting on the market, collections systems requiring the producer to take back used products, prevention of waste, and specify compulsory treatment at their EoL in order to reduce waste to be disposed of. Particularly for EoL-vehicles and waste electrical and electronic equipment, there are also minimum numbers for recycling rates explicitly defined[59] which has presented producers with a new challenge but also offer possibilities. Such a positive chance is, besides product recycling as business model itself, for instance, the development of new models dealing with e.g.retrodistribution and / or disassembling. Because of the legal requirement to recycle (regardless which option is finally chosen), the need for processing this waste heap evolves. An often cited problem linked with processing of waste electrical and electronic equipment is 'imported e-waste in developing countries'. *In these countries, because of lack of adequate infrastructure to manage waste safely, these wastes are buried, burnt in open air or dumped into surface water bodies. Crude 'backyard' recycling practices, which are not efficient and are highly polluting are also used in material recovery activities.*[60] However, by principle producers especially located in the European Union are not allowed to export WEEE if proper treatment according the European state-of-the-art is not assured.[61] Nevertheless, the problem exists, though.

Directive 2005/32/EC is a general a framework for the setting of ecodesign requirements for energy-using products which they have to comply with in order to be allowed of being put to

[55] see European Parliament and European Council (2003a), Art. 2 (3).
[56] see European Parliament and European Council (2006b).
[57] see European Parliament and European Council (2000).
[58] see European Parliament and European Council (2003b).
[59] see ibid., Art.7 and see European Parliament and European Council (2000), Art.7
[60] Nnorom/Osibanjo (2008), p.843.
[61] see European Parliament and European Council (2003b), Art.6 (5).

market[62] This regulation does not immediately affect product recycling as EoL-treatment itself, but can exacerbate the marketing of remanufactured products. If a set of regulations is newly issued or an existing set of regulations is tightened and a product, intended for reuse, is covered by definition under these regulations, then a previously legally compliant remanufactured product might not being allowed of getting marketed anymore. If in case of noncompliance with the legal standard product adaption is possible, placing to market of this product is allowed to continue on; if not, product recycling withdraws as viable option.

Of course, every coin has two sides. This means that the legal restriction narrows companies' space of action. On the microeconomic level of business entities, this impediment might represent a considerably huge drawback, but from the macroeconomic perspective this limitation is beneficial in respect to (discounted) opportunity cost of future damages caused by unregulated continuation of current behaviour. It seems to be favourable to 'spend effort in terms of lost revenue' sourced from environmentally questionable activities if the linked, usually bigger negative consequences in future can be avoided (see similar argumentation in the Stern Review in respect to climate[63]).

Another powerful control not addressed yet are not normative aspects of legislation. Societal ideals, expressed in politically and legislatively imposed regulations, especially in form of taxes on primary material consuming production techniques also create a relative advantage of both product recycling and material recycling.

After analysing the transformation involved in the recycling process and briefly summarising the legal framework with its chances and limits, the output side will be scrutinised. As a matter of course, a reconditioned product has to meet the requirements of a marketable product. Apart from the legal framework dealing with putting on the market[64], remanufactured products must be able to yield a price on market. Not only the (scarcity of) supply of a certain good defines its value but also the demand.[65] This means that lack of demand can exacerbate, if not make it impossible to adopt product recycling. Unless there is a market, a remanufactured product has no inherent economic value and is just nugatory waste. Of course, this argument is also valid on the input side since demand for EoL-products for product recycling is also kind of market (remanufacturer on the demand side and consumer on the supply side). But precondition for this input-sided demand is demand on the output-side which means that a remanufactured product must be marketable (typical economic constellation – consumer on the demand side and producer on the supply side).

Firstly, recycled products must enjoy customers' acceptance. As it is obvious, recycled products are in competition to newly manufactured products. Hence, they must equally fulfil (or exceed) customer's quality expectations, as newly manufactured products do. E.g. an only subjectively sensed inferiority in terms of quality, located in customer's individual perception would severely exacerbate market acceptance. Thus, remanufactured products' qualitatively equal state must be verifiable and able being communicated.

In dependence on the position within the value creation chain, this proof may form an obstacle. Regarding a stage at the very beginning of the value creation chain, e.g. raw material, equal specifications like e.g. technical characteristics are more easily to check and also more easily

[62] see European Parliament and European Council (2002), Art.1.
[63] see Stern (2006), pp.416.
[64] Remanufactured products must comply with legal warranty
[65] see Kistner/Steven (2002), p.151.

to declare by trend. In respect to technically complex products manufactured at a higher point in the value creation chain, this proof of qualitative equivalence between 'new' and 'recycled' is harder to show.[66] In his argumentation, Kaufmann stresses the supposedly negative expectations of customers which hurry ahead of remanufactured prodcuts. But luckily, product's subjectively perceived quality, which, frankly speaking, equals to satisfaction of customer's needs and expectations, is not only defined solely by the product itself, but also determined by company's surrounding process and, in consequence, its reputation[67] – Kaufmann doesn't consider this important point. If a company is able to build up experience in the field of recycling and, more importantly, is able to communicate this, then customer may get confidence in product recycling, it drops the stain of minor quality and overcomes this structural handicap. Hence, if product quality is verifiably equal, this is, easily speaking, only a challenge of addressing consumer psychology and subject of PR-efforts.

If product recycling should be a viable alternative to newly manufacturing from the perspective of marketability, the price asked for a remanufactured product has to be geared to price of (the functionally same) newly manufactured one.[68] Product recyclers are assumed being price takers. Thus, the prevailing price achievable on market represents the upper threshold for all product recycling activities. A price (and cost, respectively) for recycled products significantly higher than for newly manufactured ones will probably risk to economically fail. Only if appreciation of saving natural resources and preserving environment by applying recycling techniques creates a certain willingness-to-pay, higher prices (or cost) are enforceable.

As a general rule, marketing of a particular product only succeeds if there is demand. Usually, this demand is depicted in the so called product life cycle. Unfortunately, this economic terminology conflicts with the technical terminology used in Ecodesign. That's why for the purpose of the current paper the following product life cycle will be called *economic product life cycle*. Such a typical economic product life cycle is shown in Figure 3.4.

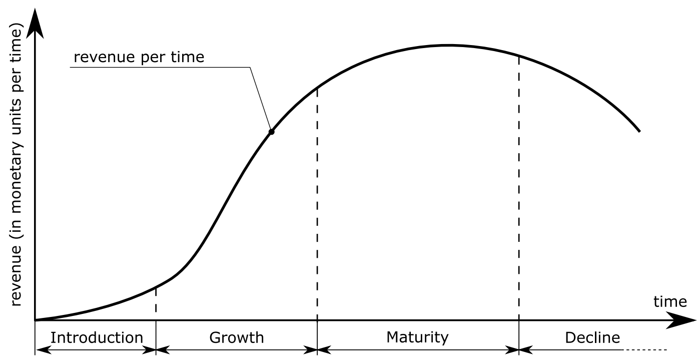

Figure (3.4): *Economic product life cycle with its 4 main phases depicting revenue over time, according* KOTLER/BLIEMEL (1995)*, p.560 and* LILIEN/RANGASWAMY (2004)*, p.175*

A typical economic product life cycle consists of the phases *introduction*, *growth*, *maturity* and *decline*. However, sometimes in literature a fifth phase of *saturation* is inserted before *decline*. In

66 see KAUFMANN (2002), p.166.
67 see BRUNNER/WAGNER (2004), pp.1.
68 see KAUFMANN (2002), p.170.

general, a product life cycle depicts revenue over time of a particular market and product. Assuming ceteris paribus a fixed price for a product, the curve shows the amount of products sold on a certain market (per time period). The typical S-shaped curve bases on the diffusion and adoption of innovations in markets[69] and, therefore, the rate of customers deciding to (re-)purchase the product. In the first phase of introduction, the new product must perform better than already existing products, otherwise the customer wouldn't perceive an incentive to buy. In the final phase of decline, sales are diminishing and may either result in stagnation of sale at a very low level or even drop to zero. In both cases, the product lacks customer's interest because customers face (inter alia) more competitive products. This superiority in comparison to incumbent products, at least in a single quality aspect, is the direct consequence of technical progress. Shifting customer interest also leads to increased retirement of used products, an essential for product recycling. But, without chances for future marketing, companies have to quit the provision of out-of-date products.

If the maximal benefit derived from product recycling should be harvested only on basis of a single economic product life cycle, a possible way would be stopping production of originally manufactured products in advance of product's end-of-life and substituting newly manufactured products by remanufactured ones. But, in turn this brings up the challenge of optimally determining the point in time where to stop originally producing without risk of loosing mature sales and stockpiling remanufactured products because of ceased demand.

As pointed out in the penultimate paragraph, technical progress triggers the beginning and the end of the economic product life cycle. This progress is, however, not a single happening in time, but rather a continuous process spanning industrial sectors. The pace of its proceeding is often summarised as innovation dynamics. The faster technical development progresses, the more frequent products are replaced by following innovations.[70]

Fortunately, there are two approaches at disposal which are able to counteract 'premature plummeting of marketability of remanufactured products because of technical progress'. The first option in the course of product recycling is to adopt the recycled product in a way so as product's function and its specifications are levelled to current state-of-the-art. This challenge, also called upgrading, addresses mainly the design department which is supposed to anticipate possible future technological developments in product design and to implement interfaces so as adoption is easily possible.[71] This claim directly points to modular design and (company-internal) standardisation of intra-product interfaces. The second way of incentivising customers to buy a technologically slightly out-dated product is to offset the quality drawback in comparison to its qualitatively superior follow-up product so as product's competitiveness is sustained. Even if a change in the underlying technological paradigm takes place, the identification of 'better products', which is basically a comparison of invested resources, must be standardised by means of product's function in order to enable a fair comparison.

Under the assumption that a product only belongs to one disjunct technological paradigm, the ultimative constraint of product recycling is reached when this technological paradigm changes. Of course, there is a transition period where product recycling still may succeed but this is only possible because of relative competition advantages of the old-technology products. Since only satisfaction of customer's need or, in other words, utility value for customer is relevant on markets

[69] see Kotler/Bliemel (1995), p.565.
[70] see Kaufmann (2002), pp.227.
[71] see ibid., p.220.

(see Figure 3.5), success of product recycling might be slightly prolonged in case of such paradigm changes if and only if this quality drawback incurred during the entire additional use phase is offset by a accordingly lower effort for acquisition.

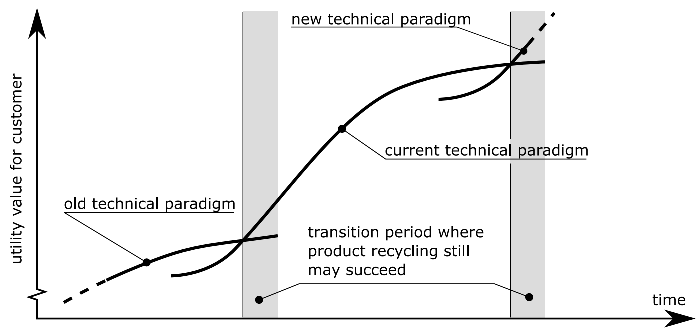

Figure (3.5): *Change of technological paradigm along time, on the basis of* STEPHAN (2009)*, p.16*

As seen before, technical progress exacerbates the implementation of product recycling. The faster successional technology emerges, the earlier the structural limits of product recycling are reached.

If the marketability of whole products ceases, reusing components and subassemblies might move in the centre of interest. This niche always exist then and only then if components of an out-dated product, which can not be marketed anymore, are used in products where the state-of-the-art meets the same technological level / paradigm of the components (common parts).[72] In this context, an alternative design approach is to use remanufactured components in the development of a new product ('design around existing components') which functionality is in line with the intended functionality of the new product and which are available in the extent needed. This way of designing avails itself of common parts within the product portfolio over time. Not only components originally designed in-house but also components of competitors may be harnessed. However, particularly the latter approach requires the clearing out of any information asymmetry in respect of parts / components of competitive manufacturer. Of course, the paradigm of structure follows function (→ customer focus) must be valid for a new product. But there are doubtlessly many ways to provide product's function demanded by the market. If in the early stage of product definition the EoL-strategy 'reusing' is already integrated (e.g. common parts with design reuse), the reconditioned component originating from older parts of the product portfolio can be regarded as kind of predefined bought-in part and either reused in the original, in a secondary product or, alternatively, also in product with common parts.[73] This approach automatically generates demand on the input side of the process 'product recycling'.

Apart from increasing acceptance of remanufactured products in already existing markets, as described above, another way of boosting marketing potential is identifying new market segments. Especially markets with a lower level of technical development are predestined for draining sales volumes of remanufactured products. Because of lower quality requirements sales might be still possible.

[72] see KAUFMANN (2002), p.268.
[73] see WU/KIMURA (2007), p.1.

A last stimulus for the implementation of both product recycling and material recycling as well is scarcity of certain primary resource needed as input flow for newly manufacturing. If availability of certain primary input factors is not given in the amount needed and substitution is no option, recycling is a remedy out of this dilemma.

The last object from the perspective of process view to be discussed is the input side of product recycling. Without the availability of products at their end of life, product recycling is doomed to fail. The existence of waste is a fundamental precondition.

Looking back in history, it becomes clear that reusing is no new idea. The phenomenon of reusing used products is as old as manhood. Careful handling with scarce resources has always been subject of economic acting. The today's fundamentally new aspect is that the argumentation originates in the ecological / environmental consequences caused by abundant economic acting. The challenge for businesses is the identification of future value creation by closing material and energy flows.[74]

Product recycling intends to close the material loops at high level. This demands that used products at their end-of-life flow back so as they can be reconditioned and remarketed as 'recycled products'. Due to its nature, EoL-products are only available with a certain time delay after newly manufacturing. This time delay, namely product's useful life, underlies several influences. Amongst others, physical wear, fatigue and fiscally allowed depreciation influence the average duration of the use phase.

Also, economic obsolescence, triggered by technical progress, can impact the timespan of satisfying customer's needs. The existence of new, more efficient products may force user, especially in the field of B2B, to replace products before reaching their physical end-of-life only because of competitive reasons. Besides cost for the new product, cost are also incurred because of required changes in organisation. Here, a typical trade-off between introducing the new product or continuation of use of inefficient technology may emerge.[75]

The number of those products flowing back automatically defines an upper limit for the number of reconditioned products. The quantity of refluent products is influenced by a set of parameters. These parameters are

- total number of products sold in the past
- customer's behaviour during use phase
- customer's behaviour at EoL
- retrodistribution / transport

This backflow of products even endures when the marketing of originally produced products ceases. The backflow continues as long as the last product, sold just before production stopped, returns.

A typical utilisation scenario according to Kaufmann describes as follows: In the centre of interest is the amount of newly manufactured products sold along time. Step by step, an inventory of originally produced products builds up in the market. After expiration of the first use phase, the formerly new products are either returned to the remanufacturing site or sold on the second-hand market.[76] Due to the stochastic character which specifies duration of product's use phase,

[74] see KAUFMANN (2002), p.125.
[75] see ibid., p.200.
[76] see ibid., p.197.

products sold at the same point in the product life cycle don't return compulsory at the same time, again. These returnings to remanufacturing site must be distinguished in products eligible for remanufacturing and products seriously damaged and, hence, not eligible for remanufacturing. The former part is subsequently reconditioned and marketed again, and increases the stock of products in second use originating from the second-hand market. Only if there are no prospects of future sales, returned or even remanufactured products must be discarded.

As depicted in Figure 2.3, there are several reasons for the retirement of a product in use. Congruent with Kaufmann are the reason 'product defect', 'replacement due to better secondary product' and 'no future need of product'.[77] Amendatory, the reason 'replacement due to changed fashion' must be added. 'Product defect' and 'replacement due to better secondary product' are conceivable starting and end points for product recycling efforts aiming to recover the entire product and to remarket it again. If fashion is the trigger impulse for retirement, remanufacturing, at least of components, is not excluded from the set of practicable operation alternatives. The exclusion from future use hits only parts and components responsible for fashion compliance. Furthermore, one aspects which comes to the fore is the fact that (only with exception of products retired because of defect) these used products have a residual functional potential. This circumstance may indicate a lower effort required for reconditioning than in comparison to reconditioning of defect products.

If product recycling is regarded as viable option, it requires, apart from technical know-how, infrastructure for those technical and logistic processes. In order to sustain profitably, the invested capital for infrastructure must be refunded. Dependent on the invested capital, this claim moves the call for high quantities in the centre of interest[78] (→ economies of scale) As already implied, the amount of refluent products is a key for success. In order to yield economies of scale to gain a competitively low cost structure, an appropriately high number of used products must flow back. This back flow is influenced by several parameters. In Figure 3.6, a comprehensive diagram listing those parameters is shown.

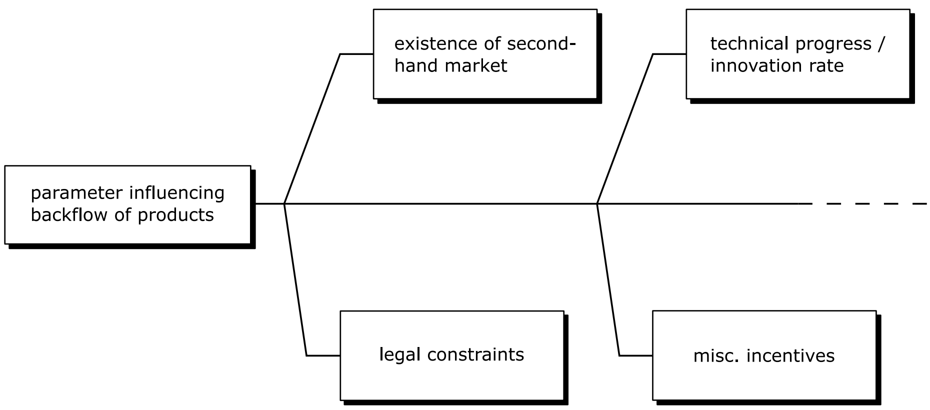

Figure (3.6): *Parameters influencing the backflow of used products*

A main player counteracting product recycling is the 'existence of second hand markets' which possible absorbs needed back flow of required EoL-products. Facilitatively, a high technical

[77] see KAUFMANN (2002), p.201.
[78] see ibid., p.181.

progress boosts backflow because of high replacement rates. An argument already addressed is legal constraints, which have impact on the backflow of used products, as well. On the micro level, there are mutual agreements like e.g. leasing contracts, on the macro level there may exist universally valid obligations like e.g extended producer responsibility which directly or indirectly force the customer to return the used product and obliges the producer to take it back.[79] Conditional upon law, up until now producers had solely had certain responsibilities in terms of e.g. safety and warranty which were mainly resident in the first phases of product life. Exceeding the use phase and extending producer's responsibility to the entire life cycle is also discussed as possible answer to the waste dilemma. Article 8 of the 2008 Directive on Waste also lists the corresponding duties. First of all, extended producer responsibility may force the producer of a product[80] to accept returned products and its waste that remains after those products have been used, as well as to accept the financial responsibility for the subsequent management of the waste and related activities. These measurements can also be amended by obliging producers to publicly provide information about product's recyclability (reusability and eligibility for material recycling). This means that transferring responsibility from, at the moment, the general public to the individual producer would cause a change in attitude towards recycling at product's end-of-life. Without extended producer responsibility the incentive scheme prefers disposal and incineration, and recycling only in case of economic advantages. Extended producer responsibility forced by law would lead to internalised cost for end of life treatment, and, hence, create on the one hand an economic incentive to decrease this 'new cost unit', and, on the other hand, would generally give recycling techniques an edge. Additionally, from the perspective of competition, producer's obligation to provide recycling related information is a very strong incentive for themselves to become involved in recycling on an individual, intra-company basis since revelation of information could possibly erase the competitive head start on the market.

A last category influencing the backflow is '*miscellaneous incentives*' where factors like e.g. existence of public waste collection system (an alternative way to get rid of a used product with seemingly the least effort) or monetary incentives (e.g. deposit, repurchase bonus,...) are summarised. A logistic structure doubtlessly required is a proper retrodistribution system which coordinates and manages the backflow of used products. For some products and product groups the establishment of such collection systems is already demanded by law (e.g. batteries and accumulators, electric and electronic cars, vehicles at their EoL), but for a big part of products it is still voluntary. Easy speaking, the acceptance of engaging in retrodistribution activities among customers depends on the extent of incentives to return and the set of alternative options for disposal.[81]

Summarisingly, in the preceding disquisition, the tension between innovations and product recycling became tangible since innovations are precondition and constraint of product recycling at the same time.[82] The structural frame for successfull product recycling is formed by the time between two innovations with significant increase in performance and / or changed technical paradigm. Within this frame, value generation flourishes if the alternative production process *product recycling* is organised as effectively and efficiently as newly manufacturing comparable products.[83] Furthermore, the probability for product recycling to succeed increases if product

[79] see EUROPEAN PARLIAMENT AND EUROPEAN COUNCIL (2008b), Art. 8, or KAUFMANN (2002), p.157

[80] According to Directive 2008/98/EC, Art. 8, a producer of a product is any natural or legal person who professionally develops, manufactures, processes, treats, sells or imports products.

[81] see ibid., p.214.

[82] see ibid., p.260.

[83] see ibid., p.281.

recycling is supported by the manufacturer of the original product. In this case, it is not necessary to newly gain and build up product and process know-how from scratch. However, the key finding is: The lower innovation dynamics in a special sector and the lower the ratio of product life and time between significant innovations, the higher the probability of successfully realising systematical product recycling.[84]

Besides quantities flowing back for product recycling, the economic (as well as ecological) efficiency is massively influenced by the effort required for implementing the product recycling processes. On the one hand, there is the main field of logistic challenges and, on the other hand, there are technical questions to answer. If a company commits itself to the alternative production process '*product recycling*', this aspect must be considered particularly in design stage.

For the sake of completeness, Kaufmann points to the following: If a product is damaged that seriously that more than 50 % of its parts can't get reused and thus have to be replaced by newly manufactured parts and components, this recycling process can hardly be called product recycling. On the contrary, if products are remanufactured following the principle 'two into one', this process definitely may be called product recycling. However, it has to be noted that the average effort for disassembling, cleaning and testing increases per output unit. It follows that economic efficiency is the higher, the less altered a refluent product is.[85] Kaufmann omits to explicitly point to the fact that product recycling without use of certain newly manufactured products is impossible. Provision of product function is always accompanied by wear, fatigue and other phenomenons resulting in a decreased future functional potential.

Economic efficiency has regularly appeared in the above argumentation. Besides logistic processes, a main contributor to efficiency are on-site processes for product recycling which are mainly determined by the design, the arrangement of parts and components and type of connections. Those parameters influence whether product recycling can be implemented as efficient industrial process and how much effort must be invested therefore. In consequence, products which already anticipate product recycling as an end-of-life-option and which are designed for reuse will probably succeed in implementing product recycling.[86] Technical arguments, which also represent a pivotal aspect of product recycling haven't been addressed in the recent chapter. Those will be mentioned in later chapters.

As comprehensively seen before, managing product recycling calls for anticipating future application and estimating time between innovations with significant increase in performance, and hence, identification of future economic opportunities. If all these challenges are successfully addressed, then product recycling is just a production alternative as viable and efficient as newly manufacturing. If not legally imposed, recycling is always an economically determined decision. The driving force behind implementation of recycling activities in the economic system is always the expectation of future benefits.[87]

In the next chapter we will turn towards the technical transformation stage involved in product recycling.

[84] see KAUFMANN (2002), p.261.
[85] see ibid., p.279.
[86] see ibid., p.280.
[87] see ibid., p.170.

3.2 Key steps for successfull product recycling

In order to turn to the rather technical part of this thesis again, in the next chapter the technical key steps required for successfull product recycling are briefly described. The main aim of remanufacturing is reclaiming product's full functional potential as pictured in Figure 2.8.

STEINHILPER (1988) introduces and defines 5 key steps for successfull product recycling, which are:[88]

- disassembling
- cleaning
- testing
- reconditioning
- and reassembling

Those key steps are (almost) self-explaining. However, one fundamental working step is still missing – namely, collecting (aka retrodistribution). All these processes categorised just above can't be applied if there are no products to be remanufactured at hand. Hence, collecting is as important as the other key steps and deserves to be called in the same breath. The position of *product recycling* within the framework of life cycle thinking is displayed in Figure 3.7.

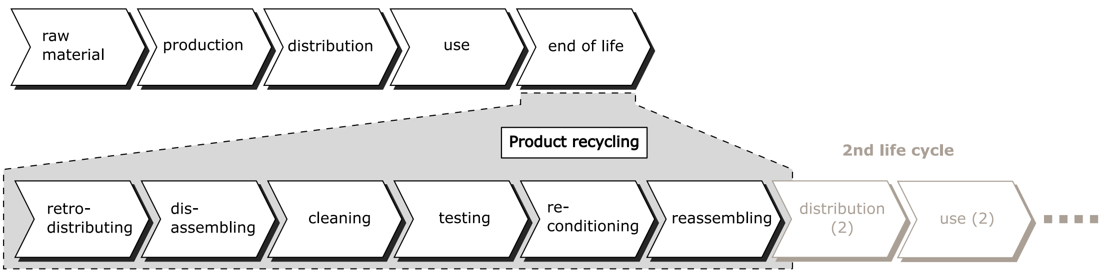

Figure (3.7): *Position of product recycling in the frame of Life cycle thinking, on the basis of* WIMMER/ZÜST (2001)*, p.21*

The sequence of these process steps is performed independently of the state of the used products. This means that the processes which each used products' parts has to run through are standardised, irrespective of parts' extent of damage. Subsequently, a compact explanation follows.

3.2.1 Retrodistributing

As already underlined above, successful remanufacturing can only start if the used parts to be remanufactured are available on-site. In one of the previous paragraphs used products (=waste, in the general linguistic usage) were identified as precondition for product recycling. Thus, the task of *retrodistributing* summarises all action responsible for bringing back used products from the customer to the gate of the remanufacturing site. This includes activities like e.g. transfer of property, picking up and transporting.

[88] see STEINHILPER (1998), pp.42.

In comparison to economy's historic evolution, this claim is an absolute novelty. Usually, efforts have been invested in order to identify and develop new distribution channels to enhance allocation and, in consequence, to boost sales. The other way round, to collect goods at the customer's place and transport them back to site, has not been in the middle of interest. Today, miscellaneous collecting systems, differing in their extent of institutionalisation, already exist like e.g. for end-of-life vehicles, single use cameras and used house hold appliances ('white and brown goods'). For products covered by Directive 2000/53/EC (EoL- vehicles) or Directive 2002/96/EC (WEEE) distinct collection points are established, asked for by law. For the latter product group each producer can decide on individual basis whether he organises the taking back on his own or (economically) contributes in the collective system.[89]

Besides the collective setting for e.g. WEEE, there is also the possibility to individually organise retrodistribution. For the organisation of these retrodistribution systems, which basically depend on the retrodistribution strategy chosen, generally, two basic settings are conceivable. The first one incorporates transport directly from the customer or, at least, from distinct points in his proximity back to the remanufacturing plant. For instance, 'deposit bottles', a best-practise example for reusing with distinct consumer take over points in food retailing, or 'toner cartridges', making use of incumbent post service provider (with take over point in either the local post office or even the own flat / office when a parcel service is engaged) are directly rerouted to the (re-)manufacturing plant where all process steps required for product recycling are performed. Alternatively, the remanufacturing steps can also be spatially split. This means that used products are collected and disassembled locally, and only those parts and components eligible for further remanufacturing are transported to the main plant. The second alternative distinguishes itself by lower transport effort but higher requirements regarding quantities of refluent products (→ economies of scale). Therefore, the retrodistribution strategy must carefully be chosen so as the overall optimum is yielded.

3.2.2 Disassembling

Regardless of the chosen retrodistribution strategy, the used and retrieved product needs to get dismantled so as it is properly prepared for further treatment.

First of all, the process of disassembling is defined as the separation of parts along their intended junction interface[90] which was defined in the design stage and realised in the production stage. Since sustaining the shape of parts is indispensably important for remanufacturing, such techniques as shredding and subsequent automatically sorting according e.g. material's density or other specifications is no option at all. If anything, disassembling must follow more or less the reverse way of assembling. Regarding the efficiency argumentation, it would be desirable that disassembling activities are as automatable as assembling processes. The hypothesis that each disassembling workflow is automatable when the according assembling workflow is automatable is refuted immediately. The assumption of reversing the workflow is only valid for the sequence of tasks, but not for the techniques applied.[91]

In general, joining technology distinguishes two main groups of connections. They are:

[89] see EUROPEAN PARLIAMENT AND EUROPEAN COUNCIL (2000), Art.5 and EUROPEAN PARLIAMENT AND EUROPEAN COUNCIL (2003b), Art.5 (2c)
[90] see STEINHILPER (1988), p.69.
[91] see ibid., p.70.

- non-detachable connections
- detachable connections

It is obvious that, for example, welding is an automatable joining technique. But, in contrast, the same technical appliance is not eligible to disconnect the assembled parts. Furthermore, the working conditions, which are dependent on the extent of product's soiling, contamination by toxics and superficial corrosion, are crucial for disassembling.

This disassembling process has to be accomplished until the entire assembly is separated to the very single part level if this is possible in a non-destructive manner.[92] However, Steinhilper's claim bases on the assumption that all parts which are able to be disassembled without destroying the part itself are relevant for future reusing. Regrettably, he denies the trade-off between future benefit and effort to be invested. In certain cases, it may be clearly obvious that a certain part is e.g. not eligible for reconditioning in particular, and, hence, for remanufacturing in general because of efficiency concerns although it may be possible to non-destructively disassemble it. In consequence, only those parts are allowed of getting disassembled which promise a future benefit.

The rest, which nolens volens also must get processed, is treated in the next best way – as defined in the VDI recycling cascade (see Figure 2.9) – which is material recycling. In case of residual subassemblies, a further disassembling may be necessary if the materials of parts, which constitute these subassemblies, are not compatible for a common material recycling process. Then, an additional effort for disassembling occurs in order to either enable in general or optimise the output of the material recycling processes.

3.2.3 Cleaning

Usually, cleaning is the successional process step of disassembling. Only those parts which are identified as utterly unusable already during the disassembling stage are not intended for cleaning and separated for material recycling. Cleaning is a fundamental precondition for proper and exact testing and can consist of a multi-stage process. If certain parts are e.g. not worn out (i.e. no loss of functional potential) and only polluted and draggled, cleaning itself can represent all processes necessary and, besides reassembling and final testing, finish the process chain of remanufacturing. According to type and extent of soiling, there are several ways of cleaning[93]:

- dipping (in acid or alkaline bath)
- washing (e.g. with hotwater, cold cleaning solvent, petroleum aether, etc.)
- blasting (e.g. sand -, steel shot -, water jet-, dry ice blasting, etc.)
- ultra-sonic cleaning

The techniques used for cleaning in the field of remanufacturing equals to techniques and machines used in newly manufacturing. The choice of the proper cleaning technique must be in compliance with the material and surface characteristics of the parts to be cleaned. Too aggressive cleaning can cause the destruction of reusability.[94]

[92] see STEINHILPER (1988), p.48.
[93] see ibid., p.50.
[94] see ibid., p.51.

Basically, there are four parameters influencing the result of a cleaning process:[95]

- Chemical effect (e.g. due to detergents)
- Temperature influence (e.g. heat)
- Mechanical action (e.g. brushing water jet or abrasive auxiliary agents)
- Time (e.g. duration of cleaning process)

Out of the set of cleaning technologies, the ideal processes has to be chosen for each part to be remanufactured so as the proper result is yielded at as least as possible effort.

Steinhilper also pin-points that some cleaning methods like e.g. blasting contribute to increased quality of remanufactured products since the abrasive mechanism of action causes a harding of the material in proximity to the surface (strain hardening) which, in turn, results in an increased resistance against future external stress.[96]

3.2.4 Testing and sorting

The testing of cleaned parts aims for assessing the state of parts to be remanufactured and classifying them. Basically, the output categories of the testing and sorting process are:[97]

- parts not reusable / not reconditionable
- parts reusable after reconditioning
- parts directly reusable

The distinction in these categories is heavily dependent on the existence of clear specifications and objective testing criteria in order to assess the current state of the part as well as on the existence of non-destructive, 100 % check testing techniques. This claim restricts the set of testing techniques available to mainly optical testing, testing of electrical and / or geometric criteria[98] as well as techniques which test the ability of taking mechanic static/dynamic loads. Stressing parts by loads which surely occur during the upcoming use phase enhanced by an excess charge allow drawing inferences about the residual functional potential.

Those rather technical testing and sorting criteria must be extended so as also legislative concerns are taken into account. As figured out in chapter 3.1, legislative regulations can shift the status of an actually technically reusable part / subassembly to 'not reusable', if e.g. maximum allowed energy consumption or maximum containment of hazardous substances is not adhered to. Hence, the process 'testing and sorting' must also guarantee the abidance of these criteria. Therefore, appropriate tools must be at hand. For instance, this proof can be furnished either directly, via testing methods (e.g. test for chemical composition, test run evaluating energy consumption under defined conditions,...), or indirectly, via credible information about newly manufacturing. Nevertheless, non-destructible testing must be possible, as well.

[95] see Steinhilper (1998), p.48.
[96] see ibid., p.49.
[97] see Steinhilper (1988), p.51 and see Steinhilper (1998), p.52
[98] see Steinhilper (1988), p.52.

The automation of testing processes is a key for future success of product recycling. According to Steinhilper, the current testing techniques are characterised by a higher-than-average share of manual work[99] which is a severe cost factor to be reduced.

3.2.5 Reconditioning

The main task of reconditioning is the recovering of the initial functionality or regaining parts' functional potential so as an as new state is guaranteed. Under the term of '*reconditioning*' Steinhilper also summarises the case where no reconditional treatment is needed, meaning that the state and the original specifications of the newly manufactured products have not changed (see page 47, subsection *Cleaning*).

Usually, reconditioning includes machining processes like turning, milling, drilling and grinding as well as surface treatment like coating, painting and electroplating.[100] The organisation of these working tasks is similar to the processes applied in newly manufacturing.

Most times, when high quality in respect to surface appearance is demanded or when machining reserves for remanufacturing are lacking, the eligibility for reconditioning is harmed.[101] Due to the nature of machining processes and their inherent reduction of geometrical volume, parts which undergo machining remanufacturing steps have slightly changed outer dimensions. This means that e.g. due to turning the diameter of a shaft is diminished, due to milling or grinding certain distances are changed. If this alteration is within part's tolerances, the remanufacturing process do not influence product's function. Otherwise, if this alteration exceeds the tolerances, efforts must be undertaken in order to compensate this modification. For example, an answer to a shaft with decreased diameter is e.g. a bearing with slightly altered dimensions. Furthermore, the combination of remanufactured parts and additional parts which are enclosed and, hence, compensate possibly missing material may ensure the same functionality as the newly manufactured (sub-)assembly/product. But, especially in those cases where these parts underly stresses, a thorough recalculation of load-carrying capacity must provide evidence.

3.2.6 Reassembling

Dependent on the type of product recycling applied (remanufacturing of the whole product vs. remanufacturing of only certain components for utilisation in a daughter product), the last step to perform is '*reassembling*'.

This last step of remanufacturing accomplishes the reassembling of the reconditioned parts in conjunction with newly manufactured parts which replace parts not eligible for reconditioning so as a product coequal to a newly manufactured one is regained. Parts assembled in the returned product are not necessarily reassembled in the same product again but can be mixed with reconditioned parts of other retrodistributed products. This loss of product identity is characteristic for product recycling because it does not bother whether the same, in the first use phase the product constituting parts are reassembled since reconditioned parts are qualitatively equal.

[99] see Steinhilper (1988), p.52.
[100] see ibid., p.53.
[101] see ibid., p.54.

The plants and machines required for reassembling are similar to those used in the new product line. The only difference, according to Steinhilper, lies in the lower level of automation.[102]

Usually, remanufactured products run through a final testing stage which is part of the reassembling. This 100 % check is done to definitely ensure high quality and to perfectly prevent decreased functionality in comparison to newly manufactured products.[103]

Industrial remanufacturing aims for significantly lower costs in comparison to single repair action of products. Because of high labour cost, repairing is only in a negligibly small fraction of cases economically feasible anymore. Industrial remanufacturing tries to combine both the improvements in productivity and the environmental advantages of repairing by means of advancement in technology, organisation, logistics and design.[104]

3.3 Insight gained

As it became obvious, remanufactured products are in direct competitions to newly manufactured ones since they satisfy the same customers' needs. Hence, in respect to implementing product recycling in the business environment, the relative advantage is decisive. Thereof, the condition to be met by product recycling, which is the anthropogenic creation of closed loops of material and energy flows, is a higher benefit than effort to be invested. In other words, the business process 'product recycling' must be efficient and the cost must be covered by prices gained on the market. By trend, this demanded efficiency is higher if the EoL-option 'reusing' is already considered in the design stage.

An inevitable precondition for product recycling is the existence of waste / used products and its corresponding backflow, which is, inter alia, triggered by technical progress. In turn, technical progress and innovation dynamics, respectively, cause hampered chances for marketing of remanufactured products because customers face better options in form of newer products with a higher perceived utility value. Only if this disadvantage can be offset or new markets are developed, the marketability of products intended for reuse might be prolonged. It is clearly recognisable that innovations are, metaphorically speaking, blessing and cursing of product recycling at the same time.

Thus, the challenge for companies is to identify future use options, to out-weigh possible drawbacks in comparison to daughter products, to ensure the possibility for adapting product design and to build up a lean business structure so as the necessary processes of retrodistributing, disassembling, cleaning, testing & sorting and reconditioning can be performed as efficiently as possible.

[102] see STEINHILPER (1988), p.55.
[103] see STEINHILPER (1998), p.57.
[104] see STEINHILPER (1988), p.56.

4 Available methods for assessing product's reusability

The current chapter introduces methods out of the more or less broad spectrum of methods intended for the assessment of product's reusability. The selection of this very tools bases on considerations regarding the structure and the way of proceeding, which had the most influence on the following, own method to be developed.

4.1 Assessment methodology according to Steinhilper

One of the first researchers who has dealt with the topic of *reusing* is Rolf Steinhilper. In his 1987 doctoral thesis, he thoroughly analysed the topic, comprehensively discussed it and finally introduced an outlook how an 'assessment method' for product recycling could look like. His paper is mentioned for the sake of completeness and because of its fundamental nature for then succeeding research.

In the first chapters, he defines product recycling as the combination of two different recycling processes, namely on the one hand recycling in order to recover the entire part and recycling in order to recover the material stored in the used and discarded product.[105]

After an systematic study of different products like e.g. several combustion engines, power tools and household appliances, Steinhilper derives and identifies major fields of improvement where joint effort should be focused on. The main topics are

- improvements in the disassembling process
- improvements in design and
- improvements in the organisational structure and logistics of remanufacturing companies.

In order to improve the organisation of the disassembling processes, he emphasises the automatisation of dismounting processes as source of workflow rationalisation and productivity improvements so as an economically high incentive *pro* remanufacturing is yielded.[106]

Improvement in design is an important issues, as well. Roughly speaking, the design of classical products, which are not intended for reusing, focuses, apart from low production costs in general, mainly on easy processability and high eligibility for assembling. In turn, design for remanufacturing requires more diversified attention and incorporates design for disassembling, design for cleaning, design for testing and sorting, and design for reconditioning as well as the classical parameters like high eligibility for assembling and easy processability.[107]

[105] see STEINHILPER (1988), p.39.
[106] see ibid., pp.69.
[107] see ibid.

The last field is improvement in the organisational structure and logistics.[108] A massively contributing cost factor to total costs in remanufacturing – as Steinhilper identified in his research – is cost for substituting not reconditionable and, hence, not reusable parts by new ones. To diminish costs for newly manufactured parts, Steinhilper suggests two approaches to go:

- development of new reconditioning techniques in order to increase the share of reconditioned parts
- increasing the number of reusable parts by increasing the number of products to be disassembled (equal to increase the ratio of parts to be disassembled to parts to be remanufactured)

In the 'assessment' method introduced by Steinhilper, the centre of interest is focused on cost-oriented optimisation of mass flows where he intends to integrate the above findings for improving product's reusability. Under the tacit assumption that apparently all products are enabled for product recycling, he 'only' provides a computer-aided program which strives for calculating the cost optimum in remanufacturing of a certain product. Of course, in his thesis he also derives rules facilitating remanufacturing but he doesn't connect both areas so as the user of his method comes to the final decision about 'remanufacturing as an economically and environmentally reasonable activity'.

In comparison to newly manufacturing, Steinhilper identifies two key elements which distinguish remanufacturing from common production systems[109]. These are

- branching and reconsolidating of part flows (mass flows) and
- different cost and quantity structure of each single part because of its varying share of parts directly reusable, reusable after reconditioning and not reusable at all

In contrast to newly manufacturing where all (value creating) mass flows head towards the ultimative point of product assembly, the mass flows in remanufacturing first splits up due to the key process step '*disassembling*' and then consolidate again, as in newly manufacturing, in the last step of '*reassembling*'. The stochastic character of the use phase also exacerbates the predictability of mass flows of parts to be remanufactured and influences the effort to be invested in the stage '*cleaning*' and '*reconditioning*'. As already explained above, parts of dismantled products distinguishes in *parts not reusable, parts reusable after reconditioning* and *parts directly reusable*. The relative share of these three categories differs across all parts of the entire product. These hardly predictable quantities and the corresponding costs are closely linked to the categories of part's state and are responsible for the final cost structure.

Figure 4.1 demonstrates Steinhilper's model and pictures these different mass flows. In the upper part of the figure, one can see the input side of the model which is only constituted by the number of refluent products (N_{in}). The product to be remanufactured consists of $s+n$ different parts whereas during disassembling this input flow is split in parts to be further treated (n) and parts which basically are not eligible for product recycling (s) like e.g. sealings and misc. small parts. Usually, these parts should be designed in accordance with common material recycling techniques so as the least costs for treatment are incurred and the intrinsic material is still serving a useful purpose. Already in this first stage, parts are presorted in homogeneous material flows (only joint collecting of equal parts). After cleaning, all parts are tested and sorted, and classified in

[108] see Steinhilper (1988), p.65.
[109] see ibid., p.97.

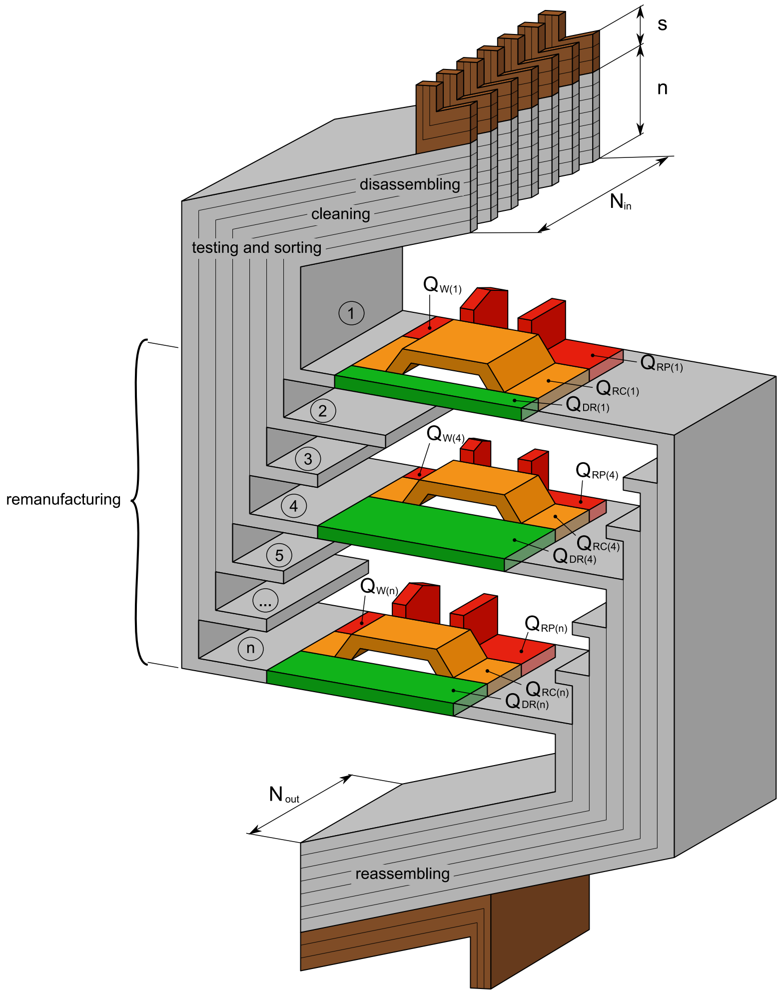

Figure (4.1): *Material flows during product recycling, adapted from* STEINHILPER (1988)*, p.99*

parts directly reusable ($Q_{DR(k)}$), parts reusable after treatment ($Q_{RC(k)}$) and parts not reusable anymore ($Q_{W(k)}$) which have to be replaced ($Q_{RP(k)}$). $Q_{..(k)}$ is the corresponding share in percent of N_{in}. After restoring part's functional potential (=reconditioning), all parts are reassembled again so as N_{out} remanufactured products are available at the output side of the entire remanufacturing process. As a matter of fact, newly manufactured parts of those segregated before in the disassembling step are remounted again.

