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Ecological and Economic Assessment of Resource Use

Remanufacturing of products

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Study: Ecological and Economic Assessment of Resource Use – Remanufacturing of products

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LIST OF ABBREVIATIONS

B2B	Business-to-Business
B2C	Business-to-Consumer
CEID	Circular Economy Initiative Deutschland
CO_2	Carbon dioxide
DIN	German Institute for Standardization (German: *Deutsches Institut für Normung*)
EEE	Electric and electronic equipment
ELV	End of Life of Vehicles Directive
EN	European standard
ERN	European Remanufacturing Network
EU	European Union
Eurostat	Statistical office of the European Union
IEC	International Electrotechnical Commission
IMDS	International Material Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KEA	Kumulierter Energieaufwand (Cumulative energy demand)
kg CO_2-eq	Kilogram CO_2 equivalents
km	Kilometre
KRA	Kumulierter Rohstoffaufwand (Cumulative raw material demand)
kWh	Kilowatt hour(s)
LCA	Life cycle assessment

m^2	Square metre
m^3	Cubic metre
MJ	Megajoule
MRO	Maintenance, repair and overhaul
NMR	Nuclear magnetic resonance
SME	Small and medium-sized enterprises
TE	Thermal energy
VDI	Association of German Engineers (German: *Verein Deutscher Ingenieure e. V.*)

SYNOPSIS

A circular economy refers to an economy that preserves resources for as long a period of use as possible as part of a closed-loop (or as closed as is possible) system. This contrasts to the traditional linear economy model (also referred to as a “throw-away economy”), which sees resources taken from the environment and processed into materials to manufacture products. These products are then disposed of as waste after use, often resulting in a higher rate of resource consumption.

This study will look at the topic of remanufacturing. Remanufacturing presents an opportunity to preserve products or components beyond their originally planned lifespan as part of an economic cycle, thus contributing to a circular economy. The findings from the study’s life cycle assessment and costing aim to support small and medium-sized enterprises (SMEs) in making decisions on important product- and process-related changes.

The study looks at the various expenses (material, energy, water) and space requirements that arise throughout a product’s entire life cycle when recycled/reused as part of remanufacturing or manufactured as a new production. The water meter from Lorenz GmbH & Co. KG, based in Ingstetten (Schelklingen), is used as a reference product. A life cycle assessment evaluates a product’s life cycle by looking at the manufacturing, transport, use and disposal phases and using indicators such as water consumption, land use, cumulative raw material demand, cumulative energy demand and global warming potential. The assessment also includes an analysis of raw material criticality and cost assessment.

The following research questions are answered:

- What expenses (material, energy, water) and space requirements arise throughout the reference product’s entire life cycle (from remanufacturing and new production)?

- What emissions (shown in CO_2 equivalents) arise for each variant (remanufacturing and new production)?

- What supply-critical raw materials for the reference products are used or saved as a result of remanufacturing or new production?
- What costs arise for the variants in question?

It turns out that the impact reprocessed water meters have on the environment is at least 90% smaller compared to newly manufactured water meters. This mainly comes as a result of the business model used by Lorenz: a model geared towards a circular economy, which the company aligns with the remanufacturing system that is fine-tuned for the properties of the water meter. The water meters are reused within the closed-loop system and reprocessed so as to ensure its use is identical in both quality and function, namely the calibrated tracking of water quantities over five to six years (for hot- and cold-water meters). A large portion of the components used (casing, mechanics, electronics) can be reused as part of this process, meaning only a small number of parts must be replaced (battery, cover). This, in turn, leads to a significant reduction in the product's environmental impact, as mentioned above. The massively reduced need for material for reprocessing also reduces raw material criticality. Reusing electronics and casings in particular makes a big difference. The advantages of remanufacturing can also be seen from an economic point of view. Lorenz refunds a variable sum to the customer depending on the condition of the water meter. This sum is chosen so as to ensure that the manufacturing costs for reprocessing amount to approximately half of the manufacturing costs for new goods, regardless of the condition of the water meter. In addition to the economic (lower manufacturing costs, reduced raw material criticality) and ecological advantages (significantly reduced impact on the environment) for the manufacturer, there is also one more advantage for the customer: refunds for returning water meters with expired calibration reduce costs for the customer. It is evident that the reprocessing of water meters by Lorenz is advantageous for all parties involved.

In more specific terms, this study builds on the following contents:

Chapter 1 provides an introduction to the topic of circular economies, explaining the background of the study and outlining the study's objectives and approach.

Chapter 2 looks at the basics of remanufacturing and explores the current state of the art and market situation. This chapter elaborates on the four main aspects that have been identified for successful remanufacturing. These are product design, collection and return systems, business models and other aspects, which includes risk factors, value perception and the availability of qualified workers.

Chapter 3 evaluates the suitability for remanufacturing for various product groups using set criteria. This assessment will also introduce an evaluation method that allows industry, SMEs and other interested groups to reproduce the evaluation process with full transparency and determine their own remanufacturing potential. This method involves an evaluation matrix that can be also be used by SMEs to review products or product groups for their suitability for remanufacturing.

Chapter 4 outlines the drivers and obstacles for remanufacturing based on literature research and an analysis of product examples. The findings in this chapter help businesses to consider and decide on whether to carry out a life cycle assessment and how the results of the assessment can be used for their own business models. Chapter 4.3 provides a practical guide in the form of a six-step plan that the relevant actors can use to develop a remanufacturing-based business model where there are no obvious product and system properties that are compatible with a closed-loop model.

Chapter 5 provides a brief introduction to the topic of life cycle assessments and goes into more detail on the assessment itself using the example of the water meter from Lorenz GmbH & Co. KG. This life cycle assessment also includes an analysis of raw material criticality and cost assessment. The results provide important information on how the methodology used to assess resource expenditure can help in the decision on whether to invest in remanufacturing.

Chapter 6 outlines the findings and uses these to propose recommended actions in business and policy that can be used to analyse potential for and ultimately implement a remanufacturing model.

This study clearly highlights that for remanufacturing to be successful, businesses must combine all four of the main identified aspects.

- **Product design:** Products that are compatible with a closed-loop model are long-lasting, easily disassembled with a modular design and can be clearly identified. These properties all make reprocessing easier.

- **Collection and return systems:** These have a huge impact on the availability of products for reprocessing. Collection costs should be as low as possible in relation to the product value and businesses should be able to plan return quotas.

- **Business model:** Remanufacturing has a different cost structure to the manufacture of new goods as production stages are eliminated, but it does involve additional costs, e.g. for returns and goods inward inspection. Customers can also perceive the products differently to new goods which, in turn, affects their perception of value and thus the purchase price.

- **Other aspects:** Legal and corporate framework conditions can influence the way return systems or warranties are designed. The availability of qualified staff is also key when it comes to remanufacturing.

If these aspects are not fulfilled, they can be systematically developed to successfully establish reprocessed products on the market. This can be seen in the water meter example. Systematically developing a collection system allowed the company to create a lucrative and ecologically advantageous business model within the market.

In order to establish an increasing number of successful products and markets for remanufacturing, the ultimate core message of the recommended actions is: promote information, innovate and collaborate.

1 INTRODUCTION

1.1 Introduction to circular economies

Although the "take, make, dispose" attitude is still prevalent throughout business and society, the term "circular economy" has been growing in significance in recent years[1].

The term refers to an economy which, in contrast to a traditional linear economy, preserves resources for as long a period of use as possible as part of a closed-loop (or as closed as is possible) system[2]. In a linear economy (also referred to as a "throw-away economy"), resources are taken from the environment for use in and by products and then disposed of as waste. Figure 1 and Figure 2 illustrate both economic models.

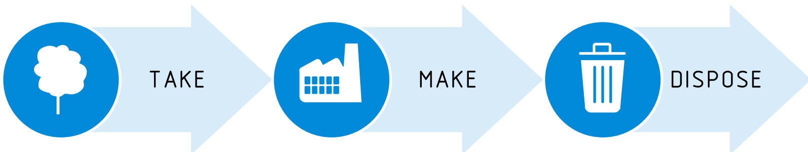

Figure 1: Linear economy model [3]

The topic of circular economies is expansive and involves considerations from lots of different perspectives. To prevent the extraction of raw materials from the environment and reduce waste and emissions as much as possible, a circular economy requires us to rethink the way we produce and consume. It seeks to use, reuse, repair, refurbish and recycle products and used materials for as long as possible. Anything that is taken from the natural world and used within the technosphere should be maintained and used as a valuable asset.

1 Cf. Lange, U. (2017), pp. 9 et seqq. & VDI e.V. (2019), pp. 2 et seqq. & Ellen MacArthur Foundation (2013a), pp. 1 et seqq.

2 Cf. Parker, D.; Riley, K.; Robinson, S.; Symington, H.; Tewson, J.; Jansson, K.; Ramkumar, S. and Peck, D. (2015), pp. 2 et seqq. & Ellen MacArthur Foundation (2013a), pp. 1 et seqq.

3 Based on Sphera (2020d).

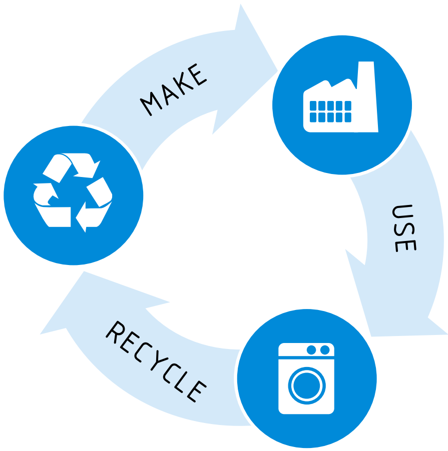

Figure 2: Circular economy model [4]

The comprehensive concept known as the 9R Framework[5] sets out ten options for a modern circular economy and is divided into three industries (cf. Figure 3). The concept offers economic, ecological and business advantages and can contribute to a company's stability in the long term[6]. It goes hand in hand with the hierarchy under the German Circular Economy Act: refuse, reuse, recycle, recover and dispose[7]. The basic idea of this hierarchy remains valid even when applied within the latest developments in European standards and legislation and their respective national counterparts[8].

The transition towards a circular economy is a systemic process. The Refuse, Rethink and Reduce options (R0 to R2) are used to optimise and redesign the areas of production, product use and logistics to create smarter solutions. To do so, knowledge throughout a product's entire life cycle is accumulated and used to develop a new product or function. The Reuse, Repair, Refurbish, Remanufacture and Repurpose (R3 to R7) concepts involve reusing or reutilising used products and product parts in an attempt to extend the product's

4 Based on Sphera (2020d).
5 Cf. Kirchherr, J.; Reike, D. and Hekkert, M. (2017), pp. 221–232.
6 Cf. Buchberger, S.; Hofbauer, G.; Mangold, L. and Truong, K. (2019), p. 18.
7 Cf. Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation and Reactor Safety) (1994).
8 Cf. Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) (2020).

life cycle or use cycle as much as possible. Individual product parts can be reintegrated at various points throughout the value-added process. The Recycle and Recover (R8 and R9) measures aim at recycling used products that cannot be reused or whose lifespan cannot be otherwise extended in order to recover raw materials or energy[9].

Circular economy

Smarter product use and manufacture	R0 Refuse	Abandonment of a product due to alternative function substitute or radically different alternative product
	R1 Rethink	Longer or more intensive use of a product
	R2 Reduce	Efficiency increase in product manufacturing and/or product use
Extend lifespan of product and its parts	R3 Reuse	Reuse of a used, functional product by another user
	R4 Repair	Repair or maintenance of a defective product
	R5 Refurbish	Restoration and improvement of the efficiency and/or appearance of a used product
	R6 Remanufacture	Reuse of reprocessed used parts in a new product with the same function
	R7 Repurpose	Reuse of reprocessed used parts in a new product with a different function
Sensible reuse of materials	R8 Recycle	Recycling of raw materials
	R9 Recover	Thermal recovery of materials

Linear economy

Figure 3: The ten options for a circular economy[10]

With regard to remanufacturing, the circular economy model involves an industrial-scale reprocessing and reuse of cores for the manufacture of a new

[9] Cf. Kirchherr, J.; Reike, D. and Hekkert, M. (2017), pp. 221–232.

[10] Based on Kirchherr, J.; Reike, D. and Hekkert, M. (2017), p. 224 & Buchberger, S.; Hofbauer, G.; Mangold, L. and Truong, K. (2019), p. 11.

product with the same function. This approach poses huge potential for producing companies in many different sectors, and this potential is yet to be fully utilised[11]. As an industrial country, remanufacturing could open up new perspectives for economic and environmentally friendly production in Germany in particular[12].

1.2 Background of the study

Although it can help businesses make significant resource savings, not all products are equally well suited for remanufacturing. Various technical, logistical or market strategy-related constraints often stand in the way, making a life cycle assessment useful.[13] A life cycle assessment quantifies the potential for resource savings and highlights any potential obstacles so that they can be resolved in a more targeted manner.

With its various obstacles and drivers, the topic of remanufacturing often stands in conflict. Trends that hinder the remanufacturing model include, for example, the miniaturisation of electronics, "smartness" at the chip level, the use of a wider range of materials or a reduced acceptance of refurbished used products. The pros of remanufacturing, on the other hand, include e.g. reductions in price, resource efficiency, a reduced carbon footprint or a sustainable, long-lasting business model. In this context, it is always recommended to compare new products and reprocessed products with one another from both an economic and ecological point of view.

Life cycle assessments and life cycle cost calculations (both aligned with one another based on their approach and methodology) are the perfect instruments for this comparison. The results can be then be configured for interpretation by industry and commercial stakeholders. Important indicators include, for example, greenhouse gas emissions, resource consumption in the form of land, water, energy and raw material use combined with costing and raw material criticality analyses.

[11] Cf. Ellen MacArthur Foundation (2013b), pp. 4–8.

[12] Cf. Buchberger, S.; Hofbauer, G.; Mangold, L. and Truong, K. (2019), pp. 1–2.

[13] Cf. Lange, U. (2017), pp. 21 et seq.

This study will look at the topic of remanufacturing and perform both life cycle assessments and life cycle costings. The findings from the study aim to support small and medium-sized enterprises (SMEs) in making decisions on important product- and process-related changes.

1.3 Study objectives and approach

The aim of the study is to carry out a comparative ecological and economic evaluation of the remanufacturing of a product in comparison to the new production of the same product.

A water meter by Lorenz GmbH & Co. KG is the subject of the study. The company manufactures and supplies water meters as both new and reprocessed products. Both product variants are examined, compared and assessed throughout their respective life cycles. These will serve as reference products for the study.

As part of the ecological assessment, researchers determine the environmental impact of the products throughout their entire life cycle in accordance with the DIN EN ISO 14040[14] and DIN EN ISO 14044[15] standards, as well as the VDI 4600[16] and VDI 4800-1[17] and 2[18] guidelines, and then compare these within set system boundaries. A suitable functional unit is defined to ensure comparability between the new and reprocessed product throughout their entire life cycle. The results are interpreted in CO_2 equivalents with a focus on greenhouse gas emissions. The study also includes a raw material criticality analysis in accordance with VDI 4800-2[19]for the supply risk aspect.

A comparative economic analysis builds on the ecological evaluation and provides an indication of the economic efficiency of remanufacturing in com-

[14] DIN EN ISO 14040:2006.
[15] DIN EN ISO 14044:2006.
[16] VDI 4600-1:2015-08.
[17] VDI 4800-1:2016-02.
[18] VDI 4800-2:2018-03.
[19] VDI 4800-2:2018-03.

parison to the new production of a product from the manufacturer's perspective. The economical evaluation also includes a comparative costing for manufacturing.

The following research questions are explored and answered:

- What expenses (material, energy, water) and space requirements arise throughout the reference product's entire life cycle from remanufacturing and new production?
- What emissions (shown in CO_2 equivalents) arise for each variant (remanufacturing and new production)?
- What supply-critical raw materials for the reference products are used or saved as a result of remanufacturing or new production?
- What costs arise for the variants in question?

Chapter 2 looks at the basics of remanufacturing and explores the current state of the art and market situation.

Chapter 3 includes an evaluation of various products to determine which product groups are well suited for remanufacturing. This assessment will also propose an evaluation method that allows industry, small and medium-sized enterprises (SMEs) and other interested groups to reproduce the evaluation process with full transparency and determine their own remanufacturing potential.

Chapter 4 outlines the drivers and obstacles for remanufacturing. The findings in this chapter help businesses to consider and decide on whether to carry out a life cycle assessment and how the results of the assessment can be used for their own business models. The process for this is outlined in chapter 4.3.

Chapter 5 provides a brief introduction to the topic of life cycle assessments and then goes into more detail on the assessment itself using the concrete example of the water meter from Lorenz GmbH & Co. KG. The results provide important information on how the methodology used to assess use of resources can help in the decision on whether to invest in remanufacturing.

The findings and recommendations gained are outlined in chapter 6.

This study's target groups are product users, machine and system manufacturers (SMEs and non-SMEs), consultancy firms and research institutions. The findings from the study also serve as a source of information for initiatives and associations, including state and national institutions and their representatives.

2 STATE OF THE ART AND MARKET SITUATION

2.1 State of the art

2.1.1 Basics of remanufacturing

Remanufacturing refers to the processing of a used product for reuse whereby the product is reprocessed using various process stages to at least the same level of quality as a new product[20]. Figure 4 illustrates the process of remanufacturing in the context of the product's life cycle.

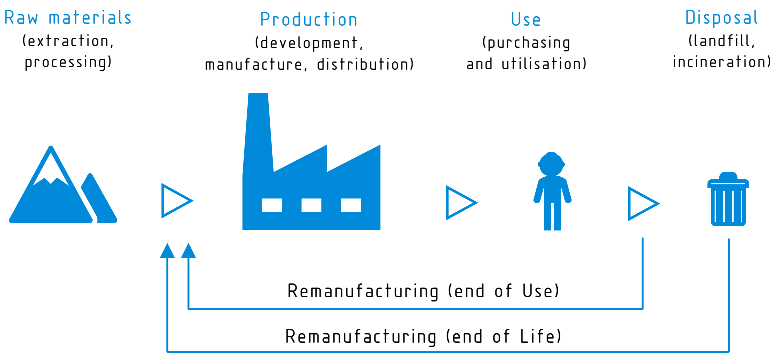

Figure 4: Illustration of remanufacturing[21]

Remanufacturing is an industrial reprocessing process and contains multiple stages. In general, the process involves disassembling collected cores, cleaning and inspecting them and then reprocessing and reassembling them (cf. chapter 2.1.2)[22]. Here, the product is dismantled in the aim of supplying a product as new.

Refurbishing, on the other hand, involves reprocessing a used product into a product of a defined, usually lower level of quality than that of a new product. Upgrading or modernisation improve the function, performance or safety of a product through adding various parts and/or equipment. The line between

[20] Cf. Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation, Housing and Reactor Safety) (2016), p. 133.

[21] Based on Lange, U. (2017), p. 9 & Steinhilper (1998) in Lindahl, M.; Sundin, E. and Östlin, J. (2006), p. 448.

[22] Lange, U. (2017), p. 9.

remanufacturing, refurbishing and upgrading is blurred, and these are often combined. A clearer distinction can be seen between remanufacturing/refurbishing/upgrading and repairs/maintenance. The latter serves only to repair defective products back to their desired condition to extend a product's lifespan. However, these do not necessarily have to be part of a closed-loop system[23].

Remanufacturing usually involves multiple process stages. The reprocessed product parts are returned to their original function. The quality of reprocessed product parts is identical to or higher than that of a new product. Similar quality assurance measures to those used for new products are implemented to ensure that reprocessed used products possess the same quality and warranty of new products[24].

To accelerate the transition towards a circular economy, remanufacturing takes into account all aspects and guidelines for the circular economy model and follows the suggestions set out therein. Making changes to a linear product lifespan and reducing the impact of a linear economy alone is not enough. A comprehensive, systematic concept is required. The economic system must work effectively on all levels. In this context, there are four important building blocks that are key to creating a circular economy according to Ellen MacArthur[25] (cf. Figure 5). While the areas of design and collection/return systems are concerned with technical aspects and constraints, the areas of innovative business models as well as internal and external system conditions deal with economic, legal, cultural and societal aspects.

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[23] Cf. Bullinger, H.-J.; Spath, D.; Warnecke, H.-J. and Westkämper, E. (2009), pp. 273–293.

[24] Cf. Lange, U. (2017), pp. 18 et seqq.

[25] Cf. Ellen MacArthur Foundation (2017).

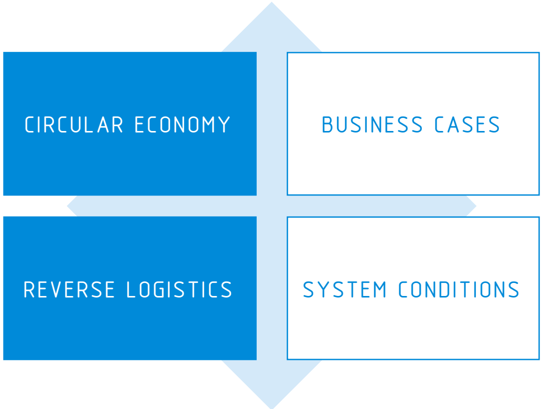

Figure 5: Building blocks of a circular economy[26]

A circular design requires innovative ways of working and advanced knowledge in relation to important product and production aspects, such as, for example, choice of material, standardised components, products designed for longevity, reuse of materials and products.

Cost-efficient, high-quality collection and return systems as well as an effective segmentation of used products reduces material loss from the system and prevents new raw materials from being extracted from the environment. This includes mechanisms such as sorting and logistics systems, storage and risk management[27].

Innovative business models not only help to increase profitability and sustainability for individual stakeholders, they also inspire other businesses. As a result, the new models will spread across the globe and will help to foster a transition towards a circular economy.

Internal and external system conditions also play a key role. In addition to legal constraints and societal requirements, aspects of market acceptance also have a huge influence over the switch towards a circular economy. The success of a circular economy also depends on the acceptance and support

[26] Based on Ellen MacArthur Foundation (2017).

[27] Cf. VDI 2243:2002-07, VDI 2343-1:2001-05, VDI 2343-2:201002, VDI 2343-3:2009-04, VDI 2343-4:2012-01, VDI 2343-5:2013-04, VDI 2343-6:2019-02 and VDI 2343-7:2013-04.

from policymakers, research and education institutions, the media and the public itself. Suggestions for motivating these external groups include, for example, educational and awareness campaigns and new collaborations that seek to incentivise businesses and customers. Suitable framework conditions are also required or must be created internally within a company itself. For example, a business must not only allow innovative thinking and creativity, they must actively promote it, even where the results of such innovation often go against the conventions of a linear economy.

A well-functioning circular economy and, by extension, remanufacturing are only possible when aspects from all four areas are taken into consideration. The challenge here is the fact that the four building blocks are not clearly separated from one another and also feature mutual interactions that work against one another. For example, technical measures can only live up to their value when implemented as part of a business model that is geared towards them. Technical aspects related to reverse logistics are also a part of product design. Employees must also be able to reflect on business models that could potentially cannibalise the market of previously manufactured new products, and do so against the backdrop of legal constraints that sometimes prevent new, circular business orientations[28].

2.1.2 Process steps and technical aspects

The remanufacturing process is basically divided into five main process steps as shown in Figure 6.

How each individual step looks exactly depends on the used product being reprocessed. Mechanical, electrical, electromechanical and hydraulic systems are often directly disassembled and fed into the cleaning, inspection, reprocessing and reassembly process steps. For mechatronic, electronic and hybrid systems, cores (used parts) are, in most cases, first subject to a goods inward inspection before the used products are passed on for disassembly[29].

[28] Cf. Technopolis Group (2016), pp. 10–16 and pp. 56–58.
[29] Cf. Lange, U. (2017), pp. 18 et seq. & Freiberger, S. (2007).

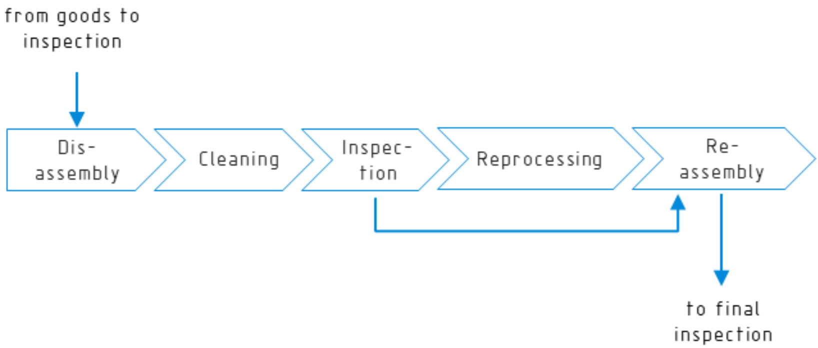

Figure 6: Main process steps of remanufacturing[30]

Cores are dismantled and sorted into individual components as part of disassembly. Here, the type of disassembly used depends on how easily the products can be disassembled (e.g. destructive or destruction-free disassembly). In both cases, this process serves to separate components, modules, subassemblies, individual materials and material mixes. The aim here is to either selectively remove undesired modules so that the remaining parts can be reprocessed or, alternatively, isolate individual modules and units so that they can be cleaned, reprocessed or further treated and replaced more effectively[31]. Non-reusable product units must be identified. These parts are removed from the process chain and assigned to a suitable recycling/recovery process. With hard-to-calculate volumes, a diverse range of used devices, inconsistent conditions of used devices (e.g. dirt, damage, rust, foreign spare parts) and used device structures that are not always easy to dismantle, disassembly differs fundamentally from assembly, where production of product quantities can be planned and scheduled. Other important topics include manual, partially automated or fully automatic disassembly, tools, use of operating supplies, degree of dismantling or workstation design, including planning, process flow and organisation[32].

Disassembled cores suitable for reprocessing are then degreased, deoiled, derusted or stripped of paint in the subsequent cleaning stage. Once cleaned,

[30] Based on Lange, U. (2017), p. 18 & Steinhilper, R. (1999).

[31] VDI 2343-3:2009-04.

[32] VDI 2343-3:2009-04.

the parts are reinspected and deemed to be either reusable (with or without reprocessing) or not reusable based on their defects. Parts that do not require any reprocessing are sent directly for reassembly. Parts that cannot be reused are replaced with new spare parts.

Using processes already predefined for the process design, other cores are reprocessed, inspected and then used in reassembly for the manufacture of a reprocessed product. Where cores are reprocessed by the original manufacturer, reassembly sometimes takes place as part of the new production line.

The final inspection serves to check the product's performance and function and ensures that these are at the same or higher level than those of a new product. In contrast to new production, quality assurance measures are carried out on every reprocessed product[33].

In addition to the flow and technical set-up of the individual process steps, the choice of materials suitable for a recirculation model is also very important. Materials must be chosen and used in a way that ensures that products can be easily dismantled at the end of their lifespan and reprocessed to achieve the same level of quality as new products. This technical aspect is incredibly important for remanufacturing and should be considered early on when designing the product and process.

A precondition for the success of remanufacturing is the identification of materials and, in some cases, the availability of full material declarations. The latter is primarily for information purposes during the disposal phase (incl. refeeding into a circular system) with regard to the recoverable nature of materials and/or compatibility with recovery models. However, remanufacturing does still produce scrap which, in turn, should also be reprocessed in the form of material recycling. Information on substances that are harmful to the environment, pollutants, toxic substances and other substances with harmful or hazardous properties is also crucial for ensuring proper use as part of the remanufacturing process. This applies for both direct use and any possible applications for further use of reprocessed parts, modules or entire

[33] **Cf. Lange, U. (2017), pp. 20 et seq.**

products. Depending on the product type, this also includes operating supplies. However, these are also worth mentioning under the point of simplicity of disassembly and ease of removal.

Reverse logistics are a very important aspect of reprocessing old parts. They are an integral part of a circular design and business model and are closely tied to the relevant legal framework (cf. chapter 2.1.3). However, reverse logistics are also based on technical aspects as a constant quantity of used products must be continuously supplied in a quality that is as consistent as possible[34].

The choice of suitable materials is a technical issue and should be made using the standard price- and quality-related criteria and in consideration of potential business models within or for a circular economy (cf. chapter 2.1.3). It is highly improbable for a business to use a higher-quality, potentially more expensive material without technical necessity for the sole purpose of achieving reprocessability by maintaining a proportionately high material value. In contrast, reverse logistics and the respective material situation at hand have significant influence over the sustainability of business models. When it comes to collecting and generating useful material and product flows, the logistics system as a whole can be very elaborate. Disassembly, however, plays a huge role in shaping both the technical requirements and business models. Disassembly both dictates the technical accessibility to product modules and determines the effort and costs in relation to the generated or potential value added.

Evaluation indicators are helpful for assessment as part of a product's development process. These indicators must be able to assess a product's entire lifespan in order to provide and improve upon the full picture. They should not just focus on the advantages in relation to individual sections of the product's life. Common indicators are based on the life cycle assessment and costing method throughout the product's lifespan (cf. chapter 3).

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[34] **VDI 2343-2:2010-02.**

2.1.3 Business models and other aspects

Circular business models take into account circular design principles and focus on combining the efficient use of resources with the company's business success.

The requirements of a circular design lead to an analysis of the product and materials and require innovation in the form of adjustments to the design and process, in turn promoting agility and competitiveness and potentially helping the company to become a technology leader. For example, businesses can use smart product design and a well-functioning reverse system to both reduce material and production costs and protect the environment. Innovative business models are flexible, proactive and integrate parts of the value chain.

To design a remanufacturing model in a way that is sustainable, new business models focus increasingly on the areas of reverse logistics for used parts, the remanufacturing process itself and the marketing of reprocessed products (cf. Figure 7). The business models must ensure that the costs for remanufacturing are in some form also worthwhile for the manufacturer. This is only achievable with efficient, better controlled, holistic processes that are well planned from the start.

One important prerequisite is a well-functioning reverse logistics system. This requires a qualified collection and return system including identification, storage and sorting as well as transport between all stakeholders in the disposal chain. In this regard, reverse logistics systems must take into account any obligations to provide proof, legal provisions and commercial and/or privately used products as well as any statutory or voluntary collection systems (organised as a whole or individually) with drop-off or pick-up systems.

Reverse logistics	Remanufacturing process	Marketing
• Degree of distribution of used parts • Continuous procurement management • Consistent return quantities over time • Quality assurance of used parts	• Technical effort/expense • Technical qualification • Resource-efficient process design • Sustainable logistics system	• Appropriate product value • Continuous adjustment of marketing/sales channels • Sales market for reprocessed products • Educational work and development of trust in quality • Dealing with product cannibalisation

Figure 7: Business areas and aspects of remanufacturing[35]

There are currently several models for the return of used parts[36]. For ownership-based return, ownership of the product remains with the manufacturer during use by the customer. The used products can also be taken back based on a service contract between the manufacturer and customer which includes reprocessing. Going further, used products can also be sent for remanufacturing directly by the customer with a reprocessing order as part of commissioned maintenance. The customer receives the same reprocessed product back. In the case of a one-to-one return, the customer must return an identical used product when purchasing a reprocessed product. This return can be used as a discount on the reprocessed product. When returning a used product, the customer receives a discount that is used to reduce the price for the reprocessed products being purchased.

To be able to offer reprocessed products at a reasonable price, there must be a consistently adequate supply of used parts over a period of time with a high quality that is as consistent as possible. This relies largely on the prevalence of products on the market. Lower product quantities on the market make reverse logistics more difficult, while too high an availability of new products reduces the demand for reprocessed products[37].

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[35] Based on Guide, V. D. R. and Wassenhove, L. N. V. (2009), pp. 10–18.
[36] Cf. Lange, U. (2017), p. 25.
[37] Cf. Lange, U. (2017), pp. 26 et seqq.

The technology of the remanufacturing process must be adapted to make it economical, e.g. with regard to the depth of reprocessing or the scope of all possible parts that can be replaced. The costs for these technological resources should not exceed the income generated by the sale of the reprocessed products. Staff must also be adequately qualified to carry out inspections of the used parts as these are generally carried out manually using visual checks.

To ensure that there is demand for reprocessed products, the products must be of a high product value. Marketing and sales channels used to promote and sell the products must be continuously adapted to customer requirements and the market situation. An established sales market for repaired, reusable and reprocessed products is incredibly important. For customers, it is sometimes difficult to see and trust reprocessed components as parts with the same level of quality as new products. This trust in the quality is therefore key for market demand. Businesses should invest heavily in education work and awareness to win over customers. They must also avoid any potential product cannibalisation so as to ensure that reprocessed products do not affect the sales of new products. Business units for new production and product reprocessing often stand in competition here. However, where new production is the company’s core business, it is not in the company’s interests to take away from this business, meaning remanufacturing is seen as a risk for the sales market.

Businesses must always consider all of these aspects under the applicable legal framework and societal requirements with regard to efficient resource use and the identification of potential for economic reuse of used products. In doing so, businesses can develop long-term business models geared towards a circular economy, even where there are certain barriers in the short term due to various legal requirements[38]. However, we can also see continuous adjustment of the laws motivating a circular economy. To give just one example, the EU circular economy legislative package entered into force on 4 July 2018. The package contains amendments to significant waste-related regulations. This includes the Waste Framework Directive (Directive

[38] Cf. Technopolis Group (2016), pp. 10–16 and pp. 56–58.

2008/98/EC) as well as the directives on packaging, used electronics, batteries, used cars and landfill[39]. The European Commission's proposed "European Green Deal"[40]programme must be noted in particular. In its essence, this document sets out a carbon-neutral Europe by 2050, requiring and promoting a rethinking of product lifespans, circular economies, corresponding product labelling as well as product approvals and restrictions. The European Green Deal solidifies laws and regulations on both a European and national level, expected to come into force from 2021 onwards.

2.2 Market relevance and market trends

The latest systematic market data collection for remanufacturing sectors was carried out as part of a European market study in 2015[41]. There is no market data collected for the following years, which was confirmed by an expert interview with Ms Waugh[42].

In order to be able to evaluate the development of the remanufacturing market, data was taken from the EU's statistical office (Eurostat) database[43]. The Eurostat database contained information on market development for the overriding sectors for the years 2015 to 2017. The basic data for 2015 from the European Remanufacturing Network (ERN)[44] market study was combined with the data from the Eurostat database, and its development for the subsequent years was calculated based on the annual change in the Eurostat data[45]. For this purpose, absolute values from the ERN study were extrapolated with the annual sector changes from the Eurostat data.

The development of the German remanufacturing market is shown in Table 1. The table only shows the remanufacturing market, not the overarching sectors. In the period from 2015 to 2017, the remanufacturing market in

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39 Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) (2020), p. 1.

40 Cf. European Commission (2020).

41 Cf. Parker, D.; Riley, K.; Robinson, S.; Symington, H.; Tewson, J.; Jansson, K.; Ramkumar, S. and Peck, D. (2015).

42 Waugh, R. (2020).

43 Eurostat SBS (2020).

44 Cf. Parker, D.; Riley, K.; Robinson, S.; Symington, H.; Tewson, J.; Jansson, K.; Ramkumar, S. and Peck, D. (2015), pp. 42–51.

45 Eurostat SBS (2020).

Germany grew in total by around 17% to more than 10 billion euros. The aviation and automotive sector saw strong growth in sales of around 20% in two years. Turnover also saw a stark increase in the engineering, medical technology and rail transport sectors. Growth was weaker in the other sectors, however.

Table 1: Sales trends in German remanufacturing market 2015–2017[46]

Sector	Sales in million euros		
	2015	2016	2017
Aviation	3,814	3,940	4,595
Automotive & heavy goods	3,478	3,573	4,117
Electrical and electronic equipment	646	581	647
Engineering	336	348	368
Medical technology	316	329	344
Rail transport	61	63	72
Furniture	66	71	70
Shipbuilding	11	12	13
Total	**8,728**	**8,917**	**10,226**

Figure 8 shows the spread of sales across the different sectors. It is based on Table 1. A total of around 98% of sales in 2017 were made in the aviation, automotive & heavy goods, electrical and electronic equipment (EEE). engineering and medical technology sectors. The aviation sector (45%) and automotive & heavy goods sectors (40%) are particularly noteworthy.

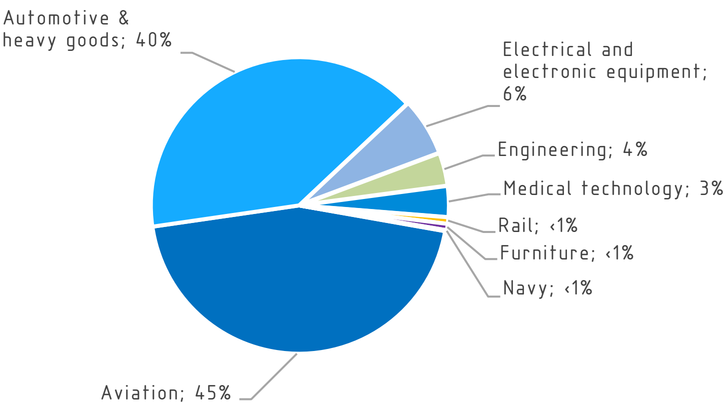

Figure 8: Sales within remanufacturing sector in Germany in 2017

46 Independent calculations from Parker, D.; Riley, K.; Robinson, S.; Symington, H.; Tewson, J.; Jansson, K.; Ramkumar, S. and Peck, D. (2015), p. 44 & Eurostat SBS (2020).

These ratios are also reflected in employee numbers (cf. Table 2), which were also calculated based on data from Eurostat[47] and the ERN study[48] using a similar process to that used for the sales figures. A large portion of employees are employed in the aviation and automotive sectors, followed by EEE, medical technology and engineering. With more than 43,000 employees and over 10 billion euros in sales (as of 2017), remanufacturing represents a significant, ever growing component of German industry.

Table 2: Employees in the German remanufacturing industry 2015–2017[49]

Sector	Number of employees		
	2015	2016	2017
Aviation	17,370	17,785	18,507
Automotive & heavy goods	16,820	15,322	16,025
Electrical and electronic equipment	4,040	4,024	4,372
Engineering	1,630	1,651	1,695
Medical technology	2,030	2,099	2,126
Rail transport	350	319	333
Furniture	550	573	556
Shipbuilding	70	81	94
Total	**42,860**	**41,855**	**43,708**

Even though sales are already high, the potential for growth in the remanufacturing sector in Germany remains very high. The reprocessing of products and product parts is extremely relevant for producing companies within the automotive, aviation, electronics and medical technology sectors. Remanufacturing is also important in other industries such as rail transport, shipbuilding and the furniture industry, albeit to a smaller extent than in the sectors previously mentioned.

[47] Eurostat SBS (2020).

[48] Cf. Parker, D.; Riley, K.; Robinson, S.; Symington, H.; Tewson, J.; Jansson, K.; Ramkumar, S. and Peck, D. (2015), p. 47.

[49] Independent calculation from Parker, D.; Riley, K.; Robinson, S.; Symington, H.; Tewson, J.; Jansson, K.; Ramkumar, S. and Peck, D. (2015), p. 47 & Eurostat SBS (2020).

3 EVALUATION OF PRODUCT GROUPS FOR REMANUFACTURING

3.1 Evaluation system

3.1.1 Selection of evaluation aspects

Numerous examples from various branches of industry clearly show the potential economic and ecological advantages of remanufacturing[50]. However, some products are better suited than others for remanufacturing.

A standardised evaluation system is necessary for determining which product groups are suitable for remanufacturing. Each product should be assessed according to the relevant criteria.

This study therefore outlines a new evaluation system in the form of an evaluation matrix. This matrix makes it possible to evaluate products against 34 criteria (cf. chapter 3.1.2). These criteria relate to product design, collection and logistics systems, business models and other aspects.

3.1.2 Development of an evaluation matrix

The matrix was developed based on the VDI 2243 (Recycling-oriented product development)[51] and VDI 2343-1 to 7 (Recycling of electrical and electronic equipment)[52] standards, taking into account the four building blocks as outlined by the Ellen MacArthur Foundation[53]. The evaluation matrix serves as the basis for a systematic product evaluation in view of a circular economy.

The evaluation matrix contains 34 evaluation criteria that can be split into four main categories:

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[50] Cf. Bindel, R. (2017) & Buchberger, S.; Hofbauer, G.; Mangold, L. and Truong, K. (2019) & Grepper, Y. (2018) & Ionaşcu, I. and Ionaşcu, M. (2018) & Lange, U. (2017) & Liebherr (2020) & Parker, D.; Riley, K.; Robinson, S.; Symington, H.; Tewson, J.; Jansson, K.; Ramkumar, S. and Peck, D. (2015) & Scheelhaase, T. and Zinke, G. (2016) & Technopolis Group (2016) & VDI e.V. (2019).

[51] VDI 2243:2002-07.

[52] VDI 2343-1:200105, VDI 2343-2:2010-02, VDI 2343-3:2009-04, VDI 2343-4:2012-01, VDI 2343-5:2013-04, VDI 2343-6:2019-02 and VDI 2343-7:2013-04.

[53] Ellen MacArthur Foundation (2017).