The core of Steinhilper's approach is the cost argument and its optimisation. Under the assumption that as many products as enter the remanufacturing site are output as well ($N_{in} = N_{out}$), a given number of products to be remanufactured on the input side causes a certain cost structure. This means that the resulting total cost summarises the cost for disassembling, the cost for cleaning as well as testing and sorting, the cost for reconditioning and cost for newly manufactured parts. In each category, there are both fixed and variable costs. Knowing demand for remanufactured products, one can easily derive demand for each relevant part k. Steinhilper argues that if the number of products on the input side would increase but, ceteris paribus, the number of products at the output side stays the same (and in consequence the total number of part k required for remanufacturing N_{out} products), the average cost will change because companies can choose from an absolute bigger number of relevant parts k. He introduces the ratio

$$R_{DA} = \frac{N_{in}}{N_{out}} = \frac{N_{out} + Z_j}{N_{out}}$$

where Z_j is an extra amount of products to be disassembled. By increasing the absolute number of Z_j, also the absolute number of parts directly reusable ($n_{DR(k)} = Q_{DR(k)} \cdot N_{in}$), the absolute number of parts to be reconditioned ($n_{RC(k)} = Q_{RC(k)} \cdot N_{in}$) and the absolute number of parts not reusable anymore ($n_{W(k)} = Q_{W(k)} \cdot N_{in}$) alters. Since, according to Steinhilper, newly manufactured parts contributes most to total cost, they are substituted first. At a certain level of R_{DA} ($\rightarrow Z_j = Z_1$), the sum of parts directly reusable and parts to be reconditioned $n_{DR(k)} + n_{RC(k)}$ equals the number of parts k ($n_{out(k)}$) required for remanufacturing N_{out} products. So, no newly manufactured parts k are needed anymore. This means that both the corresponding variable costs and fixed costs are saved.

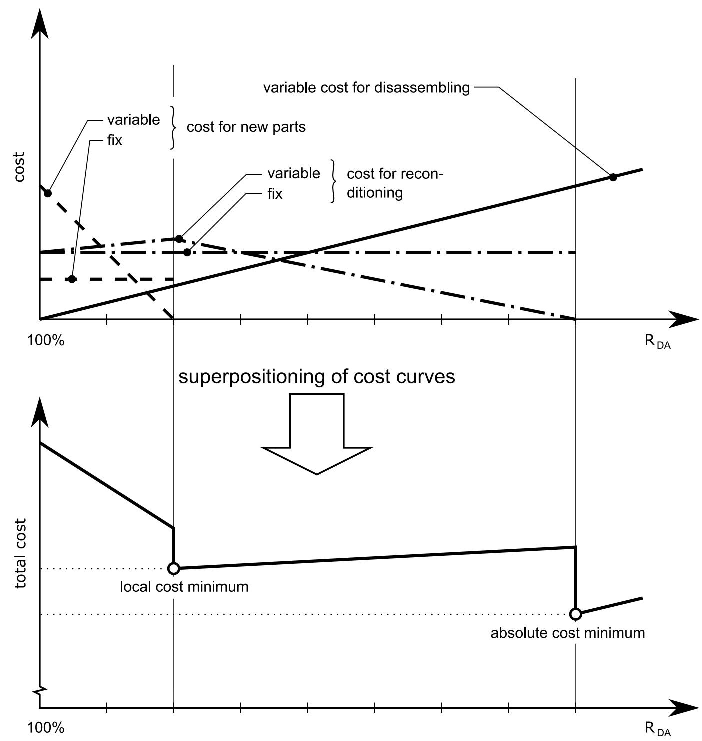

Figure (4.2): *Cost curve for a single relevant part k in dependence of R_{DA}, adapted from* STEINHILPER (1988)*, p.104*

If the ration R_{DA} is further increased, the ultimate point is reached where $Z_j = Z_2$ and the demand for parts k ($n_{out(k)}$) required for remanufacturing N_{out} products is satisfied only by parts directly reusable $n_{DR(k)}$. At this point, neither newly manufactured parts nor reconditioned parts are needed – consequently, also both fixed and variable costs for newly manufactured parts and reconditioning are avoided. Only increased effort for disassembling (as well as for cleaning and testing & sorting) is necessitated. Exemplarily, the according curve of total cost $C_{total(k)}$ along R_{DA} is shown in Figure 4.2 for a relevant part k.

Unfortunately, these optimal numbers for Z_1 and Z_2 differ throughout the set of relevant parts. The challenge in minimising the overall sum of part's total cost

$$C_{TOTAL} = \sum_{k=1}^{i} C_{total(k)}$$

is finding a $R_{DA\ opt}$ where the condition of a global cost minimum is met. For more-in-depth information about Steinhilper's cost model see STEINHILPER (1988), pp.113.

The cost curve in Figure 4.2 is the general case. However, there might also be the case where a certain part k has no parts directly reusable for reassembling or isn't capable for being reconditioned (as it is the case for those parts segregated in the disassembling stage).

A structural disadvantage of Steinhilper's model, besides neglecting of single cost contributors like e.g. cost for storage which is an increasingly important issue especially in respect to the method's underlying aim of finding an optimal additional input so as total cost for remanufacturing is lowered, is the static behaviour of the model, the approach of cost calculation and the focus on only the economic dimension in the big topic of *recycling*. Of course, focus on the economic dimension is important and necessary. But limiting the assessment of reusability on only economic aspect falls short of other pivotal decision influencing parameters. However, as an introductive model it provides valueable insights. Especially the clear structuring of remanufacturing processes involved as well as the mentioned fields of improvement for disassembling, product design and organisational structure will be used as starting point for the assessment to be later developed.

4.2 Assessment methodology according to Hartel

In contrast to Steinhilper's cost and logistic dominated method, Hartel focuses on a rather technical approach. The main goal of Hartel's method is already providing an objective assessment result in product's design stage. By means of characteristic numbers, he intends to evaluate product's eligibility for disassembling and to optimise possible future recycling processes.

The core of Hartel's assessment approach is a dual model with a quantitative and qualitative part. Both parts evaluate the disassembling-related and the recycling-related eligibility.[110] Unlike the quantitative part, the qualitative one isn't exposed to uncertainties over time. This means that qualitative characteristic numbers are calculated on basis of primarily fixed specifications derived from design criteria. In opposite, quantitative assessment is, according to Hartel, simply the estimation of future cost and future revenues of parts to be recycled. Subsequently, a brief description of Hartel's method follows.

The qualitative assessment is done in the so called 'ECO-portfolio' which consists of two distinct dimensions. The first one is named 'design-related strength' (KS) where subjects like e.g. product structure, type of connections and combination of materials influence the final result.

[110] see HARTEL (1997), p.38.

The categories in which Hartel assesses a product to be recycled, and their characteristic values, respectively, are

- characteristic value reflecting product's disassemblability (η_D)
- characteristic value reflecting complexity of product structure (η_K)
- characteristic value reflecting product's jointing structure (η_V)
- characteristic value reflecting product's material diversity (η_M)
- characteristic value reflecting product's (material) recyclability (η_R)

For each category, Hartel defines a way how to compute the final characteristic value. By means of individually allocated weights, the design-related strength KS is computed.

$$KS = f(\eta_D, \eta_K, \eta_V, \eta_M, \eta_R)$$

In addition, it is important to note that all these characteristic values can be influenced by design decisions.

The second dimension of Hartel's ECO-portfolio is the 'environmental strength' (US) which bases on kind of adopted life cycle assessment. The main contributors to environmental strength are

- ECO-points ($Oekopunkte$)
- resource correction factor (RKF_x) and
- product's useful life (ND).

The so called ECO-points, basing on a method for assessing product's environmental impact developed by Ahbe (1995), are extended by the resource correction factor. This factor takes the depletion of fossil resources into account and is only calculated for not-renewable materials. The last factor is product's useful life which is intended to standardise the environmental impact. Out of it, environmental strength (US) is

$$US = f(Oekopunkte,\ RKF_x,\ ND)$$

Now, both values, environmental strength and design-related strength, are compared against each other in the ECO-portfolio (see Figure 4.3; by definition both values range between $0 \ldots 1$). The more distant the data point to the origin of the portfolio, the better product's design.

In the quantitative part, Hartel tries to estimate cost and revenue of future recycling activities. Apparently in Hartel's opinion, cost for disassembling is a main driver for total cost; hence, he devotes a big part of his thesis to this topic. On basis of disassembling work instructions, in combination with data bases / tables listing time consumed for particular disassembling moves / actions, he calculates total time required for disassembling. Multiplied with a cost factor, the result is cost for disassembling.

He proceeds with providing the general equation for profit or loss where he details the influencing variables. Revenues for recovered materials and revenues for recovered parts intended for reuse [111] contribute positively. From the sum of those two variables, cost for material treatment

[111] Obviously, Hartel means either revenues for used parts on the second-hand market or revenues gained from selling parts to a reconditioning company; if product recycling (in the sense of reconditioning) would be meant, all corresponding cost (for e.g. cleaning, testing & sorting, reconditioning) would be missing in Hartel's approach

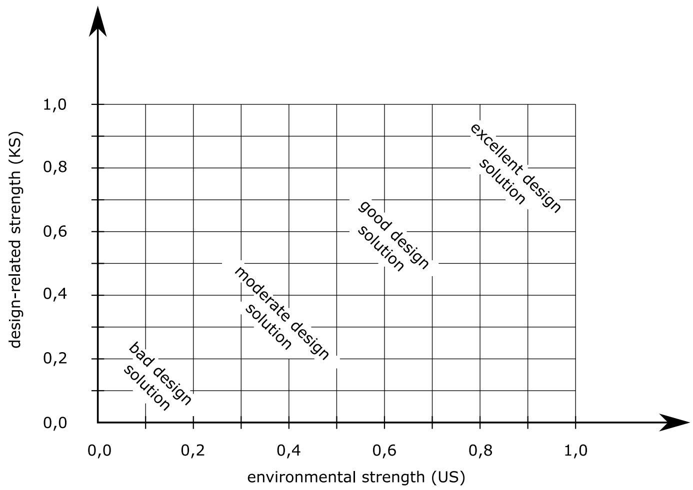

Figure (4.3): *Hartel's ECO-portfolio, adapted from* HARTEL (1997)*, p.69*

(detaching, separating and material recycling), cost for disposing and cost for logistics are subtracted.[112] Finally, he subducts cost for disassembling in a separate equation. The result reflects the eventual performance of recycling a particular product and is, at the same time, the starting point for optimising the final result. Hartel points to the direct trade-off between disassembling cost and revenues for recovered materials / recovered parts (and their connected costs for detaching, separating and material recycling). Hence, he introduces a series of optimisation approaches which are intended to find the optimal sequence of disassembling tasks.

Summarising the findings it must be stated that Hartel, although he repeatedly points to uncertainties in respect to market prices achievable for material and parts recovered is a big issue, does not provide approaches to tackle this problem. The low predictability of revenues, especially if long-term estimations are considered, proves prices as not predestinated economic measure. Incorporating the principle of opportunity cost would be way more purposeful. Hartel's approach to depict different assessment categories in portfolios is worthy of imitation, be it in a graphical way or solely in theoretical coordinate system. Hartel's insight that range of resource provision, expressed in this method by the resource correction factor (RKF_x), has influence on the assessment result, will definitely find entrance in the assessment method to be developed. However, the structural drawback of assessing the same attributes in the qualitative and quantitative dimension (i.e. assessment of disassemblability via disassembling cost and via characteristic number η_D) will be avoided.

4.3 Assessment methodology 'ENDLESS'

A more recent assessment methodology, introduced by ARDENTE/BECCALI/MAURIZIO (2003), is a method called 'ENDLESS' (End Design Leading Sustainable Selection). This tool aims to support the designer in the choice of a product with a higher recyclability potential from a set of different

[112]see HARTEL (1997), p.86.

alternatives, to find solutions which minimise the environmental impacts (and costs) of products and facilitate the recycling after product's end-of-life.[113]

The underlying model used incorporates economic, technological, and energy and environmental parameters, and synthesises the single attributes in an indicator, called 'Global Recycling Index (GRI)'. This GRI is calculated by weighing and merging the three disjunct parameters mentioned before (see Figure 4.4).

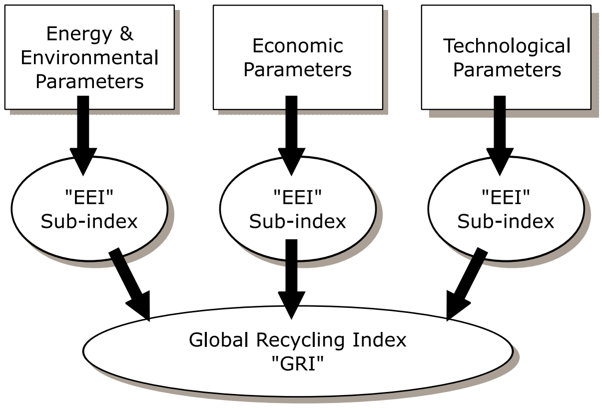

Figure (4.4): *Structure of method 'ENDLESS', according to* ARDENTE/BECCALI/MAURIZIO (2003)*, p.103*

The sub-indexes, according to the previously mentioned parameters, contributing to 'Global Recycling Index' (GRI)[114] are the

- Energy and Environmental sub-Index (EEI),
- Economic sub-Index (ESI) and
- Technological sub-Index (TSI).

These sub-indexes base on an additive multiattribute utility value analysis and are calculated for a particular functional object k (FO_k) as follows (using suffix 1 to indicate energy and environmental parameters (and their corresponding weights), suffix 2 for economic parameters and suffix 3 for technological parameters):

$$EEI(FO_k) = \sum_i w_{i,1} \cdot VF_{i,1}(p_{i,1})$$
$$ESI(FO_k) = \sum_i w_{i,2} \cdot VF_{i,2}(p_{i,2})$$
$$TSI(FO_k) = \sum_i w_{i,3} \cdot VF_{i,3}(p_{i,3})$$

$EEI(FO_k)$ ... Energy and Environmental sub-Index
$ESI(FO_k)$ ... Economic sub-Index
$TSI(FO_k)$ ... Technological sub-Index

[113] see ARDENTE/BECCALI/MAURIZIO (2003), pp.101.
[114] see ARDENTE/BECCALI/MAURIZIO (2003), pp.106.

$w_{i,1}, w_{i,2}, w_{i,3}$	...	weights related to energy and environmental parameter, economic parameter and technological parameter, respectively
$VF_{i,1}(p_{i,1})$	...	value function of energy and environmental parameter i
$VF_{i,2}(p_{i,2})$	...	value function of economic parameter i
$VF_{i,3}(p_{i,3})$	...	value function of technological parameter i

The 'Global Recycling Index' GRI, the result which the method is striving for, allows a ranking of alternatives to be assessed, and calculates as follows:

$$GRI(FO_k) = w_{EN} \cdot EEI(FO_k) + w_{EC} \cdot ESI(FO_k) + w_T \cdot TSI(FO_k)$$

$EEI(FO_k)$	...	Energy and Environmental sub-Index
$ESI(FO_k)$	...	Economic sub-Index
$TSI(FO_k)$	...	Technological sub-Index
w_{EN}	...	weights related to energy and environmental sub-index $EEI(FO_k$
w_{EC},	...	weights related to economic sub-index $ESI(FO_k$
w_T	...	weights related to technological sub-index $TSI(FO_k$

This approach provides insight insofar as multiattributive utility value analyses are powerfull tools for reducing a high number of different parameters to single expressive number which is used for decision support, and so diminish the complexity of decision making. However, this method is predestined for evaluating relative differences of alternatives. Hence, for the purpose of developing a method for the assessment of part's reusability, this approach will be not convenient since the method's final outcome has to help finding an answer whether product recycling is an efficient production alternative. But, to some extent, it will find entrance for synthesising qualitative parameters.

4.4 Insight gained

As starting point, the method according to Steinhilper provides useful insight in how to structure the proceeding in evaluating product's reusability. However, one of its main shortcomings is its sole focus on economic efficiency. The monetary assessment-only and omitting evaluation in the ecological dimension perfectly misses one of the tacit main intentions of product recycling, namely the mitigation of resource depletion and increase of resource productivity, respectively. Without analysing the environmental impact caused by implementing product recycling processes, no definitive statement about the compliance with those aims can be made.

Hartel's rather technical and very detailed approach focuses mainly on design and material criteria. Although he incorporates the environmental dimension by ECO-points and resource correction factor, both standardised by product's useful life, his method analyses the phenomenon 'product recycling' only from a production-oriented perspective. Strategic-operational issues are not taken into account at all. In a holistic approaching those concerns must not be missing.

The last method introduced in the chapter deals with multi-attribute utility value analysis, intended to reduce complexity of decision making. The use of this method will help to not only incorporate the economic and environmental dimensions (quantitative assessment) but also take into account strategical issues (qualitative assessment) and enhance, by doing so, the quality of the final assessment result.

Certainly, there are several methods more dealing with evaluating product design's EoL options. This chapter does not claim of being complete in terms of introducing methods available, but it sufficiently depicts which parameters influence the reusability of parts and how and in which way these parameters can be used for finding a final assessment result.

5 Assessment method for evaluating part's reusability

Inspired by literature quoted in the previous chapters and the quoted assessment methods developed by Steinhilper and Hartel as well as management tools applied in other fields of science, the subsequent approach for assessing part's reusability or, in other words, for assessing its eligibility for product recycling is found. The main intention of the present method is to accommodate the needs which a company is facing in the today's multipolar world and to provide a well-grounded basis for the strategic decision *pro* or *contra* product recycling. In both the design stage of a product and at the end-of-life, the application of the present methodology is possible. It also provides hints to identify weak points and demonstrates suggestions for improvement.

5.1 Structure of the developed method

Cooper's Stage-Gate-model, a systematic approach to comprehensively organise the innovation process for product development,[115] is inspiring role model for the present methodology to be developed. The structuring in clear, disjunct phases with strictly defined input and output flows of information will be adopted in the following method. Also the increasing information demand along employing the method is characteristic. In the beginning of Cooper's model, the success of a product idea is roughly estimated using only little input. Only if this intermediate result is promising, the next steps are approached; otherwise, the idea will be dropped.

The developed method has a 3-step structure. Analogously to Cooper, in the beginning only data easily available is needed so as a rough, fundamental check can be performed. If the first indications are convenient, the method will continue. The method's intention is to provide a profound basis for deciding whether to employ product recycling in the business unit or not. That is why this method comprises 3 discrete dimensions in which the test object is assessed in.

As the method progresses, so does the demand for information in respect to amount and quality of data. The single process steps must be executed in sequence since the output of the previous step is the input of the following one. In the next subchapters, the structure of each single process step is explained in detail.

5.1.1 Step 1 – 'Identifying relevant parts'

Step 1 is a rather easy one to take. Here, the main goal is to identify those parts which are relevant in terms of economic and ecological impact and where a set of basic technical preconditions is

[115] see COOPER (2002), p.146.

fullfilled. This means that only those parts are considered for further in-detail-evaluation which contribute most to effort needed in order to yield the final product and comply with technical minimum requirements. In addition, the focusing on only important parts helps saving efforts in the upcoming work steps. So as to label these parts as *relevant*, filter criteria must be established. As already shown in chapter 3.1, product recycling has two different dimensions in which it needs to be efficient. Since the initial intention of product recycling is to reduce future environmental impact in order to disburden the planet's supply and support function and to deploy acting in a sustainable manner, the ecological dimensions plays an important role. However, in our daily lives we have to act in an economic surrounding where costs and prices are omnipresent. In many areas of societal life, money forms the only incentive and criterion to decide upon. This is the reason why the economic dimension, and therefore cost (besides the set of technical basic requirements), is chosen to apply the filter parameter to. Mass and energy flows, a necessary precondition for man-made environmental impact, are always afflicted with cost. Even though correlation between economic and ecological dimension is not mandatorily strong, at least it exists in positive direction (the more material or energy is consumed, the more costs are incurred and the more environmental impact is caused). An argument underlining the eligibility of the economic dimension is the fact that information about cost is easily available and accessible. In the case of applying this method in the design stage, usually plan costs are calculated in parallel by means of empirical values. If this assessment method is used in the post-design stage, where the product's specifications are already fixed, and this tool is only used to assess the eligibility for product recycling in retrospect, more or less exact information about manufacturing cost are generally available. In both cases the economic dimension proves to be an appropriate choice.

In order to distinguish relevant parts and not-relevant parts, a filter threshold must be quantified. Applying the filter to cumulated cost is the most promising approach. Therefore, firstly, parts are sorted in accordance of their cost in descending order and cumulated cost are computed. Then, all those parts whose cumulated cost do not exceed or just marginally exceed the threshold defined in the filter rule are included into the preliminary set of relevant parts (e.g. all those parts are included in the preliminary set of relevant parts where the cumulated cost share is less than or equal to a percentage p of total manufacturing cost; usually that part succeeding the part where the cumulated cost share is just less than defined in the threshold is included, too; by doing so, it is ensured that all parts responsible for more than $p\,\%$ of total cost are taken into account). Especially in mechanical engineering where endeavours push the use of common parts (so as economies of scale are yielded), the filter rule must be applied on the whole set of common parts and, hence, on the aggregated cost of common parts ($c_k \cdot n_k$ – single unit cost of a particular part k times its quantity within a particular product). In order to find the final set of relevant parts, a check list of technical criteria (defined in a later paragraph) is applied to the preliminary set of relevant parts so as those parts which can't be remanufactured because of technical constraints are excluded from the very first beginning. Doing so avoids too much useless effort in data mining in the following steps. Only if part design of an excluded part is changed and the particular technical exclusion criterion is not valid anymore, it is reasonable to take this special part into account for further assessment.

Figure 5.1 pictures an overview of this first data processing stage in a simple way. On the input side are product specific data and, as filter, the cut-off rule in combination with a set of technical exclusion criteria. After data processing, the intended output is the set of relevant parts, which needs a more-in-depth analysis. Complementary, the set of not-relevant parts arises out of the difference between set of product constituting parts and set of relevant parts. The latter set of parts is intended not being remanufactured. If a particular part is excluded because of failing due

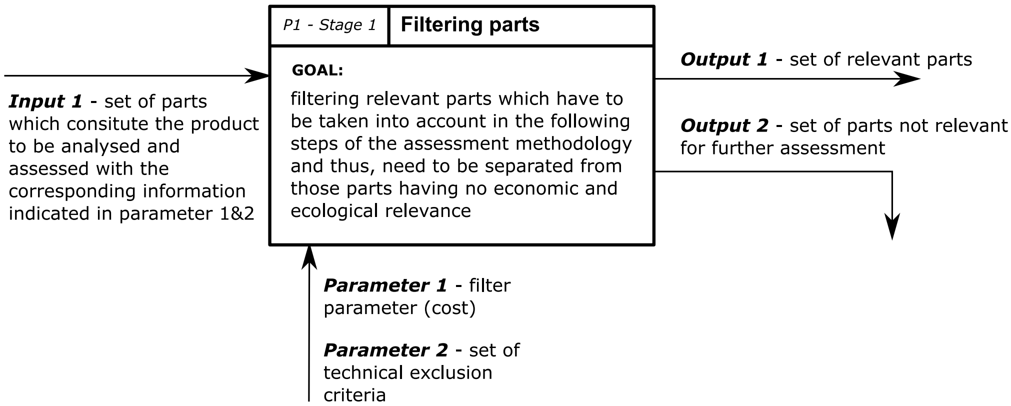

Figure (5.1): *Overview of method's evaluation stage No.1*

to technical minimum requirements, then the possibility for product recycling still exists. This is the case if design changes can be implemented. If not, then – since it is the next, most promising treatment process – material recycling is strived for.

5.1.2 Step 2 – 'Calculating effort for remanufacturing'

The main object in the current stage of the developed assessment method is to determine the total average effort required for remanufacturing a relevant part. In the context of the assessment method at hand, the term *effort* always refers to both economic and ecological effort.

As already described in chapter 3.2, product recycling requires a sequence of different process steps. Each of these key processes entail efforts which can be expressed in terms of (financial) cost and environmental impact. The contributors of effort incurred by the strategic decision *pro product recycling* are listed in chronological order (classified according their imputability / distinguished whether they comprise only directly allocable efforts or directly and indirectly allocable effort)

- not directly imputable efforts
  - effort for retrodistribution
  - effort for disassembling
  - effort for disposing / recycling
- directly imputable efforts
  - effort for cleaning
  - effort for sorting & testing
  - effort for reconditioning

As shown in Figure 5.2 this data processing step necessitates a series of input information so as the goal of this step – calculating the effort for remanufacturing – is reached.

The effort for retrodistribution is two-part. Retrodistribution implies that an entire used product is transported from customer's home where the product is released into its end-of-life to the

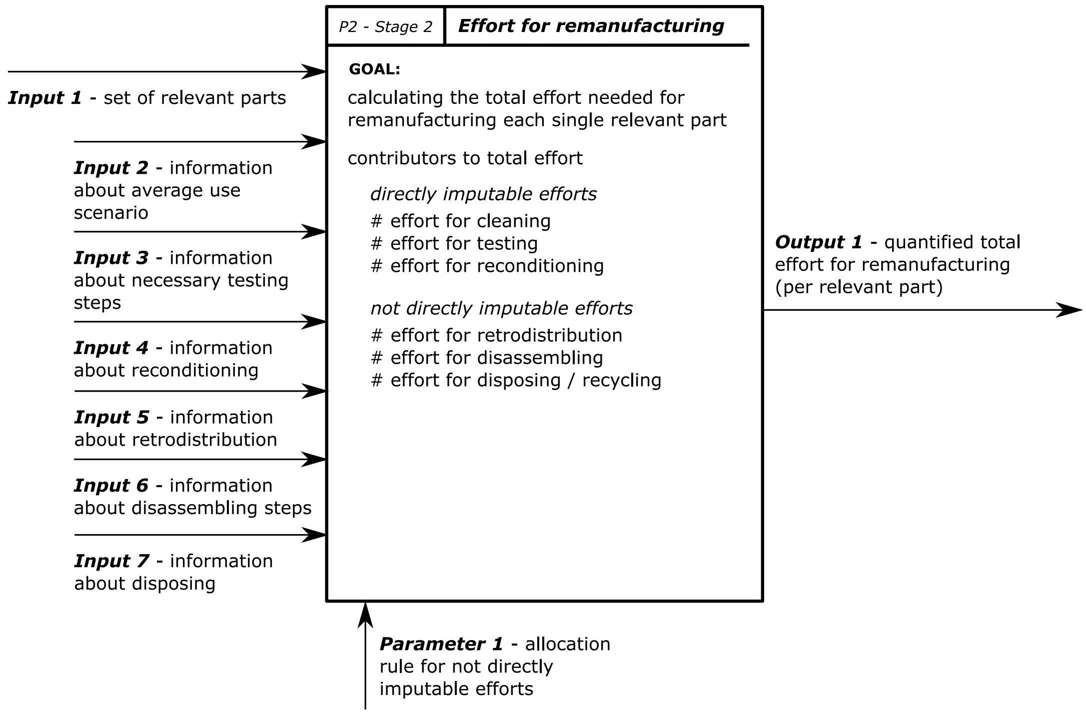

Figure (5.2): *Overview of method's evaluation stage No.2*

remanufacturing plant where the treatment takes place. As already the choice of words hints at, two different challenges are incorporated in this step. The first is a rather legal issue which deals with transfer of ownership. In the classical economic system the customer has always been the owner and holder of a product in personal union. In contrast to holding an item, only the owner has the right to dispose of his property.[116] In dependence on alternatives for using an old product at its end-of-life and/or the precedent legal framework, the transfer of ownership is possibly connected with cost (in the economic sense) enhancing total cost for remanufacturing. In general, during transfer of ownership no relevant environmental impact is resulting.Potential remedies already in place and avoiding such legal difficulties are the concept of *leasing* and the rather new concept of *product service systems*[117].

The second part of *retrodistribution* is transporting the used product. In accordance with the overall strategy for product recycling, predefining the retrodistribution strategy is essential for the planning of the transportation steps. Generally, there many structural settings how the actual logistic chain could look like. For the sake of simplicity, in this thesis only two different settings are dealt with. Setting No. 1 bases on the direct transport of used products to a centralised

[116]Legally important is the distinction of owner, aka proprietor, and holder. Property is any physical or intangible entity that is owned by a person or jointly by a group of persons. Depending on the nature of the property, only an owner of property has the right to consume, sell, rent, mortgage, transfer, exchange or destroy his or her property, and/or to exclude others from doing these things. Unlike an owner, a holder just holds a physical or intangible entity. He does not, if at all, have the same rights to consume, sell, rent, mortgage, transfer, exchange or destroy this entity. For instance, a thief may be the holder of a good, but not the owner. Ownership always bases exclusively on legal transactions, which thievery is not at all.

[117]see MANZINI/VEZZOLI (2003), pp.857.

remanufacturing plant. In contrast, the second setting has decentralised disassembling plants where used products are dismantled and presorted so as only those parts identified as eligible for product recycling are shipped to the remanufacturing plant. Making use of local disassembling plants certainly has influence on the effort structure. Obviously, transportation causes economic and environmental cost.

The next process to run in the course of product recycling is *disassembling* the used product. Detailed information about the product like e.g. its structure, the type of its connections and its materials used must be available so as the appropriate dismantling techniques as well as the optimum disassembling path and depth are chosen. A subordinate objective is to disassemble at cost as low as possible while ensuring both dismantling relevant parts with low risk of damaging and facilitating – if necessary – proper treatment of not-relevant parts (i.e. choosing an additional number of disassembling steps in order to obtain only subsets of not-relevant parts with for material recycling suitably combined material specifications).

This directly leads over to the last, not directly imputable effort – namely, disposing of not-relevant parts. Inevitably, getting rid of useless parts is a big issue because stockpiling in the warehouse is no option at all. Hence, information about materials and the corresponding information about material recycling techniques is needed so as the effort can be estimated. Fortunately, material recycling, which is the preferred way of treatment, does not necessarily cause only 'positive effort' but also a 'negative one'. This means that by selling parts intended for material recycling revenue is possibly yielded. The same is valid in the environmental dimension. Because of material recycling a 'negative environmental impact' may be gained.

However, this method aims for assessing part's eligibility for reusing (product recycling). Unfortunately, some efforts incurred emerge only because of the whole product like e.g. effort for retrodistribution and effort for disposing of not-relevant parts. In addition, allocation of effort for disassembling is challenging as well since e.g. a cost causing dismantling step can be beneficial not only for the currently demounted part but also for relevant, sequentially dismantled ones. Furthermore, possibly needed steps for disassembling caused by improper material combination of not-relevant parts (in respect to material recycling) provoke increased effort, as well. These efforts need to be allocated. Hence, an allocation rule for not directly imputable effort must ensure an equitable / fair allotting.

For all directly imputable efforts, information about the average use scenario is crucial. During the use phase parts might be altered in a way which prevents the part from getting directly used again. Such obstacles are dirt and mud as well as phenomenons like e.g. wear, fatigue, chemical reactions, etc. which alter the functional potential or, in other words, change part's initial specifications. Dependent on the extent of alteration, the effort needed for cleaning, testing and reconditioning may vary. Especially in respect to cleaning, it is essential to know part's material and surface specification so as possible interaction between part and cleaning technique is already anticipated in advance and, in consequence, negative implications are avoided. In order to facilitate testing of relevant parts, all minimum specifications must be known on the one hand. On the other hand, these specifications must be verifiable which calls for an appropriate testing technique. If a certain specification is not verifiable – neither directly nor indirectly – a s as equal as new can't be guaranteed and reusing is no viable option anymore. For example, fatigue represents such a hurdle.

By means of the information provided on the input side, the effort required for remanufacturing a relevant part is computed in both dimensions. Determing the effort in the economic dimension (i.e. evaluating cost) seems to be a task rather easy to master since accounting is a historically well positioned business task. With the aid of different accounting methods like e.g. full costing or activity based costing, an accurate result is achieved. Calculating the effort needed for product recycling in terms of environmental impact appears to be more exhausting. In order to assess the environmental impact caused by remanufacturing, a thorough life cycle assessment would be necessary. However, for the sake of method's usability, only an abbreviated form of LCA is suggested. An input-oriented analysis of material and energy flows is regarded as sufficient in order to receive a first impression about the magnitude of environmental impact.

The result of the current stage is an explicit number expressing the extent of economic and ecological effort needed for remanufacturing every single relevant part and, hence, realising the strategic decision *pro product recycling*.

5.1.3 Step 3 – 'Ranking of relevant parts'

The final stage of the present 3-step assessment method tries to find answers whether product recycling is economically and ecologically as well as strategically reasonable and feasible.

The economic and the ecological dimension provides a quantitative, the strategically a qualitative decision support. In order to assess a particular relevant part in the former two dimensions, corresponding information about newly manufacturing is required. It is important to note that the comparison of the newly manufactured and the remanufactured part is just an analysis of differences[118]. Although life cycle thinking is a valuable assistance, it is not necessary to take all single life cycle phases, from cradle to grave, and the linked efforts into account. The starting point is market demand for a certain product and, in consequence, the demand for parts constituting this particular product. For the satisfaction of (functional) needs, it is irrelevant whether it is sated with either a newly manufactured or a remanufactured part.

In the course of product recycling, it is extraneous to reconsider e.g. the effort incurred by assembling or reassembling – both parts need to get assembled in order to serve its intended purpose. Thus, effort for both tasks will most probably resemble in magnitude. Hence, these equal efforts may be neglected. The only relevant question is which processes in newly manufacturing are replaced by which processes in remanufacturing. Only those cost and those environmental impacts need to be summed up and compared. To put it in a nutshell, in following this principle, only a modification of the concept of opportunity cost is applied.

The basic equation for product recycling depicts as follows below.[119] The subsequent explanation is valid for both the economic as well as ecological dimension, but is only shown using the

[118] see VAN DER LAAN/SALOMON (1997), p.264.
[119] adopted from RUDOLPH (1999), p.16.

example of the former one:

$$\underbrace{C_{NM\ (k)} + C_{DP,\ NM\ (k)}}_{\text{newly manufacturing}} \left\{ \begin{array}{c} < \\ = \\ > \end{array} \right\} \underbrace{C_{RM\ (k)} + C_{DB\ (k)}}_{\text{product recycling}} \tag{5.1}$$

$$\begin{aligned} C_{RM\ (k)} &= C_{RD\ (k)} + C_{DA\ (k)} + C_{C\ (k)} \\ &\quad + C_{T\ (k)} + C_{RC\ (k)} + C_{DP\ (k)} \end{aligned} \tag{5.2}$$

$$C_{DP,\ NM\ (k)} \geq C_{DP\ (k)} \tag{5.3}$$

$C_{NM\ (k)}$	...	Cost for newly manufacturing part k
$C_{DP,\ NM\ (k)}$	...	Cost for disposing / recycling newly manufactured part k in the phase *end-of-life*
$C_{RM\ (k)}$	...	Cost for remanufacturing part k
$C_{DP\ (k)}$	...	Cost for disposing / recycling incurred by remanufacturing part k
$C_{DB\ (k)}$	...	Cost drawback of part k
$C_{RD\ (k)}$	...	Cost for retrodistribution of part k
$C_{DA\ (k)}$	...	Cost for disassembling part k
$C_{C\ (k)}$	...	Cost for cleaning part k
$C_{T\ (k)}$	...	Cost for testing part k
$C_{RC\ (k)}$	...	Cost for reconditioning part k

The above equation compares the two alternatives of *newly manufacturing* and *product recycling* from a macro-economic perspective. The cost components on the left side show the cost incurred by newly manufacturing. Obviously, this side consists of cost for newly manufacturing ($C_{NM\ (k)}$) and cost for disposing / recycling[120] this newly manufactured part at its end-of-life ($C_{DP,\ NM\ (k)}$). The latter cost contributor is mentioned only for the sake of completeness. However, because of the current legislation grown along history, this cost unit hasn't been within the responsibility of a manufacturer up until now. So, this cost for disposing has been born by the general public.[121] If in future the concept of extended producer responsibility is legally more binding and cost for disposing is internalised, it would enhance, at least by trend, the probability of economic success of product recycling.

On the right side of the equation, the cost structure for product recycling is illustrated in a rough outline. First of all, the cost for remanufacturing ($C_{RM\ (k)}$), which is defined more in detail just two lines below, constitute a main cost factor. Cost for retrodistribution ($C_{RD\ (k)}$) and for disassembling ($C_{DA\ (k)}$) as well as for cleaning ($C_{C\ (k)}$), testing ($C_{T\ (k)}$) and reconditioning ($C_{RC\ (k)}$) are the biggest contributors in sum to total cost for remanufacturing. However, since not all parts can be reconditioned or directly reused, a certain quota of relevant parts is routed for disposal / recycling. As a general rule, those parts should undergo material recycling. In turn, cost for disposing / recycling of not-relevant parts burdens the cost unit ($C_{DP,\ RM\ (k)}$). Fortunately, the magnitude of this right-sided cost for disposal / recycling ($C_{DP,\ RM\ (k)}$) is categorically lower than the left-sided counterpart ($C_{DP,\ NM\ (k)}$) – as shown with the equation in line 2.

The last component of the equation's right side is the cost caused by a potential drawback in comparison to a daughter product ($C_{DB\ (k)}$). As highlighted in chapter 3.1, daughter products may

[120] In the context of the current thesis, the term 'disposal' or the according verb is used in a sense which comprise all possible ways of EoL-treatment; by using this expression, it is still unspecified which EoL-option will be chosen.

[121] see HERRMANN (2002), p.62.

perform better in terms of resource and energy consumption throughout the entire life cycle than the product to be remanufactured.[122] Relativised by product function and allocated to all relevant parts, this potential drawback in terms of cost and environmental impact must theoretically be taken into account.

By comparing both sides of the equation, product recycling is then and only then reasonable and feasible if the left side is greater than the right side. The anticipated difference of both sides is the incentive to implement product recycling in company's economic everyday life.

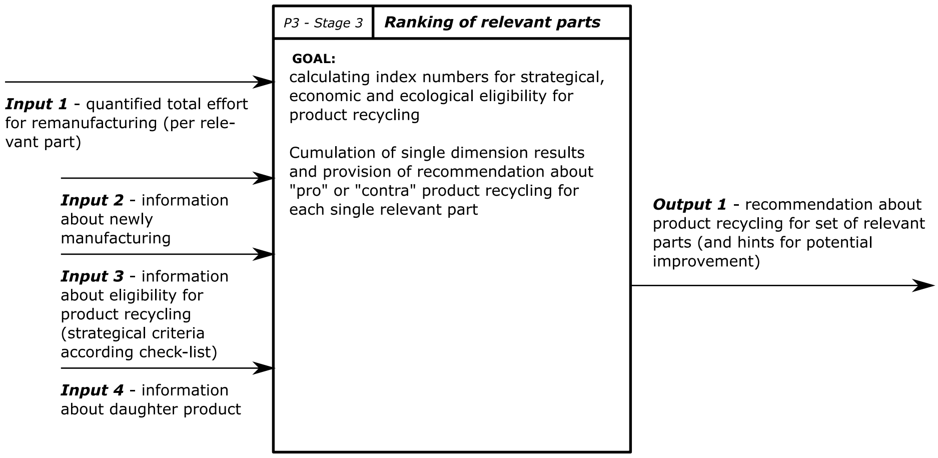

Figure (5.3): *Overview of method's evaluation stage No.3*

As shown in Figure 5.3, some information is needed for figuring out whether an economic and ecological incentive *pro* product recycling exists. Computing the ratio

$$R^*_{ECO\ (k)} \quad = \quad 1 - \frac{C_{RM\ (k)} + C_{DP\ (k)} + C_{DB\ (k)}}{C_{NM\ (k)} + C_{DP,\ NM\ (k)}} \tag{5.4}$$

$R^*_{ECO\ (k)}$	...	Economic performance indicator, range 0 ... 1
$C_{NM\ (k)}$	...	Cost for newly manufacturing part k
$C_{DP,\ NM\ (k)}$	...	Cost for disposing / recycling newly manufactured part k in the phase *end-of-life*
$C_{RM\ (k)}$	...	Cost for remanufacturing part k
$C_{DP\ (k)}$	...	Cost for disposing / recycling incurred by remanufacturing part k
$C_{DB\ (k)}$	...	Cost drawback of part k

which is basically the comparison of the scenario 'newly manufacturing' and the scenario 'product recycling' standardised to a range between 0 and 1, helps finding an answer. Each $R^*_{ECO\ (k)}$ (economic performance indicator) and $R^*_{ENV\ (k)}$ (environmental performance indicator), respectively, in the range of *0 ... 1* indicates relevant part's eligibility in the corresponding dimension. The higher this ratio, the higher the incentive to apply product recycling. A ratio less than *0* is also practically possible which expresses that remanufacturing is inferior in terms of effort to be invested.

[122] This finding bases on Life cycle thinking and also on the concept of total cost of ownership; the holistic approach prevents myopic deciding

The last outstanding dimension in which the relevant part is assessed in is the strategical dimension. By means of check-lists, which are explained in the rear part of the next chapter, the strategical eligibility ($R^*_{St(k)}$) is determined. Per definition the outcome also ranges between 0 and 1.

The final outcome is a triple of characteristic numbers which represent the eligibility for product recycling.

5.2 Detailed explanation of the developed method

The current chapter is devoted to a more-in-depth description of the developed method, first in particular to the quantitative assessment for identifying economic and ecological eligibility and afterwards to the qualitative assessment for identifying the strategical eligibility of relevant parts. In order to prove the developed method, it is applied to a practical example in the next chapter.

For the sake of compactness, the equations in the following chapter are mainly display for the economic dimension. It is important to note the explained principles are valid for both the economic and ecological dimension. Analogously to cost, all efforts dealing with ecological efforts (environmental impacts) are indexed with *'ei'* instead of *'c'*.

Cost data are supposed to be available by misc. costing methods, data about environmental impact is sourced from databases or more or less comprehensive LCAs.

5.2.1 Identification of relevant parts

As briefly explained above, the first step to take is the distinction of product constituting parts into two categories – namely, *relevant parts* and *not-relevant parts* – by means of a threshold applied to cumulated cost and a list of certain technical criteria. Usually, the bill of materials (BOM) is a helpful assistance for doing this task.

By means of a BOM, the schematical principle of identifying the relevant parts is shown in Table 5.1. Table 5.1, column 1 – 2 show (minimal) information as it is typically listed in a BOM. In the first filtering step, the only information additionally required is cost data (shown in Table 5.1, column 3), which is the basis for sorting parts in descending order ($c_1 \geq c_2 \geq \cdots c_k \geq \cdots c_n$). After calculating each part's cost share (column 4; c_k/C_{SUM}) and subsequent culmination (column 5), these cumulated numbers are ready being compared with the predefined threshold number (r_{th}). All those parts are included in the preliminary set of relevant parts which jointly contribute slightly more than r_{th}% to total cost (in Table 5.1 this threshold is reached with part *i*).