- Technical aspects and design
- Technical aspects for reverse logistics
- Business model
- Other aspects

The aim here is the holistic evaluation of the potential of products for remanufacturing. In this context, the matrix not only evaluates aspects such as, for example, the business model, it also establishes an extensive catalogue of criteria that covers both product and market aspects and takes into account the legal and economic framework conditions. Many of the criteria are mutually dependent and, when taken together, are relevant for the remanufacturing of products. The evaluation matrix serves to systematically identify aspects that both promote and hinder remanufacturing. This, in turn, allows businesses to work on resolving any aspects that may hinder remanufacturing, thus increasing the potential of products for a remanufacturing model.

The contribution of the individual aspects to remanufacturing are assessed in each of the main categories.

In the “Technical aspects and design” category (cf. Table 3), products are assessed on the materials used and modularity. This category contains a total of ten evaluation aspects (TAD-01 to TAD-10). These criteria assess the identification and handling of materials as well as the product’s modularity for full or partial reuse and/or reprocessing.

Table 3: Overview of technical aspects and design

Technical aspects and design	
Materials	
TAD-01	Material declarations available / identification of materials easily possible
TAD-02	Identification of modules easily possible
TAD-03	Hazardous/toxic substances (for handling, risk to employees)
TAD-04	Dangerous substances and substances that are harmful to the environment (potentially with legal restrictions for recirculation)
Modularity and longevity	
TAD-05	Whole product reusable – efficient disassembly and exchange of non-reusable modules
TAD-06	Whole product not reusable – efficient removal of reusable parts
TAD-07	High degree of standardisation of disassembly
TAD-08	High degree of automation of disassembly
TAD-09	Longevity of components and modules
TAD-10	Upgrade-friendly/compatible with new product generations

The "Technical aspects for reverse logistics" (cf. Table 4) looks at twelve criteria for identification (product, material, age, etc.), collection and storage systems as well as sortability and standardisation of modules (TAL-01 to TAL-12).

Table 4: Overview of technical aspects and reverse logistics

Technical aspects for reverse logistics	
Identification (product, age, etc.)	
TAL-01	Information on whereabouts of product / availability for return
TAL-02	Clear product allocation
TAL-03	Materials clearly identifiable (where no material declaration available)
TAL-04	Age and condition identifiable (technical/documentation)
Collection & return	
TAL-05	Low transport expense per product unit
TAL-06	High value in relation to collection expense
TAL-07	Established, functioning collection/return system
TAL-08	Legal regulations on collection and return
Storage	
TAL-09	Good storability
TAL-10	Plannable inventory (goods inward/outward)
TAL-11	Good sortability for disassembled modules
TAL-12	High standardisation of modules

The “Business model” category (cf. Table 5) contains an evaluation in relation to return quantities, framework conditions such as laws or regulations, market acceptance and the sales market. This looks at a total of eight aspects (GEM-01 to GEM-08).

Table 5: Overview of business models

Business models	
GEM-01	Constant and plannable return quantities
GEM-02	Constant and plannable sales market
GEM-03	Established and reliable return system in view of return and sales quantities (product responsibility spread across life cycle)
GEM-04	Structured framework conditions (laws, regulations) of return market
GEM-05	Structured framework conditions (laws, regulations) of sales market, e.g. approval criteria
GEM-06	Market acceptance of reprocessed products
GEM-07	Competition situation in sales market due to new products
GEM-08	Competition situation in sales market due to other reprocessed products

Potential risks (e.g. safety risks, malfunction risks, brand risks, value perception of reprocessed products, availability of qualified staff) are also used as further evaluation aspects (cf. Table 6). This category contains a total of four evaluation criteria (OTH-01 to OTH-04).

Table 6: Overview of other aspects

Other aspects	
OTH-01	Safety or malfunction risks caused by reprocessed products
OTH-02	Brand risk (in case of premature malfunction of reprocessed products) / branding as reprocessed product (B2C) (quality perception) [if relevant]
OTH-03	Value perception of reprocessed products (quality of upcycling, downcycling and recycling)
OTH-04	High availability of qualified employees

All information is quantitatively recorded in the evaluation matrix and qualitatively documented in text form and marked with colour coding. The quantitative evaluation is completed using a scale in whole number increments from +2 to -2. If an aspect, e.g. the identification of used materials or the availability of a material declaration, is required, an evaluation of +1 or +2 is made depending on the intensity of the aspect. If the required information is not available or an aspect hinders suitability for remanufacturing, an evaluation of -1 or -2 is made depending on the intensity of the aspect. There is also a text field for each criteria as part of the quantitative evaluation which can be used to enter any additional explanatory comments. Aspects that promote remanufacturing are shown in green, hindering aspects are in red and neutral aspects are in yellow.

The criteria can be weighted, but this is not currently implemented. Also, no threshold value is defined from which the remanufacturing potential is interpreted as fundamentally positive (or negative). Weighting factors and threshold values could be developed in the future as part of a case study with a larger number of product examples.

The evaluation matrix helps businesses to review products specifically for their suitability for remanufacturing. A structured interrogation of criteria allows for a systematic evaluation and identification of factors that promote and hinder a product's remanufacturing. The results also help businesses to make fundamental decisions on the suitability for remanufacturing. They also allow businesses to work on solutions to systematically reduce any hindering factors.

3.2 Choice of product examples

A total of eight product examples from several sectors were selected for product evaluation (cf. Table 7). The product examples cover the relevant sectors for remanufacturing and represent around 99% of the sales and workforce within the German remanufacturing industry (cf. chapter 2.2).

While some aspects, such as, for example, legal framework conditions, are typical for a certain sector, others depend directly on the respective products or individual businesses. Each product must therefore be considered on a case-by-case basis. In this context, two product examples were selected within the electronics (EEE) sector: reprocessed laptops and desktop computers. Upon first glance, these product examples are very similar. However, there are some differences when it comes to the evaluation of certain aspects.

Table 7: Overview of product examples

No.	Sector	Example product
1	Aviation	Aircraft engines
2	Automotive and heavy goods	Starters and alternators
3	Automotive and heavy goods	Combustion engines for cars and vans
4	Electrical and electronic equipment	Laptops
5	Electrical and electronic equipment	Desktop PCs
6	Engineering	Water meters
7	Medical technology	Medical devices
8	Furniture	Home and household furniture

The product examples are analysed below using the evaluation matrix developed in chapter 3.1.2. The evaluation matrix for each product example was completed in coordination with experts from the respective sectors.

3.3 Evaluation of product examples

3.3.1 Aircraft engines

In the aviation sector, the maintenance and reprocessing of engines is referred to as MRO (maintenance, repair and overhaul). There is a large global market for the maintenance of aircraft and engines. For example, sales within the aviation sector reached over 4.5 billion euros in Germany in 2017 (cf. Table 1 in chapter 2.2). The safety requirements within this sector are very high in comparison to others.

Table 8 shows the evaluation of an aircraft engine MRO that was discussed with an expert from the industry[54]. As illustrated, the reprocessing of engines has high potential for remanufacturing with an overall rating of 1.51.

The *design* of the engines is geared towards a long lifespan. Due to their high cost, it is in the operators' interest to maintain the engines. Engines are also not easily replaced and subject to long lead times due to the complexity of the products and the related high requirements, strict regulations and small number of manufacturers. Operational safety is an extremely important point, and there are strict regulations in place relating to maintenance and inspection as engine failure can have some dramatic effects, including, in a worst-case scenario, a plane crash. Aircraft engines are therefore designed

[54] Expert survey, confidential.

with longevity and ease of maintenance in mind. Due to the complexity, however, the possibilities for automation are limited, meaning there is a lot of manual labour involved with engine maintenance.

Engines are the example to be followed within the area of *reverse logistics*. Information on the whereabouts of engines is readily available due to the small number of operators (airlines). These products can be traced from the moment they are put into operation. This often takes place in real time; engine performance data is transmitted to the manufacturer or MRO operator during the flight. In most cases, when it comes to the maintenance mentioned above, maintenance on the engines is carried out on the aircraft, which reduces the need for transport and the related expense. The relevant maintenance cycle regulations ensure a high level of planability.

The *business model* for engine maintenance is also rated as very good. Due to the strict regulation of the market in relation to maintenance cycles and safety standards, and the complexity of the products involved, there is only a small number of qualified companies on the market. Consequently, the competitive pressure is low which, in turn, leads to a larger workload for suppliers and relatively long lead and waiting times for customers.

When it comes to the *other aspects* category, a lack of qualified staff poses a challenge for companies. The brand risk is categorised as high for MRO companies. Although the probability of malfunction is low, the risk is very high for the airline and MRO company.

Table 8: Evaluation matrix: aircraft engines

*RP = remanufacturing potential

		Aircraft engines	RP*
		Total potential	1.51
Technical aspects and design			1.40
Materials			
TAD-01	Material declarations available / identification of materials easily possible	Documentation of all materials available	2
TAD-02	Identification of modules easily possible	Documentation available, manageable variety of products	2
TAD-03	Hazardous/toxic substances (for handling, risk to employees)	In some repair stages, but explicitly declared with warnings	2
TAD-04	Dangerous substances and substances that are harmful to the environment (potentially with legal restrictions for recirculation)	No	2
Modularity and longevity			
TAD-05	Whole product reusable – efficient disassembly and exchange of non-reusable modules	Maintenance preserves the product in full (complex but feasible)	2
TAD-06	Whole product not reusable – efficient removal of reusable parts	Yes – product components can also be used as spare parts after end of life cycle	2
TAD-07	High degree of standardisation of disassembly	Exact regulations on maintenance processes, excellent documentation of components and maintenance steps	2
TAD-08	High degree of automation of disassembly	Relatively low, almost all manual labour, high staff expense, D check up to 50,000 working hours	-1
TAD-09	Longevity of components and modules	Neutral, regular maintenance and overhaul necessary/prescribed	0
TAD-10	Upgrade-friendly/compatible with new product generations	Yes – within an engine type, no compatibility and upgradeability for new engine models	1
Technical aspects for reverse logistics			2.00
Identification (product, age, etc.)			
TAL-01	Information on whereabouts of product / availability for return	Inventory known, few operators (airlines). Back-to-birth tracking of airlines, flight hours, routes, etc.	2
TAL-02	Clear product allocation	Yes – inventory known, few operators (airlines).	2
TAL-03	Materials clearly identifiable (where no material declaration available)	N/A	N/A
TAL-04	Age and condition identifiable (technical/documentation)	Yes – inventory known, few operators (airlines).	2
Collection & return			
TAL-05	Low transport expense per product unit	Engines typically maintained on the aircraft. Single engines can be transferred if needed	2
TAL-06	High value in relation to collection expense	Operator typically maintains the engine resulting in significantly lower expense	2
TAL-07	Established/functioning collection/ return system	Yes, operator must organise maintenance	2
TAL-08	Legal regulations on collection and return	Regulations on maintenance intervals	2

		Aircraft engines	RP*
Storage			
TAL-09	Good storability	High space requirement but no deterioration and low environmental impact	2
TAL-10	Plannable inventory (goods inward/ outward)	Regular maintenance intervals allow for efficient planning	2
TAL-11	Good sortability for disassembled modules	Yes	2
TAL-12	High standardisation of modules	Yes	2
Business models			1.88
GEM-01	Constant and plannable return quantities	Regulations on maintenance cycles result in plannable return quantities	2
GEM-02	Constant and plannable sales market	Long lead times. Anything sent for remanufacturing is sold / remains property of the user	2
GEM-03	Established and reliable return system in view of return and sales quantities (product responsibility spread across life cycle)	Yes	2
GEM-04	Structured framework conditions (laws, regulations)	Safety regulations on maintenance intervals	2
GEM-05	Structured framework conditions (laws, regulations) of sales market, e.g. approval criteria	Safety regulations on maintenance intervals	2
GEM-06	Market acceptance of reprocessed products	Maintenance is required by law and required for safety reasons	2
GEM-07	Competition situation in sales market due to new products	High workload for manufacturers, meaning no quickly surging production volumes, long waiting times, high barriers for entering the market for new actors due to safety regulations	2
GEM-08	Competition situation in sales market due to other reprocessed products	Clear number of actors – high demand, low number of qualified competitors / for used products there is often consideration for a used engine instead of expensive maintenance	1
Other aspects			0.75
OTH-01	Safety or malfunction risks caused by reprocessed products	Low – high approval requirements, established processes	2
OTH-02	Brand risk (in case of premature malfunction of reprocessed products) / branding as reprocessed product (B2C) (quality perception) [if relevant]	Probability is low but risk is extreme, also for MRO operator	0
OTH-03	Value perception of reprocessed products (quality of upcycling, downcycling and recycling)	High – same or higher quality, maintenance ensures safety and quality	2
OTH-04	High availability of qualified employees	Tendency towards a shortage of qualified staff	-1

3.3.2 Starters and alternators

Starters and alternators have been reprocessed in the automotive sector for a long time. The reprocessing of parts within this sector is generally an established market with sales of over four billion euros in Germany in 2017 (cf. Table 1, chapter 2.2).

The evaluation of the reprocessing of starters and alternators is shown in Table 9 and refers to market-based considerations and analyses, without taking into account specific product types or business models for individual actors. This evaluation is completed using reprocessed combustion engines (chapter 3.3.3). The result of the evaluation of starters and alternators reveals a good remanufacturing potential with a total value of 0.73.

The *product design* is particularly influential here due to the easy identifiability of materials, thanks in large to the widely distributed material declarations within the automotive industry based on the International Material Data System (IMDS), a globally standardised exchange and management system for material data in the automotive sector. Standardised processes for disassembly and the durability of the components also support reprocessing. However, the limited reusability of individual modules and reduced compatibility between the various models and series can be seen as weak points.

The *reverse logistics* system is rated as very good. Thanks to approvals and product declarations, as well as information on model ranges and construction years, businesses have extensive access to data on the whereabouts of the products. Transport expense for the return of the products is low and regulated by legislation on recirculation, such as the End of Life of Vehicles Directive (ELV).

The related *business models* are also rated as positive. The return market is also very well organised thanks to so-called general inspections (regular inspection of condition by certified bodies) and the ELV. However, the high number of actors on the market leads to bigger competition and pricing pressure.

For the *other aspects* category, the low risk of malfunction for reprocessed parts due to established quality assurance processes and an appropriate availability of qualified staff in particular also contribute to a good rating.

Table 9: Evaluation matrix: starters and alternators

*RP = remanufacturing potential

		Starters & alternators	RP*
		Total potential	0.73
Technical aspects and design			0.20
Materials			
TAD-01	Material declarations available / identification of materials easily possible	Yes, through IMDS	2
TAD-02	Identification of modules easily possible	Difficult due to integrated design, but modules themselves known	0
TAD-03	Hazardous/toxic substances (for handling, risk to employees)	None for mechanical elements, potentially for electronics	1
TAD-04	Dangerous substances and substances that are harmful to the environment (potentially with legal restrictions for recirculation)	None for mechanical elements, potentially for electronics	1
Modularity and longevity			
TAD-05	Whole product reusable – efficient disassembly and exchange of non-reusable modules	Yes, but product not optimised for reuse	1
TAD-06	Whole product not reusable – efficient removal of reusable parts	No	-2
TAD-07	High degree of standardisation of disassembly	Feasible due to qualified staff in standardised process	1
TAD-08	High degree of automation of disassembly	Rather low, almost all manual labour	-1
TAD-09	Longevity of components and modules	Long-lasting in principle	1
TAD-10	Upgrade-friendly/compatible with new product generations	No, as depends on model and series	-2
Technical aspects for reverse logistics			1.45
Identification (product, age, etc.)			
TAL-01	Information on whereabouts of product / availability for return	High due to approval	2
TAL-02	Clear product allocation	Yes, thanks to information on construction year and model range	2
TAL-03	Materials clearly identifiable (where no material declaration available)	N/A	N/A
TAL-04	Age and condition identifiable (technical/documentation)	Yes, thanks to information on construction year and model range	2
Collection & return			
TAL-05	Low transport expense per product unit	Disassembled product is easy to transport	1
TAL-06	High value in relation to collection expense	Relatively low expense due to established/systematic return, e.g. through workshops or disposal contractors	1
TAL-07	Established/functioning collection/ return system	Established/systematic return e.g. through workshops or disposal contractors	2

		Starters & alternators	RP*
TAL-08	Legal regulations on collection and return	ELV	2
Storage			
TAL-09	Good storability	Easy to store	2
TAL-10	Plannable inventory (goods inward/ outward)	Limited due to type diversity but good in principle	1
TAL-11	Good sortability for disassembled modules	Documentation required following disassembly	1
TAL-12	High standardisation of modules	High type diversity	0
Business models			0.75
GEM-01	Constant and plannable return quantities	Generally yes, but limited due to type diversity	1
GEM-02	Constant and plannable sales market	Generally yes, but limited due to type diversity	1
GEM-03	Established and reliable return system in view of return and sales quantities (product responsibility spread across life cycle)	Yes, through ELV	2
GEM-04	Structured framework conditions (laws, regulations)	Regular checks and exchange (if necessary) through TÜV and ELV	2
GEM-05	Structured framework conditions (laws, regulations) of sales market, e.g. approval criteria	No approval criteria (for most part)	0
GEM-06	Market acceptance of reprocessed products	Tends to be high, but missing proof/warranty system	1
GEM-07	Competition situation in sales market due to new products	Pure repair market, meaning large competition from new products	0
GEM-08	Competition situation in sales market due to other reprocessed products	Relatively large number of actors on the market, big competition	-1
Other aspects			0.50
OTH-01	Safety or malfunction risks caused by reprocessed products	Low	2
OTH-02	Brand risk (in case of premature malfunction of reprocessed products) / branding as reprocessed product (B2C) (quality perception) [if relevant]	Yes	0
OTH-03	Value perception of reprocessed products (quality of upcycling, downcycling and recycling)	Tends to be of lower quality due to wear and tear	-1
OTH-04	High availability of qualified employees	Yes	1

3.3.3 Combustion engines for cars and vans

In addition to the example for starters and alternators from chapter 0, there is one further product evaluation from the automotive sector. This evaluation was carried out in relation to the remanufacturing of combustion engines in close collaboration with HERRMANNS GmbH in Hailtingen, Germany, a company that has been specialising in the remanufacturing of automotive technology for Mercedes-Benz for decades. The evaluation looks at combustion engines, including their sensors and actuators, without any further control elements or aggregates related with the combustion engine.

The evaluation results are shown in Table 10. As these results were compiled in collaboration with the director of HERRMANNS[55], they reflect the current situation of business activity. The overall result reveals good potential for remanufacturing with a value of 0.77.

The *product design* is characterised by the good identifiability and exchangeability of combustion engine modules and components. The identification of materials or material declarations plays a more secondary role. The core of the business model lies in the identification at the component level using manufacturer information or market knowledge. Despite this complexity and wide range of variants, exchangeability is still achieved across the different model ranges. This is a unique characteristic which also influences the business model, among other things. Due to this diversity, standardised processes such as in-house standards are required. At the same time, however, there is absolutely no potential for automation as almost every individual part is different to the next from a technical standpoint (e.g. in geometry, type and version of joining system) or due to the different electrical connections. The condition of corroded fixtures and connections and the level of contamination or wear also make remanufacturing difficult.

The *reverse logistics* system is rated as very good. This is largely due to the deposit system that has been introduced. It promotes both product traceability and customer loyalty and reflects the level of quality. The only limitation is that material fatigue or internal wear is not recorded. There are no significant advantages or disadvantages in relation to transport expenses, resulting in a neutral evaluation. Storage itself is rated as very positive with the only limitation being that the wide range of parts requires a corresponding large amount of space, which makes standardisation difficult.

The *business models* are also rated as widely positive. As mentioned, the deposit system is at the core of the business models and influences the flow of goods as well as goods inwards inspections and quality assurance. The quality of the reprocessed components or products can be proven indirectly. As the components also retain their approval following remanufacturing, these only need to be inspected as part of a general vehicle inspection as

[55] **Herrmann, H. (2020).**

standard, as is the case for new products. This means the customer receives long-term proof of quality through their general vehicle inspections, provided the reprocessed parts are not objected to. However, the remanufacturing market is not transparent with regard to any direct proof of quality or warranty. There is almost no support (e.g. through proof or regulation) in the sales market directly. Market acceptance and the portrayal of brand value is only established through long-term positive customer experiences, meaning reprocessed products are not rejected during the general vehicle inspections, thus supporting the remanufacturer's reputation.

As for *other aspects*, the low risk of malfunction due to the fundamental analysis of components and standardised replacement rules for spare parts both help to support remanufacturing. An example of this is the basic exchange of cylinder head gaskets which HERRMANNS GmbH performs as standard as a form of brand management to maintain the aforementioned long-term reputation. This leads to higher costs but minimises the brand risk and also allows the company to upcycle components as part of the corresponding reprocessing in certain cases. The lack of external staff training and the resulting lack of experts are the only factors that negatively impact potential for remanufacturing. Staff qualification is based exclusively on experience as well as in-house (initial) training sessions.