In a second filtering step, it is checked whether those parts included in the preliminary set of relevant parts comply with a list of technical minimum requirements. These minimum requirements are as follows:

- eligibility for disassembling – reversibility of joints
- eligibility for testing – possibility of non-destructive testing
- eligibility for reconditioning – reversibility of part's alteration during use phase

Table (5.1): *Identification of relevant parts – schematical principle*

1	2	3	4	5	6	7	8	9
no.	name	cost	cost share	cumulated cost share	active exclusion criterion?	relevant part?	cumulated cost of rel. parts	allocation factor for common cost
1	part 1	c_1	$r_1 = \frac{c_1}{C_{SUM}}$	$\sum_{k=1}^{1} r_k < r_{th}$	—	→ yes ($RP_1 = 1$)	$\sum_{k=1}^{1} c_k \Big\|_{RP_k=1}$	c_1/C_{cum}^{max}
2	part 2	c_2	$r_2 = \frac{c_2}{C_{SUM}}$	$\sum_{k=1}^{2} r_k < r_{th}$	TEC j	→ no ($RP_2 = 0$)	$\sum_{k=1}^{2} c_k \Big\|_{RP_k=1}$	—
3	part 3	c_3	$r_3 = \frac{c_3}{C_{SUM}}$	$\sum_{k=1}^{3} r_k < r_{th}$	—	→ yes ($RP_3 = 1$)	$\sum_{k=1}^{3} c_k \Big\|_{RP_k=1}$	c_3/C_{cum}^{max}
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
k-1	part k-1	c_{k-1}	$r_{k-1} = \frac{c_{k-1}}{C_{SUM}}$	$\sum_{k=1}^{k-1} r_k < r_{th}$	—	→ yes ($RP_{k-1} = 1$)	$\sum_{k=1}^{k-1} c_k \Big\|_{RP_k=1}$	c_{k-1}/C_{cum}^{max}
k	part k	c_k	$r_k = \frac{c_k}{C_{SUM}}$	$\sum_{k=1}^{k} r_k \sim r_{th}$	—	→ yes ($RP_k = 1$)	$\sum_{k=1}^{k} c_k \Big\|_{RP_k=1}$	c_k/C_{cum}^{max}
k+1	part k+1	c_{k+1}	$r_{k+1} = \frac{c_{k+1}}{C_{SUM}}$	$\sum_{k=1}^{k+1} r_k > r_{th}$	—	→ no ($RP_{k+1} = 0$)	—	—
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
n-1	part n-1	c_{n-1}	$r_{n-1} = \frac{c_{n-1}}{C_{SUM}}$	$\sum_{k=1}^{n-1} r_k > r_{th}$	—	→ no ($RP_{n-1} = 0$)	—	—
n	part n	c_n	$r_n = \frac{c_n}{C_{SUM}}$	$\sum_{k=1}^{n} r_k > r_{th}$	—	→ no ($RP_n = 0$)	—	—

total cost $C_{SUM} = \sum_{k=1}^{n} c_k$

total cost of relevant parts $C_{cum}^{max} = \sum_{k=1}^{i} c_k \Big|_{RP_k=1}$

c_k ... cost per part k
C_{SUM} ... cumulated cost per part k = cost for entire product
r_k ... cost share of part k of cumulated cost per part
r_{th} ... threshold share / variable for cut-off rule
TEC j ... indicator for active technical exclusion criterion (indicates that criterion 'j' is active
RP_k ... auxiliary variable – indicates whether a particular part is relevant for further consideration ($RP_k = 1$) or not ($RP_k = 0$)
C_{cum}^{max} ... cumulated cost of set of relevant parts

If at least one of the above mentioned criteria is valid by principle (i.e. function immanent phenomenon), then the particular part is not eligible to be reused and finally excluded from the set of relevant parts. Only changes in design, if possible, are capable of revising this rigorous judgement.

The first indispensable prerequisite is connected with product's disassemblability in general, and the reversibility of part's jointing technique in particular (see *TEC1* in Table 5.2). Jointing is defined and distinguished in DIN 8593 et seq. For assembling, industrially most important are

- general assembling e.g. applying, inlaying, sliding-in, hooking-into,...
- filling e.g. filling-up, soaking,...
- pressing on and in (force fitting) e.g. bolted connection, clamping, clasping,...
- jointing by primary shaping e.g. effusing, moulding, galvanising, coating,...
- jointing by transforming e.g. jointly twisting, plaiting, knotting-together, nicking, seaming, crimping, riveting,...
- jointing by welding e.g. pressure welding, fusion welding,...
- jointing by soldering e.g. soft-soldering, hard-soldering/brazing,...
- glueing e.g. jointing with physical-setting adhesive, jointing with chemical-setting adhesive,...

Obviously, those parts with reversible jointings are eligible for product recycling, e.g. parts connected by screws, non-destructively reversible snap-fits, plug-in connection etc. In addition, also those parts connected with techniques reversible by link-destruction-only like e.g. (drilling of) rivets and, partly, spot welds or (stripping of) certain adhesive bonds are capable of inclusion in the set of relevant parts. Only those parts which are totally or, at least, partly destroyed in the course of disassembling must be excluded from further considerations.[123]

The next exclusion criterion deals with the irrevocable claim for non-destructive testing. Since an as good as new state of the remanufactured part must be ensured, testing is an absolutely necessary task. Unfortunately, it might be the case that certain specifications are only able being validated by means of destructive testing techniques. In newly manufacturing those testing routines are no big deal since, due to the determined production conditions, the state of the production batch can be inferred from the subset of tested objects. However, during use products are exposed to varying and in advance partly unknown environmental influences, and, hence, object of uncertainty. That's the reason why a full check of each single part's state must be accomplished. If part testing causes its destruction, then, plausibly, reusing is not possible anymore. An textbook example is fatigue. If material specifications (e.g. tensile strength or fatigue strength) are subject of a test routine, those tests usually continue until the test object breaks. Of course, stopping the the test routing in advance of destruction would be an option as well, but also the expressiveness of the result might suffer. In the best case, there are indicators which allow an estimation of residual life time. Only by recording of specification-changing environmental influences during product's life, conclusions about part's state might be drawn.

[123] Theoretically, if non-destructive disassembling is not possible it still might be the case that the remaining subassembly is eligible for reusing if and only if either no or jointly and easily reversible alterations during use phase occur, cleaning is possible without disadvantage and the same specifications like an as good as new state of all parts involved is definitely guaranteed! This special case must be assessed on individual basis!

The last criterion to be fulfilled concerns the reversibility of part specifications' alteration(s) caused by using the product. If no significant changes occur during use, then reuse is not hindered in this particular aspect. Though, in many cases changes are unavoidable. A list of technically important changes are as follows:

- wear
- fatigue
- deformation
- corrosion
- other change of functional potential

Usually, if parts are exposed to wear or are knowingly at risk of wearing-out, designing engineers strive for an easy-to-exchange design because, oftentimes, those wearing parts have shorter life times than the entire product. In consequence, easy-to-exchange design facilitates maintenance. For reusing most important is the reversibility of wear phenomenons. In special cases, several process technologies exist for reversing wear like e.g. recoating, deposition welding,... Another option, mainly used in mechanical engineering, is to cut worn parts to geometrically determined shapes and attach an additional part (e.g. recutting fretted bolt and attaching extra bush so as geometrical dimensions, as defined in the design stage, are restored). But in turn, reversing of wear is not always possible. Fortunately, this fact doesn't constrain part's reusability yet. As pointed out previously, lifetime of wear parts does not necessarily equal to product's lifetime. In case of longer wear part's lifetime, there might be a residual wear potential, or in other words, a wear reserve. If this wear reserve suffices for another entire lifetime and, preferably, significant wear-induced changes in geometric dimension can be set-off by means of adjustment devices, then the chance for reusing still exists. Only if there's neither a reversing technology nor the possibility to recut and add extra parts nor enough wear reserve, then part's reusability is hampered.

A technologically related phenomenon impeding reuse is fatigue. Fatigue summarises phenomenons in material science, where parts are subjected to cyclic loading which, in turn, causes stochastic growth of micro cracks. If a certain number of load cycles is exceeded (dependent on material specifications, part's geometry, surface finish,...), the part fails. Up until now no fatigue-reversing technologies have been developed. Design engineers have different approaches at hand so as to cope with cyclic loading.

Since fatigue can't be reversed, as mentioned above, the only chance for reusing hides in remaining load cycles allowed. Similarly to wear, an already used part can be reused if and only if a residual fatigue reserve for an entire product lifetime exists. However, attesting such a fatigue reserve needs either thorough testing or an entire record of loads already exerted during the previous lifetime(s) so as future lifetime can be estimated. Without known fatigue reserve, the part is not qualified for reusing.

The third limiter in a row for part's technical eligibility for reusing is deformation. Deformation can occur either intended and consciously (e.g. certain assembling techniques apply deforming like twisting of wire or seaming of sheet steel) or unintended (e.g. accidents during use phase causing damages, ranging from small superficial dents to rupture of part). Especially in respect to bended steel, there are several techniques which allow reversing of deformation (equals to swaging and subsequent recovery annealing). In absence of reversing techniques, the arising question is whether the deformed part still can be reused. Dependent on the extent of deformation (damage) and the consequences on part's functionality/reliability, cosmetic measures might be applied in order to yield a part serving the same initial requirements as a newly manufactured one (e.g. filling of superficial dents and repainting/recoating).

During use corrosion might cause an alteration of part's original specifications. Corrosion refers to all those phenomenons where a material is disintegrated into its constituents due to chemical reactions with its surrounding. In the most common sense of the word, the reaction of a metal and a oxidant is meant. A well known example is iron and oxygen, also referred to as rust. Corrosion can also occur in combination of ceramics and polymers although in this context it is called degradation. To a certain extent, metal corrosion resembles to wear; both are characterised by a decrease in part's volume. The only difference lies in the main agent responsible for the reduction of volume. Contrary to decomposition of polymer and ceramics, which corrosion is irreversible, corrosion of metals may get reversed by workarounds. Economically most significant is corrosion of steel, most times an undesired side-effect. Hence, due to coating (e.g. zinc) and painting design engineers try to hinder abundant corrosion. However, because of imperfections in material, production or during use it is not always possible to stop these oxidising reactions. Usually, especially in the case of steel, there is the chance to 'remove' superficial corrosion by e.g. simply polishing rusted areas and subsequent repainting, or cutting-out extremely corroded / rusted-through parts and weld-shut with an equally shaped new part. Evidently, the delimitation between industrial reconditioning and individual repairing is somehow blurred, and as long as like-new specifications of reconditioned parts are yielded, in this very aspect part's eligibility for reusing only depends on economic and ecological criteria. Returning to the technical starting point, it can be stated that only those parts are eligible for reusing which feature reversibility of corrosion or possess only minor changes due to corrosion so as part's functional reliability can be ensure for an additional entire use phase (→ 'corrosion reserve').

The last obstacle for reusing is the rather general criterion '*other changes of functional potential*'. Naturally, parts are designed intended to fulfil a particular function e.g. storage of electricity in battery / accumulator, exertion of tensile force / compressive force by spring or storage of pictures on 35 mm film. All those functions base on physical, chemical or mechanical phenomenons. The question to ask here resembles the preceding ones – whether a) those phenomenons are capable of being reversed or b) whether a certain amount of 'functional reserve' is left so as the particular part can serve an additional use phase. Only if one of the answers is 'yes', then reusing is an option for end-of-life-treatment.

Table (5.2): *List of technical exclusion criteria*

No.	category	field of application*	criterion name
TEC1	eligibility for disassembling	part	reversibility of joints
TEC2	eligibility for testing	part	possibility of non-destructive testing
TEC3	eligibility for reconditioning	part	reversibility of part's alterations during use phase
TEC3a			↪ wear
TEC3b			↪ fatigue
TEC3c			↪ deformation
TEC3d			↪ corrosion
TEC3e			↪ other changes of functional potential

The entire list, at one glance, is attached in Table 5.2. As previously mentioned, if at least one single technical exclusion criterion is active, the part must be used in another way than reusing.

In Table 5.1 an active exclusion criterion is marked in column 6 with the analogous criterion abbreviation (→ *TECj*). Only if the corresponding cell in column 6 is empty and the cumulated cost share is less or approx. equal to the predefined threshold r_{th}, the part currently regarded is relevant for further assessment. This eligibility for further analysis is indicated in Table 5.1, column 7 with '*yes*', or mathematically expressed with $RP_k = 1$.

Since only relevant parts are able to bear common costs, the cumulated cost of relevant parts (C_{cum}^{max}) is determined which, at the same time, is the basis for allocation of common cost. For transferring common cost like e.g. cost for disposing of not-relevant parts etc. to relevant parts, it is necessary to compute the ratio c_k/C_{cum}^{max} (see Table 5.1, column 9). Naturally, this key number is only calculated for relevant parts.

5.2.2 Quantitative assessment

5.2.2.1 Calculating effort for retrodistribution

The second stage comprises mainly the quantitative estimation of cost incurred whereof the allocation of not directly imputable efforts is the first main source for work load.

Calculating the effort for retrodistribution requires the selection of the optimal strategy at first. The subsequent considerations shall provide support for deciding which retrodistribution strategy to choose best. Basically, there are two alternatives at hand – retrodistribution with centralised disassembling sites or retrodistribution with local (decentralised) disassembling sites. By juxtaposing in opposite, the better alternative shall be identified. The finally developed computing algorithm indicates the optimal option to choose.

General thoughts

In the general framework of 'reusing', the choice of the retrodistribution strategy influences the processes

- transporting (sub process of retrodistribution in general),
- disassembling and
- disposing of not-relevant parts.

The cost drivers for transportation are weight and distance; the specific costs depend on the mode of transportation and are supposed to be fixed.

The cost drivers for disassembling is time required for disassembling which, obviously, is independent on the place of its application and only a consequence of design as well as jointing and soiling / alteration during use phase. The only factor deviating in the two distinct scenarios is a possible difference in labour cost.

For disposing the cost driver is weight of not-relevant parts. Since total weight doesn't change in accordance of its place of occurrence (= disassembling site), the only difference between the two retrodistribution options possibly accrue to cost for disposing. However, we assume that the preferred way of disposing is material recycling which is said to be a less labour-intensive but rather investment-intensive process. Due to the assumption of remanufacturer's high environmental awareness (= self commitment on an ecologically high level), for the sake of simplicity it is concluded that no local arbitrations are yielded.

In the next paragraphs the two alternatives are introduced in detail.

Centralised industry structure

The term 'centralised industry structure' points to the fact that there is a centralised industry site where all activities required for reusing (product recycling) are performed. Especially in respect to the retrodistribution strategy, the place for disassembling and the place for all other steps (e.g. cleaning, testing, reconditioning, etc.) coincide. Hence, the used product is (most probably via collecting hub) immediately transported from the customer to the remanufacturing site (see Figure 5.4). There, the used product is disassembled which, in turn, enables the separation of relevant and not-relevant parts. The latter are intended for disposal, indicated by the bottom right arrow in Figure 5.4.

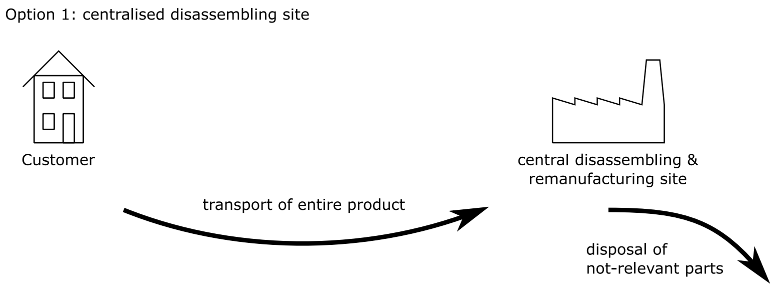

Figure (5.4): *Retrodistribution – in the context of a centralised industry structure*

The total costs incurred in the scenario 'centralised structure' (TC^{centr}) are as follows:

$$TC^{centr} = C_{RD}^{centr} + C_{DA}^{centr} + C_{DP}^{centr} \tag{5.5}$$

TC^{centr} ... total cost incurred in the retrodistribution scenario 'centralised scenario' (basis for comparison)
C_{RD}^{centr} ... total cost for retrodistribution in the centralised scenario
C_{DA}^{centr} ... total cost for disassembling in the centralised scenario
C_{DP}^{centr} ... total cost for disposing / recycling in the centralised scenario

The single contributors for the process steps retrodistributing, disassembling and disposing, respectively, are:

$$C_{RD}^{centr} = C_{TF} + \underbrace{+ \overbrace{(w_{rel} + w_{not\ rel})}^{w_{total}} \cdot \left(c_{TP,(1)}^{*,\ centr} \cdot \widetilde{d_{TP,(1)}^{centr}} + c_{TP,(2)}^{*,\ centr} \cdot \widetilde{d_{TP,(2)}^{centr}} \right)}_{C_{TP}} \tag{5.6}$$

C_{RD}^{centr} ... total cost for retrodistribution in the centralised scenario
C_{TF} ... cost for transferring ownership
C_{TP} ... cost for transporting
w_{rel} ... cumulated weight of relevant parts
$w_{not\ rel}$ ... cumulated weight of not-relevant parts
w_{total} ... total product weight ($w_{rel} + w_{not\ rel}$)

[Continuation on next page]

$c^{*,\ centr}_{TP,\ (1)}$ ... cost factor for certain mode of transportation between customer and collection hub (cost per distance and weight unit) in the centralised scenario
$c^{*,\ centr}_{TP,\ (2)}$ ... cost factor for certain mode of transportation between collection hub and remanufacturing site (cost per distance and weight unit) in the centralised scenario
$\widetilde{d^{centr}_{TP,\ (1)}}$ ... averaged cost driver for transportation between customer and collection hub (distance unit) in the centralised scenario
$\widetilde{d^{centr}_{TP,\ (2)}}$ ... averaged cost driver for transportation between collection hub and remanufacturing site (distance unit) in the centralised scenario

$$C^{centr}_{DA} \quad = \quad t^{total}_{DA} \cdot c^{*,\ centr}_{DA} \tag{5.7}$$

C^{centr}_{DA} ... total cost for disassembling in the centralised scenario
t^{total}_{DA} ... total time required for disassembling in order to perform all disassembling tasks needed
$c^{*,\ centr}_{DA}$ ... cost factor for disassembling (hourly labour rate/cost per time unit) in the centralised scenario

$$C^{centr}_{DP} \quad = \quad w_{not\ rel} \cdot c^{*,\ centr}_{DP} \tag{5.8}$$

C^{centr}_{DP} ... total cost for disposing in the centralised scenario
$w_{not\ rel}$ ... cumulated weight of not-relevant parts
$c^{*,\ centr}_{DP}$ ... cost factor for disposing not-relevant parts (cost per weight unit) in the centralised scenario

Decentralised industry structure

The second option for product recycling is a decentralised industry structure where disassembling is locally outsourced. This means that used products from a certain geographical area are shipped to a local disassembling site where they are already dismantled and separated into relevant and not-relevant parts. Only relevant parts are forwarded to the central remanufacturing site; not relevant parts are locally disposed in order to avoid the same transportation effort as in the centralised industry structure. An illustration of a decentralised structure is shown in Figure 5.5.

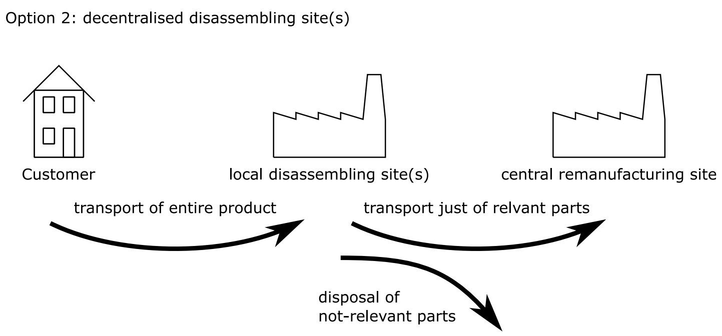

Figure (5.5): *Retrodistribution – in the context of a decentralised industry structure*

The total cost incurred in the scenario 'decentralised structure' ($TC^{decentr}$) is similar to the preceding scenario:

$$TC^{decentr} = C_{RD}^{decentr} + C_{DA}^{decentr} + C_{DP}^{decentr} \tag{5.9}$$

$TC^{decentr}$	...	total cost incurred in the retrodistribution scenario 'decentralised scenario' (basis for comparison)
$C_{RD}^{decentr}$	...	total cost for retrodistribution in the decentralised scenario
$C_{DA}^{decentr}$	...	total cost for disassembling in the decentralised scenario
$C_{DP}^{decentr}$	...	total cost for disposing / recycling in the decentralised scenario

The single contributors for the process steps retrodistributing, disassembling and disposing, respectively, are subsequently explained more in detail:

$$C_{RD}^{decentr} = C_{TF} + \underbrace{\overbrace{(w_{rel} + w_{not\ rel})}^{w_{total}} \cdot c_{TP,\,(1)}^{*,\,decentr} \cdot \widetilde{d_{TP,\,(1)}^{decentr}} + w_{rel} \cdot c_{TP,\,(2)}^{*,\,decentr} \cdot \widetilde{d_{TP,\,(2)}^{decentr}}}_{C_{transp}} \tag{5.10}$$

$C_{RD}^{decentr}$	...	total cost for retrodistribution in the centralised scenario
C_{TF}	...	cost for transferring ownership
C_{TP}	...	cost for transporting
w_{rel}	...	cumulated weight of relevant parts
$w_{not\ rel}$	...	cumulated weight of not-relevant parts
w_{total}	...	total product weight ($w_{rel} + w_{not\ rel}$)
$c_{TP,\,(1)}^{*,\,decentr}$	...	cost factor for certain mode of transportation between customer and disassembling site (cost per distance and weight unit) in the decentralised scenario
$c_{TP,\,(2)}^{*,\,decentr}$	...	cost factor for certain mode of transportation between disassembling site and remanufacturing site (cost per distance and weight unit) in the decentralised scenario
$\widetilde{d_{TP,\,(1)}^{decentr}}$	...	averaged cost driver for transportation between customer and disassembling site (distance unit) in the decentralised scenario
$\widetilde{d_{TP,\,(2)}^{decentr}}$	...	averaged cost driver for transportation between disassembling site and remanufacturing site (distance unit) in the decentralised scenario

The cumulated cost for disassembling in a decentral disassembling site are calculated as follows

$$C_{DA}^{decentr} = t_{DA}^{total} \cdot c_{DA}^{*,\,decentr} \tag{5.11}$$

$C_{DA}^{decentr}$	...	total cost for disassembling in the decentralised scenario
t_{DA}^{total}	...	total time required for disassembling in order to perform all disassembling tasks needed
$c_{DA}^{*,\,decentr}$	...	cost factor for disassembling at local disassembling site (hourly labour rate/cost per time unit) in the decentralised scenario

$$C_{DP}^{decentr} = w_{not\ rel} \cdot c_{disp}^{*,\,decentr} \tag{5.12}$$

$C_{DP}^{decentr}$	...	total cost for disposing in the decentralised scenario
$w_{not\ rel}$	...	cumulated weight of not-relevant parts
$c_{DP}^{*,\,decentr}$	...	cost factor for disposing not-relevant parts at local disassembling site (cost per weight unit)

Juxtaposition of both alternatives

In order to find the best option, both alternatives are juxtaposed in opposition and compared:

$$TC^{centr} \quad \left\{ \begin{matrix} > \\ = \\ < \end{matrix} \right\} \quad TC^{decentr} \tag{5.13}$$

TC^{centr}	...	total cost incurred in the retrodistribution scenario 'centralised scenario' (basis for comparison)
$TC^{decentr}$	...	total cost incurred in the retrodistribution scenario 'decentralised scenario' (basis for comparison)

Depending on which scenario is more cost expensive, the other one will be the one preferred. Hence, the above comparator recommends the decentral scenario while, in turn, the comparator at the bottom indicates higher economic efficiency in the centralised scenario (see equation 5.13).

For the sake of comparability of both alternatives some constraints and boundary conditions, respectively, are defined.

<u>Assumption 1:</u> It is supposed that the mathematical product of distance covered and corresponding cost factor, summed up for each distance, approximates in both scenarios.

$$\begin{aligned} & c^{*,\,centr}_{TP\ (1)} \cdot \widetilde{d^{centr}_{TP\ (1)}} + \\ & + c^{*,\,centr}_{TP\ (2)} \cdot \widetilde{d^{*,\,centr}_{TP\ (2)}} \quad = \quad c^{*,\,decentr}_{TP\ (1)} \cdot \widetilde{d^{decentr}_{TP\ (1)}} + \\ & \qquad\qquad\qquad\qquad\qquad + c^{*,\,decentr}_{TP\ (2)} \cdot \widetilde{d^{*,\,decentr}_{TP\ (2)}} \end{aligned} \tag{5.14}$$

$c^{*,\,centr}_{TP,\,(1)}$	...	cost factor for certain mode of transportation between customer and collection hub (cost per distance and weight unit) in the centralised scenario
$c^{*,\,centr}_{TP,\,(2)}$	...	cost factor for certain mode of transportation between collection hub and remanufacturing site (cost per distance and weight unit) in the centralised scenario
$\widetilde{d^{centr}_{TP,\,(1)}}$	...	averaged cost driver for transportation between customer and collection hub (distance unit) in the centralised scenario
$\widetilde{d^{centr}_{TP,\,(2)}}$	...	averaged cost driver for transportation between collection hub and remanufacturing site (distance unit) in the centralised scenario

$c^{*,\,decentr}_{TP,\,(1)}$	...	cost factor for certain mode of transportation between customer and disassembling site (cost per distance and weight unit) in the decentralised scenario
$c^{*,\,decentr}_{TP,\,(2)}$	...	cost factor for certain mode of transportation between disassembling site and remanufacturing site (cost per distance and weight unit) in the decentralised scenario
$\widetilde{d^{decentr}_{TP,\,(1)}}$	...	averaged cost driver for transportation between customer and disassembling site (distance unit) in the decentralised scenario
$\widetilde{d^{decentr}_{TP,\,(2)}}$	...	averaged cost driver for transportation between disassembling site and remanufacturing site (distance unit) in the decentralised scenario

This assumption can be justified by scrutinising the probably underlying logistical structures. Besides huge used products, which are collected on individual basis, there are most likely collecting hubs in the centralised scenario where used products are brought to in a first step and jointly forwarded in a second transportation step (in order to yield economies). Under the presumption of similar strategic considerations, collection sites in the centralised scenario are supposed to coincide with disassembling sites in the decentralised scenario – hence, the distances covered resemble in both scenarios.

Furthermore, the mode of transportation will, most probably, be the same in both scenarios (customer – collection / disassembling site and collection / disassembling site – remanufacturing site).

ASSUMPTION 2: Cost for transferring ownership equals in both scenarios.

ASSUMPTION 3: Cost for disposing / recycling equals in both scenarios; no local cost advantage attainable.

ASSUMPTION 4: Due to different economies of scale (less number of used products to disassemble in local, decentralised disassembling sites than in one single central disassembling / remanufacturing site) and due to different local hourly labour rates, the cost factor for disassembling will differ. Time required for disassembling is said to be equal in the local and central scenario. Out of it, the relationship of cost for disassembling in both scenarios is as follows:

$$C_{DA}^{decentr} = a \cdot C_{DA}^{centr} \quad \ldots \quad \text{with a} > 0 \tag{5.15}$$

$$c_{DA}^{*,\ decentr} \cdot t_{DA}^{total} = a \cdot c_{DA}^{*,\ centr} \cdot t_{DA}^{total} \tag{5.16}$$

$C_{DA}^{decentr}$ ... total cost for disassembling in the decentralised scenario
a ... cost scaling factor expressing the ratio of different labour cost levels in the centralised and decentralised scenario (with a > 0)
C_{DA}^{centr} ... total cost for disassembling in the centralised scenario
$c_{DA}^{*,\ decentr}$ ... cost factor for disassembling at local disassembling site (hourly labour rate/cost per time unit) in the decentralised scenario
t_{DA}^{total} ... total time required for disassembling in order to perform all disassembling tasks needed
$c_{DA}^{*,\ centr}$ ... cost factor for disassembling at central disassembling site (hourly labour rate/cost per time unit) in the centralised scenario

With those assumptions, the comparison of both scenarios depicts as follows (after cancelling equal terms on both sides):

$$w_{not\ rel} \cdot c_{TP\ (2)}^{*,\ decentr} \cdot \widetilde{d_{TP\ 2}^{decentr}} \quad \left\{ \begin{array}{c} > \\ = \\ < \end{array} \right\} \quad (a-1) \cdot c_{DA}^{*,\ centr} \cdot t_{DA}^{total} \tag{5.17}$$

$w_{not\ rel}$	...	cumulated weight of not relevant parts
$c_{TP,\ (2)}^{*,\ decentr}$	...	cost factor for certain mode of transportation between disassembling site and remanufacturing site (cost per distance and weight unit) in the decentralised scenario
$\widetilde{d_{TP,\ (2)}^{decentr}}$	...	averaged cost driver for transportation between disassembling site and remanufacturing site (distance unit) in the decentralised scenario
a	...	cost scaling factor expressing the ratio of different labour cost levels for disassembling in the centralised and decentralised scenario
$c_{DA}^{*,\ centr}$	...	cost factor for disassembling at central disassembling site (hourly labour rate/cost per time unit) in the centralised scenario
t_{DA}^{total}	...	total time required for disassembling in order to perform all disassembling tasks needed

Substituting $w_{not\ rel}$ by its relation to total product weight ($w_{not\ rel} = (1-s) \cdot w_{total}$), the business ratio for identifying the economically cheaper scenario, in a more general notation, looks as follows:

$$\frac{(1-s) \cdot w_{total}}{a-1} \quad \left\{ \begin{array}{c} > \\ = \\ < \end{array} \right\} \quad \frac{c_{DA}^{*} \cdot t_{DA}^{total}}{c_{TP}^{*} \cdot \widetilde{d_{TP}}} \tag{5.18}$$

$$\frac{1-s}{a-1} \quad \left\{ \begin{array}{c} > \\ = \\ < \end{array} \right\} \quad \underbrace{\frac{c_{DA}^{*} \cdot t_{DA}^{total}}{c_{TP}^{*} \cdot \widetilde{d_{TP}} \cdot w_{total}}}_{const>0} \tag{5.19}$$

s	...	ratio of relevant part's cumulated weight to total weight
a	...	cost scaling factor expressing the ratio of different labour cost levels for disassembling in the centralised and decentralised scenario
c_{DA}^{*}	...	cost factor for disassembling at central disassembling site (hourly labour rate/cost per time unit)
t_{DA}^{total}	...	total time required for disassembling in order to perform all disassembling tasks needed
c_{TP}	...	cost factor for certain mode of transportation between disassembling site and remanufacturing site (cost per distance and weight unit)
$\widetilde{d_{TP}}$	...	averaged cost driver for transportation between disassembling site and remanufacturing site (distance unit)
w_{total}	...	total product weight

s is the share (in per cent) of relevant parts' cumulated weight to total product weight ($s = [0 \dots 1]$). Obviously, this formula won't deliver mathematically satisfying results if and only if $a = 1$, hence, equation's validity is excluded in this very special case.

In addition, a must be greater than 1, so as an economic trade-off between locally vs. centralised disassembling can be yielded (for each $a < 1$ the right side of (5.17) will be negative and, in consequence, the decentralised scenario the economically first choice). The equation (5.19) is cast in a diagram in Figure 5.6. Knowing s, a and the corresponding cost factors and cost drivers for disassembling and transport, it is possible to compute the constant factor (right side in (5.19)), either choose or newly draw the dividing line and – according the intersection of s and a – choose the recommended retrodistribution strategy.

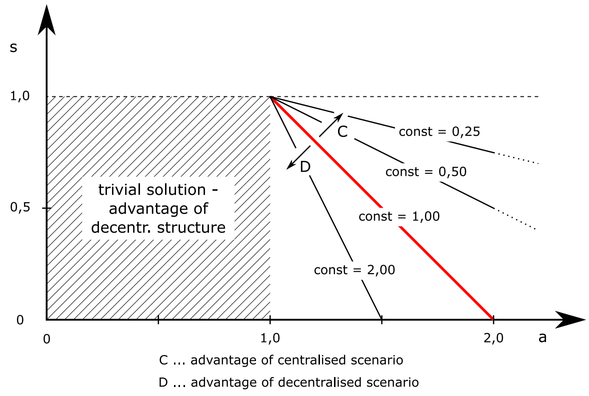

Figure (5.6): *Visualisation of decision rule*

In dependence on the chosen retrodistribution strategy, certain cost are incurred. Without going too much into depth the following sequence of cost driver emerges (partly already mentioned):

- cost for transferring ownership (C_{TF})
- cost for transporting product from the customer's to the disassembling plant ($C_{TP,\ C-D}$)
- cost for transporting relevant parts to the remanufacturing plant [optional] ($C_{TP,\ D-R\ (k)}$)
- cost for intraplant transportation [optional] ($C_{TP,\ intraplant\ (k)}$)

From the perspective of the single part level, the former two costs are common costs which need getting allocated to relevant parts. The latter ones are directly imputable cost items. The tag 'optional' is because of its dependence on the chosen product recycling strategy / retrodistribution strategy (disassembling site $\stackrel{?}{=}$ remanufacturing site) and the chosen accuracy.

For the purpose of the present method, transport cost are calculated – regardless whether the single part level or the entire product is focused on – just by multiplying the weight, the average distance between origin and destination, and a cost factor representing the mode of transportation (as shown before). Therefore, for a relevant part k the cost for transportation are as follows

$$C_{RD\ (k)} = \underbrace{(C_{TF} + C_{TP,\ C-D}) \cdot \frac{c_k}{C_{cum}^{max}}}_{\text{allocated common transportation cost}} + \underbrace{C_{TP,\ D-R\ (k)} + C_{TP,\ intraplant\ (k)}}_{\text{variable transportation cost for rel. part k}} \tag{5.20}$$

C_{TF}	...	cost for transferring ownership
$C_{TP,\ C-D}$	...	cost for transporting product from the customer's to the disassembling plant
$C_{TP,\ D-R\ (k)}$	...	cost for transporting relevant parts to the remanufacturing plant [optional]
$C_{TP,\ intraplant\ (k)}$	...	cost for intraplant transportation [optional]
c_k	...	cost per part k
C_{cum}^{max}	...	cumulated cost of set of relevant parts

The above equation is universally valid, irrelevant whether the used product is fetched using a kerb-side collection system or by means of active help on the part of customers. If customers are involved in transportation, then the take-over point moves closer to the company – this causes less cost from the perspective of companies.

5.2.2.2 Calculating effort for disassembling

The next big chunk of common cost is constituted by efforts needed for disassembling the old, used product. Knowing the position of the relevant parts within the product structure and their interfaces in terms of number and type of connections with the surrounding parts, a list of work instructions for disassembling can be generated. In general, cost for a single disassembling step is – for the purpose of the present method – simply calculated by multiplying time needed for accomplishing the step and a cost factor reflecting the technical equipment used. Before cost allocation is possible, the exact sequence of disassembling steps must be set where all interdependencies are taken into account. Such a sequence – just displayed schematically – is shown in Figure 5.7.

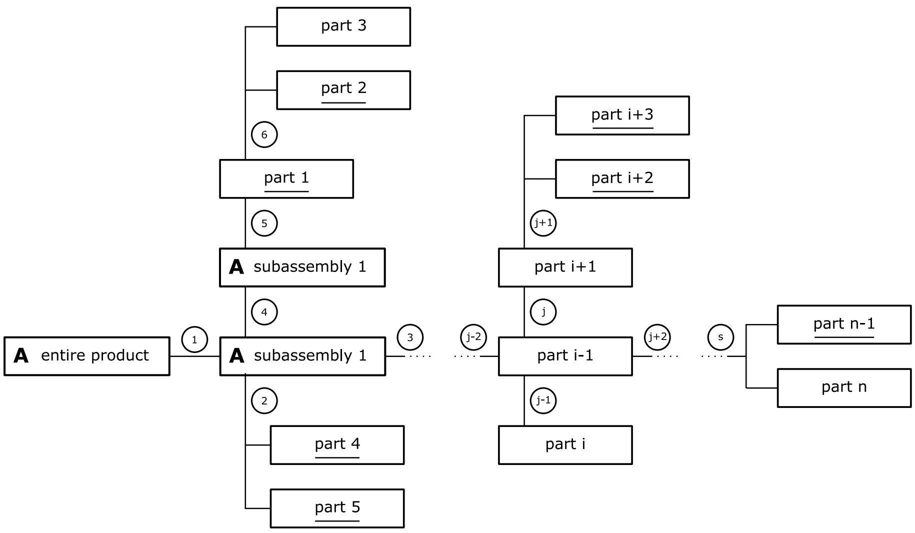

Figure (5.7): *Disassembling path of a product to be remanufactured – schematical principle*

As pictured in Figure 5.7, it is possible to visualise the sequence of disassembling steps. In this figure, boxes represent either parts or (sub-)assemblies (the latter are indicated with 'A'), while encircled numbers (and letters, respectively) model single disassembling tasks. Relevant parts are underlined.

Directly allotting cost of a certain disassembling step to the immediately dismantled part would neglect the fact that not necessarily only this part benefits from the task accomplished (see Figure 5.7, e.g. not only part 1 benefits from executing step 5, but also part 2 and 3; since part 3 is a not relevant part, cost for step 5 must be allocated only to part 1 and 2). Additionally, the direct approach fails too, since a disassembling step may be absolutely required but not resulting in a dismantled relevant part (but instead in a not-relevant one) – this effort must not be swept under the table. Hence, a more comprehensive allocation regime is necessitated. The question to answer is which relevant parts benefit from a certain disassembling step – in consequence, the corresponding beneficiaries must bear the cost load incurred by accomplishing this particular working step. The allocation principle as a function of part's manufacturing costs c_k is shown in Table 5.3.

For each disassembling task it is analysed which relevant part derives advantage from. The set of relevant parts benefiting from a particular task is marked with $B_{k,t} = 1$ in the table (e.g. column 3, 5, 8 and 11 for task 1). Doing this for every disassembling task, a kind of matrix is formed as result. This matrix is the starting point for calculating the so called *cumulated cost of beneficiaries* ($c^{ben}_{DT(t)}$); this means that for each relevant part marked with $B_{k,t} = 1$ the part cost c_k are summed up and noted in the corresponding row of the disassembling task. Expressed in mathematical terms it lists as follows

$$c^{ben}_{DT(t)} = \sum_{k=1}^{n} c_k \Big|_{B_{k,t}=1} = \sum_{k=1}^{n} c_k \cdot B_{k,t} \Big|_{t} \tag{5.21}$$

$c^{ben}_{DT(t)}$	...	cumulated part cost of beneficiaries for disassembling task t
c_k	...	cost per part
$B_{k,t}$	...	auxiliary variable indicating whether part k benefits from performing task t

Table (5.3): *Allocation of disassembling cost – schematical principle*

1	2	3	4	5	6	7	8	9	10	11	12	13	14
		part 1		part 2		⋯	part i+1		⋯	part n		cum. cost of benefi-ciary	stand. process cost
name	cost of disass. step	cost of part 1 c_1		cost of part 2 c_2		⋯	cost of part i+1 c_{i+1}		⋯	cost of part n c_n			
task T(1)	$c_{DA,\ T(1)}$	$B_{1,1} = 1$	$c^{D*}_{1,1}$	$B_{2,1} = 1$	$c^{D*}_{2,1}$	⋯	$B_{i+1,1} = 1$	$c^{D*}_{i+1,1}$	⋯	$B_{n,1} = 1$	$c^{D*}_{n,1}$	$c^{ben}_{DT(1)}$	$r_{DA,\ T(1)}$
task T(2)	$c_{DA,\ T(2)}$	–	0	–	0	⋯	–	0	⋯	–	0	$c^{ben}_{DT(2)}$	$r_{DA,\ T(2)}$
⋮	⋮	⋮		⋮		⋯	⋮		⋯	⋮		⋮	⋮
task T(4)	$c_{DA,\ T(4)}$	1	$c^{D*}_{1,4}$	1	$c^{D*}_{2,4}$	⋯	–	0	⋯	–	0	$c^{ben}_{DT(4)}$	$r_{D,\ T(4)}$
task T(5)	$c_{DA,\ T(5)}$	1	$c^{D*}_{1,5}$	1	$c^{D*}_{2,5}$	⋯	–	0	⋯	–	0	$c^{ben}_{DT(5)}$	$r_{DA,\ T(5)}$
⋮	⋮	⋮		⋮		⋯	⋮		⋯	⋮		⋮	⋮
task T(s)	$c_{DA,\ T(s)}$	–	0	–	0	⋯	1	$c^{D*}_{i+1,s}$	⋯	1	$c^{D*}_{n,s}$	$c^{ben}_{DT(s)}$	$r_{DA,\ T(s)}$
⋮	⋮	⋮		⋮		⋯	⋮		⋯	⋮		⋮	⋮
task T(m)	$c_{DA,\ T(m)}$	–	0	–	0	⋯	–	0	⋯	1	$c^{D*}_{n,m}$	$c^{ben}_{DT(m)}$	$r_{DA,\ T(m)}$

The next step to take is to standardise the task-related disassembling cost on basis of this cumulated cost number:

$$r_{DA,\ T(t)} = c_{DA,\ T(t)} / c^{ben}_{DT(t)} \tag{5.22}$$

$r_{DA,\ T(t)}$	...	standardised process cost for disassembling task t
$c_{DA,\ T(t)}$	...	cost of disassembling task t
$c^{ben}_{DT(t)}$	...	cumulated part cost of beneficiaries for disassembling task t

This ratio is used for computing the cost share of a particular disassembling task *t* which a relevant part *k* must bear ($c^{D*}_{k,t}$). This ratio is only calculated if a certain relevant part *k* is beneficiary of this particular disassembling task *t*, otherwise it is *0*.

$$c_{k,t}^{D*} = r_{DA,\ T(t)} \cdot c_k \tag{5.23}$$

$c_{k,t}^{D*}$	...	cost load allocated to part k caused from performing and benefiting of disassembling task t
$r_{DA,\ T(t)}$	...	standardised process cost for disassembling task t
c_k	...	cost per part k

Finally, the direct disassembling cost for a relevant part k ($c_{DA\ (k)}^{dir}$) are calculated by adding all $c_{k,t}^{D*}$ for a fixed k

$$c_{DA\ (k)}^{dir} = \sum_{t=1}^{m} c_{k,t}^{D*}\Big|_k \tag{5.24}$$

$c_{DA\ (k)}^{dir}$	...	direct disassembling cost for part k caused by performing all necessary disassembling tasks in order to get part k
$c_{k,t}^{D*}$	...	cost load allocated to part k caused from performing and benefiting of disassembling task t

However, it might be the case that a number u of additional cost-causing disassembling steps ($c_{DA,\ T(t)}$) is necessary so as to ensure the best result in disposing of not-relevant parts. The sum of these potential cost burdens is alloted to relevant parts by help of the common allocation factor c_k/C_{cum}^{max} defined in Table 5.1, last column. Hence, the indirect disassembling cost are as follows

$$c_{DA\ (k)}^{indir} = \frac{c_k}{C_{cum}^{max}} \cdot \sum_{t=m+1}^{m+u} c_{DA,\ T(t)} \tag{5.25}$$

$c_{DA\ (k)}^{indir}$	...	cost for disassembling caused by additional disassembling tasks in order to facilitate disposing the set of not relevant parts
c_k	...	cost per part
C_{cum}^{max}	...	cumulated cost of set of relevant parts
$c_{DA,\ T(t)}$	...	cost of disassembling task t

The final disassembling cost imposed on a relevant part k are

$$C_{DA\ (k)} = c_{DA\ (k)}^{dir} + c_{DA\ (k)}^{indir} \tag{5.26}$$

$C_{DA\ (k)}$	...	cost for disassembling per relevant part k
$c_{DA\ (k)}^{dir}$	...	direct disassembling cost for part k caused by performing all necessary disassembling tasks in order to get part k
$c_{DA\ (k)}^{indir}$	...	cost for disassembling caused by additional disassembling tasks in order to facilitate disposing the set of not relevant parts

5.2.2.3 Calculating effort for disposing / recycling

A not less important part of cost incurred, if product recycling is incorporated into the business model, is cost for disposal of both not-relevant parts and parts not reconditionable anymore because of their extent of damage. Following the recommendations of VDI, the next best treatment possibility is material recycling (as pin-pointed several times before). This way of treatment should be strived for. But to note, also cost for incinerating or dumping at land-fills must be taken into account here. Similar to other cost units mentioned before, cost for disposal of a certain part k ($C_{DP,\ RM\ (k)}$) consists of two parts, namely

- cost for disposing / recycling not-relevant parts ($c^{indir}_{DP\ (k)}$) and
- cost for disposing / recycling of part k not reconditionable anymore ($c^{dir}_{DP\ (k)}$).

The set of not-relevant parts is indirectly determined in the first process step when the set of relevant parts is identified. It is simply the difference between parts listed in the BOM and the set of relevant parts.

Each part, irrespective whether it is a relevant part not reconditionable anymore or a not-relevant part, causes certain cost for disposing ($c_{DP\ (k)}$). For the sake of simplicity, this cost is calculated (following the multiplicative approach from before) by connecting a cost driver (e.g. weight in this special case) and a cost factor reflecting the treatment method.