Table 10: Evaluation matrix: combustion engines for cars and vans

*RP = remanufacturing potential

		HERMANNS GmbH combustion engine, without electronics, only with sensors/actuators	RP*
		Total potential	0.77
Technical aspects and design			1.00
Materials			
TAD-01	Material declarations available / identification of materials easily possible	Access to IMDS not always possible, but material alone not relevant, components more relevant	0
TAD-02	Identification of modules easily possible	Important and easily possible through after-sale market and manufacturer (suitable for remanufacturing)	2
TAD-03	Hazardous/toxic substances (for handling, risk to employees)	Oils must be removed, but no problem	2
TAD-04	Dangerous substances and substances that are harmful to the environment (potentially with legal restrictions for recirculation)	Potentially oils, but clearly identifiable and/or can be removed	2
Modularity and longevity			
TAD-05	Whole product reusable – efficient disassembly and exchange of non-reusable modules	Clearly identifiable and easy to dismantle	2
TAD-06	Whole product not reusable – efficient removal of reusable parts	Clearly identifiable and easy to dismantle	2
TAD-07	High degree of standardisation of disassembly	Standardised disassembly process but large diversity of product variants	1
TAD-08	High degree of automation of disassembly	Level of contamination and/or corrosion requires manual handling	-2
TAD-09	Longevity of components and modules	Relatively large number of replacement parts / spare parts and all must work, but core product long-lasting	1
TAD-10	Upgrade-friendly/compatible with new product generations	Can be adjusted to similar product families (e.g. C-Class to E-Class works); this flexibility is part of the business model	0
Technical aspects for reverse logistics			0.91
Identification (product, age, etc.)			
TAL-01	Information on whereabouts of product / availability for return	Used part deposit system introduced, resulting in improved loyalty, also regulates product condition (deposit return depends on condition)	2
TAL-02	Clear product allocation	Product is known and/or identifiable, supplier supplies product identification with product (part of contract), specialist staff clarifies in case of any uncertainty	2
TAL-03	Materials clearly identifiable (where no material declaration available)	Materials not important, modules/components more important	N/A
TAL-04	Age and condition identifiable (technical/documentation)	Yes, due to deposit system and product allocation, but internal condition or material fatigue not possible to identify (otherwise would be full score)	1

		HERMANNS GmbH combustion engine, without electronics, only with sensors/actuators	RP*
Collection & return			
TAL-05	Low transport expense per product unit	Normal haulage	0
TAL-06	High value in relation to collection expense	Normal transport goods	0
TAL-07	Established/functioning collection/return system	Only in-house collection system, this is well established and important for business dealings, no influence through ELV	0
TAL-08	Legal regulations on collection and return	ELV does not provide any support	0
Storage			
TAL-09	Good storability	Easy to store, only issue is space requirement	1
TAL-10	Plannable inventory (goods inward/ outward)	Easy to plan due to deposit system	2
TAL-11	Good sortability for disassembled modules	Yes, after disassembly	2
TAL-12	High standardisation of modules	Essentially no standardisation, but compensated for through know-how; wide type diversity, but flexibility is installed as business model (usability of modules/components across product groups)	0
Business models			0.43
GEM-01	Constant and plannable return quantities	Yes, due to deposit system	2
GEM-02	Constant and plannable sales market	Standard market situation	2
GEM-03	Established and reliable return system in view of return and sales quantities (product responsibility spread across life cycle)	N/A	N/A
GEM-04	Structured framework conditions (laws, regulations)	Pure transfer activity, i.e. approval of incoming product remains valid	0
GEM-05	Structured framework conditions (laws, regulations) of sales market, e.g. approval criteria	Pure transfer activity, i.e. approval of incoming product remains valid, replacement part is inspected as part of later general inspection by the customer thus allowing the customer to draw conclusions on the quality of HERRMANNS GmbH	1
GEM-06	Market acceptance of reprocessed products	Acceptance present and on the rise; HERRMANNS also provides two-year warranty	1
GEM-07	Competition situation in sales market due to new products	Competition exists but depends on the product variant (e.g. vintage car vs. vans)	-1
GEM-08	Competition situation in sales market due to other reprocessed products	Increasing pressure also through new goods declared as remanufacturing products, also competitors without replacement parts and lower quality pose a problem	-2
Other aspects			0.75
OTH-01	Safety or malfunction risks caused by reprocessed products	Quality is under control from a technical standpoint but not established and hard to identify on the market, positive evaluation nonetheless due to measures e.g. through warranty	1
OTH-02	Brand risk (in case of premature malfunction of reprocessed products) /	Trust in the brand present as already well known (no change to business model since HERRMANNS was founded)	2

		HERMANNS GmbH combustion engine, without electronics, only with sensors/actuators	RP*
	branding as reprocessed product (B2C) (quality perception) [if relevant]		
OTH-03	Value perception of reprocessed products (quality of upcycling, downcycling and recycling)	Technical further developments can be incorporated, but remaining risk (e.g. material fatigue) always exists	1
OTH-04	High availability of qualified employees	In-house initial training takes a relatively long time, fundamentally different from the case for repair workshops, experience and training not available externally	-1

3.3.4 Laptops

The reprocessing of laptops is also referred to as refurbishing where only individual modules are replaced. Defective or outdated components are replaced wherever possible. Components are often simply reused as the life expectancy of electronics exceeds the period of initial use. The devices are subject to visual and technical inspections. Full-scale remanufacturing is only pursued in rare cases. The results of the evaluation are shown in Table 11 and are based on the information provided by the director of ELiProCoM GmbH[56]. The overall result reveals low potential for remanufacturing with a value of -0.23.

The evaluation of the *product design* clearly highlights the disadvantages of a highly integrated product. Some components are difficult or impossible to replace, and although the connections are standardised, the components used vary greatly. Many of the electromechanical materials, the filling materials in the plastics or even the plastics themselves are unknown. Material declarations for the electronics are generally not available and if they are, they are usually only available at the original manufacturer. While the relevant software can be easily updated, upgrading hardware components is often very difficult. For this reason, the design receives a negative rating.

The *reverse logistics* for reprocessing laptops receive an overall neutral rating. Knowledge of the buying market is almost exclusively found in the B2B market, there is no data available on the whereabouts of products for private

[56] **Horst, H. (2020).**

users. Regulations on the collection and return of used products are in place, however these do not support remanufacturing (or refurbishment and/or re-use) as they declare returned devices as waste. Re-entry onto the market or into trade is therefore too high an obstacle. This disadvantage is compensated for, however, by the relatively high product value in proportion to the product weight and the product's easy, simple transport or storage.

The *business models* receive the most negative rating of all the areas. The weak points here include in particular the limited ability to plan and schedule the return market and the resulting lack of transparency on available products and components. Acceptance of reprocessed laptops on the part of customers is largely reliant on the price as reprocessed laptops do not offer any proof or quality indices. The combination of non-transparency on availability and quality on the sales market and the overall lack of regulations or laws to support a circular economy result in the biggest challenge of establishing a functioning and trustworthy business model on a wide scale. The offered goods cannot be assessed by the end customer. Trust is also hard to obtain for reputable suppliers due to digital trading platforms and the large number of anonymous suppliers of used goods.

There is also one factor that significantly hinders the reprocessing of laptops that falls under the category of *other aspects*. The market's non-transparency and lack of framework conditions with regard to quality and warranty, as outlined above, result in an image-related risk for brand manufacturers which, in turn, means that these brands are not (and do not wish to be) active (except for in exceptional cases) in the remanufacturing market and rarely support it. Despite this, this section still comes out with a positive rating as the products have a low risk of malfunction and there is always qualified staff available for product reprocessing.

Table 11: Evaluation matrix: laptops

*RP = remanufacturing potential

		Laptops	RP*
		Total potential	-0.23
Technical aspects and design			-0.70
Materials			
TAD-01	Material declarations available / identification of materials easily possible	Highly integrated products, materials in conjunction with electronics generally unknown, mechanical and electromechanical materials are rarely known, filling materials for plastics even more rarely known, there is information via serial numbers but this depends on manufacturer- and supply chain	-2
TAD-02	Identification of modules easily possible	High product integration, modules between electronics board and casing distinguishable	-1
TAD-03	Hazardous/toxic substances (for handling, risk to employees)	Potentially present, e.g. in displays – remanufacturing is almost never carried out by third parties	0
TAD-04	Dangerous substances and substances that are harmful to the environment (potentially with legal restrictions for recirculation)	Flame retardants, PVC in cables, substances from the SVHC list, but manufacturer often knows what is contained and thus recirculation can be avoided	-1
Modularity and longevity			
TAD-05	Whole product reusable – efficient disassembly and exchange of non-reusable modules	Rarely, as highly integrated, but individual modules are replaceable and even suitable for upgrades	-1
TAD-06	Whole product not reusable – efficient removal of reusable parts	Difficult, as highly integrated, but individual components such as HDD and memory are very easily disassembled (there is a large market for disassembled components for high-cost products)	0
TAD-07	High degree of standardisation of disassembly	No, individual developments (board), interfaces are standardised	-2
TAD-08	High degree of automation of disassembly	No	-2
TAD-09	Longevity of components and modules	Some long-lasting (electronics function for long time, wear is low; classic bathtub curve), some not (casing, electrolytic capacitator)	1
TAD-10	Upgrade-friendly/compatible with new product generations	Software is update-friendly, hardware sometimes difficult to upgrade, only possible for modules that can be disassembled	1
Technical aspects for reverse logistics			0.17
Identification (product, age, etc.)			
TAL-01	Information on whereabouts of product / availability for return	Only B2B for service contracts, evaluation generally not performed, never B2C as only third-party suppliers are active here	0
TAL-02	Clear product allocation	Brand known, product details can be accessed online (e.g. via product numbers), but further information not available	1
TAL-03	Materials clearly identifiable (where no material declaration available)	No, metals and plastics can be potentially identified by sight	-2
TAL-04	Age and condition identifiable (technical/documentation)	Possible in principle (software, product generation) using product numbers, no information on condition, condition sometimes can be identified using software but this is not easy/freely available	1

		Laptops	RP*
Collection & return			
TAL-05	Low transport expense per product unit	Yes (small, stackable, lightweight), however, special handling required for batteries, which is standard	1
TAL-06	High value in relation to collection expense	Collection expense tends to be high, but value too, better ratio for B2B; worse for low-cost products	0
TAL-07	Established/functioning collection/return system	Only B2B in case of service contracts, otherwise possible via trade, voluntarily by customers, but it is not utilised, and the issue of data and trust in the whereabouts of products is an obstacle, although feasible via third-party suppliers and platforms	0
TAL-08	Legal regulations on collection and return	Not for remanufacturing, only WEEE as already declared as waste and removed from market, recirculation on market is difficult	-1
Storage			
TAL-09	Good storability	Negative impact on the environment, protection during storage, possible wear for battery to be taken into account if storage for one year	1
TAL-10	Plannable inventory (goods inward/outward)	Limited planability, only for B2B, not for B2C	-1
TAL-11	Good sortability for disassembled modules	If identification takes place then best storage possible	1
TAL-12	High standardisation of modules	Yes, in principle, except for high integration into board (e.g. RAM in the board); high standardisation for interfaces	1
Business models			-0.63
GEM-01	Constant and plannable return quantities	No, as constant flow not plannable	-1
GEM-02	Constant and plannable sales market	Yes, always demand and regulated by price	1
GEM-03	Established and reliable return system in view of return and sales quantities (product responsibility spread across life cycle)	No, as no regulation or laws to support	-1
GEM-04	Structured framework conditions (laws, regulations)	No, as no regulation or laws to support	-1
GEM-05	Structured framework conditions (laws, regulations) of sales market, e.g. approval criteria	Yes, through CE labelling, but in detail very individualised and hard to identify	-1
GEM-06	Market acceptance of reprocessed products	Medium acceptance since price and performance is low, then acceptance	0
GEM-07	Competition situation in sales market due to new products	New goods available in all price classes, meaning competition only via price vs. performance class; new goods tend to become even cheaper	-1
GEM-08	Competition situation in sales market due to other reprocessed products	Via third-party suppliers: big competition for reusable products, lots of suppliers and all regulated by price, market is not regulated so no possibility for more expensive remanufacturing products	-1

		Laptops	RP*
Other aspects			0.25
OTH-01	Safety or malfunction risks caused by reprocessed products	Often long-lasting products (exceptions, e.g. electrolytic capacitors), more issue of performance and care taken by third-party suppliers that act without framework conditions	1
OTH-02	Brand risk (in case of premature malfunction of reprocessed products) / branding as reprocessed product (B2C) (quality perception) [if relevant]	Brand manufacturers lose image, must take responsibility for all components (product responsibility), but third parties act without framework conditions	-2
OTH-03	Value perception of reprocessed products (quality of upcycling, downcycling and recycling)	Can be upgraded but lower value in comparison to new product	0
OTH-04	High availability of qualified employees	Lower requirement for qualified staff and high availability	2

3.3.5 Desktop PCs

As is the case with laptops, desktop PCs are also reprocessed and/or refurbished and reused. Despite the comparability with laptops and subsequent similar evaluations, there are still some differences between the two device types. The results of the evaluation of desktop PCs are shown in Table 12 and are also based on the information provided by the director of ELiProCoM GmbH[57]. The overall result reveals a low (albeit higher in comparison to laptops) remanufacturing potential with a value of 0.09.

The evaluation of the *product design* reveals that desktop PCs are more favourable for reprocessing than laptops. Of course, there is also little information on the electromechanical materials, filling materials and material declarations for electronics here, but the modules are more easily distinguishable than those of laptops and it is significantly easier to replace components (e.g. graphic cards or hard drives can be replaced without much effort). The relating software can be updated just as easily, and the hardware is much more easily replaced than is the case for laptops. As a result, the product design achieves an overall positive rating.

The *reverse logistics* are also conducive to remanufacturing. The evaluation is identical to that of laptops, only the modularity of desktop PCs allows for

[57] **Horst, H. (2020).**

an even higher rating when it comes to the standardisation of modules (criterion TAL-12).

The related *business models* achieve an identical rating to laptops. Both product groups are subject to the same restrictive market constraints for reprocessed products.

The rating of *other aspects* is also identical in both product groups. The risk of malfunction, brand risks and the perception of value on the part of the customer are subject to the same conditions, and the high availability of qualified staff is the same.

Table 12: Evaluation matrix: desktop PCs

*RP = remanufacturing potential

		Desktop PCs	RP*
		Total potential	0.09
Technical aspects and design			0.50
Materials			
TAD-01	Material declarations available / identification of materials easily possible	Materials in conjunction with electronics usually unknown, mechanical and electromechanical materials are rarely known, filling materials for plastics even more rarely known; manageable variations for casing materials; only slightly easier than for laptops as same issues arise, only manufacturer itself has access to data	-1
TAD-02	Identification of modules easily possible	Modules easily distinguishable, no modularity within module groups	1
TAD-03	Hazardous/toxic substances (for handling, risk to employees)	No hazard presumed for modern devices	0
TAD-04	Dangerous substances and substances that are harmful to the environment (potentially with legal restrictions for recirculation)	Potentially PVC in cables, but only known by manufacturer what is contained and thus recirculation can be avoided	-1
Modularity and longevity			
TAD-05	Whole product reusable – efficient disassembly and exchange of non-reusable modules	Modules are easily replaced, limited ability to exchange components within modules (e.g. graphic card fans, power adaptors, etc.), high replaceability but a difficult issue legally	1
TAD-06	Whole product not reusable – efficient removal of reusable parts	Modules are easily replaced	2
TAD-07	High degree of standardisation of disassembly	Yes, but no general standard due to individual designs	1
TAD-08	High degree of automation of disassembly	No	-2
TAD-09	Longevity of components and modules	Some long-lasting (electronics function for long time, wear is low; classic bathtub curve), some not (casing, electrolytic capacitator)	2
TAD-10	Upgrade-friendly/compatible with new product generations	Software easily updated, hardware replaceable	2

		Desktop PCs	RP*
Technical aspects for reverse logistics			0.25
Identification (product, age, etc.)			
TAL-01	Information on whereabouts of product / availability for return	Only B2B for service contracts, evaluation generally not performed, never B2C as only third-party suppliers are active here	0
TAL-02	Clear product allocation	Brand and product details (incl. individual modules) identifiable, but further information and details not available	1
TAL-03	Materials clearly identifiable (where no material declaration available)	No, metals and plastics can be potentially identified by sight	-2
TAL-04	Age and condition identifiable (technical/documentation)	Possible in principle (software, product generation) using product numbers, no information on condition, condition sometimes can be identified using software but this is not easy/freely available	1
Collection & return			
TAL-05	Low transport expense per product unit	Yes (small, stackable, lightweight), but not as small as laptops	1
TAL-06	High value in relation to collection expense	Collection expense tends to be high, but value too, better ratio for B2B; worse for low-cost products	0
TAL-07	Established/functioning collection/return system	Only B2B in case of service contracts, otherwise possible via trade, voluntarily by customers, but it is not utilised, and the issue of data and trust in the whereabouts of products is an obstacle, although feasible via third-party suppliers and platforms	0
TAL-08	Legal regulations on collection and return	Not for remanufacturing, only WEEE as already declared as waste and removed from market, recirculation on market is difficult	-1
Storage			
TAL-09	Good storability	Negative impact on environment, protection during storage	1
TAL-10	Plannable inventory (goods inward/ outward)	Limited planability, only for B2B, not for B2C	-1
TAL-11	Good sortability for disassembled modules	If identification takes place then best storage possible	1
TAL-12	High standardisation of modules	Yes, in principle, high standardisation for interfaces	2
Business models			-0.63
GEM-01	Constant and plannable return quantities	No, as constant flow not plannable	-1
GEM-02	Constant and plannable sales market	Yes, always demand and regulated by price	1
GEM-03	Established and reliable return system in view of return and sales quantities (product responsibility spread across life cycle)	No, as no regulation or laws to support	-1
GEM-04	Structured framework conditions (laws, regulations)	No, as no regulation or laws to support	-1
GEM-05	Structured framework conditions (laws, regulations) of sales market, e.g. approval criteria	Yes, through CE labelling, but in detail very individualised and hard to identify	-1
GEM-06	Market acceptance of reprocessed products	Medium acceptance since price and performance is low, then acceptance	0

		Desktop PCs	RP*
GEM-07	Competition situation in sales market due to new products	New goods available in all price classes, meaning competition only via price vs. performance class, and new goods tend to become even cheaper	-1
GEM-08	Competition situation in sales market due to other reprocessed products	Via third-party suppliers: big competition for reusable products, lots of suppliers and all regulated by price, market is not regulated so no possibility for more expensive remanufacturing products	-1
Other aspects			0.25
OTH-01	Safety or malfunction risks caused by reprocessed products	Often long-lasting products (exceptions, e.g. electrolytic capacitors), more issue of performance and care taken by third-party suppliers that act without framework conditions	1
OTH-02	Brand risk (in case of premature malfunction of reprocessed products) / branding as reprocessed product (B2C) (quality perception) [if relevant]	Targeted purchase of brand components possible due to modular system; however, they are generally not released	-2
OTH-03	Value perception of reprocessed products (quality of upcycling, downcycling and recycling)	Can be upgraded but lower value in comparison to new product	0
OTH-04	High availability of qualified employees	Lower requirement for qualified staff and high availability	2

3.3.6 Water meters

Lorenz GmbH & Co. KG reprocesses water meters. These are analysed as an example as part of a life cycle assessment (cf. chapter 5). Information for the evaluation of the remanufacturing potential was provided by the company[58], Table 13 shows the results.

The *product design* is very conducive to remanufacturing. The companies own products are returned and reprocessed, which means that the components used are known. Only the exact composition of the electronic components used is not fully known. The only weak point of the product design is the high degree of manual labour involved in the reprocessing.

The product group's *reverse logistics* are also conducive to reprocessing. In collaboration with a meter reading company, the meters with expired calibration are exchanged and returned. The required effort and expense here is

[58] Mauss, W. (2020).

low. Although there are currently no legal regulations on collection and return, this could be addressed in the amendment to the German Circular Economy Act.

The related *business model* is another aspect that promotes remanufacturing. Thanks to the set calibration periods, the return of products is easy to plan. The reprocessed products are also widely accepted by customers, and the quality is proven through the calibration. There are currently no other suppliers on the German market that supply reprocessed water meters.

The *other aspects* category also reveals suitability for reprocessing. The risk of malfunction for the meters is no higher than that for new products. As the product's function is the key criterion, value perception on the part of the customer is high. The required employee qualifications can also be quickly provided, meaning there is a large pool of qualified staff available. The potential for remanufacturing is rated as very good with a score of 1.68.

Table 13: Evaluation matrix: water meters

*RP = remanufacturing potential

		Water meters	RP*
		Total potential	1.68
Technical aspects and design			1.60
Materials			
TAD-01	Material declarations available / identification of materials easily possible	Return of company's own products, easy identification due to good product knowledge. Product with manageable complexity, electronics module is only exchanged based on functionality, no material-specific considerations	2
TAD-02	Identification of modules easily possible	Return of company's own products, easy identification due to good product knowledge; product with manageable complexity. Electronics module is only exchanged based on functionality, no material-specific considerations	2
TAD-03	Hazardous/toxic substances (for handling, risk to employees)	Potentially for electronics or display as explicit material declaration unknown	1
TAD-04	Dangerous substances and substances that are harmful to the environment (potentially with legal restrictions for recirculation)	Potential flame retardants for electronics, PVC in cables, substances from the SVHC list	2
Modularity and longevity			
TAD-05	Whole product reusable – efficient disassembly and exchange of non-reusable modules	Good reusability, only low reprocessing effort required in many cases	2
TAD-06	Whole product not reusable – efficient removal of reusable parts	Everything reusable in principle, except circuit boards if broken	2
TAD-07	High degree of standardisation of disassembly	Yes, due to manageable number of product variants	2

		Water meters	RP*
TAD-08	High degree of automation of disassembly	Largely manual labour	-1
TAD-09	Longevity of components and modules	Brass components long-lasting, large portion of other components are reusable, even electronics can be updated if high-end components used	2
TAD-10	Upgrade-friendly/compatible with new product generations	Technical compatibility (via standardised connections), future-proofing can be ensured through use of more powerful chips (e.g. remote reading)	2
Technical aspects for reverse logistics			1.73
Identification (product, age, etc.)			
TAL-01	Information on whereabouts of product / availability for return	High traceability via meter reading contracts and suppliers	2
TAL-02	Clear product allocation	Extensive product knowledge, manageable product variants	2
TAL-03	Materials clearly identifiable (where no material declaration available)	N/A	N/A
TAL-04	Age and condition identifiable (technical/documentation)	Yes, thanks to documentation and goods inward inspection	2
Collection & return			
TAL-05	Low transport expense per product unit	Exchange prescribed upon expiry of calibration, required effort/expense low	2
TAL-06	High value in relation to collection expense	Collection effort/expense relatively low	1
TAL-07	Established/functioning collection/return system	Via partners (meter reading company)	2
TAL-08	Legal regulations on collection and return	Currently no regulations, but amendment to German Circular Economy Act could address this	0
Storage			
TAL-09	Good storability	Low impact on environment	2
TAL-10	Plannable inventory (goods inward/ outward)	Easy to plan due to known lifespan (calibration period)	2
TAL-11	Good sortability for disassembled modules	Manageable product diversity, good sortability	2
TAL-12	High standardisation of modules	Manageable number of product variants, installation onto standardised connections	2
Business models			1.63
GEM-01	Constant and plannable return quantities	Yes, due to calibration period	2
GEM-02	Constant and plannable sales market	Yes, due to calibration period	2
GEM-03	Established and reliable return system in view of return and sales quantities (product responsibility spread across life cycle)	Via sales partners	2
GEM-04	Structured framework conditions (laws, regulations)	Currently no regulations, but amendment to German Circular Economy Act could address this	0
GEM-05	Structured framework conditions (laws, regulations) of sales market, e.g. approval criteria	Calibration requirements	2
GEM-06	Market acceptance of reprocessed products	Good acceptance of reprocessed products, customers do not distinguish between new products and reprocessed goods, function as key criterion	2
GEM-07	Competition situation in sales market due to new products	Growing market, low competition	1
GEM-08	Competition situation in sales market due to other reprocessed products	Currently no other reprocessed products on the market	2

		Water meters	RP*
Other aspects			1.75
OTH-01	Safety or malfunction risks caused by reprocessed products	No higher than is the case fo new products	2
OTH-02	Brand risk (in case of premature malfunction of reprocessed products) / branding as reprocessed product (B2C) (quality perception) [if relevant]	Low risk, no difference to new product	2
OTH-03	Value perception of reprocessed products (quality of upcycling, downcycling and recycling)	Same quality, function is key criterion	2
OTH-04	High availability of qualified employees	Low qualification required, meaning good availability of employees	1

Most actors on the market assume that reprocessing water meters is more expensive than using new devices[59]. Despite this, Lorenz has invested in the reprocessing of water meters in recent years in an effort to establish the corresponding return and sales market. By systematically building the market with the related infrastructure, the company has been able to develop a functioning business model. Lorenz is now continuing to work on improving this model. It is taking part in research into the development of a disassembly system to reduce the high effort/expense as a result of the manual labour involved, which, in turn, will lead to an improved modularity.

3.3.7 Medical devices

Within the area of medical devices, this study looks at the reprocessing of X-ray machines and nuclear magnetic resonance spectrometers. The results are shown in Table 14 and indicate that the machines studied are well to very well suited for remanufacturing with an overall value of 1.39.

The *product design* demonstrates high suitability for remanufacturing. Devices are clearly labelled and designed to have a long lifespan. The focus on B2B services also means the risks associated with handling are extremely low. There are also standards for the exchange of operating supplies and wear parts in the form of the IEC 63077 standard[60].

The product group's *reverse logistics* are also conducive to remanufacturing. Thanks to service contracts typical within this product group, information on the whereabouts of the products is available and the expected lifespan can

[59] Cf. Minol (2019a), p. 2 and Minol (2019b), p. 4.
[60] IEC 63077:2019-01-15 (draft).

be foreseen. The devices are difficult to transport and require lots of storage space due to their size, but this is justified by their high value.

Table 14: Evaluation matrix: medical devices

*RP = remanufacturing potential

		Medical devices	RP*
		Total potential	1.39
Technical aspects and design			1.50
Materials			
TAD-01	Material declarations available / identification of materials easily possible	In most cases, excluding electronics	1
TAD-02	Identification of modules easily possible	Yes, due to documentation and modular design	2
TAD-03	Hazardous/toxic substances (for handling, risk to employees)	B2B, established compliance system making identification possible and removing danger potential (in accordance with law)	2
TAD-04	Dangerous substances and substances that are harmful to the environment (potentially with legal restrictions for recirculation)	B2B, established compliance system making identification possible and removing danger potential; trained staff increases safety	2
Modularity and longevity			
TAD-05	Whole product reusable – efficient disassembly and exchange of non-reusable modules	Yes (standard IEC 63077), but complex products including electronics	1
TAD-06	Whole product not reusable – efficient removal of reusable parts	Yes (standard IEC 63077), but complex products including electronics	1
TAD-07	High degree of standardisation of disassembly	Yes (standard IEC 63077), but complex products including electronics	1
TAD-08	High degree of automation of disassembly	Yes (standard IEC 63077), but complex products including electronics	1
TAD-09	Longevity of components and modules	Yes, as known and taken into account	2
TAD-10	Upgrade-friendly/compatible with new product generations	Yes (standard IEC 63077), but complex products including electronics	2
Technical aspects for reverse logistics			0.92
Identification (product, age, etc.)			
TAL-01	Information on whereabouts of product / availability for return	Yes (B2B, whereabouts known, often service contracts)	2
TAL-02	Clear product allocation	Yes (B2B, whereabouts known, clear labelling)	2
TAL-03	Materials clearly identifiable (where no material declaration available)	Yes, for larger modules, but excluding electronics	1
TAL-04	Age and condition identifiable (technical/documentation)	Yes (documentation and service contracts as B2B, age known)	2
Collection & return			
TAL-05	Low transport expense per product unit	Depends on size (not for NMR, yes for X-ray replacement modules)	0
TAL-06	High value in relation to collection expense	Yes, as expensive and intrinsically valuable devices	2
TAL-07	Established/functioning collection/return system	Differs case-by-case and regionally	0
TAL-08	Legal regulations on collection and return	IEC 63077, but no established return quotas	1
Storage			
TAL-09	Good storability	Negative impact on environment, protection during storage, potentially unwieldy devices	0

		Medical devices	RP*
TAL-10	Plannable inventory (goods inward/ outward)	Plannable due to service contracts, but uncertainty through lack of return system	1
TAL-11	Good sortability for disassembled modules	To an extent, as products highly individualised	0
TAL-12	High standardisation of modules	To an extent, as products highly individualised	0
Business models			1.38
GEM-01	Constant and plannable return quantities	Plannable due to service contracts, but uncertainty through lack of return system	1
GEM-02	Constant and plannable sales market	Similar planability to the sales market for new products but different target markets	2
GEM-03	Established and reliable return system in view of return and sales quantities (product responsibility spread across life cycle)	Partially plannable through service contracts	1
GEM-04	Structured framework conditions (laws, regulations)	IEC 63077	2
GEM-05	Structured framework conditions (laws, regulations) of sales market, e.g. approval criteria	IEC 63077	2
GEM-06	Market acceptance of reprocessed products	IEC 63077	2
GEM-07	Competition situation in sales market due to new products	Can arise in low-income countries	1
GEM-08	Competition situation in sales market due to other reprocessed products	Can arise through IEC 63077	0
Other aspects			1.75
OTH-01	Safety or malfunction risks caused by reprocessed products	Low, as controlled (IEC 63077)	2
OTH-02	Brand risk (in case of premature malfunction of reprocessed products) / branding as reprocessed product (B2C) (quality perception) [if relevant]	Low, as controlled (IEC 63077)	2
OTH-03	Value perception of reprocessed products (quality of upcycling, downcycling and recycling)	Good, as controlled (IEC 63077)	2
OTH-04	High availability of qualified employees	High requirement, but manufacturer and remanufacturer identical, allowing for access to a large pool of qualified employees	1

The above gives rise to a *business model* suited to reprocessing as the related service contracts provide good knowledge of the return and sales markets. Return guidelines are outlined in the IEC 63077[61] standard.

The category of *other aspects* also receives a very positive rating. Standardisation means the risk of malfunction and thus the brand risk is extremely low, and this, in turn, leads to a high value perception by the customer. Reprocessing is typically performed by the device manufacturer. Companies

[61] IEC 63077:2019-01 (draft).

therefore also have access to a wide pool of qualified employees for remanufacturing.

3.3.8 Home and household furniture

The evaluation of reprocessing of home and household furniture is shown in Table 15. As is apparent, this product group achieves a negative rating with an overall value of -0.29. The market for reprocessed furniture in Germany is currently very small (cf. chapter 2.2).

The *product design* tends to be non-conducive to remanufacturing due to the wide variety of products. Replacing parts or components is also difficult for the most part and often involves a large amount of work; there are no standardised modules nor uniform/consistent product concepts.

The product group's *reverse logistics* is currently another hindering factor for remanufacturing. Information on the whereabouts of products is in the best case available in the B2B sector. The transport expense is mostly high in proportion to the value of the products, and the storage of bulky parts requires lots of space. It is also extremely difficult to efficiently warehouse the products due to the lack of standardisation of parts and the wide variety of products.

This leads to many hindering factors for the related *business models*. Although competitive pressure within the remanufacturing market is low, the market is almost non-existent. Due to the lack of structuring within the return and sales market, planning is almost impossible. It should still be noted, however, that the industry is striving towards corresponding business models and has welcomed the idea of a circular economy[62]. An evaluation of the portfolio or select individual portfolio products by manufacturers that are planning concrete measures, or already have these in place, would lead to evaluation results adjusted accordingly that were not available when the project was being completed.

In contrast, the category of *other aspects* receives a positive rating. The safety risk is low. Reprocessed furniture is perceived as positive and high-

[62] **Cf. IKEA (2019), p. 1.**

quality. There is also a sufficient selection of qualified employees for reprocessing as it is basically no different from new production.

Table 15: Evaluation matrix: home and household furniture

*RP = remanufacturing potential

		Furniture	RP*
		Total potential	-0.29
Technical aspects and design			-0.50
Materials			
TAD-01	Material declarations available / identification of materials easily possible	Rarely, as wide variety of products	-2
TAD-02	Identification of modules easily possible	Neutral, as wide variety of products, but manageable complexity of modules	0
TAD-03	Hazardous/toxic substances (for handling, risk to employees)	Rarely	1
TAD-04	Dangerous substances and substances that are harmful to the environment (potentially with legal restrictions for recirculation)	Potentially through use of plastics, colours or wood treatment, but tends to be low-risk	0
Modularity and longevity			
TAD-05	Whole product reusable – efficient disassembly and exchange of non-reusable modules	Exchange usually difficult without dismantling, new product lines make this possible, however	0
TAD-06	Whole product not reusable – efficient removal of reusable parts	Exchange usually difficult without dismantling, new product lines make this possible, however	0
TAD-07	High degree of standardisation of disassembly	Rarely	-1
TAD-08	High degree of automation of disassembly	Very rarely	-2
TAD-09	Longevity of components and modules	Yes, but depending on product quality	1
TAD-10	Upgrade-friendly/compatible with new product generations	No	-2
Technical aspects for reverse logistics			-1.42
Identification (product, age, etc.)			
TAL-01	Information on whereabouts of product / availability for return	Partially B2B, never B2C	-1
TAL-02	Clear product allocation	Partially B2B, never B2C	-1
TAL-03	Materials clearly identifiable (where no material declaration available)	No, but manageable material options, tendency increasing, however	-1
TAL-04	Age and condition identifiable (technical/documentation)	No, but visual evaluation possible	-1
Collection & return			
TAL-05	Low transport expense per product unit	Relatively high expense, bulky	-1
TAL-06	High value in relation to collection expense	Low value, relatively high expense	-2
TAL-07	Established/functioning collection/return system	Non-existent	-2
TAL-08	Legal regulations on collection and return	Non-existent	-2
Storage			
TAL-09	Good storability	Negative impact on environment, protection during storage and space requirement	0

		Furniture	RP*
TAL-10	Plannable inventory (goods inward/ outward)	No	-2
TAL-11	Good sortability for disassembled modules	No, due to wide variety of products	-2
TAL-12	High standardisation of modules	No	-2
Business models			-0.50
GEM-01	Constant and plannable return quantities	No, as return of furniture effectively does not exist (bulky waste?)	-2
GEM-02	Constant and plannable sales market	No, only common market requirements	-1
GEM-03	Established and reliable return system in view of return and sales quantities (product responsibility spread across life cycle)	No	-2
GEM-04	Structured framework conditions (laws, regulations)	No	-2
GEM-05	Structured framework conditions (laws, regulations) of sales market, e.g. approval criteria	No, but also not necessary	0
GEM-06	Market acceptance of reprocessed products	Medium, as acceptance depends on price	0
GEM-07	Competition situation in sales market due to new products	Appearance, price and quality only partially comparable to new products	1
GEM-08	Competition situation in sales market due to other reprocessed products	No noticeable market available to date	2
Other aspects			1.25
OTH-01	Safety or malfunction risks caused by reprocessed products	Often long-lasting, more an issue of appearance, trends	1
OTH-02	Brand risk (in case of premature malfunction of reprocessed products) / branding as reprocessed product (B2C) (quality perception) [if relevant]	Only brand manufacturers lose image, no-names unaffected, more an issue of trends	1
OTH-03	Value perception of reprocessed products (quality of upcycling, downcycling and recycling)	Reprocessed pieces of furniture tend to be positively received	1
OTH-04	High availability of qualified employees	Possible for wide selection of specialist staff	2

3.4 Overall evaluation

The evaluation of all example products is compiled in Table 16. The quantitative evaluation of the product examples differs greatly. While some products (e.g. water meters, engines and medical devices) display high potential for remanufacturing, remanufacturing potential for other product groups (e.g. furniture and laptops) is low.

It is not just individual aspects, such as product design, that are crucial for a high remanufacturing potential. Other aspects such as an effective reverse logistics system with knowledge on the whereabouts of the products to be reprocessed as well as a functioning business model with plannable procurement and sales markets and a positive perception of quality by the customer must also be in place.

Assessments of the impact of individual aspects on the suitability for remanufacturing can be put into the evaluation matrix, and this can then be used to derive measures for improvement. For example, for the furniture product group, it is clear that the area of reverse logistics is a huge challenge. By modifying the business model, for example through the use of leasing or maintenance contracts, access to information on the whereabouts of the products can be improved while establishing a reverse logistics system and thus the procurement market, which in turn would lead to a significant increase in the potential for remanufacturing.

Table 16: Compilation of evaluations of all example products

		Aircraft engines	Starters and alternators	Combustion engines	Laptops	Desktop PCs	Water meters	Medical devices	Home and household furniture
	Remanufacturing potential	1.51	0.73	0.77	-0.23	0.09	1.68	1.39	-0.29
Technical aspects and design		1.40	0.20	1.00	-0.70	0.50	1.60	1.50	-0.50
Materials									
TAD-01	Material declarations available / identification of materials easily possible	2	2	0	-2	-1	2	1	-2
TAD-02	Identification of modules easily possible	2	0	2	-1	1	2	2	0
TAD-03	Hazardous/toxic substances (for handling, risk to employees)	2	1	2	0	0	1	2	1
TAD-04	Dangerous substances and substances that are harmful to the environment (potentially with legal restrictions for recirculation)	2	1	2	-1	-1	2	2	0
Modularity and longevity									
TAD-05	Whole product reusable – efficient disassembly and exchange of non-reusable modules	2	1	2	-1	1	2	1	0
TAD-06	Whole product not reusable – efficient removal of reusable parts	2	-2	2	0	2	2	1	0
TAD-07	High degree of standardisation of disassembly	2	1	1	-2	1	2	1	-1
TAD-08	High degree of automation of disassembly	-1	-1	-2	-2	-2	-1	1	-2
TAD-09	Longevity of components and modules	0	1	1	1	2	2	2	1
TAD-10	Upgrade-friendly/compatible with new product generations	1	-2	0	1	2	2	2	-2

		Aircraft engines	Starters and alternators	Combustion engines	Laptops	Desktop PCs	Water meters	Medical devices	Home and household furniture
Technical aspects for reverse logistics		2.00	1.45	0.91	0.17	0.25	1.73	0.92	-1.42
Identification (product, age, etc.)									
TAL-01	Information on whereabouts of product / availability for return	2	2	2	0	0	2	2	-1
TAL-02	Clear product allocation	2	2	2	1	1	2	2	-1
TAL-03	Materials clearly identifiable (where no material declaration available)	N/A	N/A	N/A	-2	-2	N/A	1	-1
TAL-04	Age and condition identifiable (technical/documentation)	2	2	1	1	1	2	2	-1
Collection & return									
TAL-05	Low transport expense per product unit	2	1	0	1	1	2	0	-1
TAL-06	High value in relation to collection expense	2	1	0	0	0	1	2	-2
TAL-07	Established/functioning collection/return system	2	2	0	0	0	2	0	-2
TAL-08	Legal regulations on collection and return	2	2	0	-1	-1	0	1	-2
Storage									
TAL-09	Good storability	2	2	1	1	1	2	0	0
TAL-10	Plannable inventory (goods inward/ outward)	2	1	2	-1	-1	2	1	-2
TAL-11	Good sortability for disassembled modules	2	1	2	1	1	2	0	-2
TAL-12	High standardisation of modules	2	0	0	1	2	2	0	-2
Business models		1.88	0.75	0.43	-0.63	-0.63	1.63	1.38	-0.50
GEM-01	Constant and plannable return quantities	2	1	2	-1	-1	2	1	-2
GEM-02	Constant and plannable sales market	2	1	2	1	1	2	2	-1
GEM-03	Established and reliable return system in view of return and sales quantities (product responsibility spread across life cycle)	2	2	N/A	-1	-1	2	1	-2
GEM-04	Structured framework conditions (laws, regulations)	2	2	0	-1	-1	0	2	-2
GEM-05	Structured framework conditions (laws, regulations) of sales market, e.g. approval criteria	2	0	1	-1	-1	2	2	0
GEM-06	Market acceptance of reprocessed products	2	1	1	0	0	2	2	0
GEM-07	Competition situation in sales market due to new products	2	0	-1	-1	-1	1	1	1
GEM-08	Competition situation in sales market due to other reprocessed products	1	-1	-2	-1	-1	2	0	2
Other aspects		0.75	0.50	0.75	0.25	0.25	1.75	1.75	1.25
OTH-01	Safety or malfunction risks caused by reprocessed products	2	2	1	1	1	2	2	1
OTH-02	Brand risk (in case of premature malfunction of reprocessed products) /	0	0	2	-2	-2	2	2	1

		Aircraft engines	Starters and alternators	Combustion engines	Laptops	Desktop PCs	Water meters	Medical devices	Home and household fur-
	branding as reprocessed product (B2C) (quality perception) [if relevant]								
OTH-03	Value perception of reprocessed products (quality of upcycling, downcycling and recycling)	2	-1	1	0	0	2	2	1
OTH-04	High availability of qualified employees	-1	1	-1	2	2	1	1	2

The example with laptops and desktop PCs shows that there are some fundamental similarities within this product category. Commonality can be found in the areas of reverse logistics, business models and other aspects in particular. Both examples are from the field of electrical engineering and therefore have similar framework conditions. However, they also display significant differences, particularly within the area of product design. Due to the higher level of integration, the identification of modules and materials is more complex for laptops than it is for desktop PCs. This, in turn, affects the ability to replace individual components, meaning the evaluation of laptops resulted in a lower score. It achieves a score of -0.23 in comparison to 0.09 for desktop PCs.