As already illustrated above on basis of indirect disassembling cost, the total cost for disposing of not-relevant parts is again allocated by aid of the general allocation rate, defined in Table 5.1, last column. Thus, the cost for disposing of not-relevant parts is

$$c^{indir,\ cum}_{DP\ (k)} = \sum_{k=i+1}^{n} c_{DP\ (k)} \tag{5.27}$$

$c^{indir,\ cum}_{DP\ (k)}$	...	cumulated cost for disposing not-relevant parts
$c_{DP\ (k)}$	...	cost for disposing part k

Allocated to a single relevant part k it is

$$c^{indir}_{DP\ (k)} = \frac{c_k}{C^{max}_{cum}} \cdot c^{indir,\ cum}_{DP\ (k)} \tag{5.28}$$

$c^{indir}_{DP\ (k)}$	...	cost for disposing not relevant parts allocated to relevant part k
c_k	...	cost per part
C^{max}_{cum}	...	cumulated cost of set of relevant parts
$c^{indir,\ cum}_{DP\ (k)}$	...	cumulated cost for disposing not-relevant parts

The direct cost share of disposing a damaged part k not eligible for reconditioning anymore is computed by simply multiplying the cost of the according treatment step for part k ($c_{DP\ (k)}$) and its probability of occurrence ($P_{RP\ (k)}$) – so, direct cost for disposing are as follows. $P_{RP\ (k)}$ is the cumulated probability of occurrence of damages not reconditionable of a particular relevant part k (see section 5.2.2.7 for more details).

$$c_{DP\ (k)}^{dir} = P_{RP\ (k)} \cdot c_{DP\ (k)} \tag{5.29}$$

$c_{DP\ (k)}^{dir}$	...	cost for disposing relevant part k forced to be substituted because of unreconditionable or unusable state
$P_{RP\ (k)}$	...	replacement probability because of unreconditionable or unusable state of relevant part k
$c_{DP\ (k)}$	...	cost for disposing part k

The sum of both forms the total cost for disposing burdened on a relevant part k:

$$C_{DP,\ RM\ (k)} = c_{DP\ (k)}^{dir} + c_{DP\ (k)}^{indir} \tag{5.30}$$

$C_{DP,\ RM\ (k)}$	...	cost for disposing per relevant part k
$c_{DP\ (k)}^{dir}$	...	cost for disposing relevant part k forced to be substituted because of unreconditionable or unusable state
$c_{DP\ (k)}^{indir}$	...	cost for disposing not relevant parts allocated to relevant part k

5.2.2.4 Calculating effort disadvantage

As argued before, in special cases it is reasonable to consider a potential drawback in comparison to a daughter product in order to ensure holistically approaching. For verifying this hypothesis some assumptions must be defined. In this rather theoretical thought the customer is said to be a utility-oriented individual who solely behaves rationally on the market and focuses only on product's utility value. This utility value is expressed as functional potential in relation to efforts required during the entire product life cycle. Supposedly, rational customers try to minimise total cost of ownership. So, they avoid a distorted view by only focusing on the purchasing price (directly linked to production costs as lower threshold) but also consider expenses occurring during the use phase like e.g. cost for energy, etc.

At a first glance companies are tempted to only focus on production cost in evaluating the feasibility of product recycling. However, this approach is too myopic since customers are prerequisite of economic success and they decide upon different incentives than businesses. So, even use phase-related cost are indispensable in the present method.

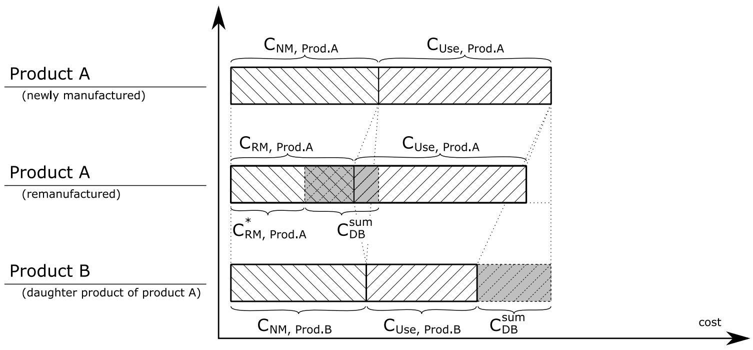

Figure (5.8): *Relative disadvantage of remanufactured products in comparison to daughter products – schematical principle*

In Figure 5.8 an example of this special case where a remanufactured products suffers from an efficiency drawback is shown. Starting point is a newly manufactured product A with its cost structure, as shown in the figure. The left side of the upper bar shows all the efforts a manufacturer needs to invest in order to provide market with this newly manufactured product A ($C_{NM,\ Prod.A}$), the right side is the effort occurring during use phase which customers have to bear ($C_{Use,\ Prod.A}$). Assuming feasibility of product recycling, the bar in the middle shows exemplary the same for a remanufactured product (for each $C_{RM,\ Prod.A} \leq C_{NM,\ Prod.A}$ product recycling is feasible). It is obvious that – without change in product A's specification – the effort incurred during use must be the same for both the newly manufactured and the remanufactured product. Focusing only on those two sums, in this constellation product recycling appears to be efficient and competitive.

The next hypothetical step is presuming the existence of a daughter product B. In general, daughter products emerge, inter alia, from improving already existing products and are said to be better either in terms of functional potential or in efficiency, meaning that it uses less investment during the entire life cycle. In order to avoid a biased comparison, only those products are allowed to be check against which are perceived as real alternatives from the customer's point of view. An important precondition is that both products are in the same performance category. If the regarded daughter product has an increased functional potential, both efforts for product provision and product use ($C_{NM,\ .}$ and $C_{Use,\ .}$) have to be standardised so as a fair basis for comparison is established. Of course, due to certain phenomenons like e.g. sort of technical economies of scale, more powerful products are able to provide function – and hence, satisfaction of customer's need – on average more efficiently. [124] But this case is excluded by demanding resemblance and commensurability of preceding and succeeding product from customer's perspective.

Such a daughter product B – which meets the previous conditions – is shown in Figure 5.8 in the bottom bar. For each manufacturing cost of product B higher than cost for remanufacturing of product A ($C_{NM,\ Prod.B} > C_{RM,\ Prod.A}$) the remanufactured product A seems to be the more competitive one if and only if provision cost are the basis for deciding. However, because of increased efficiency product B may perform better during use ($C_{Use,\ Prod.A} > C_{Use,\ Prod.B}$). If the total of both use phase-related and provision-related cost of product B exceeds the corresponding sum of the newly manufactured product A, then product recycling of product A is anyway a viable alternative – but, firstly, this special case is not interesting at all and, secondly, violates the assumption of increased performance and efficiency, respectively. Only a total of product B less than the total of product A is of peculiar interest.

From the perspective of market, the entire product A suffers from a structural disadvantage in the extent of C_{DB}^{sum} in comparison to product B. If the same competitiveness of A and B is strived for, this drawback must be considered. So, the upper threshold of cost for remanufacturing product A is $C^*_{RM,\ Prod.A}$. This threshold is computed by subtracting this disadvantage from manufacturing cost of product A

$$C^*_{RM,\ Prod.A} = C_{NM,\ Prod.A} - C_{DB}^{sum}. \tag{5.31}$$

$C^*_{RM,\ Prod.A}$	...	basis to compare product A not eligible for upgrading and intended for product recycling to in case of existence of more efficient daughter product
$C_{NM,\ Prod.A}$	...	cost for newly manufacturing product A
C_{DB}^{sum}.	...	cost drawback of product A in comparison to a more efficient product B under the premise of providing the same functionality

[124] keyword *effort degression*: e.g. on average a mini van is able to transport a person more cost-efficiently in comparison to a car

Hence, only for each $C_{RM,\ Prod.A} \leq C^{*}_{RM,\ Prod.A}$ product recycling of product A is a reasonable activity under the precondition of an existing, more efficient daughter product B. Thus, the example of remanufacturing product A, shown in Figure 5.8, wouldn't be a strategically good decision.

As consequence, this structural disadvantage must be allocated to relevant parts so as the remanufactured, preceding product A is as competitive as the succeeding product B. This cost is calculated using the common allocation factor, as defined in Table 5.1, last column.

$$C_{DB\ (k)} = C^{sum}_{DB} \cdot \frac{c_k}{C^{max}_{cum}} \tag{5.32}$$

$C_{DB\ (k)}$	...	cost drawback per relevant part k in case of existence of a more efficient daughter product B
C^{sum}_{DB}.	...	cost drawback of product A in comparison to a more efficient product B under the premise of providing the same functionality
c_k	...	cost for newly manufacturing product A
C^{max}_{cum}	...	cumulated cost of set of relevant parts

Amendatory, it is required to note that this allocation of drawback is only necessary if product recycling of the entire product is intended and this drawback can't be attributed to a single part or subassembly which can't be substituted by a more efficient one because of design or technology restrictions.

5.2.2.5 Calculating effort for cleaning

Under the term of *effort for cleaning* all efforts caused because of cleaning activities are summarised. Similar as for disassembling, for each treatment step and relevant part a sequence of necessary cleaning steps is defined on basis of information derived from use phase. For the sake of simplicity it is assumed that all information about cost (and environmental impact, respectively) is available. If not, common methods for determing cost or environmental impact have to be applied.

The principle of computing cost for each relevant part k incurred by *cleaning* is again equal to the previous approaches for computing effort – it is simply multiplying the cost factor ($c^{*}_{C,\ t}$) for each working step t with its cost driver ($d_{C\ (k),t}$) and summing up. E.g. *cleaning* cost per relevant part k are depicted schematically in Table 5.4.

$$C_{C\ (k)} = \sum^{t} c^{*}_{C,\ t} \cdot d_{C\ (k),t} \tag{5.33}$$

$C_{C\ (k)}$	...	cost for cleaning relevant part k
$c^{*}_{C,\ t}$	...	cost factor of cleaning process t
$d_{C\ (k),t}$	...	cost driver of cleaning process t

Table (5.4): *Calculating effort for cleaning – schematical principle*

1	2	3	4	5	6
no.	name	task	cost factor $c^*_{C,\ t}$	cost driver $d_{C\ (k),t}$	cum. cost per rel. part k
1	part 1	task 1	$c^*_{C,\ 1}$	$d_{C\ (1),1}$	↓
2		task 2	$c^*_{C,\ 2}$	$d_{C\ (1),2}$	$\sum_t c^*_{C,\ t} \cdot d_{C\ (1),t}$
3	part 2	task 3	$c^*_{C,\ 3}$	$d_{C\ (2),3}$	↓
4		⋮	⋮	⋮	
⋮		task j	$c^*_{C,\ j}$	$d_{C\ (2),j}$	$\sum_t c^*_{C,\ t} \cdot d_{C\ (2),t}$
u	part i	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮
v		task m	$c^*_{C,\ m}$	$d_{C\ (i),m}$	$\sum_t c^*_{C,\ t} \cdot d_{C\ (i),t}$

5.2.2.6 Calculating effort for testing

Computing the effort for *testing and sorting* is equal to the previous sections.

The sequence of working steps in the stages *cleaning* and *testing and sorting* are applied to the relevant part irrespective its state. So, all relevant parts experience the same treatment so as equal conditions for later reconditioning are set. The provision of a schematical table showing the procedure of calculating effort for testing is omitted because of space saving reasons since it is in accord with Table 5.4 (only replacing of the corresponding cost factor and cost drivers necessary).

The analogue procedure is:

$$C_{T\ (k)} = \sum^{t} c^*_{T,\ t} \cdot d_{T\ (k),t} \tag{5.34}$$

$C_{C\ (k)}$	...	cost for testing relevant part k
$c^*_{C,\ t}$	...	cost factor of testing process t
$d_{C\ (k),t}$	...	cost driver of testing process t

5.2.2.7 Calculating the effort for reconditioning

In order to calculate the (total) effort for reconditioning ($C_{RC\ (k)}$), the following approach is introduced. In general, the calculation of effort for reconditioning (abbreviated with RC) uses cost factors caused by the process ($c^*_{RC\ (k),t}$), cost drivers ($d_{RC\ (k),t}$) and probability of occurrence ($p_{RC\ (k),t}$). Additionally, in case of irreversibility of damages the flawed part must be substituted; this causes cost for replacement ($c_{RP\ (k),t}$, indexed with RP). The last variable used in the subsequent paragraphs is number of additional use phases ($N_{(k),t}$) indicating the amount of functional reserve.

By principle, the occurring damages can be distinguished, on the one hand, in the two categories

- reversible damages

- not reversible damages and, thus, causing finite residual life time

and, on the other hand, in

- function immanent damages and
- randomly occurring damages (caused by user behaviour).

In conjunction of those two categorisations, the following scenarios for reconditioning emerge (see Figure 5.9). These introduced scenarios differ in the way of calculating the effort to be invested – an explanation is following.

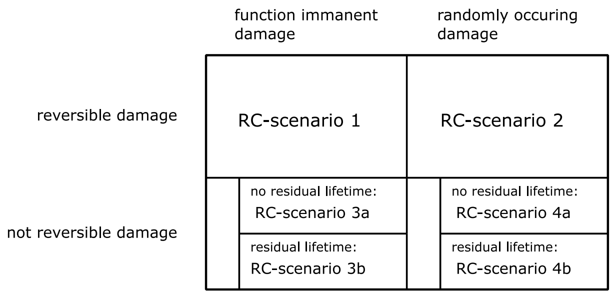

Figure (5.9): *Overview of different scenarios for reconditioning*

RC-Scenario 1: Although function immanent damages are incurred, it is possible to recondition the particular part to an 'as good as new state' and reverse the connected disadvantages. Because of its functional immanence the probability of occurrence is always $p_{RC\ (k),t} = 1$. Thereof, the cost incurred are calculated as

$$C_{RC\ (k),t} = c^*_{RC\ (k),t} \cdot d_{RC\ (k),t} \cdot p_{RC\ (k),t}$$

$$\ldots \text{ with } p_{RC\ (k),t} = 1$$

$C_{RC\ (k),t}$	...	cost of reconditioning task t per relevant part k
$c^*_{RC\ (k),t}$	...	cost factor of task t for reconditioning relevant part k
$d_{RC\ (k),t}$	...	cost driver of task t for reconditioning relevant part k
$p_{RC\ (k),t}$	...	probability of occurrence of a damage requiring reconditioning task t to be performed

RC-Scenario 2: Scenario 2 is similar to scenario 1 and differs only in damages' probability of occurrence. Since damages of this category are only appearing with a definite probability, the cost for reconditioning calculates totally equally to scenario 1 with the only difference of other values for $p_{RC\ (k),t}$ (ranging between 0 and 1).

RC-Scenario 3a: Scenario 3 splits up in two subcategories. Parts with not reversible, function immanent damages and no residual lifetime (no remaining functional reserve) don't need to be evaluated since they are already excluded in method's first filtering step.

RC-Scenario 3b: A similar description as in scenario 3a apply to parts in the current category. Although parts suffer from not reversible, function immanent damages, enough residual functionality is left so as this part can serve for a definite number of additional use phases ($N_{k,t}$). Because of damage's irreversibility, the part has to be disposed and replaced after these additional use phases are spent. However, some auxiliary treatment processes might be necessary so as the effort to be invested calculates as

$$C_{RC\ (k),t} = c^*_{RC\ (k),t} \cdot d_{RC\ (k),t} \cdot (1 - p_{RC\ (k),t}) + c_{RP\ (k),t} \cdot \frac{1}{N_{(k),t} + 1} \cdot p_{RC\ (k),t}$$

$$\ldots \text{ with } p_{RC\ (k),t} = 1$$

$C_{RC\ (k),t}$ ... cost of reconditioning task t per relevant part k
$c^*_{RC\ (k),t}$ ... cost factor of task t for reconditioning relevant part k
$d_{RC\ (k),t}$ ... cost driver of task t for reconditioning relevant part k
$p_{RC\ (k),t}$ ... probability of occurrence of a damage requiring reconditioning task t to be performed
$c_{RP\ (k),t}$ ... cost for replacing relevant part k
$N_{(k),t}$ ... number of residual use phases

RC-Scenario 4a: Unfortunately, similar to scenario 3a, parts with not reversible damages and no residual lifetimes are doomed to get disposed. Nevertheless, since this kind of damage doesn't occur with perfect certainty, there is the chance to reuse those parts unaffected. As consequence, only the share of damaged parts needs replacement.

$$C_{RC\ (k),t} = c^*_{RC\ (k),t} \cdot d_{RC\ (k),t} \cdot (1 - p_{RC\ (k),t}) + c_{RP\ (k),t} \cdot p_{RC\ (k),t}$$

$$\ldots \text{ with } p_{RC\ (k),t} = [0 \ldots 1)$$

$C_{RC\ (k),t}$ ... cost of reconditioning task t per relevant part k
$c^*_{RC\ (k),t}$ ... cost factor of task t for reconditioning relevant part k
$d_{RC\ (k),t}$ ... cost driver of task t for reconditioning relevant part k
$p_{RC\ (k),t}$ ... probability of occurrence of a damage requiring reconditioning task t to be performed
$c_{RP\ (k),t}$ ... cost for replacing relevant part k

RC-Scenario 4b: The last scenario features parts with not reversible, randomly occurring damages which, nonetheless, allow a certain number of additional lifetimes. Only after consumption of these extra lives, the part needs replacement. Hence, effort incurred by this type of damages (supportive treatment processes taken into account for the sake of completeness) reads as

$$C_{RC\ (k),t} = c^*_{RC\ (k),t} \cdot d_{RC\ (k),t} \cdot (1 - p_{RC\ (k),t}) + c_{RP\ (k),t} \cdot \frac{1}{N_{(k),t} + 1} \cdot p_{RC\ (k),t}$$

$$\ldots \text{ with } p_{RC\ (k),t} = [0 \ldots 1)$$

$C_{RC\ (k),t}$ ... cost of reconditioning task t per relevant part k
$c^*_{RC\ (k),t}$ ... cost factor of task t for reconditioning relevant part k
$d_{RC\ (k),t}$ ... cost driver of task t for reconditioning relevant part k
$p_{RC\ (k),t}$ ... probability of occurrence of a damage requiring reconditioning task t to be performed
$c_{RP\ (k),t}$ ... cost for replacing relevant part k
$N_{(k),t}$ ... number of residual use phases

To be precise, it is to note that $N_{(k),t}$ must always be the minimum number of technically possible and marketable additional life times, so as cost is allocated properly.

Beginning with the list of technical exclusion criteria in the category *eligibility for reconditioning* (see Table 5.2, criteria *TEC3 ff*) and in combination with extended use phase-related information, possible changes in part's specification (damages) are listed and categorised according the above distinction. Subsequently, the proper reconditioning techniques are derived and, if possible, cost factor ($c^{*}_{RC,t}$) as well as a cost driver ($d_{RC\ (k),t}$) are identified. For sure, those data must be available for all treatment processes. However, a part might be reused in its just cleaned state as it currently is. Hence, there is neither a explicit cost factor nor a cost driver for 'reconditioning processes'. Only if processing steps are necessary (e.g. flattening of worn surfaces), those computing variables are not void.

If a condition equal to its original state can't be yielded and no functional reserve is remaining (i.e. all remaining 'additional lifetimes' are already spent / consumed), the part must be disposed ($c^{dir}_{DP\ (k)}$ → see section 5.2.2.3). Therefore, the variable $P_{RP\ (k)}$ is defined (note: $P_{RP\ (k)} \neq p_{RC\ (k),t}$). This variable represents the cumulated probability of not reconditionable damages of relevant part k and already incorporates the depreciation effect of additional lifetimes.

However, the necessary set of very general equations looks like as follows:

$$C_{RC\ (k)} = \sum^{t} C_{RC\ (k),t} \tag{5.35}$$

$$P_{RP\ (k)} = min\left(\sum^{t} p_{RC\ (k),t} \cdot \frac{1}{N_{(k),t}+1};\ 1\right) \tag{5.36}$$

$C_{RC\ (k)}$	...	cost of reconditioning per relevant part k
$C_{RC\ (k),t}$	...	cost of reconditioning task t per relevant part k
$P_{RP\ (k)}$	...	probability of replacement relevant part k
$p_{RC\ (k),t}$	...	probability of occurrence of a damage requiring reconditioning task t to be performed
$N_{(k),t}$	...	number of residual use phases

Table (5.5): *Calculating effort for reconditioning – schematical principle for relevant part k*

1	2	3	4	5	6	7	8	9	10	11
no.	description of damage	description of task	prob. of occur-rence	scenario	number of additional life times	cost factor $c^{*}_{RC,\ (k),t}$ <unit>	env. cost factor $ei^{*}_{RC,\ (k),t}$ <unit>	cost driver $d_{RC\ (k),t}$ <unit>	cost per task $C_{RC\ (k),t}$ <unit>	env. imp. per task $EI_{RC\ (k),t}$ <unit>
cost for reconditioning										
1	damage 1	task 1	$p_{RC\ (k),1}$	SC1	—	$c^{*}_{RC,\ (k),1}$	$ei^{*}_{RC,\ (k),1}$	$d_{RC\ (k),1}$	↓	↓
⋮		⋮	⋮	⋮	⋮	⋮	⋮			
f	damage f	task f	$p_{RC\ (k),f}$	SC3b	$N_{k,f}$	—	—	—	↓	↓
⋮		⋮	⋮	⋮	⋮	⋮				
u		task u	$p_{RC\ (k),u}$	4b	$N_{k,u}$	$c^{*}_{RC,\ (k),u}$	$ei^{*}_{RC,\ (k),u}$	$d_{RC\ (k),u}$		
total cost for reconditioning									$C_{RC\ (k)}$	$EI_{RC\ (k)}$

Particularly in respect to the last line of above equations, it seems to be curious that a total probability of occurrence greater than 1 (left term inside the minimum function) is possible. That is because part's occurrence of damage is handled as single, independent event – in practice, a particular relevant part can suffer from different (more than one) not reversible flaws whereas it needs only one-time replacement.

Exemplarily, the principle is shown in Table 5.5 using only one single relevant part k.

5.2.2.8 Calculating effort for newly manufacturing

In order to assess the economic and ecological eligibility of remanufacturing a particular product (or rather part), a precondition is the knowledge about its cost and environmental impact caused by newly manufacturing – the basis to compare the remanufactured product / part with. Usually, this information is sourced from company's design department and / or cost accounting. If the data required isn't available – as it expectedly is the case for environmental impact – an analogous calculation approach, as it is performed in the previous steps, must be applied.

For the sake of simplicity, only raw material ($c_{NM\ (k)}^{cum.\ mat.}$) and processing ($c_{NM\ (k)}^{cum.\ process.}$) is moved into the centre of focus. By means of technical drawings and work instructions, a list of materials and process steps, respectively, is set out in writing which forms the basis for the subsequent calculation. The multiplication of cost factor and cost driver in each category forms the wanted result, again.

$$C_{NM\ (k)} = c_{NM\ (k)}^{cum.\ mat.} + c_{NM\ (k)}^{cum.\ process.} \tag{5.37}$$

$$c_{NM\ (k)}^{cum.\ mat.} = \sum_t c_{NM,\ t}^{mat.*} \cdot d_{NM\ (k),t}^{mat.} \tag{5.38}$$

$$c_{NM\ (k)}^{cum.\ process.} = \sum_t c_{NM,\ t}^{process.*} \cdot d_{NM\ (k),t}^{process.} \tag{5.39}$$

$C_{NM\ (k)}$	...	cost for newly manufacturing relevant part k
$c_{NM\ (k)}^{cum.\ mat.}$	...	cumulated material cost for newly manufacturing relevant part k
$c_{NM\ (k)}^{cum.\ process.}$	...	cumulated processing cost for newly manufacturing relevant part k
$c_{NM,\ t}^{mat.*}$	...	cost factor for material t
$d_{NM\ (k),t}^{mat.}$	...	cost driver for material t and relevant part k
$c_{NM,\ t}^{process.*}$	...	cost factor for process t
$d_{NM\ (k),t}^{process.}$	...	cost driver for process t and relevant part k

Table 5.6 shows briefly the concept for calculating the cost for manufacturing using a single relevant part k.

5.2.3 Qualitative assessment

5.2.3.1 General notes

Complementary to the quantitative dimensions, the present method also comprises a qualitative assessment of certain criteria. This assessment is adapted from the so called utility value analysis as it is described in RINZA/SCHMITZ (1977). A utility value analysis delivers an optimal performance when the best choice, influenced by different parameters, has to be done among a set of

Table (5.6): *Calculating effort for manufacturing – schematical principle*

1	2	3	4	5	6
no.	name	task	cost factor $c^*_{C\ t}$	cost driver $d_{C\ (k),t}$	cum. cost per rel. part k
cost for material					
1	part k	material 1	$c^{mat.*}_{NM,\ 1}$	$d^{mat.}_{NM\ (k),1}$	↓
⋮		⋮	⋮	⋮	
⋮		material m	$c^{mat.*}_{NM,\ m}$	$d^{mat.}_{NM\ (k),m}$	$\sum_t c^{mat.*}_{NM,\ t} \cdot d^{mat.}_{NM\ (k),t}$
cost for processing					
⋮		task 1	$c^{process.*}_{NM,\ 1}$	$d^{process.}_{NM\ (k),1}$	↓
⋮		⋮	⋮	⋮	
⋮		task t	$c^{process.*}_{NM,\ t}$	$d^{process.}_{NM\ (k),t}$	$\sum_t c^{process.*}_{NM,\ t} \cdot d^{process.}_{NM\ (k),t}$
total cost for newly manufacturing					$C_{NM\ (k)}$

alternatives.[125] Especially, if non-pecuniary aspects have to be analysed, a utility value analysis offers a profound basis for decision-making.

However, the nature of utility value analyses inherent is the possibility of choosing among several alternatives. In the current case of assessing parts' eligibility for product recycling the question is not to choose the best part among the product constituting parts, but to figure out whether it is economically, ecologically and strategically reasonable to remanufacture a particular part. The former two quantitative dimensions need support and extension by qualitative ones – an area where utility value analyses are predestinated. But because of the mentioned limitation, only an adapted version is applied.

A challenge at the very beginning of such an analysis is the transformation of object's single attributes into measurable numbers. Hence, it is highly recommended to firstly identify those parameters and criteria which influence the final decision, to transform the criteria's attributes and then to aggregate this characteristic numbers. By structured proceeding an elusive problem can be 'cut into small pieces', which are more easily to handle. Figuratively, this method's structure equals a tree and its branches, respectively. After determining a utility value for each single criterion, these numbers are aggregated so as a single number for decision support is provided. There are several ways of aggregation which aren't explained here (for more-in-depth-information see RINZA/SCHMITZ (1977)).

The simplest way of aggregating is an addition of each single utility value U_i

$$U_{sum} = \sum_{i=1}^{n} U_i \tag{5.40}$$

A structural disadvantage of aggregation by addition is the possible substitution of utility values. This means that a high utility value of parameter i can outweigh a low utility value of parameter $i+1$ – this fact must be kept in mind! If certain minimum requirements have to be met, the

[125] see RINZA/SCHMITZ (1977), p.19.

multiplicative approach delivers more promising and satisfying results.

$$U_{sum} = \prod_{i=1}^{n} U_i \tag{5.41}$$

In a first attempt the big topic of *product recycling* was structured following a strict branching. By assistance of the brainstorming technique, the detected parameters were split into criteria which were split again into subcriteria. After several times rethinking and restructuring a 2-level structure in two disjunct main fields (strategical and technical incentives) with additive cumulation of the single utility values was identified. Unfortunately, this approach didn't perform in a satisfactory manner. Additionally, a maxim of utility value analyes – the avoidance of double assessment – was violated by assessing the same technical criteria in both the quantitative (economic eligibility) and qualitative dimension (technical incentive). That's why the first draft was scrapped and a slenderised, more elegant approach with assessment focusing only on strategical criteria was found. Moreover, also the way of additively cumulating single utility values was partly discarded and replaced by the multiplicative one. A thorough description follows – every criterion and its implications on product recycling is explained.

5.2.3.2 Assessing the strategical incentives

In assessing products' reusability, the strategical dimension is as important as the economic and ecological dimension. Herein, all parameters, which are limitedly influenceable by a single company, are collected and distinguished in two categories. The so called 'strategical exclusion criteria' are minimum requirements which a product has to meet. The second, not that obligatory category comprises rather soft criteria which indicate an incentive to incorporate product recycling into the business model. In contrast to the first, compulsory category, here only 'inclusion criteria' are present. All these parameters are – directly or indirectly – intricately woven with the *'magic triangle of economy'* consisting of customers, competitors and suppliers. Unless other indicated, the criteria mentioned below are applied to the entire assembly.

The exclusion criteria, at one glance, are

- lifetime-related eligibility,
- return-related eligibility and
- market-related eligibility,

and are explained immediately below.

The category of soft criteria contains only material supply-related incentives and is explained later. As already brought up in a previous paragraph, for assessing product's and part's strategical eligibility, a multiplicative cumulation approach is chosen. Furthermore, exclusion criteria are scaled binarily, the inclusion criteria are measured according a finer partitioning between 0 and 1 (for more information on the scaling see the tables in the addendum). This means for the final result in the dimension strategical eligibility, that all single criteria must be satisfyingly fulfilled so as to yield a positive decision *'pro product recycling'*.

The first parameter in the group of strategical exclusion criteria is **lifetime-related eligibility**. In this respect, the *ratio of product lifetime to market lifetime* decides about eligibility for reusing.

Herein, the term *product lifetime* means the span of time in which the product satisfies customer's needs (=lifetime until product retirement). Usually, this period is affected by technical specifications and user behaviour. The expression *(remaining) market lifetime* comprises that time period in which a product is marketed successfully. The main drivers of market lifetime are competitive product alternatives and / or in-house innovations. These alternative products exacerbate sale or, at least, cause heavy competitive disadvantages to the regarded product. Hence, a ratio significantly lower than 1 is the minimum condition to be met. The amendment *'significantly lower'* refers to the claim that still a remaining market time must be existent so as the remanufactured product can be sold (see Figure 3.4 for graphical details). Though, the lower this ratio of product lifetime to market lifetime, the better it is for product recycling. This finding is easy to justify – assuming the feasibility of infinitely repeatable product recycling (i.e. the functional potential is fully refreshed every time), then a low ratio of product lifetime to market lifetime means a frequent using of the same initial input which is needed for newly manufacturing a particular product. So to say, higher economies of scale are yielded over time. However, the construct of infinitely repeating product recycling is a rather theoretical one, but the intension is clearly perceptible. By trend, also the investments made for building-up infrastructure for remanufacturing pays off since relatively more remanufactured products are marketed. In respect to this ratio, the only challenge lies in finding the extent of both product lifetime and market lifetime. The former one is seemingly easier to identify because it depends on design criteria. The main difficulty is accurately anticipating market lifetime, which is impossible at all. The only remedy is estimating and approximating market lifetime on basis of historical data.

However, in fast moving industries this minimum requirement can't be fulfilled. As mentioned before, chances for product recycling are restricted by innovations. Higher performance and efficiency, which come along with innovations, are structural disadvantages for products to be remanufactured. This obstacle might be overcome if parts or subassemblies responsible for this drawback can be identified and substituted. Hence, *upgradability* to technology's state-of-the-art is crucial for economic success. From a technical perspective, upgradability is facilitated by modularised product structure and predefined interfaces between subassemblies. Only if neither a proper life time ratio nor the possibility for upgrading exists, the eligibility for reusing is void.

Customers have on both the input side and output side of the transformation process *product recycling* a crucial role to play. On the input side they are jointly responsible for the backflow of used products and determine the **return-related eligibility** of products. This eligibility depends on the *incentive for customers to return [the] product*. By means of legal constraints or monetary incentives like e.g. repurchase or return of deposit, the backflow of used products is stimulated. Furthermore, the logistics of refluent products absolutely need a sophisticated *collecting system for used products* so as product recycling might successfully be established. Product service systems which generally base on the legal construct of 'using' instead of 'owning' might facilitate the backflow of used products, as well

Market-related eligibility is also a key issue of business strategy and strategical incentives, respectively. Product recycling is doomed to fail if customers do not accept remanufactured products for whatever reasons. Thus, the criterion *acceptance of remanufactured products* plays an important role. Remanufactured products are more likely being accepted if customers's awareness about environmental issues is highly shaped.

Another criterion closely related to the former one is *sales dominating parameter*. This criterion reflects customer's attitude towards a product and which purpose it embodies from the perspective of customers. The application of product recycling is perfectly in line with 'function dominated' products. Dominance of product's function is especially prevailing in the business-to-business market or other markets where economic or functional performance are the main drivers in the purchase decision-making processes. In opposite, product recycling is more likely to fail if aesthetics (trend / fashion) and emotions dominate the purchase. In turn, this last limitation pin-points to a subcriterion on part level which enables remanufacturing of fashion-dominated products. In case of a relatively low ratio of product lifetime to market lifetime (see first criterion of exclusion criteria), product recycling is no big deal, even for fashion-dominated products. Contrarily, in a fast fashion-changing environment, only the outer appearance might limit product's reusability, although the inner function-relevant technological paradigm is still up-to-date. In case of significantly shorter 'fashion market lifetime' than 'technological market lifetime' only the *influence of fashion on part* is relevant for remanufacturing. Usually, parts of the outer surface are responsible for product's optic, haptic and general occurrence. Hence, mainly parts in product's inside have the chance of getting successfully reconditioned.

Since exclusion criteria's explanation is terminated (a list is also found in the addendum, Table B.1), the last set of strategical criteria is expounded. This set of criteria, named **safety of material supply**, which is applied on part level, provides a more or less strong incentive for incorporating product recycling in the business model. The higher this number, the better company's position within the market place becomes since several threats, because of material supply, are weakened. As already the name points to, this parameter deals with criteria on the input side of the economic entity 'business'. Every business would be faced with ruin, if no input to be transformed is available.

Global allocation of primary material sources is the first criterion addressing this risk. Business have a huge incentive to apply product recycling if availability of raw materials drops or is at risk to drop. Availability is influenced by the amount of reserves at hand and its annual consumption rate as well as total number and reliability of sources. The former argument is dedicated to an own (sub-)criterion. Few sources in politically unstable countries expose a company to high logistical risk. Then, companies have a high incentive to become more independent and 'cut the cord'. A key number for assessing this risk (and its explanation where it is sourced and how it is computed) is appended in addendum, chapter A.2.

The *existence of reclaiming techniques* (i.e. reclaiming raw materials from waste) is essential, as well. If there are no such techniques, the dependency on primary resources stays very high. In a finite environment with limited resources, the need for certain raw materials will lead to conflicts in the more or less far future – thus, lacking of reclaiming techniques represents a high incentive for product recycling. However, the subcriterion *supply horizon of primary material* also influences this special incentive. This supply horizon reflects the time until mankind runs out of primary raw materials. In appendix A.1, Table A.4, the range for selected, industrially important raw materials is computed. A longer availability range of particular materials cause decreasing, a shorter range cause the increase in incentive for product recycling. Here, also the *replaceability by material with longer supply horizon* plays an important role. If substitution of material (especially in times of scarcity) is possible, the stimulus for applying reuse plummets again.

An overview of these criteria and the according scales are attached in the addendum, Table B.2 and B.3. Summarising the above findings for soft strategical criteria, it is to note that these incentives are also kind of risk assessment. Like mankind, also businesses intend to minimise the risk they are exposed to. Product recycling might help to diversify risk and lower it accordingly.

The final outcome of assessment of strategical criteria is calculated as follows

$$R^*_{St\ (k)} = \prod^{j} U_j \tag{5.42}$$

where U_j is the single utility value of each strategical criterion.

5.2.4 Final ranking and interpretation of results

The main aim of the current methodology is to find a clear answer whether product recycling is a reasonable activity. Hence, the preceding subresults must get concentrated in order to provide a single number representing the basis for decision-making.

As already briefly mentioned, the process of 'product recycling' must be economically, ecologically and strategically efficient. This means that total cost (in the economic as well as ecological sense) must be lower for product recycling than for newly manufacturing. This is expressed by the ratios $R^*_{ECO\ (k)}$ and $R^*_{ENV\ (k)}$, respectively, representing the economic and ecological effectiveness. Per definition, only the range $[0 \ldots 1]$ is interesting for the method's purposes since in this range product recycling is performed efficiently. The closer the final result to 1, valid for all dimensions, the better the eligibility for product recycling.

The final summary, where all characteristic index numbers are compacted, looks schematically as shown in Table 5.7. The first two columns are self-explaining, column 3 and 4 list, for the sake of lucidity, the total cost for newly manufacturing and remanufacturing part *k* while column 5 and 6 show the corresponding numbers for the environmental impact incurred. Out of this numbers the two ratios $R^*_{ECO\ (k)}$ and $R^*_{ENV\ (k)}$ are calculated and displayed in column 7 and 8. Column 9 depicts the outcome of the strategical assessment, while the next column (column 10) lists possibly active technical exclusion criteria. Only if values between $(0 \ldots 1$ are prevailing in column 7 – 9 and no technical exclusion criteria is active, then the overall eligibility for product recycling is positive.

Table (5.7): *Summary of method's outcome – schematical principle*

1	2	3	4	5	6	7	8	9	10	11
no.	name	economic effort		ecological effort		characteristic index numbers				overall eligibility
		newly man.	reman.	newly man.	reman.	econ.	ecol.	strat.	tech.	
1	part 1	$C^{total}_{NM\ (1)}$	$C^{total}_{RM\ (1)}$	$EI^{total}_{NM\ (1)}$	$EI^{total}_{RM\ (1)}$	$R^*_{ECO\ (1)}$	$R^*_{ENV\ (1)}$	$R^*_{St\ (1)}$	—	$FD_{(1)}$
2	part 2	$C^{total}_{NM\ (2)}$	$C^{total}_{RM\ (2)}$	$EI^{total}_{NM\ (2)}$	$EI^{total}_{RM\ (2)}$	$R^*_{ECO\ (2)}$	$R^*_{ENV\ (2)}$	$R^*_{St\ (2)}$	TEC_x	no
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
i	part i	$C^{total}_{NM\ (i)}$	$C^{total}_{RM\ (i)}$	$EI^{total}_{NM\ (i)}$	$EI^{total}_{RM\ (i)}$	$R^*_{ECO\ (i)}$	$R^*_{ENV\ (i)}$	$R^*_{St\ (i)}$	—	$FD_{(i)}$

In a second more detailed table, more information about active technical exclusion criteria (column 3), cost for remanufacturing in total (column 11) and the according main cost contributors (column 5, 7 and 9) are shown. In this overview, the total cost for remanufacturing a relevant part *k* (column 11: total per part – $C_{\sum k}$) are broken down on main process level. By computing the share of total cost for remanufacturing for each single main cost contributor, it is intended to enable quickly identifying those processes contributing most. The two greatest cost units are highlighted in bold.

If a relevant part k is technically (referring to technical exclusion criteria) and strategically (referring mainly to strategical exclusion criteria) eligible but only fails because of too less economic efficiency, then those two highlighted cost contributors mark the first fields of optimisation.

Table (5.8): *Summary of method's outcome (apportionment) – schematical principle*

1	2	3	4	5	6	7	8	9	10	11	12	13
no.	name	active TEC?	econ. feasible?	effort for retrodistribution		effort for disassembling		effort for cleaning		total per part	current cost share	required cost share
				in €	in % of total	in €	in % of total	in €	in % of total	in €		
1	part 1	—	[yes|no]	$c_{RD,(1)}$	$r_{RD,(1)}$	$\mathbf{c_{DA,(1)}}$	$\mathbf{r_{DA,(1)}}$	$c_{C,(1)}$	$r_{C,(1)}$			
2	part 2	TEC_j	no	—	—	—	—	—	—			
3	part 3	—	[yes|no]	$c_{RD,(3)}$	$r_{RD,(3)}$	$\mathbf{c_{DA,(3)}}$	$\mathbf{r_{DA,(3)}}$	$\mathbf{c_{C,(3)}}$	$\mathbf{r_{C,(3)}}$			
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
i	part i	—	[yes|no]	$c_{RD,(i)}$	$r_{RD,(i)}$	$c_{DA,(i)}$	$r_{DA,(i)}$	$c_{C,(i)}$	$r_{C,(i)}$			
				effort for testing		effort for reconditioning		effort for disposing				
				in €	in % of total	in €	in % of total	in €	in % of total			
(1)				$c_{T,(1)}$	$r_{T,(1)}$	$\mathbf{c_{RC,(1)}}$	$\mathbf{r_{RC,(1)}}$	$c_{DP,(1)}$	$r_{DP,(1)}$	$c_{RM\ (1)}$	r_1	r_1^*
(2)				—	—	—	—	—	—	—	—	—
(3)				$c_{T,(3)}$	$r_{T,(3)}$	$c_{RC,(3)}$	$r_{RC,(3)}$	$c_{DP,(3)}$	$r_{DP,(3)}$	$c_{RM\ (3)}$	r_3	r_3^*
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮			
(i)				$\mathbf{c_{T,(i)}}$	$\mathbf{r_{T,(i)}}$	$\mathbf{c_{RC,(i)}}$	$\mathbf{r_{RC,(i)}}$	$c_{DP,(i)}$	$r_{DP,(i)}$	$c_{RM\ (i)}$	r_i	r_i^*

Additionally, the last columns in Table 5.8 provide hints at which extent optimisation is necessary. Column 12 shows the cost share of total cost for newly manufacturing (see Table 5.1, column 4) for each relevant part k. In the last column, the ratio of total cost for remanufacturing a relevant part k and the total cost for newly manufacturing the entire product is determined. By doing so, the user of the method gets a glimpse of how the cost structure in production needs to change by fixed efforts for remanufacturing ceteris paribus (as previously calculated) so as remanufacturing this very part would be efficient. With exception of Table 5.7, where the ecological effort is already included, the foregoing explanation is again valid for the numbers dealing with ecological effort / environmental impact.

The last step of technical documentation is creating a report for each relevant part$k$ where, for a last time, the part is verbally described, its strengths are juxtaposed to its weaknesses and, in case of proving its inefficiency for product recycling, proposals for optimisation are provided. All those levers which the design engineer is able to influence, are described in the next chapter. They are the technical basis for improvement.

5.2.5 Hints for optimising part's performance for product recycling

Obviously, product recycling is a deeply technical process – this is why a technical consideration must not be missing. In respect to product recycling, literature provides valuable assistance and food for taught in identifying pivotal parameters and criteria which enable reusability by trend.[126]

At a glance, the main parameter influencing technical eligibility are (in chronological order)

- eligibility for disassembling,
- eligibility for cleaning,
- eligibility for testing,
- eligibility for disposing / recycling of not relevant and not reconditionable parts, and
- eligibility for reconditioning.

which are detailed below. In Figure 5.9, a check list with criteria necessary for enhancing product's and part's reusability, respectively, is displayed.

Table (5.9): *List of technical criteria for optimising technical eligibility*

No.	category	field of application	criterion name
T1.1	eligibility for disassembling	asm	easiness of handling product
T1.2			containing (toxic) auxiliary materials
T1.2a			↪ accessibility of drain point
T1.2b			↪ possibility of complete draining
T1.3			number of different joints
T1.4			number of different mating directions
T1.5			complexity of assembly structure
T1.6		part	recognisability of joints
T1.9			accessibility of joints
T1.11			effort for unlocking (qual. description)
T1.12			easiness of handling part
T1.13			usability of standardised tools for disassembling
T1.13			total numbers of joints
T1.14			number of different joints
T1.15			need of simultaneously unlocking joints
T2.1	eligibility for cleaning	part	soiling tendency
T2.1a			↪ cleanability of surface
T2.1b			↪ avoidance of corners and undercuts
T3.1	eligibility for testing	part	possibility of automated testing
T4.1	eligibility for disposing / recycling of not-relevant parts	asm	number of different materials
T4.2			↪ compatibility of materials for common recycling process
T4.3			recyclability of materials
T4.4			labelling of materials
T5.1	eligibility for reconditioning (regarding alterations during use phase)	part	reversibility (or mitigation by consideration in advance) of part's alterations during use phase
T5.1a			↪ wear
T5.1b			↪ fatigue
T5.1c			↪ deformation
T5.1d			↪ corrosion
T5.1e			↪ other changes of functional potential

Eligibility for disassembling comprises a set of criteria applied to the entire assembly. The next five criteria are solely dedicated to analyse the whole product. The first 'assembly criterion' is *easiness of handling [the] product*. In a disassembling scenario rather dominated by manual labour, parts intended for remanufacturing should be designed in a way so that a factory worker is able to manually handle them without suffering serious damages because of permanent overloads. This claim is not always possible – hence, at least defined spots on the parts surface for mounting lifting tools are preferable so as parts can get lifted (-out) without damages for the part itself, the residual assembly and, of course, the employee. In a disassembling scenario dominated by

[126] see MABEE/BROMMER/KEAT (1999), pp.361, TÜRCK (1990), pp.218 and WIMMER/ZÜST (2001), pp.65

automated disassembling plants the claim for easy handling is also crucial. The more complex the movements needed for dismantling the product is, the more cost intensive the disassembling gets.

A criterion which possibly influences all subsequent working steps is *containing (toxic) auxiliary materials*. This only forms a disadvantage in product recycling if and only if *accessibility of [the] drain point* is bad and there is no *possibility of complete draining*.

A high *number of different joints* is often a guarantor for increased workload needed for disassembling. Different joints usually require different disassembling tools, and, as a consequence, tool change inbetween. Frequent tool changes drive time which, in turn, drives cost and diminishes productivity. The same is valid for *number of different mating directions*. It is favourable to place a product to be disassembled only once before starting the disassembling sequence. If all disassembling movements have the same direction, an optimum is reached. Each change of location and placement costs time and results in lowered productivity. This claim should not be extended to the level of 'atomic granularity'. It only demands as few as possible mating directions in one disassembling step. If a product consists of subassemblies with different mating directions, the above claim might also be fulfilled. If the used product is first dismantled into its subassemblies and then further disassembled to the single part level, then it is no contradiction to the claim of only one mating direction. The second disassembling step needs repositioning anyway.

The *complexity of [the] assembly structure* is the last criterion in the set of 'assembly criteria for disassembling'. The optimal structure is a flat hierarchy with only one single connecting element in the core. However, in the majority of cases this call is not really realisable. Hence, a highly modularised assembly structure is convenient, as well. In such a structure, only few but standardised interfaces are present, cross-linkages are avoided.

The subset of criteria for parts influencing the eligibility for disassembling starts with claiming the *recognisability of joints*. If joints are not easily recognisable, neither factory worker nor optical-guided industrial disassembling robots are able to detect them in short time. These exacerbated working conditions result in increased disassembling time and cost.

Closely linked to the previous criterion is the *accessibility of joints*. An efficient disassembling step bases on the direct accessibility of the joint so as the corresponding disconnecting movements are performed properly.

One of the most important criteria in respect to disassembling is *reversibility of joints*. Since product recycling presupposes the integrity of parts, it is not allowed to harm part's sound condition during disassembling. Joining techniques most eligible for remanufacturing are always reversible as a matter of principle like e.g. screws, some types of snap fits, plug-in connections and many more. If total reversibility is not ensured, the sole destruction of the connection joint is also acceptable. But if neither the first nor the second way is possible, an at least partly destruction of the part to be remanufactured is unavoidable. Demolition of parts is the worst case and epitomises an irrevocable exclusion of the set of parts eligible for remanufacturing (→ technical exclusion criterion – already considered in the step 'Identifying relevant parts').

Effort for unlocking is the next criterion to consider. The effort needed for locking and unlocking screws or snap-fits is usually equal in magnitude. In opposite, joints like e.g. welding seams, spot welds, glue lines or even corroded and geometrically altered screws do not score that well. If effort to be invested is comparable to effort needed for newly assembling, top scores are obtained.

Easiness of handling part is also a criterion on part level. Easy handling facilitates product recycling enormously (similar argumentation as for criterion on assembly level).

If standardised tools are used, a significant part of tool costs for designing and manufacturing special tools is saved. Special tools are oftentimes limited in functional range and dedicated to only one single disassembling task. Hence, high *usability of standardised tools* is the optimum which – if product recycling shall turn into a viable alternative – should be strived for.

A low *number of joints* also eases the implementation of remanufacturing since not many costly disassembling steps are needed. Equal to the argumentation on assembly level, the *number of different joints* is also on part level a cost driver for tool change. The less different joints, the better for product recycling.

The last criterion influencing the eligibility for disassembling is a historically rather new stumbling block. Due to the introduction of injection moulding of plastic parts and the search for cheap assembling methods, a recently widely used joining technique is snap-fitting which has extremely alleviated efforts for assembling. However, the other side of the coin are often exacerbated conditions for disassembling since simultaneously unlocking of those snap-fits is required in order to non-destructively dismantle the particular part.

Disassembling is followed by cleaning – hence **eligibility for cleaning** is the next main field to be dealt with. Although it is an own category, there are only a few criteria to be assessed. The linchpin here is the *soiling tendency*. If a part doesn't get soiled during the use phase, there is no need for cleaning. Only if parts are polluted, the two subcriteria come to the fore. The cleaning method must be chosen in dependence on the extent of pollution. The only characteristics subjected to influence is the *cleanability of [its] surface / removal of painting, rust*. Smooth and hard surfaces where dirt can't adhere facilitate the cleaning result. If only water or compressed air is needed to achieve a satisfying result, then this is an optimum. In opposite, surfaces which change chemically in proximity to the outmost layer when in contact with the cleaning agent or surfaces with an extremely rough finish tend to make cleaning impossible.

A perfect cleaning result is only achieved if dirt and mud rinses off without barrier. Thus, the *avoidance of corners and undercuts*, where dirt may cluster, is crucial in the achievement of good cleaning results.

In order to record part's state, testing is a necessity. In consequence, the **eligibility for testing** reflects the compliance with the following testing criteria. The *possibility of non-destructive testing* is – as the claim for non-destructive disassambling – an 'exclusion criterion' already mentioned and assessed. Only if non-destructive testing is possible, compliance with or difference to part's original specifications can be stated. Only if part's post-use condition is able being identified, the basis for reusing is provided.

The *possibility of automated testing* also improves the score in eligibility for testing. Automated testing avoids human error but needs strictly defined objective testing criteria. Especially in respect to optical and haptic occurrence, the automation of testing seems to be difficult. Also the size of parts to be tested might form an obstacle for automation.

It's an inevitable reality that not all parts are able of getting reused. That's why also other EoL-treatment must be taken into account when eligibility for product recycling should be enhanced. Thus, **eligibility for disposing / recycling** is another parameter to consider. The *lower the number of different materials* in a product, the first criterion in this field of improvement, the higher are chances for avoided extra effort needed for preparing the residual assembly for e.g. material recycling (e.g. extra disassembling steps required). If a high number of different materials is not avoidable, then at least those should be combined which have common characteristics for material recycling or do no cause poor quality of the recycled material (→ *compability of materials for common recycling process*) *Recyclability of materials* itself is also a claim facilitating EoL-treatment. If material recycling is not possible, only the options incinerating and dumping in landfills is left. A fact hampering material recycling is not knowing which material a particular part consists of. That's why *labelling of material* is also an enhancement towards better reusability.

The true value creation in product recycling takes place in the step of reconditioning where an as good as new state is targeted. If alterations of part's specification occur during the use phase these phenomenons must be reversed so that the quality of a reconditioned part meets the same high standards as newly manufactured one does. The linchpin in respect to **eligibility for reconditioning** is the *occurrence of alterations during use*. If no alterations in comparison to newly manufactured parts are identified, this part is qualified for direct reuse – this is a theoretically possible, but not very likely case. During use a number of phenomenons arises which change part's characteristics. In case of non-reversible effects, part's reusability is not necessarily hampered, but a series of preconditions must be fulfilled so as the part is passed on for future reusing. Only if these functional potential diminishing phenomenons can't be reversed and the previous preconditions can't be met, reconditioning of this particular part is doomed to fail (as already mentioned). Among technicians *wear* is such a 'persona [obiectum] non grata'. Inter alia, wear generally arises when two parts have a relative velocity unequal to zero. By means of abrasive effects, one part causes the alteration of the other part. In doing so, wear is always accompanied by a reduction of volume and geometric attributes. Dependent on the extent of wear and part's material, it might be reversed using techniques like e.g. coating, surface welding or simply machining and complementing with auxiliary part(s). If it is not possible to reverse wear, there is a last possibility to use the worn part again. If the particular part possesses a sufficiently high wear reserve for an entire additional use phase and, supplementary, the possibility of adjustment is given, then this used part is ready to be reused again. Only if wear can't be reversed and the wear reserve is too low or no information about remaining wear reserve is available, the intended process of product recycling fails. Bearing this argumentation chain in mind, it is possible to already anticipate the phenomenons in the design stage so as to generally promote reuse.

Fatigue incorporates the same, even not worse challenges. Similar to wear, fatigue is no impediment for product recycling if the phenomenon can be reversed. However, reversing fatigue is an impossible task. The only option left is using fatigued parts in an additional use phase if and only if the fatigue reserve is sufficiently high. Fatigue is a well examined phenomenon and comprehensive calculation models for estimating technical lifetime in total already exist. The only hurdle in this dilemma is the information asymmetry between product recycler and use phase-related data. Only if reliable information about workload during use is available, it is possible to recalculate the residual lifetime. Lacking this information, it is very hard to assess the trustability of fatigued parts. Hence, if fatigue occurs during the use phase and no trustworthy data is at hand, fatigued parts must be excluded from future reuse.

Deformation may also emerge in product life. In general, it is distinguished into intended and accidental deformation. The former one might exemplarily result from jointing techniques, where e.g. a sheet metal strip is bended, so as form or force closure is gained. The latter one occurs because of accidental local overloads. In both cases, product recycling strives for reversing the effects. The next categorisation to do is to differentiate between parts responsible for optical and haptic appearance and parts needed for function fulfilment. The first class does not demand that high standards in respect to degree of reversibility. For instance, if a metal covering was dented and battered, it is flattened and perhaps newly painted. Although on atomic level the remanufactured part differs from the newly manufactured one, the functional performance of the recycled part is the same. Higher standards are demanded if the particular part is involved in product's functional structure. Reversing deformation is – at least in the case of metals – accompanied by cold work hardening and embrittlement. By means of thermal treatment it is possible to reverse these effects again. It is essential to consider these effects. If deformation is not reversed to an as good as new level and there is no 'functional reserve', then the only alternative remaining is to dispose this part (→ exclusion criterion).

The subcriteria next to last in the class *eligibility for reconditioning* is *corrosion*. Corrosion appears only in connection with metals, mainly steel, in its negative appearance. Chemical effects cause alteration of the outmost layer of part's surface. If corrosion is only small in magnitude and reversible, then eligibility for reconditioning does not suffer. In opposite, corrosion can cause the total destruction of parts and, hence, is not reversible anymore. In this case corrosion turns into an exclusion criterion. Like in other areas of mechanical engineering, the combination of metals with different electro-chemical potential is crucial in design for product recycling and has to be kept in mind during designing.

Last but not least, the subcriteria *'other change of functional potential'* summarises all effects causing change in part's specification, but not mentioned above. If decreased functional potential is observed, but the potential is regained, no consequences are resulting. If the remaining functional potential suffices for a next use phase, it is also all right. Only if reversibility of functional potential is inhibited by various reasons, this last subcriterion turns into a 'exclusion criterion'. An example for this last case are e.g. non-rechargeable batteries or all kind of films basing on photo-chemical effects. Again, already during design those negative effects just mentioned might get mitigated.

5.3 Insight gained

The current chapter was dominated by the intention to thoroughly introduce and explain the developed method for assessing product's reusability. To be precise, the result is not an overall statement referring to the whole product, but assesses the product on single part level. The assessment comprises an efficiency evaluation in the economic, ecological and strategical dimension and provides, by doing so, a clear recommendation whether product recycling of this particular part is a reasonable activity.

6 Empiric application of the developed methodology – Case study 'single use camera'

In order to prove the usability of the developed method and to test it, it is subsequently applied to single use camera which function is taking only one single series of pictures. A picture of this camera chosen is shown in Figure 6.1.

During the development of the assessment method introduced in chapter 5, the primary focus rested on incorporating all relevant parameters influencing the method's expressiveness and to comprehensively depict the corresponding processes. The quantification of those parameters does not have influence on the method, while lacking of essential parameters does. In respect to this case study, the claim of perfectly depicting entirely correct input values is not raised. Wherever possible and available, data is taken from literature of expert interviews; missing values are estimated by educated guess. If values are adhered with high uncertainties, a plausibility check will be performed so as the influence on the result is discovered.

Figure (6.1): *Picture of a single use camera, own photography*

6.1 Product data of 'single use camera'

The data shown in Table 6.1 is necessitated in order to perform the method developed in chapter 5. Whereever possible, the basic information displayed is directly sourced from the manufacturer; in the current case study it is FUJIFILM Holdings Corporation.

In total, this single use camera consists of 27 different parts. The film itself is excluded from considerations since it is usually taken out in the photo laboratory where the outer housing is partly destroyed and the tape used for developing the pictures. All other parts incorporated in a 35 mm-film role are supposed to be not-relevant.

Table (6.1): *Product data – case study 'single use camera'*

1	2	3	4	5	6
no.	name	mass (in g)	material	cost (in €)	environmental impact (in MJ)
1	PCB with flash	13	PCB	5,40E-01	3,72E+01
2	back plate	12	HIPS	1,20E-01	1,50E+00
3	film reel holder	11	HIPS	9,60E-02	1,38E+00
4	battery	11	alkaline	9,60E-02	9,90E-02
5	front cover	9	HIPS	7,20E-02	1,13E+00
6	insert of front cover	4	HIPS	6,00E-02	5,00E-01
7	lens holder	4	HIPS	2,40E-02	5,00E-01
8	reel wheel	1	HIPS	2,40E-02	1,25E-01
9	flash slider	1	HIPS	2,40E-02	1,25E-01
10	lens groundplate	1	HIPS	2,40E-02	1,25E-01
11	flash slider support plate	<1	HIPS	1,20E-02	4,02E-02
12	display covering	<1	HIPS	1,20E-02	4,02E-02
13	flash cover	<1	HIPS	1,20E-02	4,02E-02
14	flash indicator	<1	HIPS	1,20E-02	4,02E-02
15	display wheel	<1	HIPS	1,20E-02	4,02E-02
16	lens down holder	<1	HIPS	1,20E-02	4,02E-02
17	lens shutter	<1	HIPS	6,00E-03	4,02E-02
18	view finder lens 2	<1	HIPS	6,00E-03	4,02E-02
19	gear wheel	<1	HIPS	6,00E-03	4,02E-02
20	lever 1	<1	HIPS	6,00E-03	4,02E-02
21	lever 2	<1	HIPS	6,00E-03	4,02E-02
22	bolt	<1	HIPS	3,00E-03	4,02E-02
23	view finder lens 1	<1	HIPS	3,00E-03	4,02E-02
24	lens	<1	HIPS	3,00E-03	4,02E-02
25	torsion spring 1	<1	steel	3,00E-03	6,33E-03
26	torsion spring 2	<1	steel	3,00E-03	6,33E-03
27	tension spring	<1	steel	3,00E-03	6,33E-03
	total	72		1,20E+00	4,33E+01

Table 6.1, column 3 shows the mass of each single part. These numbers are figured out by weighing each single part with a common household scale.[127] The mass of parts 11 – 27 can not exactly be determined since their mass is lower than the scale's accuracy. Thus, those parts are jointly weighed (cumulated mass of parts 11 – 27: 5 g). It is assumed that this number splits in 4,5 g for parts made of HIPS (parts 11 – 24) and 0,5 g for those made of steel (parts 25 – 27). Furthermore, it is assumed that all parts in one material category equally contribute to the cumulated mass of 4,5 g and 0,5 g, respectively – this assumption is required later on for determining environmental impact numbers. As consistency check the mathematically calculated total is compared with the measured mass of all parts. Since these two numbers are on a par, the scale's accuracy is not biasing the result.

Unfortunately, it was not possible to get convenient data about the camera's cost structure. Hence, the total manufacturing cost was estimated in a first step and afterwards broken-down to the single part level using estimations of relative cost shares. The starting point for estimating total production cost is the retail price, which was € 7,90. Assuming that the whole sale price is somewhat around € 4,00 and 60% is the cost share responsible for production, then production cost accounts for € 2,40. In this amount, there are the cost for assembling and the cost for the film still included. Less these costs, an estimated total for manufacturing all parts is found in the height of € 1,20. In a second step all parts were aligned and sorted according their estimated value. By free guess, cost shares were alloted which allows the computation of manufacturing cost per part (see Table 6.1, column 5). The estimates of these shares are found in the addendum, Table B.5.

In the last column of Table 6.1 (column 6), numbers of environmental impact caused by newly manufacturing are listed. More details on the calculation, especially on the sourcing of data, follows in section 6.9.

Table (6.2): *Alteration related information – case study 'single use camera'*

1	2	3	4
no.	name	description of alteration	probability of occurrence
1	PCB with flash	corroded battery contact	0,01
		fatigued flash switch	0,01
		fatigued bending contacts	0,01
		exhausted flash light	0,05
		bad functionality	0,03
4	battery	corroded battery contact	0,01
		to low charge	0,50
		low but sufficiently high charge	0,49
5	front cover	broken snap fit	0,10
		scratched or flawed surface	0,20
6	insert of front cover	broken snap fit	0,10
		scratched or flawed surface	0,20

Alteration related information (see Table 6.2) is important for calculating the total effort for remanufacturing. In this context, 'alteration related information' describes changes of the product / deviations of product's initial state incurred. Knowing these numbers is essential for evaluating part's reusability. However, for performing the current case study, this informations is not available. Hence, possible damages are listed and according probability numbers representing their likeliness of occurrence are assigned, both on free guess. This assumptions might impose a great threat to the validity of the method's final result. That's why the sensibility of changing these probability values on the outcome is checked in the section 6.11.

[127] Household scale used in this case study: digital scale 'IKEA HAJDBEY', weight increment = 1 g

Furthermore, information about the cost structure and the linked environmental impact of certain processes needed to perform product recycling is required. The chosen processes (and their according numbers) for the current case study are explained directly when needed in the following sections. It is assumed, additionally, that no overhead effort, neither economic nor environmental, finds entrance in the calculation. Since manufacturing plant and remanufacturing plant coincide[128], the overhead effort for newly manufacturing and remanufacturing is supposed to equal in magnitude. Although these numbers increase absolute effort, the final result will not change due to neglecting them since the used method bases on comparison where only differences are crucial.

6.2 Identification of relevant parts

As explained in the beginning of chapter 5, relevant parts are identified by means of effort for manufacturing in combination with a list of technical exclusion criteria. For identification of relevant parts, a cumulated contribution rate of $r_{th} = 80\%$ is used. The intermediate calculation steps are not listed here, but in the addendum (see Tables B.6 and B.7). That part which cumulated contribution share exceeds the defined threshold is highlighted in bold. In combination with Table 5.2 'Technical exclusion criteria', those parts of the current case study 'single use camera' relevant for further consideration are identified; the result is pictured in Table 6.3.

So as to enhance the presentiveness, in Figures 6.2 and 6.3 the single parts are pictured and neatly arranged (for the sake of recognisability, the parts are displayed in two distinct figures; otherwise, the distinguishability would severely suffer because of the smaller scaling).

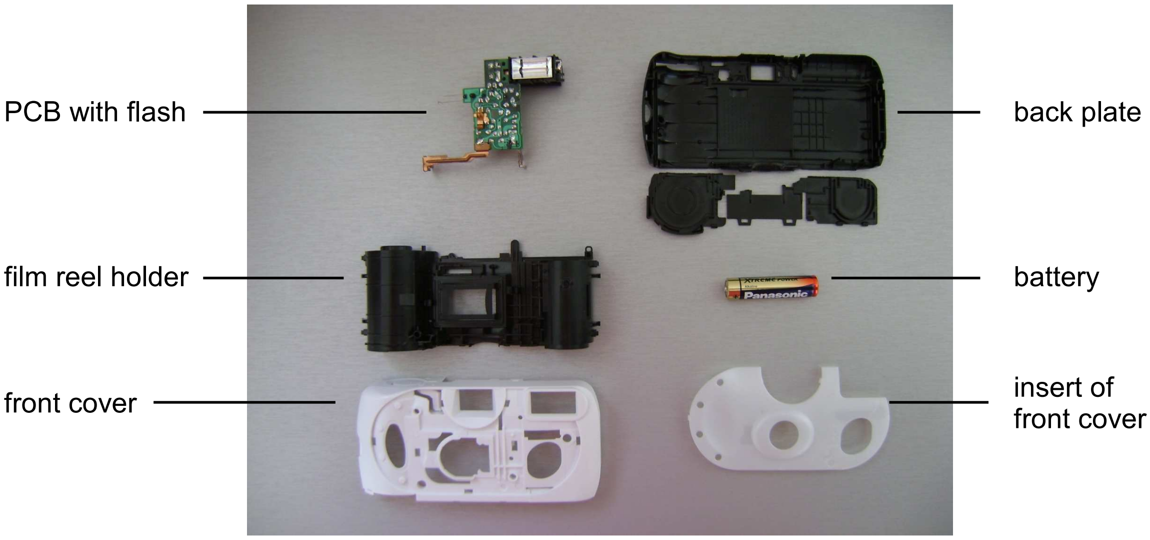

Figure (6.2): *Picture of single use camera constituting parts (overview part 1)*

From cost perspective, this single use camera would have 6 relevant parts to take into account in the further assessment; from environmental perspective, it would be only one (see Table 6.3). Hence, the economic dimension is the pivotal one for preselecting the set of relevant parts. Though, because of an active technical exclusion criterion for part 2 and 3 (precondition *TEC1:*

[128]see FUJIFILM HOLDINGS CORPORATION (2009), p.37.

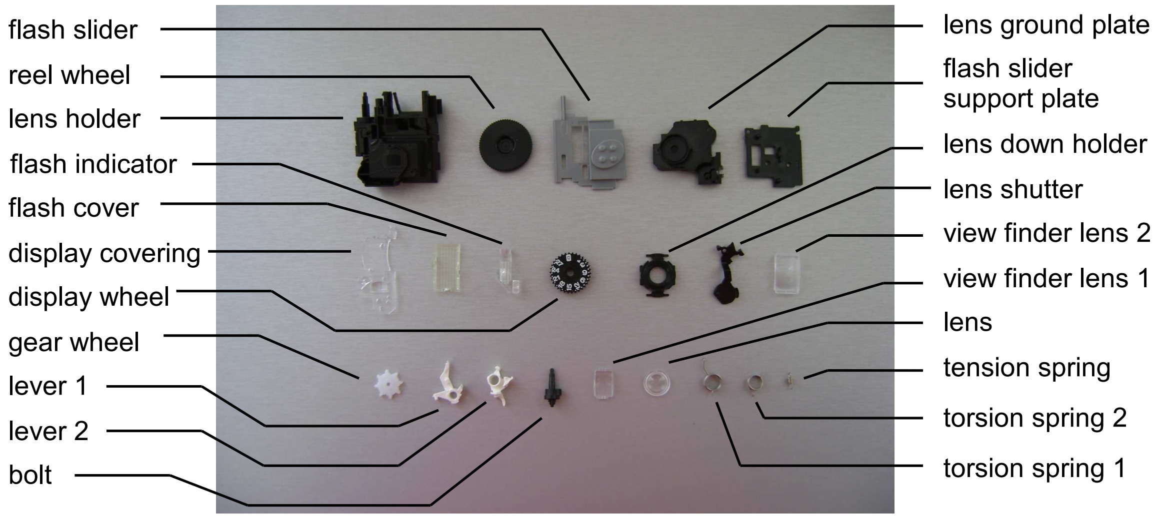

Figure (6.3): *Picture of single use camera constituting parts (overview part 2)*

Table (6.3): *Identification of relevant parts – case study 'single use camera'*

1	2	3	4	5	6
no.	name	cumulated cost share (in %)	cumulated share of environmental impact (in %)	active exclusion criterion?	relevant part?
1	PCB with flash	45,00	**86,00**	—	yes
2	back plate	55,00	89,47	TEC1	no
3	film reel holder	63,00	92,65	TEC1	no
4	battery	71,00	92,88	(TEC3e)	yes
5	front cover	77,00	95,48	—	yes
6	insert of front cover	**82,00**	96,63	—	yes
7	lens holder	84,00	97,79	—	no
8	reel wheel	86,00	98,08	—	no
9	flash slider	88,00	98,37	—	no
10	lens groundplate	90,00	98,66	—	no
11	flash slider support plate	91,00	98,75	—	no
12	display covering	92,00	98,84	—	no
13	flash cover	93,00	98,93	—	no
14	flash indicator	94,00	99,03	—	no
15	display wheel	95,00	99,12	—	no
16	lens down holder	96,00	99,21	—	no
17	lens shutter	96,50	99,31	—	no
18	view finder lens 2	97,00	99,40	—	no
19	gear wheel	97,50	99,49	—	no
20	lever 1	98,00	99,58	—	no
21	lever 2	98,50	99,68	—	no
22	bolt	98,75	99,77	—	no
23	view finder lens 1	99,00	99,86	—	no
24	lens	99,25	99,96	—	no
25	torsion spring 1	99,50	99,97	—	no
26	torsion spring 2	99,75	99,99	—	no
27	tension spring	100,00	100,00	—	no

Table (6.4): *Allocation factors for common cost – case study 'single use camera'*

1	2	3
no.	name	allocation factor for common cost
1	PCB with flash	0,70
2	back plate	—
3	film reel holder	—
4	battery	0,13
5	front cover	0,09
6	insert of front cover	0,08

reversibility of joints violated because of (hidden) welding seam), this number finally lowers to 4. Part 4, the battery, features also non-reversibility to its initial state (→ TEC3e: *other changes of functional potential* – not rechargeable battery), but it is assumed that it can be used for another additional lifetime. Due to the technical exclusion the final cost share of relevant parts lowered from 80 % to approx. 64 % (= € 0,768 / € 1,200) whilst the share of environmental impact even exceeds the defined threshold of 80 % (38,9 MJ / 43,3 MJ = 89 %).

6.3 Calculating effort for retrodistribution

In compliance with the overall strategy for product recycling, the retrodistribution strategy is chosen and the single steps required are explained more in detail.

The true utility of a single use camera (or analog camera, in general) is photographically capturing moments and later recalling these moments by means of printed pictures. Thus, the customer's need is not satisfied by the camera itself, but by the developed pictures – the product which the customer is finally interested in.

Hence, in the product system 'single use camera' the customer is actively involved in the first part of retrodistribution. He actively contributes to transportation and hands in the used camera at distinct points. From this particular collecting point, the single use camera is shipped to the development laboratory where the film is dismantled and prepared for later developing, and the residual assembly is intended for disposal (in the classical scenario without product recycling).

Identifying effort for product recycling is an analysis of differences. Since up to this special point no differences between the classical sequence of end-of-life treatments and working steps needed for product recycling are noticeable; no cost has been incurred yet. Neither cost for transferring ownership nor additional cost for the first part of the retrodistribution route arise.

The first cost which is actively incurred by product recycling is cost for transporting the used camera from the photo-laboratory to the next processing step. In the case of FUJIFILM, the used single use camera is forwarded to a collecting hub, located in Tilburg (NL). This shipment is done either by means of incumbent post service or, alternatively, by parcel services.[129] From FUJI's Netherland plant, the entire camera body is shipped to Greenwood, SC (US) where certain parts are reused while the material from the remaining parts is recovered.[130] In order to estimate

[129] see FUJI PHOTO FILM CO., LTD. (2009), p.4.
[130] see FUJIFILM HOLDINGS CORPORATION (2009), p.37.

the effort incurred, the retrodistribution scenario illustrated in Table 6.5 is supposed, regardless which and how many (sub-)companies are actually involved.

Table (6.5): *FUJI retrodistribution scenario – case study 'single use camera'*

1	2	3	4	5	6	7
no.	description	range	mode	distance (in km)	cost factor (in €/t·km)	factor for environ. impact (in MJ/t·km)
1	transport from laboratory to logistics centre of service provider engaged	all parts	truck	250	0,0521	2,7
2	transport from logistics centre to FUJI plant Tilburg (NL)	all parts	truck	1085	0,0521	2,7
3	transport from FUJI plant Tilburg (NL) to seaport Rotterdam (NL)	all parts	truck	80	0,0521	2,7
4	transport from seaport Rotterdam (NL) to seaport Charleston, SC (US)	all parts	freight ship	6850	0,0513	0,17
5	transport from seaport Charleston, SC (US) to Greenwood, SC (US)	all parts	truck	290	0,0521	2,7
	transport by truck (no.s $1+2+3+5$)	all parts	truck	1705	0,0521	2,7
	transport by freight ship (no. 4)	all parts	freight ship	6850	0,0513	0,17

Distances for the transport steps 1,2,3 and 5 are sourced from a internet-based route planning service[131]; transport distance for step 4 is roughly estimated using another internet-based distance calculator.[132] It must be kept in mind, that the distances listed are calculated on basis of the Austrian market. If those values are considered as average distances, then this retrodistribution scenario is not only valid for Austria, but also a majority of European countries and covers them as well. Since no information about sales number of FUJI's different geographic market segments in Europe is known, this estimate must suffice for a first rough estimate.

The modes of transportation are 'by truck' and 'by (transoceanic) freight ship'. Cost data is derived from expert interviews,[133] whilst factors for environmental impact are sourced from a database.[134] Determining the threshold load density for both transport modes and figuring out the average product density[135] helps figuring out whether volume or mass is the restricting transport factor. In this case study, mass is the limiting factor. Thus, a mass efficiency in the height of $\eta_T = 80\,\%$, taking into account that load capacity is also consumed by transport packaging, is considered as sufficient. On basis of these numbers gained from interviews complemented by own considerations, the cost factors for both transport modes (see Table 6.5) can be determined.[136]

In order to prove the chosen retrodistribution strategy (centralised remanufacturing plant in Greenwood, SC (US)) as appropriate, some assumption must be forestalled here. The missing

[131] Google Maps (2010).
[132] Luftlinie.org (2010).
[133] Interviews with Mr. M. Winkler and Mr. W. Eggenberger: For a first, rough approximation, cost for transport by truck (24 tons cargo load and approx. 100 m^3 loading volume) can be calculated using a cost factor of €1,- / 40 to-truck·km (rule of thumb); shipping a 40 ft ISO container (26500 kg cargo load and 67,7 m^3 loading volume) from seaport Rotterdam to U.S. east coast is appraised with roughly €7500,-
[134] ECOINVENT (2008).
[135] Threshold load density for truck $\rho_{truck}^{th} = 24000\,kg/100\,m^3 = 240\,kg/m^3$; threshold load density for ISO-container $\rho_{ISO-container}^{th} = 26500\,kg/67,7\,m^3 \approx 390\,kg/m^3$ and average product density $\rho_{camera} = 0,072\,kg/15,8\cdot 10^{-3}\,m^3 \approx$ $\approx 450\,kg/m^3$; $\rho_{ISO-container}^{th} < \rho_{truck}^{th} < \rho_{camera} \rightarrow$ mass is limiting loading factor
[136] Cost factor for truck transport $c_{truck}^{*} = 1\,€/(24\,t\cdot km\cdot 80\,\%) = 0,0521\,€/t\cdot km$; Cost factor for ISO-container transport $c_{ISO-container}^{*} = 7500\,€/(26,5\,t\cdot 6850\,km\cdot 80\,\% = 0,0513\,€/t\cdot km$;

information is cost rate for disassembling in the centralised scenario ($c^{*\,centr}_{DA} = €\,60,-$per hour) and time to perform all disassembling tasks needed ($t_{total} = 24\,s$; see Table B.9)

Total product weight ($w_{total} = 0,072\,kg$, see Table 6.1) and total weight of relevant parts ($w^{cum}_{rel} = 0,037\,kg$, see Table B.8). Furthermore, it is assumed that labour cost in a decentralised scenario is on average higher at a rate of $a = 1.2$.

With this information equation 5.19 is calculated. The left-side term amounts to

$$\frac{1-s}{a-1} = \frac{1-\frac{0{,}037\ kg}{0{,}072\ kg}}{1,2-1} = 2,43 \tag{6.1}$$

while the right side is

$$\begin{aligned}\frac{c^{*}_{DA}\cdot t_{total}}{\sum^{j} c^{*}_{TP(i,j)}\cdot \widetilde{d_{TP(j)}}\cdot w_{total}} &= \\ &= \frac{€60,-/h\cdot\frac{1\ h}{3600\ s}\cdot 24\ s}{(0,0521\frac{€}{t\cdot km}\cdot 1705\,km + 0,0513\frac{€}{t\cdot km}\cdot 6850\,km)}\cdot \\ &\cdot \frac{1}{\frac{1\ t}{1000\ kg}\cdot 0,072\ kg} = 12,6\end{aligned} \tag{6.2}$$

It is obvious that the centralised scenario enjoys an advantage (left side: 2,43 < right side: 12,6). Depicted in the diagram, the result looks as shown in Figure 6.4.

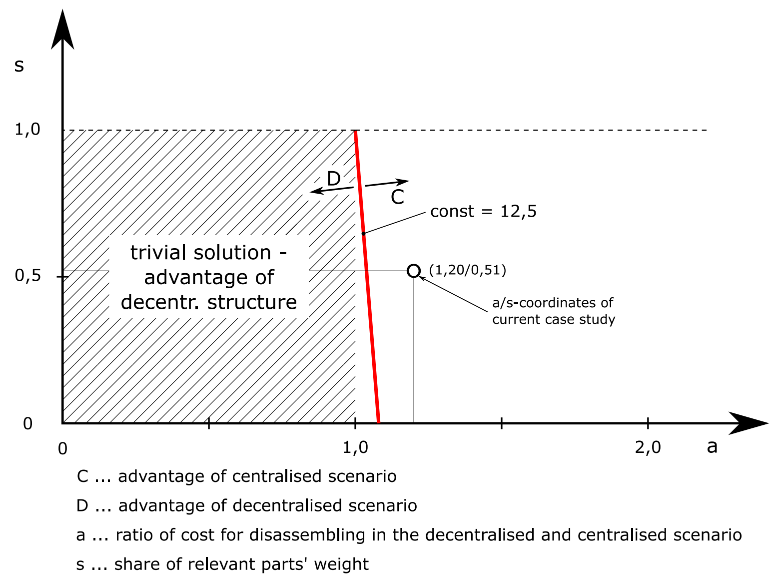

Figure (6.4): *Visualisation of decision rule – case study*

Because of the chosen retrodistribution strategy, efforts for all distances shipped have to be allocated to all relevant parts using the allocation factors defined in Table 6.4, last column. Using equation 5.6 analogously and the above numbers, the overall effort for retrodistribution totals to (with $C_{TF} = 0$)

$$C_{RD} = C_{TF} + \tag{6.3}$$

$$+ \underbrace{\overbrace{\sum_{k=1}^{i}\sum^{j} w_k \cdot c^*_{TP(i,j)} \cdot d_{TP(j)}}^{\text{direct cost caused by transport}} + \overbrace{w_{not\ rel} \cdot \sum^{j} c^*_{TP(i,j)} \cdot d_{TP(j)}}^{\text{indirect cost caused by transport}}}_{\text{cost for transport accoring retrodistribution scenario (see Table 6.5)}} = \tag{6.4}$$

$$= \cdots = 0,0163 + 0,0154 = €\,0,0317$$

$$EI_{RD} = + \underbrace{\overbrace{\sum_{k=1}^{i}\sum^{j} w_k \cdot ei^*_{TP(i,j)} \cdot d_{TP(j)}}^{\text{direct env. impact caused by transport}} + \overbrace{w_{not\ rel} \cdot \sum^{j} ei^*_{TP(i,j)} \cdot d_{TP(j)}}^{\text{indirect env. impact caused by transport}}}_{\text{env. impact for transport accoring retrodistribution scenario (see Table 6.5)}} = \tag{6.5}$$

$$= \ldots = 0,2134 + 0,1262 = 0,3396\,\text{MJ} \tag{6.6}$$

The resulting numbers are shown in Table 6.6 and 6.7. Column 5 always depicts the directly caused effort, column 6 shows the effort caused by transporting not relevant parts already allocated to the single relevant parts. The last column is the sum of direct and indirect effort.

Table (6.6): *Calculating cost for retrodistribution for each relevant part ($C_{RD\ (k)}$)*

1	2	3	4	5	6	7
no.	name	weight (in g)	alloc. factor	direct cost (in €)	indirect cost (in €)	total cost (in €)
1	PCB with flash	13	0,70	0,0057	0,0108	0,0165
4	battery	11	0,13	0,0048	0,0019	0,0068
5	front cover	9	0,09	0,0040	0,0014	0,0054
6	insert of front cover	4	0,08	0,0018	0,0012	0,0030
	set of not relevant parts	35	⟶	⟶	↑ 0,0154 ↑	
	sum of cost for transporting					**0,0317**

6.4 Calculating effort for disassembling

As demanded by the developed method, a sequence of disassembling tasks is defined now. By using this list, it is possible to illustrate the sequence of tasks and its interdependencies within the part in an overview diagram. Because of the size of both the full list of tasks as well as the

Table (6.7): *Calculating environmental impact for retrodistribution for each relevant part ($EI_{RD\ (k)}$)*

1	2	3	4	5	6	7
no.	name	weight (in g)	alloc. factor	direct env. impact (in MJ)	indirect env. impact (in MJ)	total env. impact (in MJ)
1	PCB with flash	13	0,70	0,0750	0,1174	0,1923
4	battery	11	0,13	0,0634	0,0209	0,0843
5	front cover	9	0,09	0,0519	0,0156	0,0676
6	insert of front cover	4	0,08	0,0231	0,0130	0,0361
	set of not relevant parts	35	⟶	⟶	↑ 0,1669 ↑	
	sum of env. impact for transporting					**0,3803**

diagram, they are attached in the appendix (see appendix, Table B.9, and figures B.1 and B.2, respectively).

It is assumed, that the disassembling is manually accomplished. For each disassembling step the time required (including non-productive time for e.g. tool change and presorting of parts) was evaluated, recorded and the corresponding process costs were computed. In addition, an overall non-productive time for e.g. positioning at the beginning and misc. additional supportive tasks is added. Since the main part is manual labour, it is of inevitable importance that the working place is sufficiently lighted so as all joints are easily recognised. That's why it is assumed that 1 pc. 30 W energy saving lamps is used for providing illumination.

The following factors are used for calculating the effort for disassembling:

- cost factor for disassembling: $c^*_{DA\ 1} = €\,60,-$per hour
- factor of environmental impact – electricity: $ei^*_{DA\ 1} = 11,5$MJ / kWh[137]

The set of not-relevant parts consists (almost) only of parts made of HIPS. The only exception are three tiny springs made of steel which may cause problems in the succeeding material recycling steps. However, it is assumed that those parts are separated magnetically so as no drawback for further processing is yielded. This means that no additional disassembling steps than those needed for recovering all relevant parts are necessary.

A short summary of disassembling cost is shown in Table 6.8. The extended table with allocation of disassembling cost is appended (see Table B.10).

Table (6.8): *Summary of effort for disassembling for each relevant part k ($C_{DA\ (k)}$ and $EI_{DA\ (k)}$)*

1	2	3	4
no.	name	$C_{DA\ (k)}$ (in €)	$EI_{DA\ (k)}$ (in MJ)
1	PCB with flash	2,21E-01	1,59E-03
4	battery	8,34E-02	2,91E-04
5	front cover	5,20E-02	2,93E-04
6	insert of front cover	4,33E-02	1,30E-04
	total cost / total env. impact	4,00E-01	2,30E-03

[137] ECOINVENT (2008).

6.5 Calculating effort for cleaning

In general, neither users' behaviour nor camera's function per se cause extremely soiling of its parts. The rather compact and 'sealed-off' design prevents the inner parts from common dirt. Hence, only parts of the outer surface are exposed to interactions with its surrounding like e.g. customers or environment. In the present case study, these parts are the back plate, the front cover and its insert, the reel wheel, flash slider and to a certain extent the lens down holder. Those parts are expose to dust, dirt and grease and would need some cleaning action. Since this set of parts hardly overlap with the set of relevant part, there are only two parts left which need analysis.

For the present case study, each single relevant part is analysed and the corresponding cleaning steps are derived from. A summary of the results is shown in Table 6.9,

For cleaning the front cover and the insert of front cover, the processes of choice are cleaning by dipping bath and mechanically stripping of foil. The first task is a rather manual one; hence, only labour cost are incurred. Contrarily, a dipping bath needs more input. The processes and their according factors are:

- stripping of foil
  - cost factor of stripping: $c^*_{C\ 1} = €70,-$ per hour
- dipping bath
  - cost factor for dipping bath: $c^*_{C\ 3} = €100,-$ per hour[138]
  - factor of environmental impact – detergent: $ei^*_{clean\ 2} = 25$ MJ / kg[139]
  - factor of environmental impact – tap water: $ei^*_{C\ 2} = 6,7$ MJ / m^3[140]

The consequential numbers are shown in Table 6.9, the comprehensive table is attached in the appendix (see Table B.11).

Table (6.9): *Summary of effort for cleaning relevant parts ($C_{C\ (k)}$ and $EI_{C\ (k)}$)*

1	2	3	4
no.	part	$C_{C\ (k)}$ (in €)	$EI_{C\ (k)}$ (in MJ)
1	PCB with flash	—	—
2	back plate	—	—
3	film reel holder	—	—
4	battery	—	—
5	front cover	1,78E-01	1,32E-01
6	insert of front cover	5,66E-02	7,84E-02
	total cost / total env. impact	2,33E-01	2,10E-01

6.6 Calculating effort for testing

In the course of the present case study, almost only optical testing methods, run by skilled factory workers, come into action. This testing process primarily focuses on the sound condition of

[138] Note: Cost for auxiliary process material already in process cost incorporated
[139] ECOINVENT (2008).
[140] Ibid.

the snap fits, part's filigree details and state of surface quality. Therefore, good illumination is necessary so as e.g. surface irregularities are immediately perceived. That's why 2 pcs. 30 W energy saving bulbs are used.

The only exception are the printed circuit board and the battery which are subject of more sophisticated electrical testing methods. It is assumed that a testing device (e.g. akin to a PC) with a 500 W power supply is employed. The factors used in the computation are:

- optical testing
  - cost factor for optical testing: $c^*_{T,\,1} = € 70,-$ per hour
  - factor of environmental impact – electricity: $ei^*_{T,\,1} = 11,5$MJ / kWh[141]
- electrical testing
  - cost factor for electrical function testing: $c^*_{T,\,2} = € 120,-$ per hour
  - environmental impact of electrical function testing – electricity: (see above)

A summary of the findings is shown in Table 6.10, the entire table is attached in the appendix again (see Table B.12).

Table (6.10): *Summary of effort for testing relevant parts ($C_{T\ (k)}$ and $EI_{T\ (k)}$)*

1	2	3	4
no.	part	$C_{T\ (k)}$ (in €)	$EI_{T\ (k)}$ (in MJ)
1	PCB with flash	1,58E-02	5,40E-03
4	battery	6,67E-02	1,28E-04
5	front cover	9,72E-02	9,58E-04
6	insert of front cover	9,72E-02	9,58E-04
	total cost / total env. impact	4,19E-01	7,41E-03

6.7 Calculating effort for reconditioning

Analysing a random used single use camera, the following damages could be observed (subselection of most frequent damages / flaws): broken snap-fit, scratched surface, fatigued trigger, corroded battery contact, broken connectors, exhausted flash light, stamped expiration date, etc. For each damage mentioned, its probability of occurrence was estimated by educated guess[142] and a possible treatment process set.

Unfortunately, all damages found are more or less irreversible. Of course, some damages could be fixed but only in a way not compliant with the claim for 'as-good-as-new-state'. Here, the only way to recondition is to replace the share of flawed parts by new ones. Hence, the effort incurred by substituting a not reconditionable part because of one particular damage is exactly the effort for newly manufacturing times the probability of damage occurence.

Again, in the addendum the entire table about relevant parts, their damages and corresponding probabilities (see also Table 6.2) is depicted. Subsequently, only a brief summary is shown (see Table 6.11), the full tables can be found in the addendum (see table B.13 to B.16).

[141] ECOINVENT (2008).

[142] However, even if the estimates are guessed educatedly, unfortunately no profound statistical data is underlying. Though, for first valuation of irreversible damages – which are definitely occurring – it provides appreciated insights. But, this ambiguity must be kept in mind when interpreting the results!

Table (6.11): *Summary of effort for reconditioning relevant parts ($C_{RC\ (k)}$ and $EI_{RC\ (k)}$)*

1	2	3	4
no.	part	$C_{RC\ (k)}$ (in €)	$EI_{RC\ (k)}$ (in MJ)
1	PCB with flash	5,94E-02	4,09E+00
4	battery	7,25E-02	7,47E-02
5	front cover	2,52E-02	3,94E-01
6	insert of front cover	1,80E-02	1,50E-01
	total cost / total env. impact	1,75E-02	4,71E+00

6.8 Calculating effort for disposing / recycling

All those parts not relevant for product recycling or not reconditionable anymore must be disposed of. It is assumed that those parts are recycled (→ material recycling for recovering inherent material). The driver of the corresponding efforts is solely part's weight. The factors, which determine the effort, are chosen as follows:

- economic cost factors[143]
  - cost for recycling HIPS — $c_{DP}^{*\ HIPS}$ = € 100,- per ton[144]
  - cost for recycling steel — $c_{DP}^{*\ steel}$ = € 50,- per ton[145]
  - cost for recycling PCB — $c_{DP}^{*\ PCB} = €175,-$ per ton
  - cost for recycling an alkaline cell (battery) — $c_{DP}^{*\ battery} = €50,-$ per ton[146]
- environ. cost factors[147]
  - environ. effort for recycling HIPS — $ei_{DP}^{*\ HIPS}$ = -75 MJ / kg
  - environ. effort for recycling steel — $ei_{DP}^{*\ steel}$ = -8,8 MJ / kg
  - environ. effort for recycling PCB — $ei_{DP}^{*\ PCB}$ = 100 MJ / kg
  - environ. effort for recycling an alkaline cell (size AAA) — $ei_{DP}^{*\ battery} = 4,5$ MJ / kg[148]

In Table 6.12, the efforts incurred by EoL-treatment (i.e. material recycling in this case study) of not relevant parts are listed. The overall effort is € $2.44 \cdot 10^{-3}$ in the economic dimension and -2,59 MJ in the ecological dimension. Although these numbers are negligible, the allocation to the set of relevant parts by means of common allocation factor is pictured in Table 6.13, column 3 and 4.