In principle, it is clear that remanufacturing is, for the most part, more worthwhile for expensive and modular products that can be disassembled. There is often already a spare parts market for these products. The repair and reprocessing industry have been able to both develop business models and positively implement/use the product features for remanufacturing.

Such a market is yet to be established for low-cost products in many cases. However, this is possible as shown by the example of the water meter (cf. section 3.3.6). Cooperation with other actors can help to secure the return and recirculation of products. The water meter product design makes it possible to reprocess used water meters, which can then be resold to the end customer by meter reading companies. Here, customers do not distinguish between new and reprocessed products as the same level of performance is ensured.

4 FACTORS THAT PROMOTE AND HINDER REMANUFACTURING

The path from linear product use towards a closed-loop system is often long and winding. Although remanufacturing offers both economic and ecological opportunities, in some cases it can also have some negative effects. It is therefore necessary to carry out a systematic and comprehensive evaluation for each product (cf. chapter 3.1.2 and chapter 5.1). The results of this evaluation can then be used to identify factors that promote or hinder remanufacturing.

4.1 Drivers for remanufacturing

The probability that remanufacturing has a positive effect is always high where the relevant product design is based on the premise of increasing resource efficiency, closing material cycles and avoiding waste. When it comes to product-related and technical constraints (cf. chapter 2.1.2), remanufacturing is largely worthwhile for products that:

- Consist of materials that can be recycled
- Do not contain toxic substances
- Have a modular design
- Are easy to disassemble and dismantle
- Use wear-resistant materials or components in view of a longer and repeated product use period
- Are easy to maintain and repair

In principle, life cycle considerations in general and life cycle assessments are required for identifying whether a product is suitable for remanufacturing, especially when it comes to ecological aspects (cf. chapter 5.1). The life cycle assessment quantifies the ecological effects and the potential for resource savings. This assessment takes into account all technical and, where applicable, economic aspects of the product's life cycle.

In addition to life cycle assessment data for material and raw material reprocessing, the corresponding production processes also impact the environment. Processes such as sorting, disassembly or repairs also play an important role. It is not only the ecological impact and resource use for individual processes that plays a decisive role; their effect across one or several product life cycles is crucial. For example, the choice of a new material that is compatible with a closed-loop system can generate high pollution from the extraction of the required primary raw materials, whereas transport expenditure can be reduced through a reduction in weight. The new material can also reduce any impact on the environment in comparison to the extraction of the primary raw materials through its recovery. This may be the case for individual materials, product modules or entire products.

In order to be able to compare the resource efficiency of a newly manufactured and a reprocessed product, the respective life phases of both products must be assessed side by side. If applicable, additional life phases of the reprocessed product must also be taken into account. This may include either the remanufacturing of the entire product or only the reprocessed modules or components.

In addition to the technical and process-related aspects, this assessment can also be used to derive systematic and logistical factors that are conducive to remanufacturing but which lie outside the confines of the direct life cycle assessment-related evaluations. This includes well-functioning collection and return systems that ensure a steady supply of used parts over time with a quality that is as consistent as possible. Qualified staff is also required to inspect the used parts. An effective collection and return logistics system, including storage, sorting and transport between the parties involved, helps to ensure a sustainable remanufacturing model.

Finally, as a central element of economic operations, business models are also decisive factors for remanufacturing. These are often only noticeable, however, when the necessary technical or logistics-related requirements have been met. However, it is very difficult to finance a well-functioning logistics system without already existing business models. This dilemma results in the lack of business models being seen more as a preventative factor. However, if these models exist and are recorded and can be presented, they represent a strong driver for remanufacturing and therefore promote a circular product design. Conversely, it is improbable that a suitable business model can be automatically derived from a product idea that aims for circularity.

The independent evaluation results from chapter 3.3 clearly show that existing business models are distinctly supportive drivers for remanufacturing. An example of a functioning business model is that of Lorenz with its remanufacturing of water meters, which allows the company to continuously make product improvements. Through creativity and courage to implement new business sequences and investments, the company was able to remove any perceived obstacles preventing remanufacturing. Without a business model, the evaluation would have resulted in a lower score and would have been considered to be a preventative factor as no circular model could be derived from the existing product properties.

Where there are still no product cycles as evidence for a functioning business model, the most important drivers are ideas, creativity and the courage to change something in the product technology and logistics so as to create a sustainable business model. This suggests that products that are less complex and have the potential for continuous changes are most suitable for establishing a gradual recirculation. Complex products or product systems are therefore considered to be a preventative factor (cf. chapter 4.2).

Where reprocessed products that are produced, refurbished and marketed with a corresponding business model are already available, procurement and sales markets should also be established with long-term and sustainable business success. An established sales market, a trust in the quality on the part of the customer and continuous adjustment of marketing and sales channels to customer requirements and the market situation are all factors that promote remanufacturing. This also applies for new products. Quality promises and price adjustments can create good brand awareness for a secondary product. Customers subsequently do not consider reprocessed products to be a lower-quality or cheaper option in comparison to new products and instead deem them to be of a similar or even higher quality. Brands or businesses that profess to be resource-efficient and champions of climate action, and can back this up with facts without compromising on the quality and function of their products, help to promote stability and sustainability within a modern society. Europe in particular is dependent on raw material imports and it obtains a large number of materials through imports (see also results on raw material criticality in chapter 5.3.2). Remanufacturing and a circular economy both enable businesses to still offer products to meet demand and at a stable price despite this high dependence on imports. They allow product manufacturers and suppliers to eliminate their dependence on procurement costs beyond their control and fluctuating raw material availabilities.

4.2 Obstacles for remanufacturing

One factor that hinders remanufacturing is the interplay between missing technical and logistics-related boundary conditions and the lack of business models geared towards recirculation (cf. chapter 4.1). External constraints such as a lack of customer acceptance or restrictive regulations and requirements also play a role.

When it comes to product properties and technical constraints, the following obstacles are worth highlighting:

- High integration of materials and product functions without modularisation that prevent separation as part of disposal

- High integration and miniaturisation, e.g. in electronics, coupled with missing technical solutions for recycling all materials separately

- The use of a wide range of materials, in particular as part of low material flows, that is not conducive to an economical logistics system

- Integrated "smartness" or sensors at the chip level that do not last as long as the rest of the product but which determine the product's function and cannot be separated (different periods of function combined in one product without modularisation)

Although miniaturisation and dematerialisation does promote resource efficiency, it should be noted that these traits pose a hindrance when it comes to remanufacturing and closed-loop systems. This is primarily due to the fact that they make it more difficult to exchange parts and reprocess products so that products or product components can be used over several life cycles. Each individual product part determines the lifespan of the entire product. This means that the part with the shortest lifespan defines the lifespan of the whole product where there is no option to separate, disassemble or repair the product.

In addition to product design, the following logistics-related and system-related obstacles must be noted:

- Loss of product relation after sale, such as in the consumer market
- Lack of options for return/recirculation
- Mixed collection systems in event of wide variety of products
- Complex or costly transport or reverse logistics
- Unplannable or hard-to-calculate return quantities
- Conflicts or different interests in collaboration across the value chain
- Information deficits, insufficient transparency in value chain

For comparative consideration of the life cycles of both new and reprocessed products, it is clear that individual processes or materials should not be compared with one another. Instead, analysis should look at all effects throughout the entire life cycle (cf. chapter 5). This leads to certain obstacles as manufacturers or remanufacturers often no longer have any relation to the product after sale. Both either have to rely on external collection systems or must introduce these to the market themselves, which is generally unfeasible for individual actors. Either products cannot be identified at all, are destroyed or so rich in variety that reprocessing is too diverse and too complex. This also prevents businesses from developing an economically sound model.

The direct logistics costs in relation to product values to be gathered can also pose an obstacle. Examples include bulky goods or products with very low material quantities per unit, especially where these are widely distributed.

As deduced from chapter 4.1, the economic aspects represent the biggest obstacles for remanufacturing. By themselves, they rarely motivate businesses to invest in or make changes to technology or logistics in an attempt to make them more compatible with a closed-loop system. These aspects include:

- Lack of structures within the business, e.g. no reverse logistics, storage capacities or goods inward inspection
- Unclear responsibilities
- Lack of specialist staff or lack of retraining measures
- Lack of acceptance of reprocessed used products
- Lack of incentive for businesses to develop new business models
- Low primary raw material costs or undetected raw material risks
- Risk of product cannibalisation in that circular products reduce the market share of new products
- Negative aspects as part of life cycle assessment illustration
- Legal barriers

The more simply the products and product systems are designed, the easier it is to identify business models. However, the market trend generally leans more towards a higher complexity, more “smartness” and function integration, meaning that value chains and the relevant stakeholders and sequences within the product’s life cycle become more complex and multifaceted.

There are challenges across multiple levels. These challenges range from cognitive barriers on the part of consumers and operative barriers on the part of the company all the way to regulatory obstacles at an economic level, and they are often mutually influential[63]. There is often a conflict of objectives

[63] Cf. Fasko, R. (2015), pp. 3 et seqq. & Scheelhaase, T. and Zinke, G. (2016), pp. 51 et seqq. & Weber, T. and Stuchtey, M. (2018), pp. 17 et seqq.

between the technical possibilities, economic profitability, quality and product function and ecological aspects. Operative structures in and between businesses need to be changed. To do so, businesses must develop new capabilities to be able to resolve the conflict of objectives arising from the life cycle standpoint. This also requires resources, expertise and widespread acceptance from the actors involved and it poses a bigger obstacle than the challenge of overcoming technical or purely financial hurdles. These aspects and conflicts of objectives are a huge challenge for established companies in particular as this involves changes to organisational structures[64]. This means that flexible and adaptable SMEs tend to have more opportunity to implement a successful remanufacturing model than large corporations, provided that the economic hurdles for SMEs are not too high.

According to the Circular Economy Initiative Deutschland (CEID)[65], there is also one system-related obstacle that must be highlighted. The financial assessment of circular business models often results in too low a score as the standard evaluation and risk models and indicators of business financing cannot reflect central concepts of remanufacturing. For example, current evaluation methods for business models are generally based on classic numerical values such as fixed assets. It must be accepted, however, that a company's value is less often generated via fixed assets for remanufacturing. The evaluation of new circular business models therefore does not adequately reflect current key figures.

The cognitive barriers of the market and/or customer represent another obstacle. Low user acceptance or a lack of demand for reprocessed products do not give businesses any incentive to develop such[66]. Going further, each actor throughout the entire value chain must do their part. This means conflicts of objectives must be resolved across all companies involved throughout a product's life cycle, and often not every company can generate direct added

[64] Cf. Weber, T. and Stuchtey, M. (2018), p. 18.
[65] Cf. Weber, T. and Stuchtey, M. (2018), pp. 18–19.
[66] Cf. Scheelhaase, T. and Zinke, G. (2016), pp. 52–53.

value for themselves. A value transfer can be helpful for countering this obstacle. This transfer must be initiated from a fiscal point of view and thus by way of policy.

The system level (e.g. tax system, policy or laws) represents another obstacle, but this can only be influenced by individual actors to a limited extent. Current regulations and standards set inadequate incentives for circular economies. Examples includes the strict taxation of work and the relatively low taxation of resources. This promotes consumption and disadvantages business models based on repairs or remanufacturing. Outside of the legislative framework, there is, in many cases, a lack of accepted (industry) standards that enable a reliable implementation of innovative business models across the different sectors. Other shortfalls include:

- Multiple gaps in knowledge in relation to circular concepts in theory and practice
- Insufficient dissemination of available knowledge throughout society
- Strong cultural barriers such as status symbols for consumers[67]

To overcome these barriers, a shift in values towards more sustainable consumption models with an understanding of quality is required, where the attribute “new” is not necessarily a criteria of quality. The separation of waste in the private sector can be taken as an example of cultural barriers. It excludes the disposal of used electronic devices via household waste. This leads to valuable materials lying unused in cupboards for years as the hurdles standing in the way of reusing or recycling these are too high[68]. If there were a desire for a circular economy in society and it acted accordingly, the hurdles preventing recirculation would not be too high, and this would result in new approaches to reverse logistics and improved product design enabling companies to increasingly implement successful remanufacturing models.

[67] Cf. Weber, T. and Stuchtey, M. (2018), p. 20.
[68] Cf. Scheelhaase, T. and Zinke, G. (2016), p. 53 & Weber, T. and Stuchtey, M. (2018), p. 18.

Finally, it is important to mention the obstacles posed by global trade chains, which involve insufficient or inconsistent standards, for example. There are also differing perceptions of value and economic constraints that cannot be influenced by individual companies or governments alone[69].

4.3 How to introduce a circular product system

Overall, the issue of drivers and obstacles for remanufacturing poses the question of how interested businesses, particularly SMEs, can go about developing circular business models and establishing a remanufacturing system.

The findings from chapters 4.1 and 4.2 show that the biggest hurdle lies in the interplay between the lack of circular product properties and insufficient or imperceptible business models. It is difficult to develop one without the other.

It also appears that less complex products or product systems can be gradually made circular more easily. This is due to the fact that if products/systems are too complex and there are too many actors, the hurdles are too high, removing any viable pathway for defining new business models. Such models are, however, still possible, as shown by the positive score given to the remanufacturing of aircraft engines. When introducing these business models, however, they must be simple and easy to understand to allow businesses to quickly convince investors, but still containing facts and arguments to make them believable. Complex product and system life cycles make it difficult to do this. In this respect, it can be presumed that entering the field of remanufacturing via the standard route of finding and defining a business model and subsequently implementing this through products and systems rarely leads to success.

Practical experience from numerous businesses with regard to life cycle analyses has led to the definition of the following steps as a viable pathway towards circular product systems (Figure 9). This methodical process can also be used for complex product systems. Ultimately, business models are

[69] Cf. Ionaşcu, I. and Ionaşcu, M. (2018), pp. 357 et seqq. & Weber, T. and Stuchtey, M. (2018), pp. 356–372

all about piquing interest and laying out the basic arguments, and this can be cut out from the complexity and communicated in a logical, systematic manner.

Step 1	Perform life cycle analysis
Step 2	Identify weak points (relevant product and system aspects, hotspots)
Step 3	Identify how to influence weak points
Step 4	Simulate effects from influences and changes
Step 5	Transfer findings from simulation into real-life conditions
Step 6	Derive business models

Figure 9: Practical guide for introducing a circular product system, the six-step plan

The steps involve the following in more detail:

(1) The first step should be to carry out a life cycle analysis or life cycle assessment of a product or product system. The complexity of the product or system is insignificant here and only involves the necessary time and effort required to complete such a study. Modern LCA tools and the corresponding databases cover almost all common materials, energies, logistics and production processes.

(2) The results of the life cycle analysis should be investigated in relation to all levels of detail of the product model and on all logistical and system-related aspects. Here, absolute numbers for calculated indicators are less relevant. It is more about the relationships between and the origin (environmental aspects) of the individual contributions throughout the life cycle. This so-called hotspot analysis (weak-point analysis) using ecological indicators has the advantage that various technical and systemic aspects can be compared with one another. For example, energy consumption in kWh, transport emissions in km or quantities of

used material in kg can be compared in the same unit using the global warming potential indicator. The values of the global warming potential unit can be compared with one another or within one section of the life cycle or with reference to the full life cycle, allowing businesses to determine their significance.

(3) Using the indicators of the life cycle analysis, the hotspots are examined to determine which contributions dominate and how these can be influenced. For example, using modern LCA tools, simulations are a conceivable method for communicating the effects of material changes and their subsequent impact of energy, logistics and production processes.

(4) This analysis and simulation of influences leads to a list of possible measures that could bring with them system improvement. Improvement can be deemed to include, for example, the reduction of greenhouse gas quantities or a lower resource use. These ecological aspects make it possible to objectively assess products or systems using the indicators against subjective indicators such as profit maximisation for individual actors within the life cycle or price minimisation without regard to quality.

(5) Methods of solution finding and creativity promotion can be used to identify opportunities for implementation and develop business models. Examples of creativity techniques include brainstorming (loud technique)[70] or 6-3-5 Brainwriting (quiet technique)[71]. These techniques can be used to find new ideas based on the basic principles of team, space and process as part of the “design thinking” approach[72]. However, discursive methods are also conceivable, such as morphological boxes[73] or relevance tree analyses[74], which systematically represent brainstorming and problem-solving techniques that follow a logical sequence. Combinations of both technique approaches should also be noted, such as

[70] Cf. Clark, Ch. H. (1989), pp. 10 et seqq.
[71] Cf. Higgins, J. M. and Wiese, G. G. (1996), pp. 10 et seqq.
[72] Cf. Sachse, P. and Specker, A. (1999), pp. 10 et seqq.
[73] Cf. Zwicky, F. (1966), pp. 8 et seqq.
[74] Cf. Schmidt, G. (2000), pp. 10 et seqq.

the Disney method[75], whereby a problem or an idea is considered from the perspective of different roles (e.g. from the view of realists, critics and dreamers). The list of suitable methods is long, and the choice depends on the specific case at hand. The intention here is to start to think about or allow all options and not be restricted by the constraints of the given boundary conditions for the respective actual state.

(6) The most promising approaches and implementation routes towards new circular business models from step five are chosen and processed so that they can be implemented through changes to products, logistics or sections of the life cycle. These can also be used to find investors as the found business models are based on comprehensible and solid, fact-based analytics.

[75] **Cf. Dilts, R. B.; Epstein, T. and Dilts, R. W. (1994), pp. 9 et seqq.**

5 LIFE CYCLE ASSESSMENT, CRITICALITY AND COST EVALUATION

5.1 Introduction to the topic of life cycle assessment

In principle, a life cycle assessment is an instrument for recording, evaluating and illustrating environmental impacts. It forms a basis for comparisons, target setting or internal and external communication. According to DIN EN ISO 14040[76], a life cycle assessment is used to determine the scope of objective and assessment, perform an analysis of a created life cycle inventory, assess the corresponding impact and perform a final interpretation (cf. Figure 10).

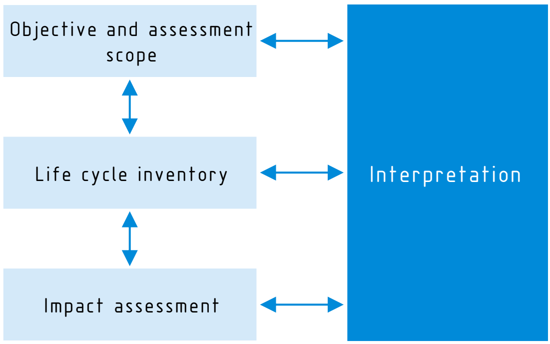

Figure 10: Phases of a life cycle assessment in accordance with DIN EN ISO 14040

Determining the scope of objective and assessment is essential for any further work as this stage sets out the system limits to be taken into account. The subsequent life cycle inventory then records all necessary inputs (raw material and energy flows) and outputs (waste, emissions, etc.). Depending on the defined system boundaries, this analysis is carried out across all stages of life for the product in question, from "cradle to grave". The impact assessment is used to identify the environmental impact of each component of the life cycle inventory using impact categories (e.g. global warming potential or stratospheric ozone depletion). The final interpretation then identifies the most important issues, highlighting recommended actions and addressing potential limitations of the analysis.

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[76] DIN EN ISO 14040:2006.

These and all other steps of the life cycle assessment are carried out based on the specifications set out in DIN EN ISO 14040 “Life cycle assessment – principles and framework”[77] and DIN EN ISO 14044 “Life cycle assessment – requirements and guidelines”[78].

Determining the scope of objective and assessment involves, for example (based on DIN EN ISO 14044):

- Determination of issues and objective of assessment to ensure clear understanding of contents
- Target group of life cycle assessment results (e.g. SMEs) to clarify who the recipient or user can or should be
- Description of assessed products and assessed systems
- Definition of functional unit that has a large influence over the result as it defines the quantified value to which all calculated environmental impact indicators refer
- Determination of system boundaries for the purposes of defining which process steps are considered and which do not contribute to the result and/or are not considered
- Requirements of data quality, level of detail and scope to provide an impression of quality and reliability of results
- Determination of fundamental assumptions, e.g. relating to individual life cycle phases, for assessment of stability and validity of results
- Regional and time aspects for assessment of the translatability for other areas
- Handling of data gaps, cut-off criteria, allocation methods, etc. for assessment of quality, stability and validity of results

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77 DIN EN ISO 14040:2006.
78 DIN EN ISO 14044:2006.