143 Interview with sales representatives of 5 Austrian waste removal companies (15.4.2010): Information about market prices for removal are partly convergent but also differ significantly in some cases. On basis of the information gained, the prices (and cost, respectively) listed in the itemisation are set.

144 The information received differs significantly; the price ranges between € 90,- and € 210,-; since the amounts of waste purely emerge (no contamination by other materials) and, thus, the material is perfectly predestined for regranulating, the lower limit is chosen as the appropriate one.

145 Disposal of clean scrap steel is usually for free; however, because of the small amounts available (3 steel springs weighing less than 1 g) a handling lump sum in the amount of €50,- per ton is set

146 The taking back of old consumer batteries is for free; however, a handling lump sum in the amount of € 50,- per ton is supposed.

147 ECOINVENT (2008); if not indicated else

148 According to SCHOLL/BAUMANN/MUTH (1997), the environmental impact caused by the entire LC of an alkaline battery, sized AAA (LR03), ranges between 0,12 and 0,17 MJ / cell; this impact is supposedly equally allocated to the life cycle phases 'raw material', 'manufacturing', and 'EoL' (each phase bears one third). Using the weight of the battery (11 g; see Table 6.1), the factor of environmental impact per mass unit can be calculated.

Table (6.12): *Calculating total effort for EoL-treatment of not-relevant parts ($C_{DP\ (k)}^{indir}$ and $EI_{DP\ (k)}^{indir}$)*

1	2	3	4	5	6	7	8	9
no	name	weight (in g)	material	EoL treatment	cost in (in €/kg)	env. impact (in MJ/kg)	cost (in €)	env. impact (in MJ)
2	back plate	12	HIPS	mat. recycling	0,100	-75,0	1,20E-03	-9,00E-01
3	film reel holder	11	HIPS	mat. recycling	0,100	-75,0	1,10E-03	-8,25E-01
7	lens holder	4	HIPS	mat. recycling	0,100	-75,0	4,00E-04	-3,00E-01
8	reel wheel	1	HIPS	mat. recycling	0,100	-75,0	1,00E-04	-7,50E-02
9	flash slider	1	HIPS	mat. recycling	0,100	-75,0	1,00E-04	-7,50E-02
10	lens groundplate	1	HIPS	mat. recycling	0,100	-75,0	1,00E-04	-7,50E-02
11	flash slider support plate	<1	HIPS	mat. recycl.	0,100	-75,0	···	···
12	display covering	<1	HIPS	mat. recycl.	0,100	-75,0	···	···
13	flash cover	<1	HIPS	mat. recycl.	0,100	-75,0	···	···
14	flash indicator	<1	HIPS	mat. recycl.	0,100	-75,0	···	···
15	display wheel	<1	HIPS	mat. recycl.	0,100	-75,0	···	···
16	lens down holder	<1	HIPS	mat. recycl.	0,070	-75,0		
17	lens shutter	<1	HIPS	mat. recycl.	0,100	-75,0	$\downarrow \sum_{k=11}^{24}$	$\downarrow \sum_{k=11}^{24}$
18	view finder lens 2	<1	HIPS	mat. recycl.	0,100	-75,0		
19	gear wheel	<1	HIPS	mat. recycl.	0,100	-75,0	···	···
20	lever 1	<1	HIPS	mat. recycl.	0,100	-75,0	···	···
21	lever 2	<1	HIPS	mat. recycl.	0,100	-75,0	···	···
22	bolt	<1	HIPS	mat. recycl.	0,100	-75,0	···	···
23	view finder lens 1	<1	HIPS	mat. recycl.	0,100	-75,0	···	···
24	lens	<1	HIPS	mat. recycl.	0,100	-75,0	···	···
	cum. weight (HIPS)	$\sum$=4,5					45,0E-05	-33,8E-02
25	torsion spring 1	<1	steel	mat. recycl.	€0,050	-8,8		
26	torsion spring 2	<1	steel	mat. recycl.	€0,050	-8,8	$\downarrow \sum_{k=25}^{27}$	$\downarrow \sum_{k=25}^{27}$
27	tension spring	<1	steel	mat. recycl.	€0,050	-8,8	···	···
	cum. weight (steel)	$\sum$=0,5					25,0E-06	-44,0E-04
	total efforts for disposing not-relevant parts						34,8E-04	-25,9E-01

Table (6.13): *Summary of effort for disposing ($C_{DP\ (k)}$ and $EI_{DP\ (k)}$)*

1	2	3	4	5	6	7	8
no.	name	$C_{DP\ (k)}^{indir}$ (in €)	$EI_{DP\ (k)}^{indir}$ (in MJ)	$C_{DP\ (k)}^{dir}$ (in €)	$EI_{DP\ (k)}^{dir}$ (in MJ)	$C_{DP\ (k)}$ (in €)	$EI_{DP\ (k)}$ (in MJ)
1	PCB with flash	2,44E-03	-1,82E+00	1,43E-03	1,43E-01	3,87E-03	-1,68E+00
4	battery	4,34E-04	-3,24E-01	1,94E-03	3,49E-02	2,37E-03	-2,89E-01
5	front cover	3,26E-04	-2,43E-01	2,21E-04	-2,36E-01	5,46E-04	-4,79E-01
6	insert of front cover	2,71E-04	-2,02E-01	8,40E-05	-9,00E-02	3,55E-04	-2,92E-01
	total effort for EoL-treatment	3,48E-03	-2,59E+00	3,67E-03	-1,48E-01	7,15E-03	-2,74E+00

The summary of effort for disposal is shown in Table 6.13. The direct effort for disposing parts not reconditionable anymore is sourced from Table B.17 (see addendum) and listed in columns 5 and 6. Total effort for disposal per relevant part *k* is quoted in the last columns.

6.9 Calculating effort for newly manufacturing

So as to figure out which production scenario is superior, either newly manufacturing or product recycling, it is important having a basis to compare data with. The last numbers missing deal with newly manufacturing. For the economic dimension information is already at hand and is sourced Table 6.1. However, some calculations still need to be done. Information about environmental impact of newly manufactured parts must be generated first. Therefore, some assumption and data are required. For the sake of simplicity, only processing and material is taken into account.

The following required information about environmental impact is sourced form the ECOINVENT data base. In the first listing only impact data about 'materials' are listed,

- environmental impact of an average PCB – $ei^{*\ PCB}_{NM} = 2860 \frac{MJ}{kg}$
- environmental impact of HIPS – $ei^{*\ HIPS}_{NM} = 96 \frac{MJ}{kg}$
- env. impact of an alkaline cell, size AAA (material) — $ei^{*\ battery/mat.}_{NM} = 4,5 \frac{MJ}{kg}$[149]

in the second one are those for processing:

- environmental impact of wave soldering – $ei^{*\ wave\ sold.}_{NM} = 392 \frac{MJ}{m^2}$
- environmental impact of injection moulding – $ei^{*\ inj.\ mould.}_{NM} = 29 \frac{MJ}{kg}$
- env. impact of an alkaline cell, size AAA (process) — $ei^{*\ battery/proc.}_{NM} = 4,5 \frac{MJ}{kg}$[150]

The table with the comprehensive information about environmental impact of each relevant part during newly manufacturing (as well those parts excluded because of technical restriction) is attached in the appendix (see Table B.18). Though, a brief overview is provided here as well.

Table (6.14): *Summary of effort for newly manufacturing relevant parts k ($C_{NM\ (k)}$ and $EI_{NM\ (k)}$)*

1	2	3	4
no.	name	$C_{NM\ (k)}$ (in €)	$EI_{NM\ (k)}$ (in MJ)
1	PCB with flash	0,540	37,195
2	back plate	—	—
3	film reel holder	—	—
4	battery	0,096	0,099
5	front cover	0,072	1,125
6	insert of front cover	0,060	0,500
	total cost / total env. impact	0,768	38,919

As all quantitative assessment is accomplished, the next step is to evaluate the strategical eligibility of the single use camera.

[149] see footnote 148
[150] see footnote 148

6.10 Assessing product's strategical eligibility

First of all, the most important strategical criteria are those which can cause exclusion of product recycling. Hence, the list is quickly gone through and product's eligibility (and, if necessary in conjunction with part's eligibility) determined. For the sake of replicability, brief notes are attached.

Table (6.15): *Assessment of product's strategical eligibility (exclusion criteria)*

no.	category	field of application*	criterion name	0	1
SEC 1	lifetime related eligibility	asm	ratio product / market lifetime [1]		✓
SEC 1a			↪ upgradability [2]	—	—
SEC 2	return-related eligibility	asm	incentive for customer to return product [3]		✓
SEC 3			existence of collection system for used products [4]		✓
SEC 4	market-related eligibility	asm	acceptance of remanufactured products [5]		✓
SEC 5			sales dominating parameter [6]		✓
SEC 5a		part	↪ influence of fashion on part (in comb. with SEC 1)[7]	—	—
			strategical incentive for reusing :		✓

1) ... although the technique of taking a picture used in single use cameras is already technologically replaced by digital cameras, there still exists a steady market; hence, the ratio of product life to market life is rather low, which indicates a relatively good eligibility for remanufacturing

2) ... high incentive for customer to return single use camera, at least to a predefined hand-over point since the camera is not the product which the customer is interested in; customer is interested in the developed pictures which he will get after returning the camera to a development laboratory

3) ... existence of defined hand-over points; retrodistribution system already established; even if not it wouldn't be a big deal to introduce a new one

4) ... although people buying single use cameras can't even be called rather environmentally conscious, the fulfilment of a certain function (e.g. taking pictures) is in the foreground of the sales decision; hence remanufactured products face a certain acceptance

5) ... since single use cameras are not up-to-date technology in taking pictures, fashion plays only a minor role and is no dominant factor for the buying decision

Fortunately, all crucial criteria are passed successfully. According to the method's claim, all criteria's utility values U_i reach the requested value 1. Thus, also the multiplicative aggregation delivers the preliminary value 1.

The next step is to evaluate the list of strategical soft criteria (see Table 6.16). It is clearly perceptible that the PCB as well as the battery have a relatively high incentive for reusing. Keeping in mind the multiplicative aggregation those two numbers are quite high. Since the strategical exclusion criteria were all evaluated with '1', the just calculated numbers represent the the performance in the strategical dimension.

Table (6.16): *List of strategical (soft) criteria (inclusion criteria)*

			PCB with flash [1]	battery [2]	front cover [3]	insert of front cover [4]
No.	category	name	1	4	5	6
SR1		global allocation of primary material sources	0,52	0,45	0,52	0,52
SR2	material	existence of reclaiming technique	1,00	1,00	0,25	0,25
SR2a	supply - related	↪ supply horizon of primary material	0,90	1,00	0,90	0,90
SR2b	incentives	↪ replaceability by material with longer supply horizon	0,90	0,80	0,50	0,50
			0,42	**0,36**	**0,06**	**0,06**

1) … PCBs consist of numerous single parts containing different materials; for the basis plate, like e.g. epoxy resin (on crude oil basis) and glass fibres, and metals (also heavy metals) like e.g. copper, cadmium, gold, platin are used; it is assumed that crude oil and copper class among main components; hence the strategical assessment bases on those two materials. Global allocation of crude oil and copper is indifferent (see Table A.7; in both cases approx. only 20 % of the total number of countries produce more than 80 % of the annual consumption) In respect to epoxy resin, crude oil has less practical replaceability; in case of future increasing scarcity, copper is replaceable by other electrically conducting metals; hence, crude oil's characteristic number is selected for assessment

2) … The current battery is a alkaline battery with the main materials zinc and manganese oxide; mangan's global allocation of depletion sites is intermediate, as it is for zinc (see Table A.7; less than 25 % of all mines produce more than 80 % of world mine output). By trend, man won't deplete manganese, but zinc is a very scarce resource! Of course, there are other ways of storing energy (e.g. NiMH, Li-ion) but neither lithium nor nickel performs significantly better in availability; hence substitutability is also limited.

3) … The basis for HIPS is crude oil; as already figured out, crude oil is allocated indifferently; fortunately, HIPS is enabled getting reclaimed quite well; although the supply horizon of crude oil is not that promising, carbon hydrogens are not anymore that dependent on crude oil as they used to be decades ago; thus there is replaceability to a certain extent

4) … see note 5

6.11 Summary of findings

In this last step of assessment, a summary of all results is provided, first in a break down (see Table 6.17), and afterwards more in detail (see Tables 6.18 and 6.19). It becomes immediately clear when watching the characteristic index numbers in Table 6.17, column 7 – 9 ($R^*_{ENV\ (k)}$, $R^*_{ECO\ (k)}$ and $R^*_{ST\ (k)}$, respectively) that for the current case study for all relevant parts only the economic dimension is pivotal. From the strategical perspective as well as the environmental perspective, product recycling would be a viable production alternative. Across the board, environmental impact incurred by remanufacturing is lower than the one for manufacturing. All characteristic numbers in the environmental dimension are close to '1'. This fact states the ecological reasonability of the measure (under the current numbers and assumptions) and also that effort for newly manufacturing exceeds effort for product recycling under the current assumption by far. Consequently, the poor quality data and high number of assumptions / rough estimates with their the corresponding uncertainties has little effect on the final outcome in the environmental dimension.

Also for the strategical dimension relatively high incentives *pro product recycling* are yielded for the printed circuit board as well as for the battery. Because of its replaceability and technological opportunities for reclaiming from waste, parts consisting of HIPS suffer a relative strategical drawback in respect to product recycling. But, reusing HIPS parts is no contradiction in general if the part performs well in the economic and ecological dimension.

Only in the economic dimension, significant disadvantages, especially for the parts 'battery', 'front cover' and 'insert of front cover', are perceptible. If these parts should be optimised for reusing, drastic changes in either design (→ design for reusing) or in the processing settings, necessary in the course of product recycling, are required. A deeper look into detail is provided for the economic dimension in Table 6.18 and for the ecological dimension in Table 6.19. Up until now, only the PCB has qualified in all relevant dimensions for getting remanufactured.

Table (6.17): *Summary of method's outcome – case study*

1	2	3	4	5	6	7	8	9	10	11
no.	name	economic effort		environmental impact		characteristic index numbers				overall eligibility
		newly man.	reman.	newly man.	reman.	econ.	ecol.	strat.	tech.	
1	PCB with flash	0,54	0,46	37,19	2,61	0,15	0,93	0,42	—	yes!
2	back plate	—	—	—	—	—	—	—	TEC1	no!
3	film reel holder	—	—	—	—	—	—	—	TEC1	no!
4	battery	0,1	0,23	0,1	-0,13	0,00*	2,28	0,36	—	no!
5	front cover	0,07	0,36	1,13	0,12	0,00*	0,9	0,06	—	no!
6	insert of front cover	0,06	0,22	0,5	-0,03	0,00*	1,05	0,06	—	no!

*… R-indexes are capped at the value '1' and '0', respectively; because of negative total effort, per definition a higher value than '1' could be yielded; however,the limiting does not change the outcome since '1' is the best result to achieve; because of possibly higher total effort for remanufacturing than for newly manufacturing, per definition a value less than '0' could be yielded; however,the limiting does not change the outcome since '0' is the worst result to achieve

Table (6.18): *Summary of method's outcome (economic apportionment) – case study*

1	2	3	4	5	6	7	8	9	10	11	12	13
no.	name	active TEC?	econ. feasible?	effort for retrodistribution		effort for disassembling		effort for cleaning		total per part	current cost share	required cost share
				in €	in % of total	in €	in % of total	in €	in % of total	in €		
1	PCB with flash	—	yes	0,0165	3,6%	**0,2213**	**48,3%**	0,0000	0,0%			
2	back plate	TEC1	—	—	—	—	—	—	—			
3	film reel holder	TEC1	—	—	—	—	—	—	—			
4	battery	—	no	0,0068	2,9%	**0,0834**	**36,1%**	0,0000	0,0%			
5	front cover	—	no	0,0054	1,5%	0,0520	14,5%	**0,1778**	**49,6%**			
6	insert of front cover	—	no	0,0030	1,4%	0,0433	19,9%	**0,0556**	**25,5%**			
				effort for testing		effort for reconditioning		effort for disposing				
				in €	in % of total	in €	in % of total	in €	in % of total			
(1)				**0,1583**	**34,6%**	0,0594	13,0%	0,0027	0,6%	0,4582	45,0%	38,2%
(2)				—	—	—	—	—	—	—	10,0%	—
(3)				—	—	—	—	—	—	—	8,0%	—
(4)				0,0667	28,8%	**0,0725**	**31,3%**	0,0019	0,8%	0,2312	8,0%	19,3%
(5)				**0,0972**	**27,1%**	0,0252	7,0%	0,0006	0,2%	0,3582	6,0%	29,9%
(6)				**0,0972**	**44,7%**	0,0180	8,3%	0,0004	0,2%	0,2175	5,0%	18,1%

Table (6.19): *Summary of method's outcome (environmental apportionment) – case study*

1	2	3	4	5	6	7	8	9	10	11	12	13
no.	name	active TEC?	env. feasible?	effort for retrodistribution		effort for disassembling		effort for cleaning		total per part	current effort share	required cost share
				in MJ	in % of total	in MJ	in % of total	in MJ	in % of total	in MJ		
1	PCB with flash	—	yes	1,9E-1	7,4%	0,0E+0	0,0%	0,0E+0	0,0%			
2	back plate	TEC1	—	—	—	—	—	—	—			
3	film reel holder	TEC1	—	—	—	—	—	—	—			
4	battery	—	yes	8,4E-2	66,2%	0,0E+0	0,0%	0,0E+0	0,0%			
5	front cover	—	yes	6,8E-2	58,9%	0,0E+0	0,0%	1,3E-1	114,8%			
6	insert of front cover	—	yes	3,6E-2	133,4%	0,0E+0	0,0%	7,8E-2	289,4%			
				effort for testing		effort for reconditioning		effort for disposing				
				in MJ	in % of total	in MJ	in % of total	in MJ	in % of total			
(1)				5,4E-3	0,2%	4,1E+0	156,8%	-1,7E+0	64,4%	2,6E+0	86,0%	6,0%
(2)				—	—	—	—	—	—	—	3,5%	—
(3)				—	—	—	—	—	—	—	3,2%	—
(4)				1,3E-4	0,1%	7,5E-2	58,7%	-2,9E-1	224,9%	-1,3E-1	0,2%	*
(5)				9,6E-4	0,8%	3,9E-1	343,2%	-4,8E-1	417,7%	1,2E-1	2,6%	0,3%
(6)				9,6E-4	3,5%	1,5E-1	554,1%	-2,9E-1	1080,4%	-2,7E-2	1,2%	*

Notes: * … negative required cost share not possible (effort for remanufacturing negative because of allocation effect of indirect efforts for EoL-treatment of not relevant parts)

general remark: ad cost shares: effort for EoL-treatment can cause a negative effort; that's why it is possible that single positions contribute more in absolute numbers than the total effort; that's why cost shares greater than 100 % can occur

In Tables 6.18 and 6.19, for each process step necessary in the course of product recycling like e.g. 'retrodistribution', 'disassembling', 'cleaning', 'testing', 'reconditioning' and 'disposing' the efforts incurred are reported separately (columns 5 –10). For easier identification of the most costly contributors to total cost for remanufacturing, the two most expensive cost units are highlighted in bold. It is apparent that 'disassembling', 'cleaning' and 'reconditioning' are high 'cost perpetrators' while in contrast 'retrodistribution' and 'disposing' doesn't account for that high.

In column 11, total costs for remanufacturing a relevant part k are shown. Next to it (column 12), the current cost share of total cost for newly manufacturing this very part is displayed. In order to provide a first glimpse at which rate of cost structure, at ceteris paribus chosen assumptions and constraints, remanufacturing would be an economically reasonable decision, the ratio of total cost for remanufacturing and total cost for newly manufacturing all product constituting parts is listed in the last column.

For the last time, in the following chapters relevant parts are discussed, strength and weaknesses listed, and last but not least, potential fields of improvement identified.

6.11.1 Discussion of part *'PCB with flash'*

In terms of product's function, the printed circuit board with its integrated flash seems to be one of the most important parts, since it is by far the most expensive one in the set of product constituting parts. The function of this part is to provide flash light support while taking pictures in dark surroundings. By preselecting the flash slider, a bending contact is closed (brass-coloured spot in the middle next to the left edge of the board, left picture) and when the trigger is pulled, by lever the left-side bending contacts close the circuit and cause the desired flash of light.

Among the set of relevant parts, the printed circuit board is the only one eligible for reusing since all preconditions, i.e. the efficiency in both the economical as well as the ecological dimension

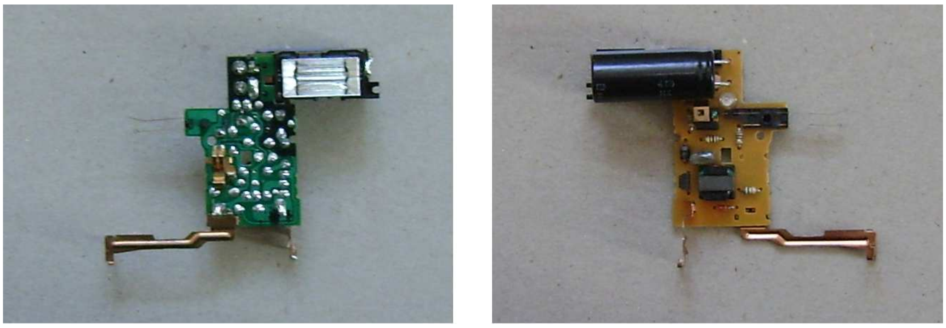

Figure (6.5): *Picture of PCB with flash, own photography*

and neither technical nor strategical exclusion criteria are active.

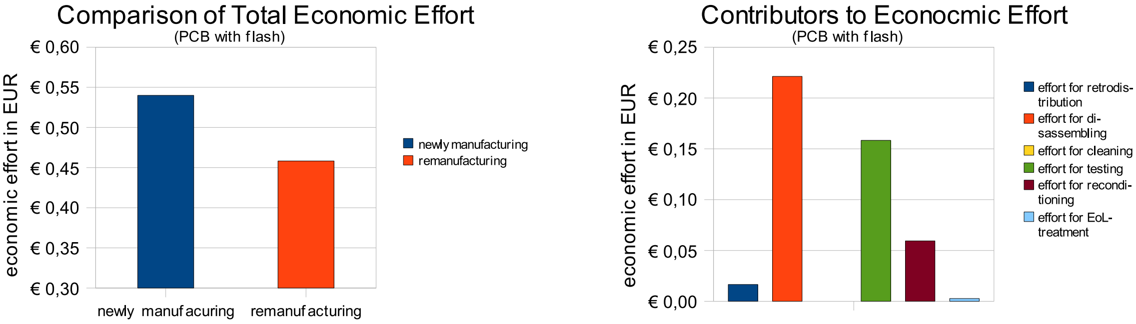

Figure (6.6): *Diagram: Comparison of total economic effort (PCB with flash)*

As depicted in Figure 6.6, left image, there is a small advantage of the remanufactured version in comparison to the newly manufactured one. The right-sided diagram reveals optically that effort for disassembling and effort for testing (under the chosen assumptions) contribute most to the final result. If future improvements are desired, these two fields of process volunteer for optimisations since only here significant effect might be gained. A cost unit with high uncertainties in respect to data quality is 'reconditioning' with its assumption in respect to defect probability (see Table 6.2) Even with those relatively high assumptions, the economic effect on the total is rather low. Only an increase from currently assumed total damage probability of 11 % to approx. 25 % could erase the actual cost advantage of remanufacturing. The estimates for the retrodistribution scenario are also afflicted with relatively high uncertainties. But even drastic changes (e.g. doubling of effort incurred) has little impact on the final assessment result.

In Figure 6.7, left diagram, the comparism of environmental effort is imaged. Because of the huge difference in magnitude, it is almost not worth mentioning. However, the most contributing process is reconditioning, which is mainly dominated by replacement cost since genuine reconditioning (in the meaning of reversing damages) is not possible.

As already pointed to, the tasks 'disassembling' and 'testing' might be responsive for optimisation. In respect to the former task, it is important to note that not only improvement of the direct accessibility is important but also disassembling steps needed for enabling proper material recycling of not relevant part. Since the printed circuit board is the most expensive part, it also would have to bear the majority of common cost.

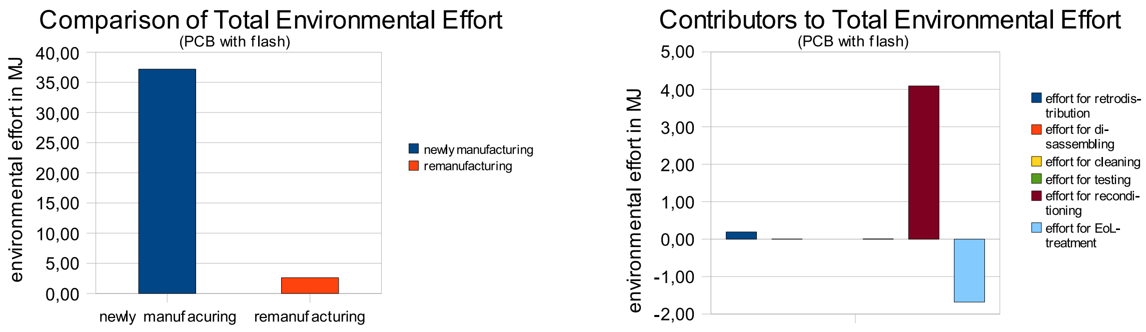

Figure (6.7): *Diagram: Comparison of total environmental effort (PCB with flash)*

Testing also causes a significantly high cost load. Ensuring a high reliability of the components is crucial since customer's satisfaction is dependent on the proper functioning of the flash. Decreasing testing cost might be yielded when optimised testing routines are applied by automated devices. However, this argument calls for high batches so as economies are earned.

Another strength are the missing cleaning cost. Since the printed circuit board is quite sealed-off by design, no fundamental soiling tendencies are observed. The last field of major enhancement is cost for reconditioning. Especially in respect to the damage 'bad functionality', caused by failed components, the PCB might perform better if components with higher electrical reliability are used.

6.11.2 Discussion of part *'back plate'*

The back plate is a part of the camera's outer surface, made of HIPS. So, inter alia, it provides stability for the entire product, protection against outer impacts and provides, in combination with the film reel holder (part 3) a sealed 'chamber' for storing the film reel. On the bottom of the camera, there are 3 bendable lids – two for accessing the right- and left-sided film reel chamber and one to access the battery. Additionally, on the outside warning notes are printed in several languages and film's expiration date is engraved on the bottom.

Originally, if only referred to production cost, the back plate would be member of the set of relevant parts. Though, due to the chosen connection technique with the film reel holder (reversible snapfits and two non-destructively irreversible welding spots as well as one welding / glue line – see Figure 6.8, arrows indicated with '(WS)'), remanufacturing is no option at all. Furthermore, due to the design with bendable lids in connection with material choice, the fringes are at risk to embrittle. After numerous bending cycles the hinges tear off and result in an irreversible damage (see Figure 6.8, arrows indicated with '(H)').

In order to think about quantitatively assessing this part's eligibility for reusing, this weak spots must be solved. Maybe a potential solution bases on jointing by sliding so as welding spots / glue lines are avoided at equal conditions in respect to stability and seclusion (sensitivity of film!). Another weakness already perceptible now is the engraved expiration date. In opposite to the general warning notes on the back, the expiration date is valid only once. Applying the expiration date by a very adhesive sticker might be a proper remedy. Due to part's position on product's outer shell, the back plate is exposed to flaws and scratches causing high effort for testing and sorting as well as replacing since reconditioning is not possible. A possible remedy is the 'functional out-sourcing' of the optical and haptic occurrence to an additional part (→ covering with foil).

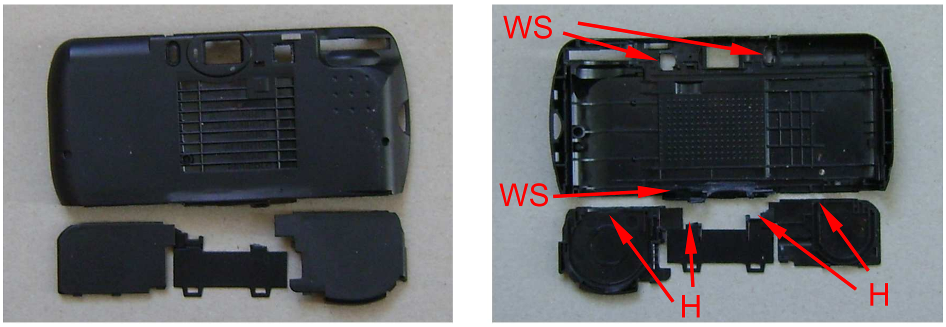

Figure (6.8): *Picture of back plate with defect hinges (H) and broken weldseam (WS)*

6.11.3 Discussion of part *'film reel holder'*

As already partly mentioned in the above part's discussion, the film reel holder serves for shaping the right- and left-sided film chamber. Auxiliary, it conduces as basis for the lens assembly (lens ground plate, lens, lens shutter,...) and the printed circuit board.

Figure (6.9): *Picture of film reel holder with broken weldseam (WS)*

Already pointed to, the film reel holder fails getting assessed since the technical exclusion criterion responsible for assessing the jointing technique is active. As already suggested, a design change towards sliding jointing might be of help. Another spot for possible improvement is the way of connecting the lens assembly and the printed circuit board. The former is attached by two snap fits with bad accessability. Those snap fits also suffer from too slender dimensions – they might easily break. If those impediments are removed, this part might be technically destined for reusing since it is not at risk of soiling (inner part), provides only 'shape' and no cost causing main contributors are recognisable yet (i.e. no function-immanent wear, fatigue, deformation,...). As part from product's inner without changes during use phase, it is predestinated for reusing. The only potential drawback might reside in elevated cost for disassembling.

6.11.4 Discussion of part *'battery'*

This alkaline battery serves the purpose of providing grid-independent electricity for operating the flash light.

Figure (6.10): *Picture of battery, own photography*

Since the product's only energy consumer is the flash light, an optional gadget used only when desired by the customer, the possibility exists that the majority of back flowing products feature batteries with residual charge. Technically, alkaline batteries are rechargeable; so, if this special type of battery is not rechargeable because of whatsoever reasons, they are easily substitutable.

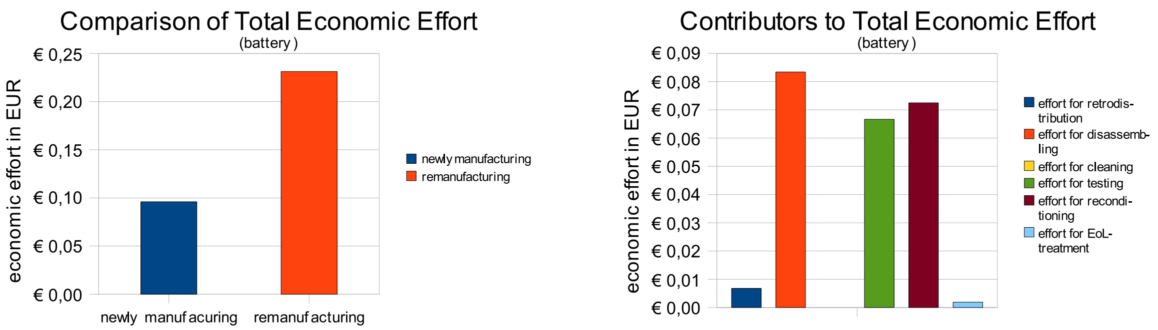

Figure (6.11): *Diagram: Comparison of total economic effort (battery)*

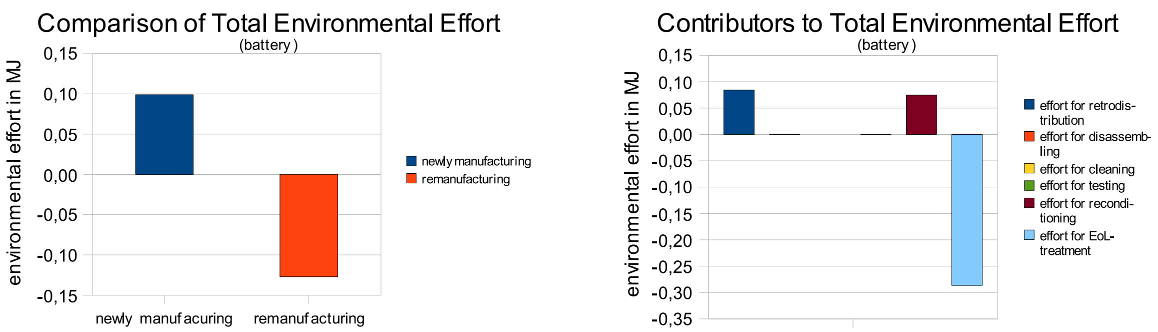

Figure (6.12): *Diagram: Comparison of total environmental effort (battery)*

Casting a glance on the diagrams, the economic dimension might cause objections. Relatively high cost for disassembling, followed by cost cost for testing and reconditioning (mainly cost for substituting in the current setting) prove the current design inefficient for product recycling. From current perspective, cost for disassembling are hardly to lower. But, if rechargeable batteries are used, cost for testing and reconditioning will be significantly plummet. At the moment, high effort is incurred for identifying those parts not able to serve an additional use phase. As consequence, those parts must be sorted out, disposed and replaced by new ones. If rechargeable batteries are use, this effort would disappear because all used batteries are reuseable, regardless of the current charge level. Hence, only those need replacement which are truly damaged (i.e. corroded contacts because of battery acid) – a weighty drop in cost is succeeding.

Again, as a consequence of allocating common effort, environmental impact of remanufacturing is really low.

6.11.5 Discussion of part *'front cover'*

The front cover, made of HIPS, is a part of the outer surface and, hence, provides the same functions as the back plate (e.g. stability, protection). In addition, in conjunction with 'insert of front cover' it is the body stop of the flash slider.

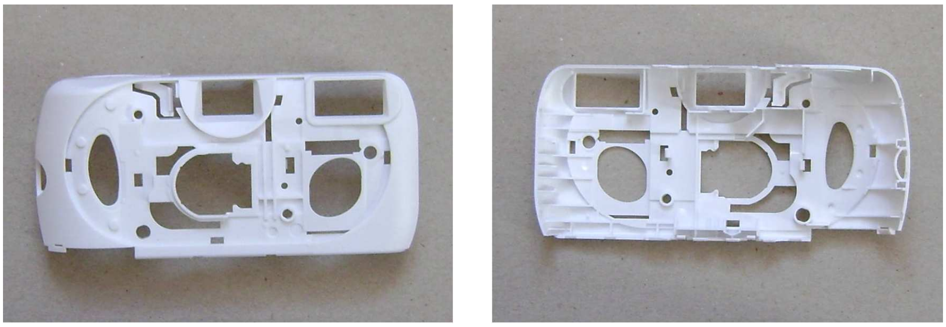

Figure (6.13): *Picture of front cover, own photography, own photography*

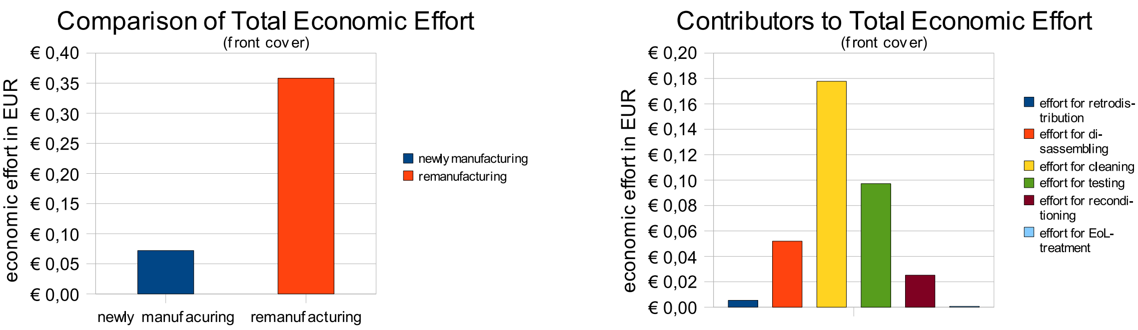

Figure (6.14): *Diagram: Comparison of total economic effort (front cover)*

In the current setting, product recycling would be an economically futile decision since cost incurred are 5 fold as high as for newly manufacturing. Cleaning is the process that causes the most cost. This especially because of sharp corners on the outer surface. The next two cost units are responsible for testing (because of checking high number of snap fits and superficial

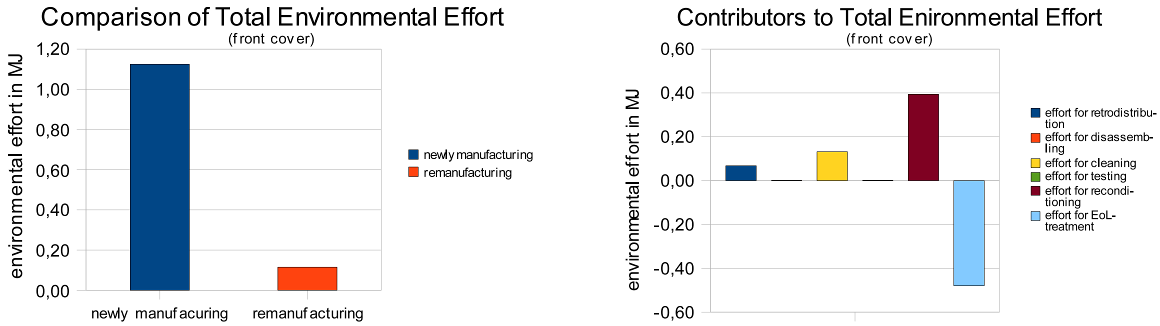

Figure (6.15): *Diagram: Comparison of total environmental effort (front cover)*

appearance) and disassembling (because of high number of snap fits). Again, environmental effort incurred is neglectingly low (see diagram in Figure 6.15).

Potential enhancement might be detected in the field of jointing (jointing between front cover, film reel holder and back plate). There, 5 female snap fits and 2 male snap fits safeguard the proper coherence. By changing the jointing technique, potential cost savings might be yielded. Furthermore, altering the currently not understandable assembly structure (merging front cover and insert of front cover) might cause reduced cost for cleaning since those pivotal corners disappear. Unfortunately, possible superficial scratches and flaws need optical manual testing, which takes some time. Gaining improvements here is hard to achieve. Furthermore, those damages are also irreversible – only the option 'replacing' is left for flawed parts. But again, the 'functional out-sourcing' in form of a superficial foil, as proposed earlier on, might remedy.

6.11.6 Discussion of part *'insert of front cover'*

The last part in the set of relevant parts is 'insert of front cover'. As the front cover and back plate, it also belongs to product's surface. Apart from the functions already mentioned twice, it probably is one of the most important parts responsible for optical and haptic appearance. Furthermore, it provides information about the flash slider's state by means of an elevated writing.

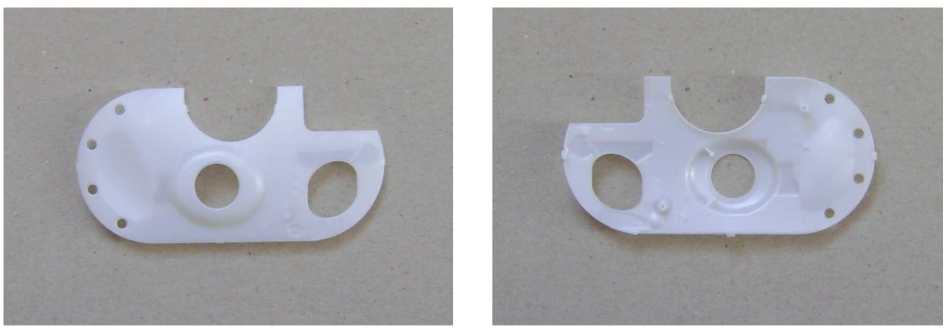

Figure (6.16): *Picture of insert of front cover, own photography*

The greatest cost contributor reads 'cost for testing'. Because of part's superficial position, it is at risk of getting scratched. Especially due to the lifted lens protection hemline irreversible damages might be attracted. Disassembling is a quite tricky task. That's why another solution for jointing the 'insert of front cover' and 'front cover' should be strived for. Five male snap fits and two centring pins are the perpetrators for increased cost load. The surface is really smooth and so, in case, easy to clean. Recondition seems to be not possible, while material recycling is a viable option (HIPS-only part). By merging the front cover and its insert, the eligibility for reusing rises by trend because of cost cumulation in newly manufacturing and omission of additional disassembling, cleaning and testing task.

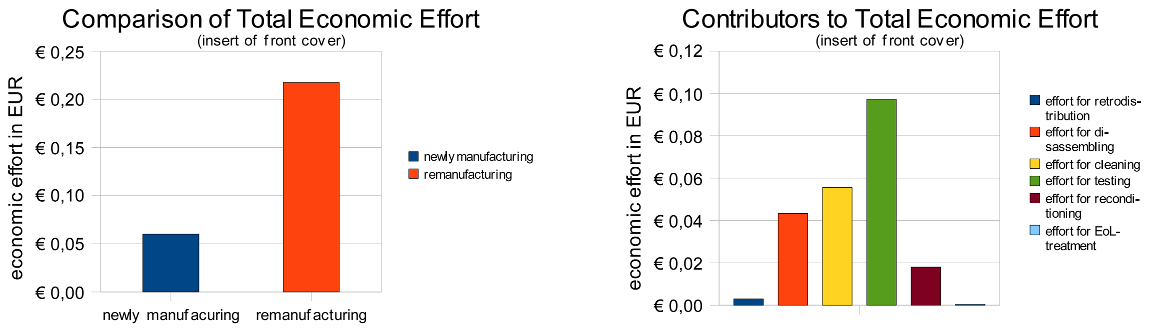

Figure (6.17): *Diagram: Comparison of total economic effort (insert of front cover)*

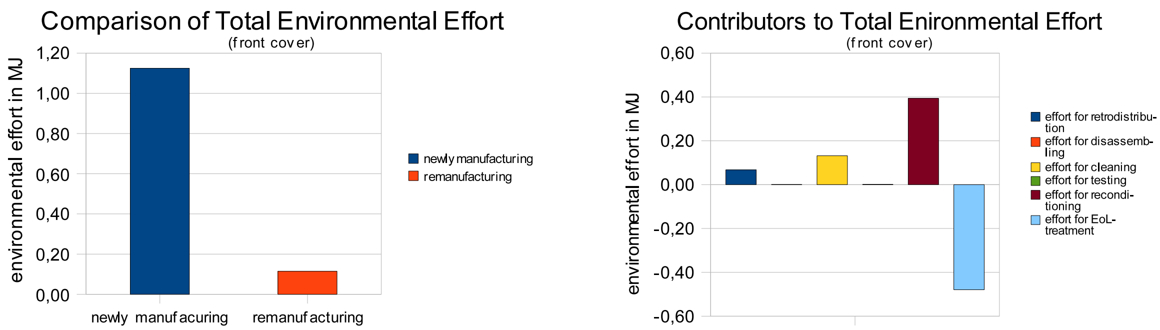

Figure (6.18): *Diagram: Comparison of total environmental effort (insert of front cover)*

6.12 Insight gained

Under the current numbers and assumptions, it seems that product recycling of this very single use camera is a deeply environmentally reasonable business process. Through the set of relevant parts, the ecological efficiency is pretty good. Admittedly, the strategical incentive is not bad at all, but it is also not very promising (except part 'PCB with flash'). Especially for the parts made of HIPS, this is because of the existence of a high quality reclaiming technique. Only the economic dimension is really stained by bad performance. Just the part 'PCB with flash' is economically eligible for product recycling. If product recycling of all other relevant parts is strived for, significant changes in product design are compulsory.

7 Resume

In the course of this thesis, in which firstly the theory was worked through, and secondly other methods introduced were discussed, the fact has revealed that product recycling is a highly complex business process. Incorporating product recycling in business' everyday life influences a whole series of company departments, let alone all. Product recycling as a future end-of-life strategy needs the unconditional support of the executive board to succeed.