- Determination of environmental impact categories to be considered
- Evaluation processes and illustration of results to ensure a better understanding of the results
- Selection of parameters and influence factors for sensitivity analysis for assessment of relevance

The study's framework is set out by defining the functional unit and the scope of assessment. These remain in place for the duration of the study. Also according to the DIN EN ISO 14040/44 standards, these iteration loops are customary for life cycle assessments and serve primarily to reconcile the determination of objectives and scope with the final result, which always depends on the gained findings, available data and the necessary assumptions made.

Analogous to the ecological evaluation, the economic analysis is also carried out based on the same scope of assessment and the same functional unit. This ensures consistency between the ecological and economic analyses.

5.2 Definition of objectives and scope of comparative life cycle analyses

5.2.1 Objective of comparative life cycle analyses

The objective of life cycle analyses (life cycle assessment) is to compare the environmental impacts of newly manufactured and reprocessed water meters from Lorenz GmbH & Co. KG. The life cycle assessment and subsequent evaluation is carried out in accordance with DIN EN ISO 14040[79], DIN EN ISO 14044[80] as well as VDI 4600[81] and VDI 4800-1[82] and 2[83]. This makes it possible to reveal the potential for quantitatively reducing environmental impacts and resource needs through remanufacturing.

[79] DIN EN ISO 14040:2006.
[80] DIN EN ISO 14040:2006.
[81] VDI 4600-1:2015-08.
[82] VDI 4800-1:2016-02.
[83] VDI 4800-2:2018-03.

In addition to the environmental impacts, the assessments also analyse raw material criticality and economic aspects.

The study's target groups are machine and system manufacturers, product users and consultancy and research institutions. The findings from the study can be used as a source of information by initiatives and associations and state/national institutions and their representatives.

5.2.2 Assessment scope

5.2.2.1 Assessed products

The subject of the study is water meters from Lorenz GmbH & Co. KG. Lorenz supplies both surface-mounted meters (impeller meters) and flush-type meters (measuring capsules). Both meter types differ in their construction, but their function is fundamentally the same: they measure the quantity of water flowing through. Both meter versions are reprocessed and resold by Lorenz. The meter's calibration is extremely relevant here as this is the only way to guarantee that the measured flow rate is correct. A hot-water meter's calibration is valid for five years, after which the meter must be replaced or recalibrated. This study looks at surface-mounted meters (Figure 11).

Figure 11: Lorenz surface-mounted meter

5.2.2.2 Description of function and definition of functional unit

The function of water meters is to record the volume of water that flows through them for the purposes of recording consumption. To correctly record the water quantities, water meters must be regularly calibrated. The calibration of hot-water meters is valid for five years and six years for cold-water meters. Once the calibration period has expired, the device must be replaced and recalibrated.

Derived from this function, the functional unit is defined as the calibrated recording of water flow quantities over a period of five years. The function of the calibrated recording can be fulfilled by both newly manufactured and reprocessed water meters, provided these have a valid calibration.

5.2.2.3 System boundaries

The system limits include process sequences for the manufacture, use and disposal of new and reprocessed water meters. Figure 12 and **Figure 13** illustrate the system boundaries for the life cycles of both systems in question.

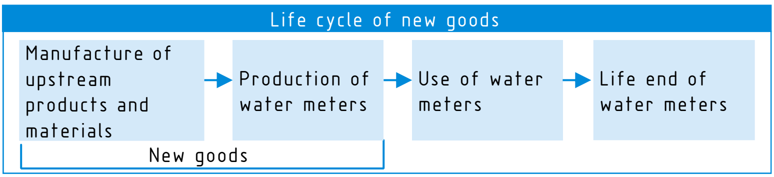

Figure 12: System boundaries for the life cycle of newly manufactured water meters

The linear approach illustrated in chapter 1 (Figure 12) is clearly distinguishable from the product loop of the remanufacturing approach (**Figure 13**).

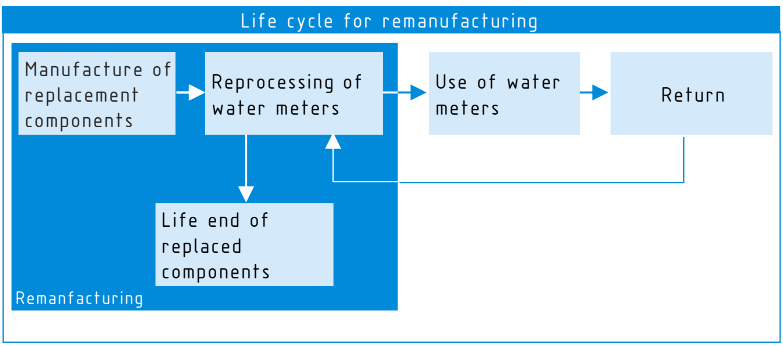

Figure 13: System boundaries for the life cycle of reprocessed water meters

The manufacturing process steps for a new meter are shown in Figure 14 in detail. Following receipt, the materials are inspected by Lorenz employees (goods inward A-I). The brass components are then processed (A-II). The electronics are installed with software (A-III). The meters are then put together (A-IV). The finished water meters are inspected and calibrated (A-V). Defects or imprecise meters are detected as part of quality assurance and reprocessed if needed (A-VI). The calibrated meters are cleaned and disinfected using pasteurisation and can then be shipped.

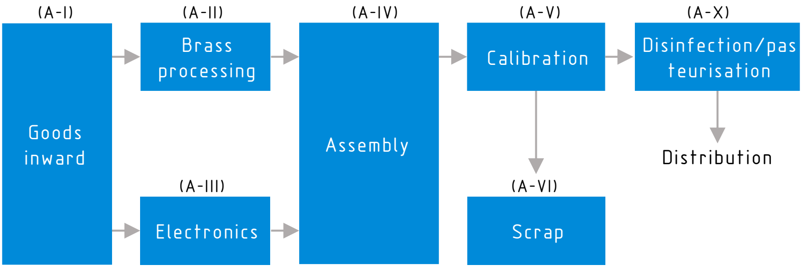

Figure 14: Process sequence for manufacturing a new water meter

After use, usually once the calibration period has expired, the water meter at the customer premises is replaced. In the case of remanufacturing by Lorenz, the old meters are then returned for reprocessing. The returned water meters can either undergo simple or extensive reprocessing.

Simple reprocessing of water meters is outlined in detail in Figure 15. The meters are inspected and then reprocessed depending on their condition (B-I). For this purpose, the meters must only be cleaned (B-II). They are then recalibrated, disinfected and shipped without the need for any other reprocessing steps (B-IV, B-X). In some cases, the hydraulics of the water meters must be replaced (B-III). To do so, the cover is removed and the hydraulics are then mechanically cleaned. The hydraulics can then be reused.

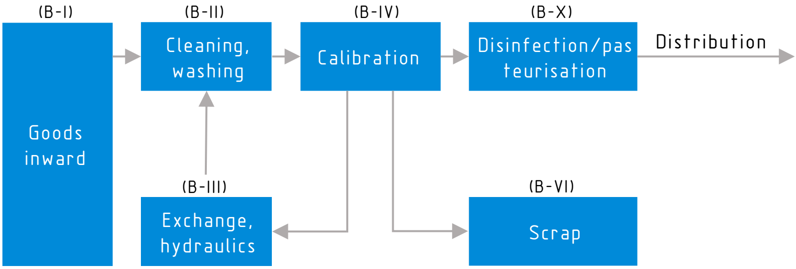

Figure 15: Process sequence for simple reprocessing of a water meter

Around a quarter of returned meters must be heavily reprocessed. Figure 16 shows the more extensive process sequence for reprocessing water meters in detail. Steps C-I to C-IV from Figure 16 correspond directly to the cleaning and replacement steps for hydraulics in Figure 15. Further additional reprocessing steps then follow depending on the condition of the meter. These include: replacing the cover (C-V) and, if necessary, the dial, device number plate, the Data Matrix code and the conformity label (C-VI). An electrical inspection of the electronics and radio units must also take place. In some cases, the software must be updated or the electronics must be completely replaced (C-VII). Depending on the condition of the meter, the battery may also need to be changed (C-VIII). The water meters must then be calibrated (C-IX).

This can result in a small amount of scrap (C-XI), but this does not differ for reprocessed and new products. Before the goods can be shipped, the water meters must finally be disinfected once more (C-X). Depending on the condition, not all water meters go through all process steps. Only around 10% of all returned meters go through all reprocessing steps, including the changing of the battery.

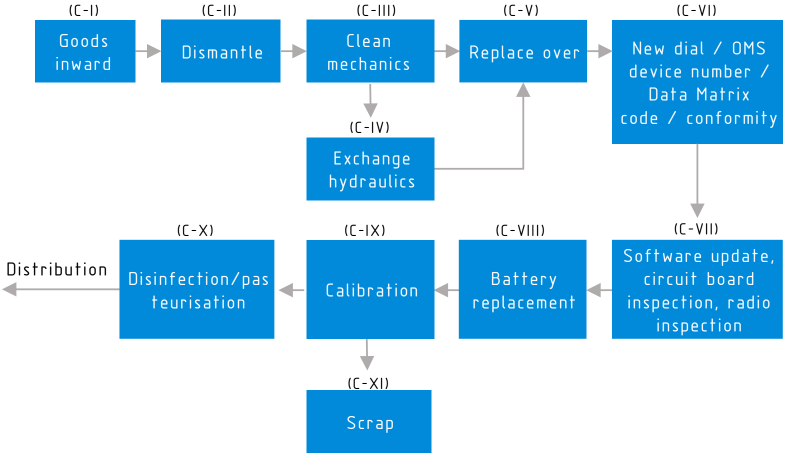

Figure 16: Process sequence for heavy reprocessing of water meter

The distance for the shipping and return of the water meters is identical for all cases and is set at 145 km. This corresponds to the average transport distance for goods in Germany[84].

The thermal energy required for disinfection is represented by natural gas, for electrical currents a German network mix is used. As part of the scenario analyses (chapter 5.3.4), variation is made between the energy systems which demonstrates the special situation for Lorenz with the use of biogas and waste heat.

The additional process steps for reprocessing result in changes in resource needs, environmental impact and costs. The environmental impacts of an average reprocessing sequence is considered as the base case as part of this study. Average reprocessing here refers to the reprocessing steps arising at Lorenz. Here, 75% of the water meters require simple reprocessing and the remaining 25% require heavy reprocessing. Analyses of the various reprocessing sequences are performed within the framework of scenario analyses (chapter 5.3.4).

[84] Cf. Hütter, A. (2016), p. 48.

5.2.3 Life cycle inventory

5.2.3.1 Models, allocation, cut-off criteria, impact assessment

The GaBi software and related databases[85] are used to create the life cycle assessment models. Datasets for Germany are used as the water meters are manufactured, reprocessed and used in Germany. There are no available datasets for the sapphires used as bearing jewels. The dataset for the extraction of gold is modified by way of an economic allocation for the purpose of the assessment as comparably complex extraction processes (as is the case of gemstones) can be assumed here. The gold dataset is scaled in a linear fashion with a factor that is derived from the comparison of the average prices for gold and sapphires. No further allocations are carried out beyond this as no joint production occurs in the primary system in question.

In line with the guidelines set out in VDI 4800-1[86], waste materials that are utilised as part of a downstream product system are considered up to their recording. Waste materials to be removed are recorded within the system in question. All available energy and material flow data is recorded for processes within the system boundaries.

The following indicators are used to evaluate the results:

- The **"cumulative energy demand" (CED)** as an evaluation indicator of energy input: evaluation is carried out in accordance with the VDI guideline VDI 4600[87].

- The **"cumulative raw material demand" (CRD)** as an evaluation indicator of raw material input: evaluation is carried out in accordance with the VDI guideline VDI 4800-2[88].

[85] Sphera (2020b).
[86] VDI 4800-1:2016-02.
[87] VDI 4600-1:2015-08.
[88] VDI 4800-2:2018-03.

- **Land use**, subdivided into settlement and agricultural areas, follows the guidelines set out in the VDI guideline VDI 4800-2[89].

- The **greenhouse gas emissions** in CO_2 equivalents: evaluation is carried out in accordance with the IPCC report from 2013[90].

- **Water**: blue water consumption takes place in accordance with the guidelines set out in VDI guideline VDI 4800-2[91].

An additional evaluation of the supply criticality for the raw materials and other materials included in the life cycle inventory is also completed. This evaluation is carried out in accordance with the VDI guideline VDI 4800-2[92]. This is then followed by an economic assessment of the life cycles, which, in terms of system boundaries and reference system, is based on the determinations and descriptions of the ecological evaluation(see chapter 5.2.3.4).

5.2.3.2 Data collection and life cycle inventory for ecological evaluation

Data for the manufacture and reprocessing of water meters is collected in close collaboration with Lorenz GmbH & Co. KG in Ingstetten (Schelklingen). Based on currently available information, Lorenz is the only company in Germany that both manufactures and reprocesses water meters.

A process flow was designed for data collection and then agreed in coordination with Lorenz (cf. chapter 5.2.2.3). All material inputs and outputs and energy sources in the respective process steps were recorded and reviewed. The period of collection refers to 2019 and was determined based on real consumption data. The quality of the collected foreground data is therefore rated as very good. A parts list is also created for the manufacture of new water meters containing all parts used with their mass and material type.

The background system data is based on the latest version of the GaBi databases (service pack 40, 2020)[93]. The datasets represent the current state of

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89 VDI 4800-2:2018-03.
90 IPCC (2013).
91 VDI 4800-2:2018-03.
92 VDI 4800-2 (2018).
93 Sphera (2020a).

the art in energy supply, material manufacturing and the industrial production and machining processes for the 2019 reference year.

5.2.3.3 Databases and software

Life cycle assessment models are created using the GaBi 9 software[94]. The related GaBi 2020 databases (service pack 40) provide up-to-date life cycle inventory data for the background systems[95]. Detailed information on the modelling principles and quality requirements are available in the so-called GaBi Modelling Principles[96].

5.2.3.4 Data collection and cost items for the economic evaluation

The economic analysis is based on the same scope as the life cycle assessment. The collected data on mass and energy flows are expanded to include cost data. Both the economic and ecological analyses are carried out based on the same system boundaries to ensure both analyses are consistent.

Lorenz provides the customer with a refund, the amount of which depends on the condition of the returned water meter. The reprocessing steps are set out in chapter 5.2.2.3. In the case of heavy reprocessing in particular, process steps such as steps C-VI (allocation of a new OMS device number and conformity check) and C-VII (software update and circuit board check) outlined in Figure 16 are considered. Whether or not these steps cause costs to arise is not relevant from an ecological point of view. These cost items are recorded in the economic analysis while they are ignored for the ecological analysis.

The scope of the economic and ecological analyses is therefore the same. However, consideration is given at different levels of aggregation to protect sensitive data, among other things. The consistency of the economic and ecological analyses is therefore ensured while preserving confidentiality.

[94] Sphera (2020b).
[95] Sphera (2020a).
[96] Sphera (2020c).

5.2.4 Sensitivity analyses

The basis of the ecological evaluation is the basic scenario in which the manufacture of the water meters is compared with the average reprocessing. Lorenz's average reprocessing effort/expense is taken as the basis for reprocessing, whereby the respective shares of simple and heavy reprocessing are combined in the life cycle assessment model.

Sensitivity analyses are carried out based on this basic scenario to evaluate the stability of the model and the results. Here, simple reprocessing is first compared with heavy reprocessing. Various energy scenarios (use of electricity from renewable sources, use of biogas and off-load thermal energy (TE)) and the impact of longer transport distances for the shipping and return of the water meters are taken into account. Simple reprocessing with reduced CO_2 is taken as the best case, with energy coming from renewable sources and off-load thermal energy being used for disinfection.

By combining simple processing and the use of renewable energy sources, this represents the smallest ecological impact for reprocessing in line with the current state of the art. This is then compared with the worst case: heavy reprocessing of the water meters with transport distances for shipping and returns of 500 km. Both of these cases together demonstrate the range of ecological impacts associated with the reprocessing of water meters at Lorenz. Table 17 provides an overview of the respective model configurations for the performed sensitivity analyses.

Table 17: Name and scope of sensitivity analyses

No.	Name	Scope
1	Simple reprocessing	Only simple reprocessing taken into account
2	Heavy reprocessing	Only heavy reprocessing taken into account
3	Best case	Simple reprocessing, renewable energy sources, off-load thermal energy
4	Worst case	Heavy reprocessing, long transport distances (500 km instead of 145 km)
5	TE biogas	Use of biogas (instead of natural gas)
6	TE off-load	Off-load use of thermal energy (surplus thermal energy from other heat storage plants)
7	Long transport routes	Transport distance for shipping/return 500 km (instead of 145 km)

5.3 Results of comparative life cycle analyses

5.3.1 Results of ecological evaluation of basic scenario

The ecological analysis is carried out based on the basic scenario and compares the manufacture of new water meters with the average outputs generated for the reprocessing of water meters by Lorenz. The results are shown in Table 17. This clearly shows that reprocessing leads to a reduction of more than 90% in the environmental impact in all considered impact categories in comparison to the manufacture of new goods.

The greenhouse gas emissions for the individual life cycle phases in kg CO_2 equivalent are shown as a graph in Figure 17. The manufacture of new goods in particular causes high greenhouse gas emissions.

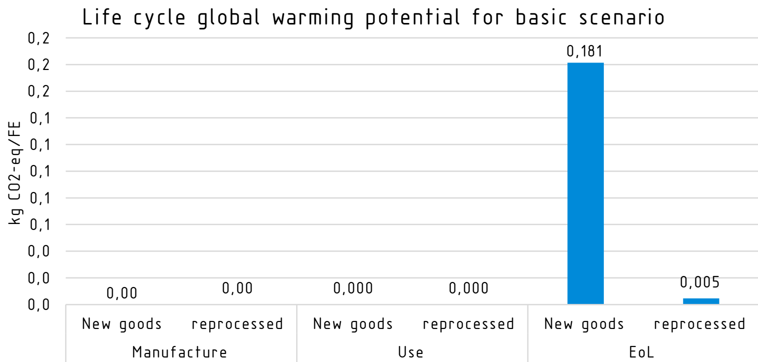

Figure 17: Greenhouse gas emissions of life cycle phases, basic scenario

The greenhouse gas emissions caused as part of the manufacture of new goods are analysed in detail in Figure 18. Some of the outlined processes or the manufacture of parts are performed in the upstream chain, others are carried out at Lorenz internally. This is grouped in the figure accordingly: electronics, batteries and bearing jewels are additionally purchased, the environmental impacts therefore arise in the upstream. Brass is purchased as part of brass production, but processing is carried out internally. Both externally manufactured components and the actual assembly of parts at Lorenz are included in the assembly block, therefore combining upstream chains and internal processes. The water meters are disinfected and tested internally at Lorenz.

Figure 18 shows that the electronics alone cause around half of the greenhouse gas emissions for the manufacture even though they only weigh 9 g. In contrast, pre-production and processing of the brass parts for the casing generate around 1 kg of greenhouse gas emissions with a weight of 268 g. Despite their extremely low mass of 0.04 g, the sapphire bearing jewels require 0.16 kg of CO_2 equivalents. This is due to the expensive extraction of sapphire, although the gold dataset is adapted via the price ratio. The manufacture and delivery of batteries and assembly, including production of any additional parts used, each cause around 0.3 kg CO_2 equivalents. Disinfection and testing cause very low greenhouse gas emissions in comparison.

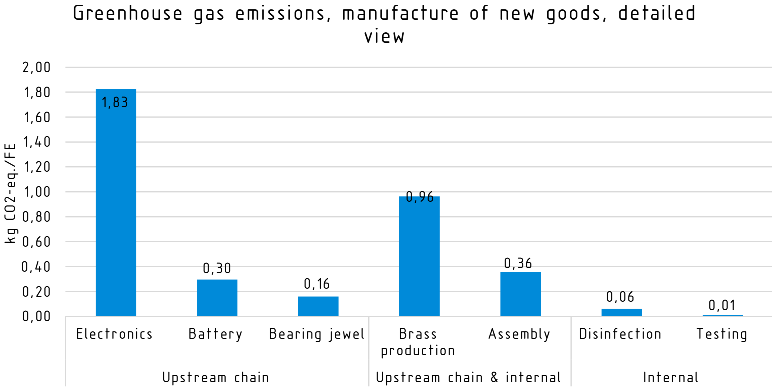

Figure 18: **Detailed view of greenhouse gas emissions, manufacture of new goods**

Only the water meter's cover (manufacture of this causes 0.11 kg of CO_2 equivalents) and the battery are replaced as part of reprocessing; the remaining components can be used further. This leads to the high potential for reduction of environmental impact outlined.