However, especially by means of applying the developed method to a practical example, the limitations and short comings have been revealed so as a list of desiderata can be formulated. First of all, more precise cost data would be desirable. Especially in those cases in which a close run is gained, precise data would enhance confidence in the final result. This claim directly leads over to the next field of future research. Estimating and forecasting backflows of used products intended for reuse would contribute positively to achieve the former goal. In accounting, cost are always connected with certain production / processing batches. Since product recycling has to compete with newly manufacturing in magnitude of economic and environmental effort to be invested for yielding a particular process output, it is totally understandable that those economies of scale also needs to be lifted – simply for the sake of comparism's fairness. Especially addressing the developed method, it would rebound to method's advantage if it also better incorporates the different branches of future use of remanufactured products. Product recycling intended for reestablishing and, in consequence, reusing the entire product is a viable option. However, there might also be the case in which only certain spare parts are in the centre of interest. In general, for the sake of usability, the current method must be implemented in a computer-supported version, so as effort for using the method is lowered and the barrier preventing the daily use in design departments is phased out. On data side, better estimates about probability of damages' occurrence would also better the final result. Helpful support in this field of data mining is warmly welcomed. Though product recycling is the the end-of-life treatment to go for, in some cases it might not be as reasonable as material recycling. Especially if damages do not occur with perfect certainty and are tainted with though technically possible but extremely expensive processes, an easy-to-use decision rule would help to choose the best option.

Although the previous pages are jammed with different information dealing with product recycling, the final result also leaves many questions unanswered. A lot of research must be undertaken to enable product recycling as main EoL treatment. But fortunately, even the longest way to go starts with the first step.

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A Addendum A – World resource data

A.1 Mineral resource data

In the following three tables an overview over the consumption pattern as well as the remaining amount of fossil resources is shown. The data is mainly sourced from

[1] **Kimball, Suzette M. et al:** Mineral Commodity Summaries 2009 – U.S. Geological Survey, Washington: United States Government Printing Office 2009 (abbreviated: MCS 2009)

[2] **Kesler, Stephan:** Mineral resources, economics and the environment, New York: Macmillan 1994

[3] **Weber, L./Zsak, G.:** World Mining Data 2008, Wien: Bundesministerium für Wirtschaft und Arbeit 2008 (abbreviated: WMD 2008)

[4] **Weber, L./Zsak, G.:** World Mining Data 2009, Wien: Bundesministerium für Wirtschaft und Arbeit 2009 (abbreviated: WMD 2009)

For the sake of better understanding, a few terms are subsequently defined:

- *Mineral raw materials* are per definition economically valuable mineral constituents of the earth's crust.
- *Resource* is a concentration of naturally occurring material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.
- *Reserve base* is a part of an identified resource which meets minimum physical and chemical criteria. It encompasses those parts of resources which have a reasonable potential for becoming economically available within the planning horizon.
- *Reserves* are that part of the reserve base which could be economically extracted or produced at the time of determination.

Unless other indicated, the annual consumption data for the year 1992 is sourced from [2], for 2002 from [3] and for the years 2003 – 2007 from [4]. Consumption for 2008 is extracted from [1]. However, if the 2008 world mining data [3] is compared with the corresponding 2009 data [4], it is apparent that data for the years 2003 – 2006 differs. According to the authors, the 2009 report is more accurate, hence, that's why this report is chosen as preferred source.

Furthermore, on basis of of this consumption data, a regression analysis is accomplished so as

1. to figure out consumption trends,
2. to estimate the consumed amounts of resources during 1993 and 2001 (interpolation) as well as
3. to estimate future consumption (extrapolation).

The principle of regression analysis is shown in Figure A.1. Scenario (a) shows a positive consumption trend (annual increase of depleted amount by slope of regression line) and scenario (b) shows the opposite.

Using data about reserves and reserve bases, respectively, sourced from [2], and subtracting the consumed amounts (the reported as well as the estimated ones), the remaining reserves and reserve bases are estimated (level as of 2009)

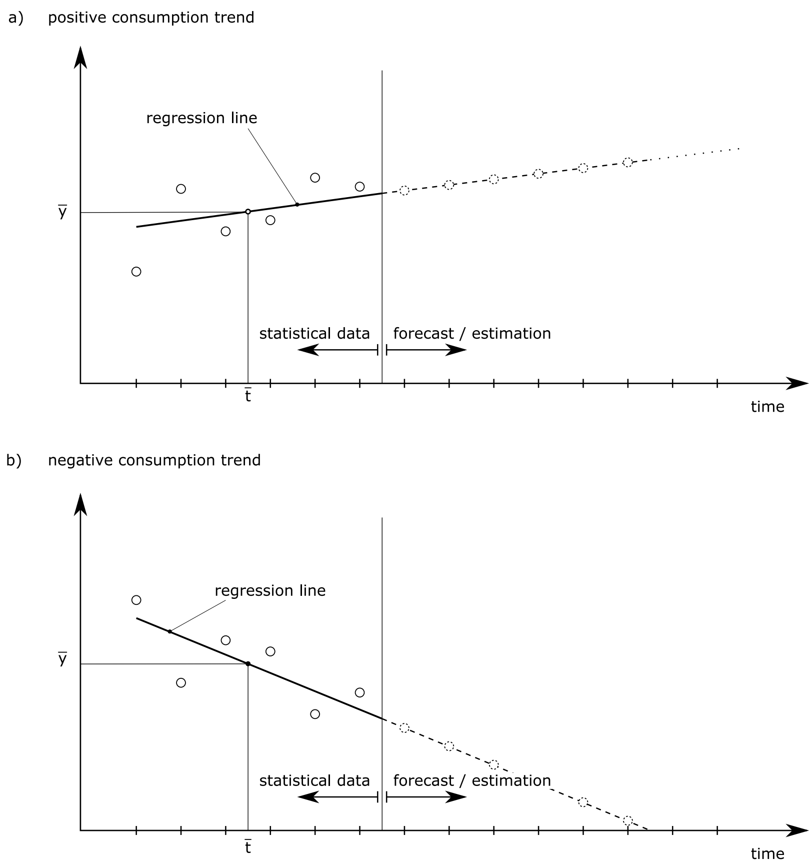

Figure (A.1): *Scheme of regression analysis*

Especially data about world wide available amounts of fossil resources is difficult to find. The only two reliable sources found are KESLER (1994) and KIMBALL ET AL (2009). Since the calculations' final aim is to give a rough forecast about resource availability, a sufficiently accurate data base is required. The younger reserve and reserve data, respectively, sourced from [1], is supposed to be more capable of depicting the current global state of resource depletion and future resource availability. Hence, this data is used as primary source. However, not for each resource listed in the tables this information is at hand. Thus, in case of lacking, the estimated data, basing on Kesler's numbers, and reported as well as estimated consumption is used as starting point instead.

Presupposing stable trends, the time until mankind runs out of currently known reserves (as well as reserve bases) is computed using a simple approach on basis of arithmetic series. Starting from the 2009 consumption level (a_0), using the slope as arithmetic increment (d) and comparing the cumulated sum of all members of the finite arithmetic sequence with the amount of reserve and reserve base (S_n), respectively, the index n indicates the time of resource availability.

$$\begin{aligned} S_n &= a_0 + a_1 + a_2 + \cdots + a_n = \\ &= a_0 + (a_0 + d) + (a_0 + 2 \cdot d) + \cdots + (a_0 + n \cdot d) \\ S_n &= \sum_{i=0}^{n} a_i = \sum_{i=0}^{n} (a_0 + i \cdot d) = \cdots = \\ &= (n+1) \cdot \left(a_0 + \frac{n}{2} \cdot d \right) \end{aligned} \tag{A.1}$$

As it is obvious, the above equation is a 2^{nd} degree polynomial which roots are the solution looked for. After some transformation the following equation evolves:

$$n_{1,2} = \frac{-\left(\frac{d}{2} + a_0\right) \pm \sqrt{\left(\frac{d}{2} + a_0\right)^2 - 2 \cdot d \cdot (a_0 - S_n)}}{d} \tag{A.2}$$

However, there might be also the case where a negative consumption trend ($d < 0$) is observed. If this is the case, there are again two scenarios possible. Though diminishing resource depletion over time it may happen that, nonetheless, the entire resource reserve is emptied. Then, the above equation is still valid. In the second scenario, the annual consumption rate might drop by trend to zero even before the entire global resource deposits are exhausted. This fact is noted separately, amended by the number of years in parentheses when global consumption reaches zero by trend. All information about resource availability is rounded to integers. As last step, the resources are categorised (see Table A.1 for threshold values) so as to enable handy use of data in the developed method.

Table (A.1): *Threshold values for categorising fossil resources' provision range*

time horizon		
lower threshold (in years)	upper threshold (in years)	Category name
0	25	Cat. A
25	50	Cat. B
50	75	Cat. C
75	>75	Cat. D

However, there are some sources of error which influences the calculated time frame. In the following list, they are briefly mentioned with their corresponding direction of changing the calculated outcome:

- resource deposits not discovered yet will increase the reserves and reserve bases, respectively (→ increase of availability)

- higher commodity prices than during the past years will, in turn, influence the economical feasibility of exploiting today's not competitive fossil resource sites, e.g. oil sands (→ increase of availability)
- higher commodity prices than during the past years will also lead to a shift in demand if substitution of future high-price resources is possible (→ increase of availability)
- improvement of exploration technology in terms of enhanced exploitation efficiency will increase the amount of resources available (→ increase of availability)
- ignoring future increase in resource productivity because of better technology (→ increase of availability)
- ignoring of co-products during smelting e.g. silver as byproduct of magnetic iron ore (→ increase of availability)

In general, the outcome must be questioned critically(!). Despite kind of dubiety of the data, it allows to catch a first glimpse of the pace of resource depletion.

Notes for Table (A.2):

1) … according to KESLER (1994) the 1992 worldwide consumption of chromium is 1,28E+07 t (gross weight); for the same time period the USGS Mineral Year Book 1996 states a 1992 chromite consumption of 1,11E+07 t, assuming an average Cr_2O_3 content of 44 weight-% the annual chromium consumption accounts to 4,88E+06 t (MYB96 data is supposed to be more accurate and therefor chosen as starting point); according to WEBER/ZSAK (2008) the 2002 global chromium consumption is 5,66E+06 t (net weight C_2O_3); according to YOUNG, J.E.: Rohstoffe aus der Erde, in: R., BROWN/L. STARKE, editors: Zur Lage der Welt 1992; Fischer Verlag 1992, 137 – 167 the 1990 consumption is 3,8E+06 t; hence the outcome is considered as valid in magnitude!

2) … consumption data for 2002 – 2008 sourced from corresponding USGS Mineral Commodity Summaries of the following year

3) … contradiction in data sourced from Kesler and WMD2009: According to Kesler the1992 world production of iron ore (crude ore) is 8,45E+08 t; according to WMD the 2002 world production of contained iron is approx. 75 % of Kesler's 1992 level; this seems to be an error/inconsistency of the data; hence the 1992 iron ore production is sourced from USGS MYB 1994

4) … platinum group metals are platinum, palladium, rhodium, ruthenium, iridium and osmium

5) … world mine production and reserve/reserve base, respectively, is the total of the minerals ilmenite and rutile (expressed in contained TiO_2)

6) … volume – mass conversion for crude oil according to WMD 2008, p.2: 1 bbl = 0,1429 metric ton

7) … 2008 consumption data sourced from US. Energy Information Administration; report „Annual Energy Review 2008“, p.315

8) … conversion of cubic feet into cubic meter according WMD2008, p.2: 1 cubic feet = 0,028317 m^3

Notes for Table (A.4):

1) … Kesler's reserve, reserve base and world resource data in metric tons of crude ore; conversion into metric tons iron content by using an average factor of 52 weight-% (according to USGS MYB 1994; comparison of world data for producted iron crude ore and contained iron, Table 17)

2) … according to Kesler the world resource (5,00E+06 metr. t) would be smaller than the reserve and reserve base, respectively (5,50E+06 metr. t and 1,20E+07 metr. t); but this is impossible; hence it is assumed to be an error

3) … world mine production and reserve/reserve base respectively is the total of the minerals ilmenite and rutile (expressed in contained TiO_2)

4) … Kesler provides no information about reserve base for coal (including lignite), hence, data according to WRI in Welt-Ressourcen: Fakten, Daten, Trends, ökologisch-ökonomische Zusammenhänge; in MCS also no information about coal reserve is available, thus sourced from US Energy Information Administration; conversion 1 short ton = 0,9072 metr. ton, according to WMD 2009, p.3

5) … volume – mass conversion for crude oil according to WMD 2008, p.2: 1 bbl = 0,1429 metric ton

6) … conversion of cubic feet into cubic meter according WMD2008, p.2: 1 cubic feet = 0,028317 m^3

7) … instead of Kesler's data (→ n/a) reserve and reserve base according ASPO Deutschland e.V (`http://www.energiekrise.de/news/forum/html-docs/oelschiefer/blendinger_nco.html`); information about world resource according to Kesler

8) … implausible reserve and reserve base data; proven amount of fossil minerals already consumed greater than Kesler's 1992 level of reserve and reserve base, respectively

Notes for Table (A.5):

1) … not entire depletion of fossile reserve by trend; calculation on basis of regression – neglection of constant, low-level consumption; in brakets number of years until zero-consumption (by trend)

Table (A.2): Annual consumption of fossil resources in the years 1992 and 2002 – 2008

1	2	3	4	5	6	7	8	9	10	11	12
	year	**1992**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**regression**	
	unit	source: Kesler			source: WMD				source: MCS	mean	slope
bauxite	metric ton	1,05E+08	1,47E+08	1,59E+08	1,68E+08	1,74E+08	1,85E+08	1,95E+08	2,05E+08	1,67E+08	6,11E+06
cadmium	metric ton	2,00E+04	1,70E+04	1,83E+04	2,11E+04	1,99E+04	1,97E+04	1,88E+04	2,08E+04	1,95E+04	2,31E+01
chromium [1)]	metric ton	4,88E+06	5,66E+06	6,62E+06	7,71E+06	8,39E+06	8,43E+06	9,54E+06	9,46E+06	7,59E+06	3,02E+05
cobalt	metric ton	2,48E+04	5,18E+04	5,03E+04	5,67E+04	6,26E+04	6,55E+04	6,23E+04	7,18E+04	5,57E+04	2,81E+03
columbium (niobium) [2)]	metric ton	1,40E+04	2,99E+04	3,28E+04	3,40E+04	3,87E+04	4,45E+04	6,04E+04	6,00E+04	3,93E+04	2,76E+03
copper	metric ton	8,90E+06	1,35E+07	1,37E+07	1,46E+07	1,49E+07	1,51E+07	1,55E+07	1,57E+07	1,40E+07	4,37E+05
gold	metric ton	2,17E+03	2,53E+03	2,52E+03	2,41E+03	2,47E+03	2,35E+03	2,33E+03	2,33E+03	2,39E+03	1,01E+01
indium [2)]	metric ton	1,40E+02	3,35E+02	3,70E+02	4,05E+02	5,00E+02	5,80E+02	5,63E+02	5,68E+02	4,33E+02	2,88E+01
iron ore [3)]	metric ton	4,98E+08	6,34E+08	6,64E+08	7,50E+08	8,22E+08	9,29E+08	1,04E+09	2,20E+09	9,42E+08	6,48E+07
lead	metric ton	3,20E+06	2,87E+06	3,13E+06	3,14E+06	3,31E+06	3,54E+06	3,56E+06	3,80E+06	3,32E+06	3,19E+04
lithium	metric ton	5,60E+03	2,71E+04	3,14E+04	3,28E+04	3,50E+04	4,02E+04	4,15E+04	2,74E+04	3,01E+04	1,98E+03
magnesium compounds [2]	metric ton	3,09E+06	3,32E+06	3,46E+06	4,27E+06	4,21E+06	4,06E+06	4,39E+06	4,46E+06	3,91E+06	8,93E+04
manganese	metric ton	1,88E+07	1,21E+07	1,03E+07	1,09E+07	1,16E+07	1,19E+07	1,27E+07	1,40E+07	1,28E+07	-3,79E+05
mercury	metric ton	4,80E+03	2,22E+03	1,35E+03	1,45E+03	1,35E+03	1,35E+03	1,39E+03	9,50E+02	1,86E+03	-2,39E+02
molybdenum	metric ton	1,08E+05	1,22E+05	1,31E+05	1,59E+05	1,86E+05	1,87E+05	1,93E+05	2,12E+05	1,62E+05	6,39E+03
nickel	metric ton	9,16E+05	1,30E+06	1,32E+06	1,36E+06	1,42E+06	1,48E+06	1,58E+06	1,61E+06	1,37E+06	4,27E+04
platinum group [4)]	metric ton	2,94E+02	3,87E+02	4,18E+02	4,26E+02	4,48E+02	4,58E+02	4,47E+02	4,06E+02	4,10E+02	9,45E+00
selenium [2)]	metric ton	1,80E+03	1,51E+03	1,43E+03	1,33E+03	1,39E+03	1,54E+03	1,56E+03	1,59E+03	1,52E+03	-1,68E+01
silver	metric ton	1,37E+04	1,94E+04	1,88E+04	1,98E+04	2,03E+04	1,97E+04	2,02E+04	2,09E+04	1,91E+04	4,40E+02
strontium [2)]	metric ton	2,38E+05	3,90E+05	4,70E+05	5,51E+05	4,94E+05	5,85E+05	5,11E+05	5,12E+05	4,69E+05	1,98E+04
tantalum [2)]	metric ton	4,10E+02	1,54E+03	1,21E+03	1,51E+03	1,26E+03	1,40E+03	8,15E+02	8,15E+02	1,12E+03	3,50E+01
thallium [2)]	metric ton	1,55E+01	1,50E+01	1,50E+01	1,20E+01	1,00E+01	1,00E+01	1,00E+01	1,00E+01	1,22E+01	-3,98E-01
tin	metric ton	2,00E+05	2,47E+05	2,47E+05	2,70E+05	2,89E+05	2,89E+05	3,00E+05	3,33E+05	2,72E+05	7,49E+03
titanium [5)]	metric ton	3,65E+06	5,55E+06	6,96E+06	6,74E+06	6,71E+06	7,41E+06	7,04E+06	6,25E+06	6,29E+06	2,12E+05
tungsten	metric ton	3,98E+04	4,46E+04	4,78E+04	6,73E+04	6,06E+04	5,77E+04	5,57E+04	5,46E+04	5,35E+04	1,22E+03
vanadium	metric ton	3,21E+04	3,45E+04	3,71E+04	4,71E+04	5,63E+04	6,23E+04	6,28E+04	6,00E+04	4,90E+04	2,06E+03
zinc	metric ton	7,37E+06	8,91E+06	9,47E+06	9,50E+06	9,90E+06	1,03E+07	1,08E+07	1,13E+07	9,69E+06	2,32E+05
coal (including lignite)	metric ton	4,74E+09	4,88E+09	5,09E+09	5,55E+09	5,86E+09	6,09E+09	6,41E+09	n/a	5,52E+09	1,00E+08
crude oil [6,7)]	metric ton	3,13E+09	3,46E+09	3,66E+09	3,75E+09	3,84E+09	3,87E+09	3,86E+09	3,85E+09	3,68E+09	4,99E+07
natural gas [8)]	m^3	2,53E+12	2,54E+12	2,69E+12	2,71E+12	2,82E+12	2,93E+12	3,01E+12	n/a	2,75E+12	2,84E+10
oil shale	metric ton	n/a	1,24E+07	1,42E+07	1,29E+07	1,28E+07	1,35E+07	1,55E+07	n/a	1,36E+07	3,84E+05
uranium	metric ton	3,46E+04	4,29E+04	4,22E+04	4,74E+04	4,88E+04	4,56E+04	4,91E+04	n/a	4,44E+04	9,49E+02

Table (A.3): *Estimation of annual consumption of fossil resources in the years 1993 – 2001 and 2009*

1	2	3	4	5	6	7	8	9	10	11	12
	year	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2009**
	unit	data calculated by means of regression (parameter see Table A.2)									
bauxite	metric ton	1,04E+08	1,10E+08	1,16E+08	1,22E+08	1,28E+08	1,35E+08	1,41E+08	1,47E+08	1,53E+08	2,02E+08
cadmium	metric ton	1,92E+04	1,92E+04	1,93E+04	1,93E+04	1,93E+04	1,93E+04	1,94E+04	1,94E+04	1,94E+04	1,96E+04
chromium	metric ton	4,45E+06	4,75E+06	5,06E+06	5,36E+06	5,66E+06	5,96E+06	6,27E+06	6,57E+06	6,87E+06	9,29E+06
cobalt	metric ton	2,65E+04	2,93E+04	3,22E+04	3,50E+04	3,78E+04	4,06E+04	4,34E+04	4,62E+04	4,90E+04	7,16E+04
columbium (niobium)	metric ton	1,07E+04	1,34E+04	1,62E+04	1,90E+04	2,17E+04	2,45E+04	2,72E+04	3,00E+04	3,27E+04	5,48E+04
copper	metric ton	9,45E+06	9,89E+06	1,03E+07	1,08E+07	1,12E+07	1,16E+07	1,21E+07	1,25E+07	1,29E+07	1,64E+07
gold	metric ton	2,28E+03	2,29E+03	2,30E+03	2,31E+03	2,32E+03	2,33E+03	2,34E+03	2,35E+03	2,36E+03	2,44E+03
indium	metric ton	1,34E+02	1,63E+02	1,91E+02	2,20E+02	2,49E+02	2,78E+02	3,07E+02	3,35E+02	3,64E+02	5,95E+02
iron ore	metric ton	2,70E+08	3,34E+08	3,99E+08	4,64E+08	5,29E+08	5,94E+08	6,58E+08	7,23E+08	7,88E+08	1,31E+09
lead	metric ton	2,99E+06	3,02E+06	3,05E+06	3,08E+06	3,11E+06	3,15E+06	3,18E+06	3,21E+06	3,24E+06	3,50E+06
lithium	metric ton	9,63E+03	1,16E+04	1,36E+04	1,56E+04	1,75E+04	1,95E+04	2,15E+04	2,35E+04	2,54E+04	4,12E+04
magnesium compounds	metric ton	2,98E+06	3,07E+06	3,16E+06	3,25E+06	3,34E+06	3,43E+06	3,52E+06	3,61E+06	3,70E+06	4,41E+06
manganese	metric ton	1,67E+07	1,63E+07	1,60E+07	1,56E+07	1,52E+07	1,48E+07	1,44E+07	1,41E+07	1,37E+07	1,07E+07
mercury	metric ton	4,34E+03	4,10E+03	3,86E+03	3,62E+03	3,38E+03	3,14E+03	2,90E+03	2,66E+03	2,43E+03	5,11E+02
molybdenum	metric ton	9,58E+04	1,02E+05	1,09E+05	1,15E+05	1,21E+05	1,28E+05	1,34E+05	1,41E+05	1,47E+05	1,98E+05
nickel	metric ton	9,30E+05	9,72E+05	1,02E+06	1,06E+06	1,10E+06	1,14E+06	1,19E+06	1,23E+06	1,27E+06	1,61E+06
platinum group	metric ton	3,12E+02	3,22E+02	3,31E+02	3,41E+02	3,50E+02	3,60E+02	3,69E+02	3,79E+02	3,88E+02	4,64E+02
selenium	metric ton	1,69E+03	1,68E+03	1,66E+03	1,64E+03	1,63E+03	1,61E+03	1,59E+03	1,58E+03	1,56E+03	1,42E+03
silver	metric ton	1,45E+04	1,50E+04	1,54E+04	1,59E+04	1,63E+04	1,67E+04	1,72E+04	1,76E+04	1,81E+04	2,16E+04
strontium	metric ton	2,64E+05	2,83E+05	3,03E+05	3,23E+05	3,43E+05	3,63E+05	3,82E+05	4,02E+05	4,22E+05	5,80E+05
tantalum	metric ton	7,57E+02	7,92E+02	8,27E+02	8,62E+02	8,97E+02	9,32E+02	9,67E+02	1,00E+03	1,04E+03	1,32E+03
thallium	metric ton	1,63E+01	1,59E+01	1,55E+01	1,51E+01	1,47E+01	1,43E+01	1,39E+01	1,35E+01	1,31E+01	9,95E+00
tin	metric ton	1,94E+05	2,02E+05	2,09E+05	2,17E+05	2,24E+05	2,32E+05	2,39E+05	2,47E+05	2,54E+05	3,14E+05
titanium	metric ton	4,09E+06	4,31E+06	4,52E+06	4,73E+06	4,94E+06	5,15E+06	5,36E+06	5,57E+06	5,79E+06	7,48E+06
tungsten	metric ton	4,09E+04	4,21E+04	4,33E+04	4,45E+04	4,57E+04	4,70E+04	4,82E+04	4,94E+04	5,06E+04	6,04E+04
vanadium	metric ton	2,76E+04	2,97E+04	3,17E+04	3,38E+04	3,59E+04	3,79E+04	4,00E+04	4,20E+04	4,41E+04	6,06E+04
zinc	metric ton	7,28E+06	7,52E+06	7,75E+06	7,98E+06	8,21E+06	8,44E+06	8,67E+06	8,91E+06	9,14E+06	1,10E+07
coal (including lignite)	metric ton	4,48E+09	4,58E+09	4,68E+09	4,78E+09	4,88E+09	4,98E+09	5,08E+09	5,18E+09	5,28E+09	6,08E+09
crude oil	metric ton	3,16E+09	3,21E+09	3,26E+09	3,31E+09	3,36E+09	3,41E+09	3,46E+09	3,51E+09	3,56E+09	3,96E+09
natural gas	m^3	2,45E+12	2,48E+12	2,51E+12	2,54E+12	2,57E+12	2,59E+12	2,62E+12	2,65E+12	2,68E+12	2,91E+12
oil shale	metric ton	9,57E+06	9,96E+06	1,03E+07	1,07E+07	1,11E+07	1,15E+07	1,19E+07	1,23E+07	1,26E+07	1,57E+07
uranium	metric ton	3,45E+04	3,55E+04	3,64E+04	3,74E+04	3,83E+04	3,93E+04	4,02E+04	4,12E+04	4,21E+04	4,97E+04

Table (A.4): *Estimation of remaining fossil resources (as of 2009)*

1	2	3	4	5	6	7	8	9	10	11	12
	unit	reserve (as of 1992)	reserve base (as of 1992)	world resource (as of 1992)	consumption 1992-2008	remaining reserve (according to Kesler & WMD)	remaining reserve base (according to Kesler & WMD)	reserve (according to MCS/EIA)	reserve base (according to MCS / EIA)	increase in reserve	increase in reserve base
bauxite	metric ton	2,30E+10	2,80E+10	5,50E+10	2,50E+09	2,05E+10	2,55E+10	2,70E+10	3,80E+10	1,32	1,49
cadmium	metric ton	5,40E+05	9,70E+05	6,00E+06	3,29E+05	2,11E+05	6,41E+05	4,90E+05	1,20E+06	2,33	1,87
chromium	metric ton	1,40E+09	6,80E+09	1,10E+10	1,12E+08	1,29E+09	6,69E+09	n/a	n/a	—	—
cobalt	metric ton	4,00E+06	8,80E+06	1,10E+07	7,86E+05	3,21E+06	8,01E+06	7,10E+06	1,30E+07	2,21	1,62
columbium (niobium)	metric ton	3,50E+06	4,20E+06	large	5,10E+05	2,99E+06	3,69E+06	2,70E+06	3,00E+06	0,9	0,81
copper	metric ton	3,10E+08	5,90E+08	2,30E+09	2,13E+08	9,73E+07	3,77E+08	5,50E+08	1,00E+09	5,65	2,65
gold	metric ton	4,40E+04	5,10E+04	7,50E+04	4,00E+04	4,00E+03	1,10E+04	4,70E+04	1,00E+05	11,76	9,09
indium	metric ton	2,30E+03	4,60E+03	n/a	5,70E+03	[8]	[8]	n/a	n/a	—	—
iron ore [1]	metric ton	7,80E+10	1,08E+11	3,76E+11	1,23E+10	6,57E+10	9,58E+10	7,30E+10	1,60E+11	1,11	1,67
lead	metric ton	6,30E+07	1,30E+08	1,40E+09	5,46E+07	8,43E+06	7,54E+07	7,90E+07	1,70E+08	9,38	2,25
lithium	metric ton	2,20E+06	8,40E+06	1,27E+07	3,99E+05	1,80E+06	8,00E+06	4,10E+06	1,10E+07	2,28	1,37
magnesium compounds	metric ton	2,50E+09	3,40E+09	large	6,13E+07	2,44E+09	3,34E+09	2,20E+09	3,60E+09	0,9	1,08
manganese	metric ton	8,00E+08	4,80E+09	large	2,39E+08	5,61E+08	4,56E+09	5,00E+08	5,20E+09	0,89	1,14
mercury	metric ton	1,30E+05	2,40E+05	6,00E+05	4,53E+04	8,47E+04	1,95E+05	4,60E+04	2,40E+05	0,54	1,23
molybdenum [2]	metric ton	5,50E+06	1,20E+07	n/a	2,39E+06	3,11E+06	9,61E+06	8,60E+06	1,90E+07	2,76	1,98
nickel	metric ton	4,70E+07	1,10E+08	1,30E+08	2,09E+07	2,61E+07	8,91E+07	7,00E+07	1,50E+08	2,68	1,68
platinum group	metric ton	5,60E+04	6,60E+04	1,00E+05	6,43E+03	4,96E+04	5,96E+04	7,10E+04	8,00E+04	1,43	1,34
selenium	metric ton	7,50E+04	1,30E+05	n/a	2,68E+04	4,82E+04	1,03E+05	8,60E+04	1,72E+05	1,78	1,67
silver	metric ton	2,80E+05	4,20E+05	n/a	3,00E+05	[8]	1,20E+05	2,70E+05	5,70E+05	—	4,73
strontium	metric ton	6,80E+06	1,20E+07	1,00E+09	6,84E+06	[8]	5,16E+06	6,80E+06	1,20E+07	—	2,32
tantalum	metric ton	2,20E+04	3,50E+04	n/a	1,70E+04	4,97E+03	1,80E+04	1,30E+05	1,80E+05	26,17	10,02
thallium	metric ton	3,80E+02	6,40E+02	6,52E+05	2,30E+02	1,50E+02	4,10E+02	3,80E+02	6,50E+02	2,53	1,59
tin	metric ton	8,00E+06	1,00E+07	n/a	4,20E+06	3,80E+06	5,80E+06	5,60E+06	1,10E+07	1,47	1,89
titanium [3]	metric ton	2,85E+08	6,00E+08	1,20E+09	9,48E+07	1,90E+08	5,05E+08	7,30E+08	1,50E+09	3,84	2,97
tungsten	metric ton	2,30E+06	3,40E+06	n/a	8,40E+05	1,46E+06	2,56E+06	3,00E+06	6,30E+06	2,05	2,46
vanadium	metric ton	1,00E+07	2,70E+07	6,30E+07	7,15E+05	9,29E+06	2,63E+07	1,30E+07	3,80E+07	1,4	1,45
zinc	metric ton	1,40E+08	3,30E+08	1,80E+09	1,51E+08	[8]	1,79E+08	1,80E+08	4,80E+08	—	2,69
coal (including lignite) [4]	metric ton	1,04E+12	1,96E+12	n/a	8,25E+10	9,59E+11	1,87E+12	9,08E+11	n/a	0,95	—
crude oil [5]	metric ton	1,42E+11	n/a	2,10E+11	5,96E+10	8,20E+10	n/a	1,92E+11	n/a	2,34	—
natural gas [6]	m^3	1,24E+14	n/a	2,62E+14	4,23E+13	8,17E+13	n/a	1,77E+14	n/a	2,17	—
oil shale [7]	metric ton	6,40E+09	2,03E+10	1,89E+12	1,81E+08	6,22E+09	2,01E+10	n/a	n/a	—	—
uranium	metric ton	2,26E+06	n/a	n/a	6,55E+05	1,60E+06	n/a	n/a	n/a	—	—

Table (A.5): *Depletion trends and estimation of resource availability (as of 2009)*

1	2	3	4	5	6	7	8	9	10	11
	unit	remaining reserve	remaining reserve base	5 yr. change (2002 – 2007)	15 yr. change (1992 – 2007)	avg. yrly. growth (5 yrs. avg.)	avg. yrly. growth (15 yrs. avg.)	availability of reserve (rounded, in years	availability of reserve base (rounded, in years	cat.
bauxite	metric ton	2,70E+10	3,80E+10	0,29	0,86	0,06	0,04	66	83	Cat. C
cadmium	metric ton	4,90E+05	1,20E+06	0,11	-0,06	0,02	0	24	58	Cat. A
chromium	metric ton	1,29E+09	6,69E+09	0,69	0,95	0,11	0,05	66	181	Cat. C
cobalt	metric ton	7,10E+06	1,30E+07	0,2	1,51	0,04	0,06	49	73	Cat. B
columbium (niobium)	metric ton	2,70E+06	3,00E+06	1,02	3,31	0,15	0,1	28	30	Cat. B
copper	metric ton	5,50E+08	1,00E+09	0,14	0,74	0,03	0,04	24	39	Cat. A
gold	metric ton	4,70E+04	1,00E+05	-0,08	0,07	-0,02	0	18	37	Cat. A
indium	metric ton	n/a	n/a	0,68	3,02	0,11	0,1	n/a	n/a	n/a
iron ore	metric ton	7,30E+10	1,60E+11	0,64	1,08	0,1	0,05	31	52	Cat. B
lead	metric ton	7,90E+07	1,70E+08	0,24	0,11	0,04	0,01	20	40	Cat. A
lithium	metric ton	4,10E+06	1,10E+07	0,53	6,41	0,09	0,14	46	86	Cat. B
magnesium compounds	metric ton	2,20E+09	3,60E+09	0,32	0,42	0,06	0,02	177	238	Cat. D
manganese	metric ton	5,00E+08	5,20E+09	0,05	-0,32	0,01	-0,03	1) (28)	1) (28)	n/a
mercury	metric ton	4,60E+04	2,40E+05	-0,37	-0,71	-0,09	-0,08	1) (2)	1) (2)	n/a
molybdenum	metric ton	8,60E+06	1,90E+07	0,58	0,78	0,1	0,04	29	51	Cat. B
nickel	metric ton	7,00E+07	1,50E+08	0,22	0,73	0,04	0,04	30	53	Cat. B
platinum group	metric ton	7,10E+04	8,00E+04	0,16	0,52	0,03	0,03	82	89	Cat. D
selenium	metric ton	8,60E+04	1,72E+05	0,03	-0,13	0,01	-0,01	1) (85)	1) (85)	n/a
silver	metric ton	2,70E+05	5,70E+05	0,04	0,47	0,01	0,03	10	21	Cat. A
strontium	metric ton	6,80E+06	1,20E+07	0,31	1,14	0,06	0,05	9	15	Cat. A
tantalum – niobium	metric ton	1,30E+05	1,80E+05	-0,47	0,99	-0,12	0,05	56	70	Cat. C
thallium	metric ton	3,80E+02	6,50E+02	-0,33	-0,35	-0,08	-0,03	1) (25)	1) (25)	n/a
tin	metric ton	5,60E+06	1,10E+07	0,21	0,5	0,04	0,03	14	26	Cat. A
titanium	metric ton	7,30E+08	1,50E+09	0,27	0,93	0,05	0,04	54	88	Cat. C
tungsten	metric ton	3,00E+06	6,30E+06	0,25	0,4	0,05	0,02	36	63	Cat. B
vanadium	metric ton	1,30E+07	3,80E+07	0,82	0,96	0,13	0,05	86	164	Cat. D
zinc	metric ton	1,80E+08	4,80E+08	0,21	0,46	0,04	0,03	13	32	Cat. A
coal (including lignite)	metric ton	9,08E+11	1,87E+12	0,31	0,35	0,06	0,02	86	141	Cat. D
crude oil	metric ton	1,92E+11	n/a	0,11	0,23	0,02	0,01	38	n/a	Cat. B
natural gas	m^3	1,77E+14	n/a	0,19	0,19	0,03	0,01	48	n/a	Cat. B
oil shale	metric ton	6,22E+09	2,01E+10	0,25	n/a	0,05	n/a	143	284	Cat. D
uranium	metric ton	1,60E+06	n/a	0,14	0,42	0,03	0,02	25	n/a	Cat. B

A.2 Classification of mineral resources in dependence of political stability in their country of origin

For companies it is important to ensure a certain steadiness and security in supply of raw materials. In the following table indicators for a subset of mineral resources are calculated. These aggregate indicators depict the certainty or uncertainty, respectively, of resource provision of mineral resources in dependence of political stability in their country of origin. Information about political stability and corresponding classification of resource sources by means of this stability indicator are according *World mining data* (see section A.1 for information regarding the source).

By means of this stability indicator, the annual production is split in dependence of its origin in the categories *extremly critical*, *critical*, *fair* and *stable*. In order to calculate an aggregated number the annual production of the years 2002 - 2006 is sumed-up in each category and the relative share of each category in relation to total production is computed. By means of weights (as shown below) an aggregated number is identified. According to WEBER, L./ZSAK, G. (WMD2009, pp.20), a significant share of mineral resources originates from countries with extremely critical or critical political stability. Since political stability influences safety of resource provision, it important to figure out which mineral resource is mainly depleted in politically extremely critical and politically critically countries.

Table (A.6): *Weights for aggregating political stability*

cat.	weight
extr. critical	9
critical	6
fair	1
stable	1

The weights in Table A.6 are individually chosen. The choice ensures that there is more emphasis on politically extremely critical and politically critical countries. The final number (shown in Table A.7, last column) displays the stability or security of provision, respectively, of a certain mineral resource. The outcome is a number between *0 . . . 1* whereas a number near *1* indicates a high political instability while proximity to *0* marks high political stability.

So as to catch a glimpse on the national concentration of resource provision, for each resource the number of countries producing (more than) 80 % of the total annual production is named. To increase the expressiveness, also the number of countries producting the entire annual procution is cited. These numbers base on WMD 2009, pp.187.

Table (A.7): *Classification of mineral resources in dependence of political stability in their country of origin*

Bauxite	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	2,40E+07	6,71E+06	1,34E+06	1,38E+06	1,87E+07	5,21E+07	6,3	0,6
critical	5,72E+07	6,51E+07	1,02E+08	1,05E+08	9,07E+07	4,20E+08	50,4	3,0
fair	6,57E+07	8,69E+07	6,44E+07	6,82E+07	7,62E+07	3,61E+08	43,4	0,4
stable	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,0	0,0
number of countries producing >80 % cumulated annual production / out of total:		6/27				8,33E+08	100,0	0,45

Cadmium	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,0	0,0
critical	4,26E+03	6,28E+03	1,06E+04	9,30E+03	8,22E+03	3,87E+04	39,6	2,4
fair	1,25E+04	1,17E+04	1,05E+04	1,05E+04	1,29E+04	5,81E+04	59,5	0,6
stable	2,19E+02	3,23E+02	1,41E+02	1,53E+02	0,00E+00	8,36E+02	0,9	0,0
number of countries producing >80 % cumulated annual production / out of total:		9/20				9,76E+04	100,0	0,33

Chromium	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	3,69E+05	3,42E+05	3,29E+05	2,98E+05	1,39E+05	1,48E+06	5,5	0,5
critical	3,88E+06	3,82E+06	4,85E+06	4,88E+06	3,40E+06	2,08E+07	76,9	4,6
fair	1,19E+05	1,47E+06	1,06E+05	9,62E+04	1,59E+06	3,38E+06	12,5	0,1
stable	2,83E+05	2,75E+05	2,75E+05	2,86E+05	2,90E+05	1,41E+06	5,2	0,1
number of countries producing >80 % cumulated annual production / out of total:		4/22				2,71E+07	100,0	0,59

Cobalt	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	1,52E+04	1,52E+04	2,12E+04	2,36E+04	2,20E+04	9,73E+04	34,5	3,1
critical	2,43E+04	1,99E+04	1,47E+04	1,94E+04	1,66E+04	9,49E+04	33,6	2,0
fair	1,21E+04	1,57E+04	2,18E+04	1,76E+04	2,28E+04	9,00E+04	31,9	0,3
stable	1,00E+02	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,00E+02	0,0	0,0
number of countries producing >80 % cumulated annual production / out of total:		6/16				2,82E+05	100,0	0,60

Copper	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	1,33E+06	1,20E+06	1,01E+06	1,29E+06	4,72E+05	5,29E+06	7,4	0,7
critical	3,25E+06	3,61E+06	4,17E+06	4,28E+06	4,63E+06	1,99E+07	27,8	1,7
fair	8,81E+06	8,79E+06	9,29E+06	9,39E+06	9,93E+06	4,62E+07	64,3	0,6
stable	1,64E+05	9,80E+04	9,79E+04	1,50E+04	1,30E+04	3,88E+05	0,5	0,0
number of countries producing >80 % cumulated annual production / out of total:		10/50				7,18E+07	100,0	0,33

Gold	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	kg	kg	kg	kg	kg	kg	%	
extr. critical	3,12E+05	3,38E+05	2,54E+05	2,94E+05	1,89E+05	1,39E+06	12,4	1,1
critical	1,30E+06	1,28E+06	1,29E+06	1,28E+06	2,00E+05	5,34E+06	47,8	2,9
fair	9,19E+05	9,03E+05	8,52E+05	8,78E+05	8,52E+05	4,40E+06	39,4	0,4
stable	7,36E+03	7,45E+03	1,81E+04	1,30E+03	1,19E+04	4,60E+04	0,4	0,0
number of countries producing >80 % cumulated annual production / out of total:		14/89				1,12E+07	100,0	0,49

Continuation of Table A.7

Indium	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical								
critical	*[no data available]*							
fair								
stable								
number of countries producing >80 % cumulated annual production / out of total:			—			—	—	—

Iron ore	2002	2003	2004	2005	2006	sum	avg. weight share	
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	1,29E+07	1,35E+07	8,11E+05	6,27E+05	5,75E+06	3,36E+07	0,9	0,1
critical	4,10E+08	2,91E+08	5,07E+08	4,99E+08	5,48E+08	2,25E+09	63,0	3,8
fair	1,98E+08	3,39E+08	2,04E+08	2,40E+08	2,66E+08	1,25E+09	34,8	0,3
stable	1,34E+07	1,37E+07	1,65E+07	4,48E+05	1,80E+06	4,58E+07	1,3	0,0
number of countries producing >80 % cumulated annual production / out of total:			6/47			3,58E+09	100,0	0,47

Lead	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	3,10E+03	2,40E+03	0,00E+00	4,00E+02	1,78E+04	2,37E+04	0,1	0,0
critical	1,20E+06	1,64E+06	1,73E+06	1,82E+06	2,02E+06	8,41E+06	52,5	3,1
fair	1,58E+06	1,44E+06	1,36E+06	1,51E+06	1,51E+06	7,41E+06	46,3	0,5
stable	7,50E+04	5,10E+04	5,43E+04	0,00E+00	0,00E+00	1,80E+05	1,1	0,0
number of countries producing >80 % cumulated annual production / out of total:			5/34			1,60E+07	100,0	0,40

Lithium	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	1,26E+03	1,40E+03	1,45E+03	9,37E+02	0,00E+00	5,05E+03	3,5	0,3
critical	3,17E+03	3,10E+03	3,78E+03	5,07E+03	6,64E+03	2,18E+04	15,1	0,9
fair	2,25E+04	2,55E+04	2,34E+04	2,29E+04	2,24E+04	1,17E+05	81,2	0,8
stable	1,91E+02	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,91E+02	0,1	0,0
number of countries producing >80 % cumulated annual production / out of total:			2/8			1,44E+05	100,0	0,23

Magnesium compound	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical								
critical	*[no data available]*							
fair								
stable								
number of countries producing >80 % cumulated annual production / out of total:			—			—	—	—

Manganese	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	4,85E+04	6,37E+04	2,30E+04	2,00E+04	4,90E+04	2,04E+05	0,3	0,0
critical	8,69E+06	7,46E+06	8,71E+06	8,56E+06	6,47E+06	3,99E+07	61,0	3,7
fair	3,39E+06	5,10E+06	4,53E+06	5,33E+06	6,91E+06	2,53E+07	38,6	0,4
stable	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,0	0,0
number of countries producing >80 % cumulated annual production / out of total:			6/23			6,54E+07	100,0	0,45

Continuation of Table A.7

Mercury	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	3,27E+02	5,75E+02	2,80E+01	3,00E+01	3,00E+01	9,90E+02	10,6	1,0
critical	1,03E+03	6,87E+02	1,78E+03	1,58E+03	1,28E+03	6,35E+03	68,2	4,1
fair	8,04E+02	8,10E+02	6,50E+01	6,50E+01	6,50E+01	1,81E+03	19,4	0,2
stable	5,10E+01	2,50E+01	2,40E+01	3,40E+01	2,30E+01	1,57E+02	1,7	0,0
number of countries producing >80 % cumulated annual production / out of total:			2/9			9,31E+03	100,0	0,58

Molybdenum	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	5,00E+02	7,50E+02	5,00E+02	5,00E+02	2,70E+03	4,95E+03	0,6	0,1
critical	4,62E+04	5,21E+04	6,48E+04	6,98E+04	6,70E+04	3,00E+05	38,7	2,3
fair	7,54E+04	7,80E+04	9,40E+04	1,15E+05	1,09E+05	4,71E+05	60,7	0,6
stable	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,0	0,0
number of countries producing >80 % cumulated annual production / out of total:			4/14			7,76E+05	100,0	0,33

Nickel	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	2,07E+05	2,45E+05	2,28E+05	2,48E+05	1,53E+05	1,08E+06	15,7	1,4
critical	6,05E+05	6,53E+05	6,13E+05	6,93E+05	6,80E+05	3,24E+06	47,1	2,8
fair	4,81E+05	4,45E+05	5,32E+05	4,92E+05	5,92E+05	2,54E+06	36,9	0,4
stable	5,04E+03	3,43E+03	3,60E+03	3,50E+03	2,80E+03	1,84E+04	0,3	0,0
number of countries producing >80 % cumulated annual production / out of total:			8/25			6,88E+06	100,0	0,51

Platinum group	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	kg	kg	kg	kg	kg	kg	%	
extr. critical	5,13E+03	8,94E+03	9,56E+03	1,02E+04	1,11E+03	3,49E+04	1,6	0,1
critical	3,37E+05	3,66E+05	3,74E+05	3,96E+05	4,17E+05	1,89E+06	88,0	5,3
fair	4,44E+04	4,30E+04	4,15E+04	4,42E+04	4,72E+04	2,20E+05	10,3	0,1
stable	5,08E+02	4,61E+02	7,05E+02	8,00E+02	8,00E+02	3,27E+03	0,2	0,0
number of countries producing >80 % cumulated annual production / out of total:			2/12			2,15E+06	100,0	0,61

Selenum	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical								
critical	*[no data available]*							
fair								
stable								
number of countries producing >80 % cumulated annual production / out of total:			—			—	—	—

Silver	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	kg	kg	kg	kg	kg	kg	%	
extr. critical	3,73E+05	3,99E+05	4,09E+05	4,56E+05	1,90E+05	1,83E+06	1,8	0,2
critical	6,81E+06	1,03E+07	1,16E+07	1,20E+07	1,17E+07	5,24E+07	52,8	3,2
fair	1,18E+07	8,17E+06	7,77E+06	8,02E+06	8,01E+06	4,38E+07	44,1	0,4
stable	3,76E+05	3,76E+05	4,00E+05	4,84E+04	9,40E+04	1,29E+06	1,3	0,0
number of countries producing >80 % cumulated annual production / out of total:			9/59			9,93E+07	100,0	0,42

Continuation of Table A.7

Strontium	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical								
critical	*[no data available]*							
fair								
stable								
number of countries producing >80 % cumulated annual production / out of total:	—					—	—	—

Tant-Columb.	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	1,87E+02	1,04E+02	3,20E+01	1,34E+02	1,39E+02	5,96E+02	0,3	0,0
critical	2,70E+04	7,50E+01	3,93E+04	4,05E+04	4,20E+04	1,49E+05	73,6	4,4
fair	3,75E+03	3,66E+04	3,80E+03	4,04E+03	4,49E+03	5,27E+04	26,1	0,3
stable	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,0	0,0
number of countries producing >80 % cumulated annual production / out of total:	1/8					2,02E+05	100,0	0,52

Thalium	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical								
critical	*[no data available]*							
fair								
stable								
number of countries producing >80 % cumulated annual production / out of total:	—					—	—	—

Tin	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	8,17E+04	6,90E+04	8,09E+04	8,75E+04	9,02E+03	3,28E+05	23,9	2,2
critical	1,50E+05	1,66E+05	1,98E+05	2,05E+05	2,68E+05	9,87E+05	71,9	4,3
fair	1,48E+04	1,93E+04	7,28E+03	8,66E+03	7,42E+03	5,75E+04	4,2	0,0
stable	3,61E+02	0,00E+00	0,00E+00	0,00E+00	0,00E+00	3,61E+02	0,0	0,0
number of countries producing >80 % cumulated annual production / out of total:	4/17					1,37E+06	100,0	0,72

Titanium	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	0,00E+00	0,00E+00	0,00E+00	3,63E+04	3,70E+04	7,33E+04	0,3	0,0
critical	2,13E+06	2,10E+06	1,82E+06	1,77E+06	1,72E+06	9,55E+06	34,7	2,1
fair	3,05E+06	3,16E+06	3,04E+06	3,27E+06	3,93E+06	1,65E+07	59,8	0,6
stable	3,67E+05	3,78E+05	3,88E+05	3,10E+05	0,00E+00	1,44E+06	5,2	0,1
number of countries producing >80 % cumulated annual production / out of total:	6/16					2,75E+07	100,0	0,31

Tungsten	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	4,31E+02	2,01E+02	1,42E+02	1,65E+02	1,40E+02	1,08E+03	0,4	0,0
critical	4,05E+04	4,20E+04	5,35E+04	5,22E+04	5,94E+04	2,48E+05	91,2	5,5
fair	6,43E+02	6,84E+03	3,04E+03	3,96E+03	5,53E+03	2,00E+04	7,4	0,1
stable	2,94E+03	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,94E+03	1,1	0,0
number of countries producing >80 % cumulated annual production / out of total:	3/21					2,72E+05	100,0	0,62

Continuation of Table A.7

Vanadium	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,0	0,0
critical	3,16E+04	3,18E+04	3,73E+04	4,47E+04	4,45E+04	1,90E+05	94,2	5,7
fair	2,90E+03	2,95E+03	1,90E+03	1,50E+03	2,50E+03	1,18E+04	5,8	0,1
stable	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,0	0,0
number of countries producing >80 % cumulated annual production / out of total:		3/5				2,02E+05	100,0	0,63

Zinc	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	6,10E+03	3,10E+03	0,00E+00	0,00E+00	1,71E+05	1,80E+05	0,4	0,0
critical	3,95E+06	4,87E+06	5,71E+06	6,17E+06	6,16E+06	2,69E+07	54,9	3,3
fair	4,49E+06	4,43E+06	3,79E+06	3,94E+06	4,24E+06	2,09E+07	42,7	0,4
stable	4,59E+05	2,30E+05	2,34E+05	4,08E+04	3,57E+04	1,00E+06	2,0	0,0
number of countries producing >80 % cumulated annual production / out of total:		8/41				4,89E+07	100,0	0,42

Coal[1)]	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	2,51E+06	2,69E+06	2,31E+06	3,11E+06	3,12E+06	1,37E+07	0,3	0,0
critical	2,63E+08	2,76E+08	2,83E+08	2,99E+08	3,08E+08	1,43E+09	30,9	1,9
fair	6,49E+08	6,31E+08	6,39E+08	6,29E+08	6,28E+08	3,18E+09	68,7	0,7
stable	6,10E+06	0,00E+00	2,00E+05	0,00E+00	2,51E+05	6,55E+06	0,1	0,0
number of countries producing >80 % cumulated annual production / out of total:		11/35				4,62E+09	100,0	0,29

Crude Oil	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	5,64E+08	5,10E+08	3,63E+08	3,52E+08	4,95E+08	2,28E+09	12,4	1,1
critical	1,61E+09	1,90E+09	2,11E+09	2,24E+09	2,05E+09	9,91E+09	53,9	3,2
fair	1,11E+09	1,04E+09	1,06E+09	1,06E+09	1,27E+09	5,54E+09	30,1	0,3
stable	1,78E+08	1,52E+08	1,60E+08	1,48E+08	2,40E+06	6,40E+08	3,5	0,0
number of countries producing >80 % cumulated annual production / out of total:		19/93				1,84E+10	100,0	0,52

Natural gas	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	Mio m^3	Mio m^3	Mio m^3	Mio m^3	Mio m^3	Mio m^3	%	
extr. critical	3,09E+05	2,99E+05	1,54E+05	2,06E+05	2,17E+05	1,19E+06	9,8	0,9
critical	9,07E+05	9,70E+05	1,17E+06	1,91E+05	1,21E+06	4,45E+06	36,8	2,2
fair	1,24E+06	1,22E+06	1,18E+06	1,15E+06	1,30E+06	6,10E+06	50,4	0,5
stable	7,97E+04	7,69E+04	9,79E+04	1,00E+05	5,70E+03	3,61E+05	3,0	0,0
number of countries producing >80 % cumulated annual production / out of total:		19/85				1,21E+07	100,0	0,40

Oil shales	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,0	0,0
critical	1,50E+06	1,40E+06	1,30E+06	1,70E+06	1,90E+06	7,80E+06	11,6	0,7
fair	1,09E+07	1,28E+07	1,16E+07	1,16E+07	1,23E+07	5,93E+07	88,4	0,9
stable	3,36E+02	0,00E+00	0,00E+00	0,00E+00	0,00E+00	3,36E+02	0,0	0,0
number of countries producing >80 % cumulated annual production / out of total:		1/5				6,71E+07	100,0	0,18

Continuation of Table A.7

Uranium	2002	2003	2004	2005	2006	sum	avg. weight share	stability indicator
unit	metric ton	metric ton	metric ton	metric ton	metric ton	metric ton	%	
extr. critical	2,24E+03	2,14E+03	2,45E+03	3,15E+03	2,72E+03	1,27E+04	5,6	0,5
critical	1,04E+04	1,04E+04	1,54E+04	1,59E+04	1,08E+04	6,29E+04	27,5	1,6
fair	3,02E+04	2,97E+04	2,96E+04	3,06E+04	3,31E+04	1,53E+05	66,9	0,7
stable	2,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,00E+00	0,0	0,0
number of countries producing >80 % cumulated annual production / out of total:	6/18					2,29E+05	100,0	0,31

B Addendum B – Tables for the developed method and case study

Assessment methodology – tables

On the subsequent pages, different tables needed in the course of applying the developed method's qualitative assessment are attached.

In the first two tables, strategical criteria which the product and the single part, respectively, have to comply with more or less, are listed. In the former table (see Table B.1), there are only strong, compulsory criteria featuring a character of exclusion. If at least one criterion is active, then the particular entity just assessed is not eligible for product recycling anymore. In mathematical terms, those criteria, exclusively obliged to take either the value 0 or 1, are interlinked in a multiplicative way.

Table (B.1): *List of strategical exclusion criteria (exclusion criteria)*

No.	category	field of application	criterion name
SEC1	lifetime related eligibility	asm	ratio product / market lifetime
SEC1a			↪ upgradability
SEC2	return-related eligibility	asm	incentive for customer to return product
SEC3			existence of collection system for used products
SEC4	market-related eligibility	asm	acceptance of remanufactured products
SEC5			sales dominating parameter
SEC5a		part	↪ influence of fashion on part (in connection with *SEC1*)

Table (B.2): *List of strategical (soft) criteria (inclusion criteria)*

No.	category	field of application	criterion name
SR1	material supply - related incentives	part	global allocation of primary material sources
SR2			existence of reclaiming technique
SR2a			↪ supply horizon of primary material
SR2b			↪ replaceability by material with longer supply horizon

Table (B.3): *List of scales for strategical exclusion criteria*

lifetime-related eligibility

ratio product lifetime / market lifetime

0	1
product lifetime $\geq$ market life time (i.e. backflow of used product starts when market lifetime is already over)	product lifetime $\ll$ market lifetime (ratio less than 0,5 preferrable)

↪ *upgradability*

0	1
no upgradability possible due to design restrictions	easy upgradable due to modularised product structure / defined subassembly interfaces

return-related eligibility

incentive for customer to return product

0	1
no incentive to return because of alternative purposes	high incentive to return because return-inherent satisfaction of needs (e.g. additional services are needed in order to completely fulfil customer's need) or legal constraints (e.g. leasing contract, ...)

existence of collection system for used products

0	1
no collection network established or hardly feasible	existence of smoothly working collection network

market-related eligibility

acceptance of remanufactured products

0	1
not environmentally conscious customer	environmentally very conscious or convincible customers

sales dominating parameters

0	1
dominance of aesthetics (trend / fashion) and emotions as main decision driver while purchase	dominance of product functionality as purchase deciding argument (e.g. prevailing mostly among B2B-customers or other market segments led by rather economic / functional decision drivers)

↪ *influence of fashion on part (in conjunction with SC1!)*

0	1
high influence of fashion on part (in respect to haptic, optic and general occurence) – in general part of outer surface of fashion products	no influence of fashion on part e.g. inner part

Table (B.4): *List of scales for strategical soft criteria*

material supply-related incentives

global allocation of primary material sources

0,25	0,5	1
high number of sources in a number of politically stable countries	only a small number of sources in politically stable countries	only a few number of sources in politically unstable countries

Continuation of Table B.3

existence of reclaiming technique (from waste)

0,25	0,5	1
cheap and environmentally sound recovery technique fully established	recovery technique available, but high effort in terms of economic and ecological investment needed	no recovery technique available

↪ *supply horizon of primary material*

0,25	0,5	1
infinite supply due to renewability of raw material	availability of resources on basis of current global reserves guaranteed for more than 100 years	scarce resources (cumulated rate of depletion exceeds current global reserves within 50 years)

↪ *replaceability by material with longer supply horizon*

0,25	0,5	1
replacement easily possible		replacement not possible at all because of supply constraints, technical constraints

Assessment methodology – tables for case study

On the subsequent pages, different tables resulting from the application of the developed method are attached. As object to be assessed, a single use camera was chosen.

Table (B.5): *Estimates of cost shares – case study 'single use camera'*

1	2	3	4
no.	name	estimated cost share (in %)	estimated part cost (in €)
1	PCB with flash	45,00	0,540
2	back plate	10,00	0,120
3	film reel holder	8,00	0,096
4	battery	8,00	0,096
5	front cover	6,00	0,072
6	insert of front cover	5,00	0,060
7	lens holder	2,00	0,024
8	reel wheel	2,00	0,024
9	flash slider	2,00	0,024
10	lens groundplate	2,00	0,024
11	flash slider support plate	1,00	0,012
12	display covering	1,00	0,012
13	flash cover	1,00	0,012
14	flash indicator	1,00	0,012
15	display wheel	1,00	0,012
16	lens down holder	1,00	0,012
17	lens shutter	0,50	0,006
18	view finder lens 2 (big)	0,50	0,006
19	gear wheel	0,50	0,006
20	lever 1	0,50	0,006
21	lever 2	0,50	0,006
22	bolt	0,25	0,003
23	view finder lens 1(small)	0,25	0,003
24	lens	0,25	0,003
25	torsion spring 1	0,25	0,003
26	torsion spring 2	0,25	0,003
27	tension spring	0,25	0,003
	total	100 %	1,200

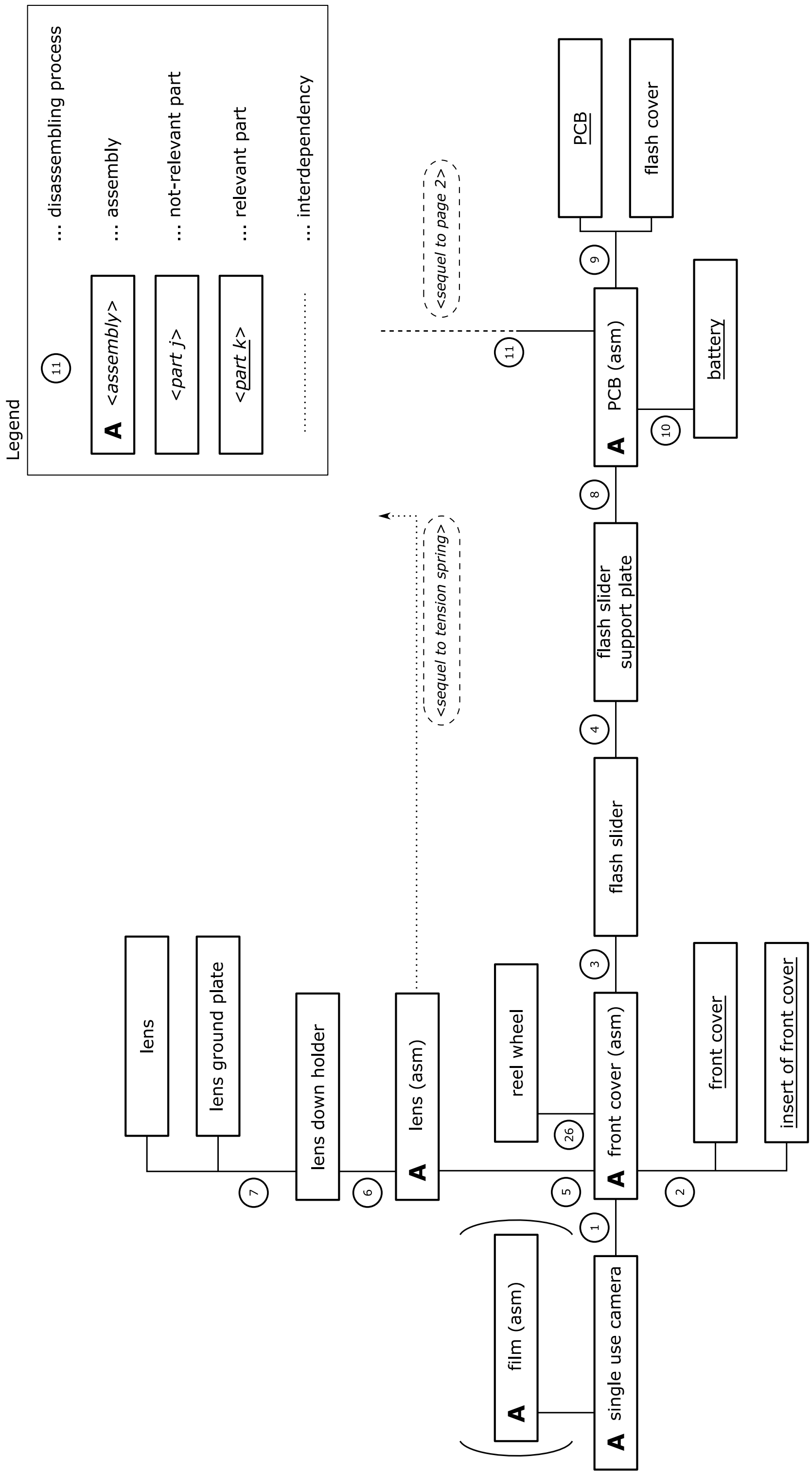

Figure (B.1): *Assembly structure/sequence of disassembling task of single use camera – page 1*

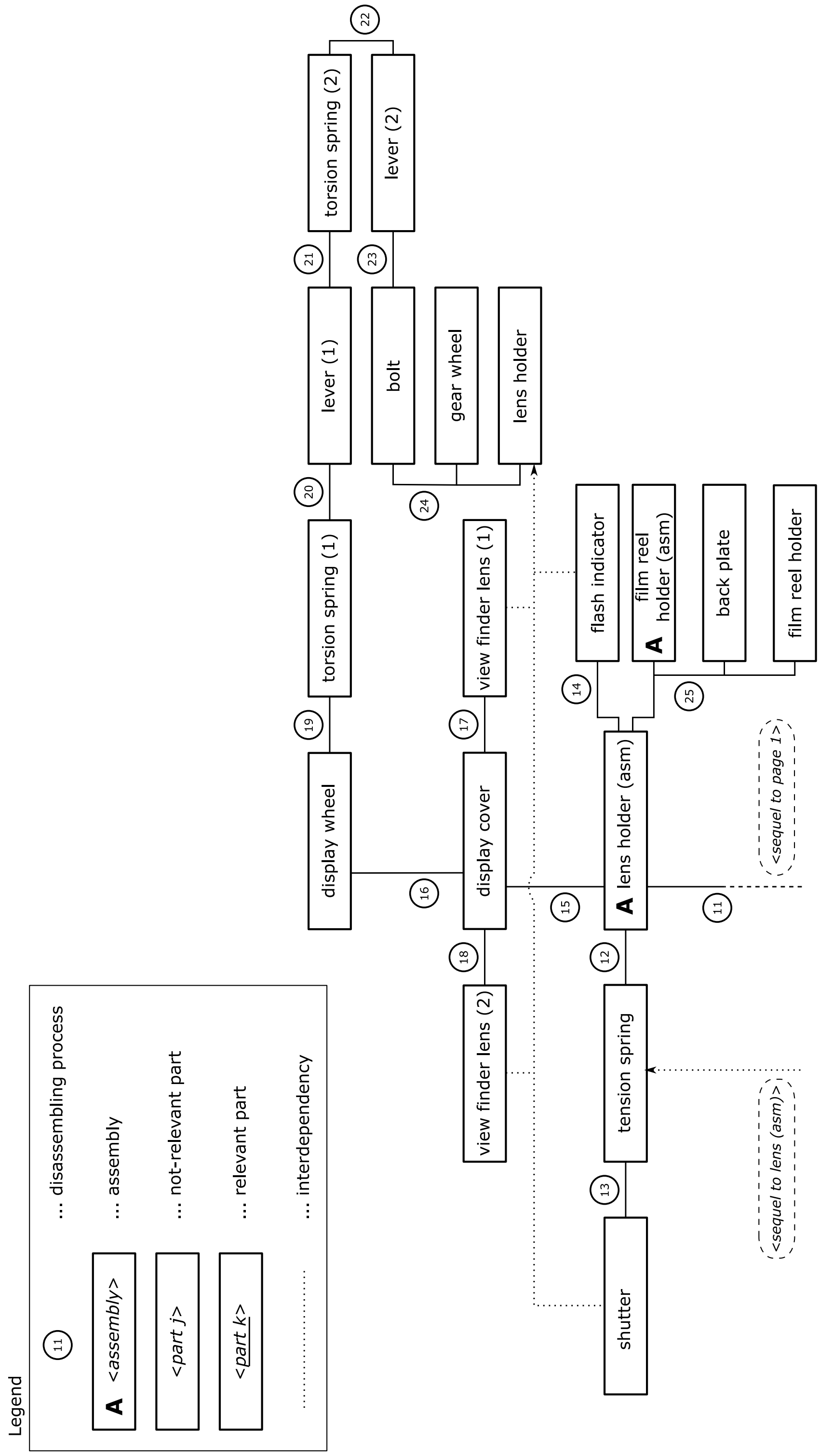

Figure (B.2): *Assembly structure/sequence of disassembling task of single use camera – page 2*

Table (B.6): *Calculating cost shares used for identifying relevant parts – case study 'single use camera'*

1	2	3	4	5
no.	name	cost (in €)	cost share (in %)	cumulated cost share (in %)
1	PCB with flash	0,540	45,00	45,00
2	back plate	0,120	10,00	55,00
3	film reel holder	0,096	8,00	63,00
4	battery	0,096	8,00	71,00
5	front cover	0,072	6,00	77,00
6	insert of front cover	0,060	5,00	82,00
7	lens holder	0,024	2,00	84,00
8	reel wheel	0,024	2,00	86,00
9	flash slider	0,024	2,00	88,00
10	lens groundplate	0,024	2,00	90,00
11	flash slider support plate	0,012	1,00	91,00
12	display covering	0,012	1,00	92,00
13	flash cover	0,012	1,00	93,00
14	flash indicator	0,012	1,00	94,00
15	display wheel	0,012	1,00	95,00
16	lens down holder	0,012	1,00	96,00
17	lens shutter	0,006	0,50	96,50
18	view finder lens 2	0,006	0,50	97,00
19	gear wheel	0,006	0,50	97,50
20	lever 1	0,006	0,50	98,00
21	lever 2	0,006	0,50	98,50
22	bolt	0,003	0,25	98,75
23	view finder lens 1	0,003	0,25	99,00
24	lens	0,003	0,25	99,25
25	torsion spring 1	0,003	0,25	99,50
26	torsion spring 2	0,003	0,25	99,75
27	tension spring	0,003	0,25	100,00
	total	1,200	100	

Table (B.7): *Calculating shares of environmental impact used for identifying relevant parts – case study 'single use camera'*

1	2	3	4	5
no.	name	environmental impact (in MJ)	share of environmental impact (in %)	cumulated share of environmental impact (in %)
1	PCB with flash	3,72E+01	86,0	86,0
2	back plate	1,50E+00	3,5	89,5
3	film reel holder	1,38E+00	3,2	92,6
4	battery	9,90E-02	0,2	92,9
5	front cover	1,13E+00	2,6	95,5
6	insert of front cover	5,00E-01	1,2	96,6
7	lens holder	5,00E-01	1,2	97,8
8	reel wheel	1,25E-01	0,3	98,1
9	flash slider	1,25E-01	0,3	98,4
10	lens groundplate	1,25E-01	0,3	98,7
11	flash slider support plate	4,02E-02	0,1	98,7
12	display covering	4,02E-02	0,1	98,8
13	flash cover	4,02E-02	0,1	98,9
14	flash indicator	4,02E-02	0,1	99,0
15	display wheel	4,02E-02	0,1	99,1
16	lens down holder	4,02E-02	0,1	99,2
17	lens shutter	4,02E-02	0,1	99,3
18	view finder lens 2 (big)	4,02E-02	0,1	99,4
19	gear wheel	4,02E-02	0,1	99,5
20	lever 1	4,02E-02	0,1	99,6
21	lever 2	4,02E-02	0,1	99,7
22	bolt	4,02E-02	0,1	99,8
23	view finder lens 1(small)	4,02E-02	0,1	99,9
24	lens	4,02E-02	0,1	100,0
25	torsion spring 1	6,33E-03	0,0	100,0
26	torsion spring 2	6,33E-03	0,0	100,0
27	tension spring	6,33E-03	0,0	100,0
	total	1,200	100	

Table (B.8): *Calculating cumulated contribution of relevant parts – case study 'single use camera'*

1	2	3	4	5	6	7	8	9
no.	name	relevant part?	mass (in g)	cost (in €)	environ. impact (in MJ)	cumulated mass (in g)	cumulated cost (in €)	cumulated environ. impact (in MJ)
1	PCB with flash	yes	13	5,40E-01	3,72E+01	13	5,40E-01	3,72E+01
2	back plate	no	12	1,20E-01	1,50E+00	13	5,40E-01	3,72E+01
3	film reel holder	no	11	9,60E-02	1,38E+00	13	5,40E-01	3,72E+01
4	battery	yes	11	9,60E-02	9,90E-02	24	6,36E-01	3,73E+01
5	front cover	yes	9	7,20E-02	1,13E+00	33	7,08E-01	3,84E+01
6	insert of front cover	yes	4	6,00E-02	5,00E-01	37	7,68E-01	3,89E+01
7	lens holder	no	4	2,40E-02	5,00E-01	37	7,68E-01	3,89E+01
8	reel wheel	no	1	2,40E-02	1,25E-01	37	7,68E-01	3,89E+01
9	flash slider	no	1	2,40E-02	1,25E-01	37	7,68E-01	3,89E+01
10	lens groundplate	no	1	2,40E-02	1,25E-01	37	7,68E-01	3,89E+01
11	flash slider support plate	no	<1	1,20E-02	4,02E-02	37	7,68E-01	3,89E+01
12	display covering	no	<1	1,20E-02	4,02E-02	37	7,68E-01	3,89E+01
13	flash cover	no	<1	1,20E-02	4,02E-02	37	7,68E-01	3,89E+01
14	flash indicator	no	<1	1,20E-02	4,02E-02	37	7,68E-01	3,89E+01
15	display wheel	no	<1	1,20E-02	4,02E-02	37	7,68E-01	3,89E+01
16	lens down holder	no	<1	1,20E-02	4,02E-02	37	7,68E-01	3,89E+01
17	lens shutter	no	<1	6,00E-03	4,02E-02	37	7,68E-01	3,89E+01
18	view finder lens 2	no	<1	6,00E-03	4,02E-02	37	7,68E-01	3,89E+01
19	gear wheel	no	<1	6,00E-03	4,02E-02	37	7,68E-01	3,89E+01
20	lever 1	no	<1	6,00E-03	4,02E-02	37	7,68E-01	3,89E+01
21	lever 2	no	<1	6,00E-03	4,02E-02	37	7,68E-01	3,89E+01
22	bolt	no	<1	3,00E-03	4,02E-02	37	7,68E-01	3,89E+01
23	view finder lens 1	no	<1	3,00E-03	4,02E-02	37	7,68E-01	3,89E+01
24	lens	no	<1	3,00E-03	4,02E-02	37	7,68E-01	3,89E+01
25	torsion spring 1	no	<1	3,00E-03	6,33E-03	37	7,68E-01	3,89E+01
26	torsion spring 2	no	<1	3,00E-03	6,33E-03	37	7,68E-01	3,89E+01
27	tension spring	no	<1	3,00E-03	6,33E-03	37	7,68E-01	3,89E+01
	total		72	1,20E+00	4,33E+01			

Table (B.9): *List of disassembling tasks (in sequential order)*

1 no.	2 description	3 note	4 time (in s)	5 cost of action (in €)	6 env. impact (in MJ)
DT 1	unlocking of front cover asm	cutting of adhesive foil / unlocking of 8 snap fits at the same time needed!	5	8,33E-02	4,79E-04
DT 2	detaching of insert of front cover	unlocking of 5 snap fits at the same time needed!	4	6,67E-02	3,83E-04
DT 3	lifting out of flash slider	no locks	1,5	2,50E-02	1,44E-04
DT 4	lifting out of flash slider support plate	—	1,5	2,50E-02	1,44E-04
DT 5	detaching of lens asm	unaccessible snap fit lug	5	8,33E-02	4,79E-04
DT 6	unlocking of lens down holder	—	3	5,00E-02	2,88E-04
DT 7	lifting out lens of lens ground plate	—	4	6,67E-02	3,83E-04
DT 8	detaching of PCB (incl. flash) and lifting out	single snap fit, easy accessible	2	3,33E-02	1,92E-04
DT 9	unlocking of flash cover	unlocking of 2 snap fits at the same time needed	2	3,33E-02	1,92E-04
DT 10	lifting out battery	—	3	5,00E-02	2,88E-04
DT 11	unlocking of lens holder asm	unlocking of 1 easy bendable snap fit	4	6,67E-02	3,83E-04
DT 12	pulling off tension spring for lens shutter	—	2	3,33E-02	1,92E-04
DT 13	pulling off lens shutter	—	1	1,67E-02	9,58E-05
DT 14	pulling off flash indicator	—	2	3,33E-02	1,92E-04
DT 15	removing display covering	unlocking of 2 snap fits at the same time needed	6	1,00E-01	5,75E-04
DT 16	pulling out display wheel	—	2	3,33E-02	1,92E-04
DT 17	pulling out view finder lens 1 (small)	—	2	3,33E-02	1,92E-04
DT 18	pulling out view finder lens 2 (big)	—	2	3,33E-02	1,92E-04
DT 19	unlocking torsion spring 1	—	3	5,00E-02	2,88E-04
DT 20	pulling off lever 1	—	2	3,33E-02	1,92E-04
DT 21	unlocking torsion spring 2	—	3	5,00E-02	2,88E-04
DT 22	pulling off lever 2	—	2	3,33E-02	1,92E-04
DT 23	pulling out bolt	—	2	3,33E-02	1,92E-04
DT 24	lifting out gear wheel	—	4	6,67E-02	3,83E-04
DT 25	unlocking film reel holder	unlocking of 4 snap fits at the same time needed!; cutting of 3 welding seams	15	2,50E-01	1,44E-03
DT 26	lifting out reel wheel	—	2	3,33E-02	1,92E-04
DTX	auxiliary process time	—	5	8,33E-02	4,79E-04
total time for completely disassembling			90		—
total effort for completely disassembling				15,0E-01	86,3E-04

Table (B.10): *Allocation of disassembling cost – example single use camera*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
			number of part															
			PCB with flash			battery			front cover			insert of front cover			CCC	SPC	CEIC	SPEI
				cost part 1 (in €)	env. i. part 1 (in MJ)		cost part 2 (in €)	env. i. part 4 (in MJ)		cost part 5 (in €)	env. i. part 5 (in MJ)		cost part 6 (in €)	env. i. part 6 (in MJ)	(in €)	(in €/€)	(in MJ)	(in MJ/MJ)
No.	CDS (in €)	EIDS (in MJ)		0,540	37,195		0,096	0,099		0,072	1,125		0,060	0,500				
DT 1	8,3E-2	4,8E-4	1	5,9E-2	4,6E-4	1	1,0E-2	1,2E-6	1	7,8E-3	1,4E-5	1	6,5E-3	6,2E-6	7,7E-1	1,1E-1	3,9E+1	1,2E-5
DT 2	6,7E-2	3,8E-4	—	0,0E+0	0,0E+0	—	—	—	1	3,6E-2	2,7E-4	1	3,0E-2	1,2E-4	1,3E-1	5,1E-1	1,6E+0	2,4E-4
DT 3	2,5E-2	1,4E-4	1	2,1E-2	1,4E-4	1	3,8E-3	3,8E-7	—	—	—	—	—	—	—	3,9E-2	3,7E+1	3,9E-6
DT 4	2,5E-2	1,4E-4	1	2,1E-2	1,4E-4	1	3,8E-3	3,8E-7	—	—	—	—	—	—	—	3,9E-2	3,7E+1	3,9E-6
DT 5	8,3E-2	4,8E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 6	5,0E-2	2,9E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 7	6,7E-2	3,8E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 8	3,3E-2	1,9E-4	1	2,8E-2	1,9E-4	1	5,0E-3	5,1E-7	—	—	—	—	—	—	6,4E-1	5,2E-2	3,7E+1	5,1E-6
DT 9	3,3E-2	1,9E-4	1	3,3E-2	1,9E-4	—	—	—	—	—	—	—	—	—	5,4E-1	6,2E-2	3,7E+1	5,2E-6
DT 10	5,0E-2	2,9E-4	—	—	—	1	5,0E-2	2,9E-4	—	—	—	—	—	—	9,6E-2	5,2E-1	9,9E-2	2,9E-3
DT 11	6,7E-2	3,8E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 12	3,3E-2	1,9E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 13	1,7E-2	9,6E-5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 14	3,3E-2	1,9E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 15	1,0E-1	5,8E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 16	3,3E-2	1,9E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 17	3,3E-2	1,9E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 18	3,3E-2	1,9E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 19	5,0E-2	2,9E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 20	3,3E-2	1,9E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 21	5,0E-2	2,9E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 22	3,3E-2	1,9E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 23	3,3E-2	1,9E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 24	6,7E-2	3,8E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 25	2,5E-1	1,4E-3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DT 26	3,3E-2	1,9E-4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DTX	8,3E-2	4,8E-4	1	5,9E-2	4,6E-4	1	1,0E-2	1,2E-6	1	7,8E-3	1,4E-5	1	6,5E-3	6,2E-6	7,7E-1	1,1E-1	3,9E+1	1,2E-5
effort for disassembling per relevant part				2,2E-1	1,6E-3		8,3E-2	2,9E-4		5,2E-2	2,9E-4		4,3E-2	1,3E-4	$\sum_{k=1}^{n} C_{DA\,(k)} =$ 1,500		$\sum_{k=1}^{n} EI_{DA\,(k)} =$ 1,500	

Explanation of abbreviations:

CDS ... cost of disassembling step

EIDS ... environmental impact of disassembling step

CCC ... cumulated cost of contributor

SPC ... standardised process cost per disassembling step

CEIC ... cumulated effort of contributors

SPEI ... standardised environmental effort per disassembling step

Table (B.11): *Effort for cleaning relevant parts ($C_{C\ (k)}$ and $EI_{C\ (k)}$)*

1 no.	2 part/treamtent	3 input per part	4 unit	5 $c^*_{C\ t}$ (in €/<unit>)	6 $ei^*_{C\ t}$ (in MJ/<unit>)	7 $d_{C\ (k),t}$ (in <unit>)	8 $c_{C\ (k),t}$ (in €)	9 $ei_{C\ (k),t}$ (in MJ)
1	PCB with flash							
	no soiling of PCB observable → no cleaning necessary	—	—	—	—	—	—	—
4	battery							
	no soiling of battery observable → no cleaning necessary	—	—	—	—	—	—	—
5	front cover							
	removing dirt and dust by means of dipping bath	tap water	m^3	—	6,7	1,0E-03	—	6,7E-03
		detergent	kg	—	25	5,0E-03	—	1,25E-01
		processing	h	100	—	5/3600	0,139	—
	removing adhesive foil	processing	h	70	—	2/3600	0,039	—
							0,178	1,32E-01
6	insert of front cover							
	removing dirt and dust by means of dipping bath	tap water	m^3	—	6,7	5,0E-04	—	3,35E-03
		detergent	kg	—	25	3,0E-03	—	7,50E-02
		processing	h	100	—	2/3600	0,056	—
							0,056	7,84E-02

Table (B.12): *Effort for testing relevant parts ($C_{T\ (k)}$ and $EI_{T\ (k)}$)*

1	2	3	4	5	6	7	8	9
no.	part/description	process description	unit	$c^*_{T\ t}$ (in € / <unit>)	$ei^*_{T\ t}$ (in MJ / <unit>)	$d_{T\ (k),t}$ (in <unit>)	$c_{T\ (k),t}$ (in €)	$ei_{T\ (k),t}$ (in MJ)
1	PCB with flash possibly corroded or bended contacts, burnt flash	electrical testing of functionality (test PC)	h	120	11,5	3/3600	0,100	0,005
		optical checking of contacts and flash (2 pcs. 30 W lamps)	h	70	11,5	3/3600	0,058	0,001
							0,158	0,005
4	battery possibly corroded contacts, checking electrical charge level	electrical testing of functionality (20 W multimeter)	h	120	11,5	2/3600	0,067	0,0001
5	front cover possible broken snap fits and or scratched surface	optical checking of surface (2 pcs. 30 W lamps)	h	70	11,5	5/3600	0,097	0,001
6	insert of front cover possible broken snap fits and or scratched surface	optical checking of surface (2 pcs. 30 W lamps)	h	70	11,5	5/3600	0,097	0,001

Table (B.13): *Calculating effort for reconditioning – part 1: PCB with flash*

1	2	3	4	5	6	7	8	9	10	11
no.	description of damage	description of task	prob. of occurence	scenario (acc. to Fig.5.9)	number of additional life times	cost factor $c^*_{RC,\,(1),t}$ <*unit*>	env. cost factor $ei^*_{RC,\,(1),t}$ <*unit*>	cost driver $d_{RC\,(1),t}$ <*unit*>	cost per task $C_{RC\,(1),t}$ (in €)	env. imp. per task $EI_{RC\,(1),t}$ (in MJ)
1	D1.1: corroded battery contact	replacing!	$p_{RC\,(1),1} = 0,01$	SC4a	—	—	—	—	0,005	0,372
2	D1.2: fatigued flash switch	replacing!	$p_{RC\,(1),2} = 0,01$	SC4a	—	—	—	—	0,005	0,372
3	D1.3: fatigued bending contacts	replacing!	$p_{RC\,(1),3} = 0,01$	SC4a	—	—	—	—	0,005	0,372
4	D1.4: exhausted flash light	replacing!	$p_{RC\,(1),4} = 0,05$	SC4a	—	—	—	—	0,027	1,860
5	D1.5: bad functionality of PCB	replacing!	$p_{RC\,(1),5} = 0,03$	SC4a	—	—	—	—	0,016	1,116
total cost for reconditioning									0,059	4,091

Table (B.14): *Calculating effort for reconditioning – part 4: battery*

1	2	3	4	5	6	7	8	9	10	11
no.	description of damage	description of task	prob. of occurence	scenario (acc. to Fig.5.9)	number of additional life times	cost factor $c^*_{RC,\,(4),t}$ <*unit*>	env. cost factor $ei^*_{RC,\,(4),t}$ <*unit*>	cost driver $d_{RC\,(4),t}$ <*unit*>	cost per task $C_{RC\,(4),t}$ (in €)	env. imp. per task $EI_{RC\,(4),t}$ (in MJ)
1	D4.1: corroded battery contact	replacing!	$p_{RC\,(4),1} = 0,01$	SC4a	—	—	—	—	0,001	0,001
2	D4.2a: too low charging level	replacing!	$p_{RC\,(4),2} = 0,40$	SC4a	—	—	—	—	0,048	0,049
	D4.2b: low but sufficiently high charging level	reusing	$p_{RC\,(4),2} = 0,59$	SC4b	1	—	—	—	0,024	0,024
total cost for reconditioning									0,072	0,075

Table (B.15): *Calculating effort for reconditioning – part 5: front cover*

1	2	3	4	5	6	7	8	9	10	11
no.	description of damage	description of task	prob. of occurence	scenario (acc. to Fig.5.9)	number of additional life times	cost factor $c^*_{RC,\,(5),t}$ <*unit*>	env. cost factor $ei^*_{RC,\,(5),t}$ <*unit*>	cost driver $d_{RC\,(5),t}$ <*unit*>	cost per task $C_{RC\,(5),t}$ (in €)	env. imp. per task $EI_{RC\,(5),t}$ (in MJ)
1	D5.1: broken snap fit	replacing!	$p_{RC\,(5),1} = 0,10$	SC4a	—	—	—	—	0,007	0,113
2	D5.2: scratched and flawed surface	replacing!	$p_{RC\,(5),2} = 0,20$	SC4a	—	—	—	—	0,014	0,225
3	D5.3: broken snap fit	replacing!	$p_{RC\,(5),3} = 0,05$	SC4a	—	—	—	—	0,004	0,056
total cost for reconditioning									0,025	0,394

Table (B.16): *Calculating effort for reconditioning – part 6: insert of front cover*

1	2	3	4	5	6	7	8	9	10	11
no.	description of damage	description of task	prob. of occurence	scenario (acc. to Fig.5.9)	number of additional life times	cost factor $c^{*}_{RC,\,(6),t}$ <unit>	env. cost factor $ei^{*}_{RC,\,(6),t}$ <unit>	cost driver $d_{RC\;(6),t}$ <unit>	cost per task $C_{RC\;(6),t}$ (in €)	env. imp. per task $EI_{RC\;(6),t}$ (in MJ)
1	D6.1: broken snap fit	replacing!	$p_{RC\;(6),1} = 0,10$	SC4a	—	—	—	—	0,006	0,050
2	D6.2: scratched and flawed surface	replacing!	$p_{RC\;(6),2} = 0,20$	SC4a	—	—	—	—	0,012	0,100
total cost for reconditioning									0,018	0,150

Table (B.17): *Calculating effort for EoL-treatment – direct effort*

1	2	3	4	5	6	7	8
no.	name	weight (in g)	$P_{RP\;(k)}$	$c^{*\,<MAT>}_{DP}$ (in €/ton)	$ei^{*\,<MAT>}_{DP}$ (in MJ/kg)	c^{dir}_{DP} (in €)	ei^{dir}_{DP} (in MJ)
1	PCB with flash	13	0,11	1000	100	1,43E-03	1,43E-01
2	back plate	12	—	—	—	—	—
3	film reel holder	11	—	—	—	—	—
4	battery	11	0,71	250	4,5	1,94E-03	3,49E-02
5	front cover	9	0,35	70	-75	2,21E-04	-2,36E-01
6	insert of front cover	4	0,30	70	-75	8,40E-05	-9,00E-02
	total cost / total env. impact					3,67E-03	-1,48E-01

Table (B.18): *Calculating effort for newly manufacturing*

1	2	3	4	5	6	7
no.	name||mat. / process	unit of cost driver	cost factor $ei^{*\,<MAT/PROC>}_{NM}$ (in MJ/<UNIT>)	cost driver $d^{<MAT/PROC>}_{NM}$ (in <UNIT>)	env. impact per mat./proc. $ei_{NM\;(k)}$ (in MJ)	env. impact per part $ei_{NM\;(k)}$ (in MJ)
1	PCB with flash					37,195
	PCB (mat.)	kg	2860	0,013	37,180	
	wave soldering	m^2	392	38,0E-06	0,015	
2	back plate					1,500
	HIPS	kg	96	0,012	1,152	
	injection moulding	kg	29	0,012	0,348	
3	film reel holder					1,375
	HIPS	kg	96	0,011	1,056	
	injection moulding	kg	29	0,011	0,319	
4	battery					0,099
	alkaline	kg	4,5	0,011	0,050	
	processing	kg	4,5	0,011	0,050	
5	front cover					1,125
	HIPS	kg	96	0,009	0,864	
	injection moulding	kg	29	0,009	0,261	
6	insert of front cover					0,500
	HIPS	kg	96	0,004	0,384	
	injection moulding	kg	29	0,004	0,116	