To ensure the reprocessed water meters are future-proof, Lorenz uses electronics with more storage space than currently required. This ensures that the electronics can meet the increasing requirements in the future. This proactive approach also allows Lorenz to avoid having to potentially replace electronics in the event of increasing requirements and keep the environmental impact of reprocessing low going forward. However, this approach does result in more expense as part of initial procurement. This additional output also translates to the ecological impact caused by electronics. Larger storage (chip, component on board) has a larger environmental impact. However, this additional output is much smaller in comparison to that involved with replacing the electronics.

5.3.2 Results of raw material criticality

An analysis in line with VDI 4800-2[97] is carried out to evaluate the raw materials used. This analysis takes into account the various geological, economic, social, political and technical aspects. Only exogenous aspects (supply and demand aspects that cannot be influenced by the business in question) are examined as part of this study. The endogenous criteria contain aspects that can be directly influenced by the business. These are not taken into account here. The raw materials are evaluated using standardised indicators between 0 and 1. An indicator value of 0 corresponds to a low criticality, an indicator value of 1 corresponds to a high criticality for a raw material and a defined criteria. The exogenous criteria are subdivided into three criteria groups:

- **Geological, technical and structural criteria:** statistical range, secondary/joint production, recycling, logistical limitations, limitations as a result of natural events
- **Geopolitical and regulatory criteria:** national concentration of reserves, national concentration of production, geopolitical risks of world production, regulatory situations for raw material projects
- **Economic criteria:** company concentrations of global production, global demand stimulus, substitutability, raw material price fluctuations

[97] VDI 4800-2:2018-03.

The relevant raw materials that are used in the product system are first determined for the evaluation of raw material criticality for the manufacture and reprocessing of water meters.

Due to the modularity as part of reprocessing, the product system is divided into parts to enable a more detailed analysis. The analysed modules include:

- Electronics (without battery)
- Battery
- Manufacture of casing and mechanics of new goods (without battery and electronics)
- Heavy reprocessing

Table 18 shows the critical raw materials used in the water meter's electronics. A total of twelve critical raw materials are used in the electronics. The average criticality of all raw materials (calculated from the average of all individual average values across all criteria) is in the middle region with a value of 0.5. It is clear that the country concentrations of production in particular poses a huge risk across almost all raw materials deemed to be critical (aluminium, chrome, cobalt, iron, palladium, platinum, silicon, zinc and tin). Price volatility also contributes to the raw material risk.

By using efficient electronics with larger storage capabilities than currently required, Lorenz proactively reduces the need to replace electronics and thus completely avoids the criticality of electronics in future product life cycles, except in cases of damage (the probability of damage occurring is not influenced by the changes made). In addition to the previously shown ecological potential, this also leads to a reduction in the raw material criticality for reprocessing as the electronics do not need to be replaced.

The raw material criticality of the batteries is shown in Table 19. Only five critical raw materials are used here. The average criticality of all raw materials (calculated from the average of all individual average values across all criteria) is also in the middle region with a value of 0.5. Despite the low number of critical raw materials, the criticality for batteries is comparable to that for the electronics. The country concentrations in particular are also classed as risky for batteries when it comes to raw material production (cobalt, indium, lithium). The technical and economic feasibility of a substitution of raw materials and the price volatility are, however, the most relevant economic risks for four out of the five raw materials (cobalt, indium, manganese, nickel). This is primarily the reason for the same overall average criticality value as for electronics.

Table 20 shows the raw material criticality for the manufacture of the casing and the mechanics of new goods. These are combined with the battery and electronics to make a water meter. Again, five critical raw materials are used here in total. The average criticality of all raw materials (calculated from the average of all individual average values across all criteria) is lower than is the case for the electronics and battery with a value of 0.4. Again here, the price volatility of raw materials is a critical aspect in particular. All other aspects, however, are lower than the corresponding values for electronics and batteries accordingly. It is also worth mentioning that brass is largely based on brass scrap as the process involves closed material loops and only small quantities (up to 10% in model used) of new materials are alloyed.

Table 18: Raw material criticality – water meter electronics

	Raw material / element	Aluminium	Chrome	Cobalt	Iron	Copper	Nickel	Palladium	Platinum	Silver	Silicon	Zinc	Tin
	Average criticality of raw material	**0.4**	**0.5**	**0.6**	**0.4**	**0.4**	**0.4**	**0.6**	**0.5**	**0.5**	**0.4**	**0.5**	**0.5**
Geological, technical and structural criteria	Ratio of reserves to global annual production	0.0	1.0	0.3	0.3	0.7	0.7	0.0	0.0	1.0	0.0	1.0	1.0
	Degree of joint/ secondary production	0.0	0.0	0.7	0.0	0.3	0.3	0.7	0.3	0.7	0.0	0.3	0.0
	Degree of distribution of functional end-of-life technology	0.3	0.3	0.7	0.3	0.3	0.3	0.7	0.7	0.3	0.7	0.7	0.7
	Economic efficiency of storage and transport	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Degree of distribution of natural distribution / producing areas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Geopolitical and regulatory criteria	Herfindahl-Hirschman Index of reserves	0.7	1.0	0.7	0.3	0.3	0.7	1.0	1.0	0.3	0.3	0.3	0.7
	Herfindahl-Hirschman Index of country production	1.0	1.0	1.0	1.0	0.7	0.3	1.0	1.0	0.3	1.0	1.0	1.0
	Political country risk	0.7	0.7	0.7	0.7	0.3	0.3	0.7	0.7	0.7	0.7	0.7	0.7
	Regulatory country risk	0.3	0.3	0.7	0.3	0.3	0.3	0.7	0.3	0.3	0.7	0.3	0.7
Economic criteria	Herfindahl-Hirschman Index of companies	0.3	0.7	0.3	0.3	0.3	0.3	0.7	0.7	0.3	0.3	0.3	0.3
	Degree of demand increase	0.0	0.3	0.3	0.0	0.3	0.3	0.3	0.7	0.3	0.0	0.0	0.3
	Technical feasibility and economic efficiency of substitutions in primary applications	0.7	1.0	1.0	0.7	0.7	1.0	0.7	0.7	0.7	0.7	1.0	0.7
	Annualised price volatility	0.7	0.7	1.0	0.7	1.0	1.0	1.0	0.7	1.0	0.7	1.0	1.0

Table 19: Raw material criticality – water meter battery

	Raw material / element	Cobalt	Indium	Lithium	Manga-nese	Nickel
	Average criticality of raw material	**0.6**	**0.7**	**0.5**	**0.4**	**0.4**
Geological, technical and structural criteria	Ratio of reserves to global annual production	0.3	1.0	0.0	0.7	0.7
	Degree of joint/ secondary production	0.7	1.0	0.0	0.0	0.3
	Degree of distribution of functional end-of-life technology	0.7	0.7	1.0	0.3	0.3
	Economic efficiency of storage and transport	0.0	0.0	0.0	0.0	0.0
	Degree of distribution of natural distribution / producing areas	0.0	0.0	0.0	0.0	0.0
Geopolitical and regulatory criteria	Herfindahl-Hirschman Index of reserves	0.7	0.3	1.0	0.7	0.7
	Herfindahl-Hirschman Index of country production	1.0	1.0	1.0	0.7	0.3
	Political country risk	0.7	0.7	0.3	0.3	0.3
	Regulatory country risk	0.7	0.3	0.3	0.3	0.3
Economic criteria	Herfindahl-Hirschman Index of companies	0.3	0.7	0.7	0.3	0.3
	Degree of demand increase	0.3	1.0	0.3	0.0	0.3
	Technical feasibility and economic efficiency of substitutions in primary applications	1.0	1.0	0.7	1.0	1.0
	Annualised price volatility	1.0	1.0	0.7	1.0	1.0

Table 20: Raw material criticality – manufacture of casing and mechanics of new goods

	Raw material / element	Chrome	Crude oil	Copper	Nickel	Zinc
	Average criticality of raw material	**0.5**	**0.3**	**0.4**	**0.4**	**0.5**
Geological, technical and structural criteria	Ratio of reserves to global annual production	1.0	0.3	0.7	0.7	1.0
	Degree of joint/ secondary production	0.0	0.0	0.3	0.3	0.3
	Degree of distribution of functional end-of-life technology	0.3	0.3	0.3	0.3	0.7
	Economic efficiency of storage and transport	0.0	0.3	0.0	0.0	0.0
	Degree of distribution of natural distribution / producing areas	0.0	0.0	0.0	0.0	0.0
Geopolitical and regulatory criteria	Herfindahl-Hirschman Index of reserves	1.0	0.3	0.3	0.7	0.3
	Herfindahl-Hirschman Index of country production	1.0	0.3	0.7	0.3	1.0
	Political country risk	0.7	0.7	0.3	0.3	0.7
	Regulatory country risk	0.3	0.3	0.3	0.3	0.3
Economic criteria	Herfindahl-Hirschman Index of companies	0.7	0.3	0.3	0.3	0.3
	Degree of demand increase	0.3	0.7	0.3	0.3	0.0
	Technical feasibility and economic efficiency of substitutions in primary applications	1.0	0.0	0.7	1.0	1.0
	Annualised price volatility	0.7	1.0	1.0	1.0	1.0

It is clear as part of the consideration of the manufacture of new goods in relation to all three modules (electronics, battery, casing) that the electronics and batteries in particular use a large number of critical raw materials. These are made future-proof as part of the transformation of new goods towards remanufacturing through the use of large storage capabilities, for example. This allows Lorenz to systematically reduce raw material criticality early on in the product design phase.

The raw material criticality for reprocessing is based on both the reprocessing scenarios shown (also shown in ecological terms), simple reprocessing and heavy reprocessing (cf. Figure 15 and Figure 16).

In the case of heavy reprocessing, the water meter's cover is removed and the battery is replaced. The criticality for the manufacture of the battery has already been outlined in Table 19. The criticality for the exchange of the cover is shown in Table 21. The cover is made from polycarbonate meaning the only critical raw material used is crude oil. The average raw material criticality lies at 0.3; price volatility is the most critical aspect here.

No materials are replaced for simple reprocessing; the water meters are only cleaned and recalibrated. There is therefore no raw material criticality in this case, with the value corresponding to a criticality of 0.

In summary, it is clear that the raw material criticality for reprocessing is significantly lower than is the case for the manufacture of new goods. This is due to the relatively low proportion of materials that are replaced. However, the future-proof design of the electronics in particular is a big factor in proactively reducing the raw material criticality.

The sapphires used as bearing jewels and the gold contained within the electronics are not included in VDI 4800-2[98]. Due to the price and the high environmental relevance of both materials, it would be beneficial to include these in the list of critical resources. However, it can be presumed that the critical values for these materials do not change the actual results in their basic statement.

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[98] VDI 4800-2:2018-03.

Table 21: Raw material criticality – heavy reprocessing

	Raw material / element	Crude oil
	Average criticality of raw material	**0.3**
Geological, technical and structural criteria	Ratio of reserves to global annual production	0.3
	Degree of joint/ secondary production	0.0
	Degree of distribution of functional end-of-life technology	0.3
	Economic efficiency of storage and transport	0.3
	Degree of distribution of natural distribution / producing areas	0.0
Geopolitical and regulatory criteria	Herfindahl-Hirschman Index of reserves	0.3
	Herfindahl-Hirschman Index of country production	0.3
	Political country risk	0.7
	Regulatory country risk	0.3
Economic criteria	Herfindahl-Hirschman Index of companies	0.3
	Degree of demand increase	0.7
	Technical feasibility and economic efficiency of substitutions in primary applications	0.0
	Annualised price volatility	1.0

5.3.3 Results of the economic evaluation

The manufacturing costs for newly manufactured water meters are compared with those for reprocessed water meters as part of the economic analysis. Data on cost items is collected at Lorenz. The manufacturing costs include material and production costs. For confidentiality reasons, the manufacturing costs are only shown as relative values and partially aggregated (especially for new goods).

The costs for reprocessing the water meters are average values with quantitative weighting for the respective expense for reprocessing.

It is clear from the exact manufacturing cost data that the reprocessing of water meters is significantly cheaper in comparison to new production. This data is not published here for confidentiality reasons. The average manufacturing costs for reprocessing equate to half of the costs for new goods.

Various reprocessing process routes (reprocessing 1 to reprocessing 4) and their respective costs are shown. Meters in good condition must go through fewer reprocessing steps and therefore result in lower reprocessing costs. However, the refund provided to the customer is also higher in this case, resulting in comparable costs for reprocessing regardless of the condition of the returned water meter. Table 22 shows the respective necessary reprocessing steps depending on the condition of the water meter. Here, simple reprocessing (reprocessing variants 1 and 1a) are highlighted in green; variants 2 to 4 represent heavy processing. The “share” column indicates the frequency of the required reprocessing steps.

Table 22: Overview of reprocessing variants

	Level of reprocessing				
	1	1a	2	3	4
Buy-back of old meters	X	X	X	X	X
Calibration	X	X	X	X	X
Label		X	X	X	X
Cover			X	X	X
Data Matrix + software update				X	X
Battery					X
Share	**50%**	**25%**	**10%**	**10%**	**5%**

Bigger refunds are provided for returns for water meters in good condition (reprocessing 1 and 1a). The reprocessing required for these meters is less extensive and in the best case only cleaning and disinfection is needed. The worse the condition of the water meter, the lower the costs for buy-back. Meters in poorer conditions do require more extensive reprocessing, however.

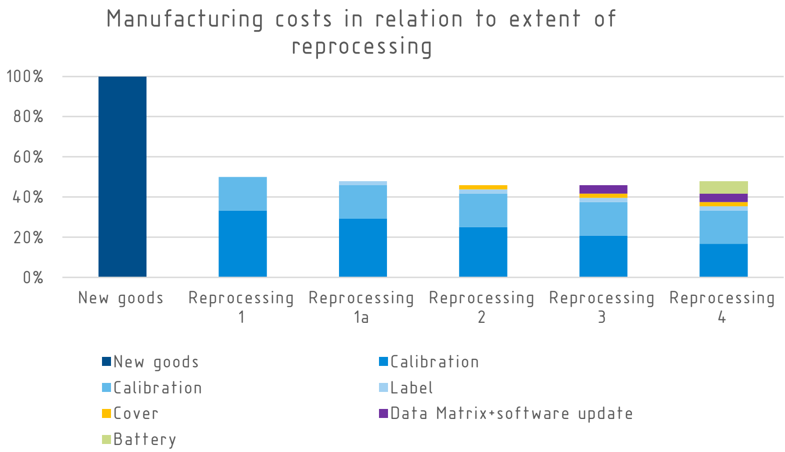

Figure 19: Detailed view of greenhouse gas emissions, manufacture of new goods

The largest pool of costs for reprocessing comes from the buy-back of used water meters and the calibration of reprocessed water meters. The amount of the refund provided for the buy-back depends on the condition of the device. Calibration also involves a calibration fee, which makes up a large portion of the overall costs for reprocessing.

5.3.4 Sensitivity analyses

The sensitivity analyses serve to review the stability of the models and the assumptions they are based on. They also show potential for improvement that can arise through the use of other energy sources, for example.

The defined sensitivity analyses mainly influence the ecological aspects and resource criticality. The variation of parameters has very little influence on economic aspects. In most cases, the quantification of impacts is not possible here due to the high level of aggregation. The cases considered are shown in

Table 17. A large portion only affect reprocessing but not the manufacture of new goods. Table 23 shows the relative change to environmental impacts for reprocessed water meters in relation to the basic scenario. For clarity, the scenarios are only labelled with their allocated numbers. In some cases, there are significant changes to the basic scenario. Here, however, it must be noted that the basic values are relatively low. Even small, absolute changes can therefore lead to large relative deviations.

Table 23: Relative change in ecological results for reprocessing

Impact category	Variants						
	1	2	3	4	5	6	7
Water consumption	-42%	126%	-33%	128%	25%	0%	2%
Settlement areas	-92%	275%	-85%	275%	0%	0%	0%
Agricultural areas	-11%	34%	205%	43%	241%	0%	9%
Metals, minerals	-23%	69%	-96%	69%	-1%	-3%	0%
Energy resources	-31%	94%	-92%	103%	-8%	-9%	9%
CED, exhaustible	-36%	109%	-89%	122%	-12%	-13%	13%
CED, regenerative	-14%	42%	152%	44%	113%	0%	3%
Global warming potential	-36%	109%	-84%	122%	-6%	-11%	13%

The difference between simple and heavy reprocessing is clear in variants 1 and 2. Simple reprocessing does not involve any replacement of parts, meaning the environmental impact is at the lowest. For heavy processing, on the other hand, parts (cover and battery) are replaced, leading to a bigger environmental impact. Despite the clear increase in variant 2, the environmental impacts of heavy reprocessing are still lower than the manufacture of new goods.

Variant 3 shows the ecological potential for the best currently conceivable reprocessing. In this best case, only water meters in good condition are reprocessed (simple reprocessing). The electrical current is generated from renewable sources, the required thermal energy is calculated as off-load (without environmental impact). This is possible by using waste heat from surrounding operations, for example, if this otherwise goes unused. The results show a mixed picture: while global warming potential, exhaustible CED, resource consumption (metals, minerals and energy raw materials), water consumption and settlement land use fall significantly, regenerative CED and the need for agricultural land increase. The increase in the need for land is due to the higher proportion of biomass in the generation of electricity. By using renewable energy sources, the regenerative CED increases, while exhaustible CED decreases accordingly. The greenhouse gas emissions in this variant are minimal: each reprocessed meter only generates 29 g of CO_2 equivalents, 9 g of which come from logistics processes. Under these assumptions, if Lorenz is striving for a CO_2-neutral reprocessing, the remaining 20 g of greenhouse gas emissions must be compensated for through offset projects. Based on an assumed compensation price of 23 euros per tonne of greenhouse gas emissions[99], this would lead to costs of around 0.05 cents per water meter. However, if the average reprocessing, as is currently carried out at Lorenz, is offset, the average costs would be 0.4 cents per water meter.

Variant 4 combines heavy reprocessing with long transport routes of 500 km (instead of 145 km) for the shipping and return of the water meters. Although this is a worst-case consideration for reprocessing, this is still significantly more environmentally friendly than the manufacture of new goods (with an approx. 90% reduction in environmental impact in all considered impact categories).

Variants 5 and 6 quantify the influence of various forms of thermal energy supply. The use of biogas leads to higher water consumption and land use. As a result, the rate of regenerative CED increases while exhaustible CED, resource requirements and global warming potential all decrease. In variant 6, the environmental impacts of thermal energy generation are allocated to another product system. This is allowed where the thermal energy generated there would otherwise remain unused. This reduces the calculated contributions to resource requirements, exhaustible CED and greenhouse gas emissions.

In variant 7, transport distances for the shipping and return of the water meters are increased from 145 km to 500 km routes. It appears that increasing distances causes a small increase in the environmental impact.

For the raw material criticality analyses, differences can only be identified for the distinction between simple and heavy reprocessing. No parts are re-

[99] **Atmosfair (2020).**

placed for simple reprocessing, thus meaning there is no raw material criticality. The covers and batteries are replaced for heavy reprocessing and this requires critical raw materials. Overall, however, it appears that reprocessing involves a much lower raw material criticality than is the case for the manufacture of new goods. This is largely due to the fact that the electronics, casing and mechanics can continue to be used. Using electronics with larger storage capabilities also ensures that they are future-proof and therefore proactively reduces raw material criticality.

There are only five different reprocessing variations for the economic consideration. The necessary reprocessing steps and the resulting costs depend on the condition of the meter. A more extensive reprocessing leads to higher costs accordingly. However, this variation in costs is offset by the flexible refund model based on the condition of the water meter. It turns out that the relative manufacturing costs for reprocessing in all considered reprocessing cases are almost identical and equate to around half of the manufacturing costs associated with new goods.

5.4 Evaluation of comparative life cycle analyses

The comparative life cycle analysis performed in this study compares the reprocessing of Lorenz GmbH water meters with the manufacture of new goods. The review of environmental impacts, raw material criticality and economic aspects allows for a comprehensive comparison here.

A variety of impact indicators are evaluated as part of the life cycle assessment (global warming potential, water consumption, land use and cumulative raw material and energy demand). This extensive evaluation makes it possible to identify and, if necessary, avoid any shift of the environmental impacts between the individual impact categories. However, the result for the reprocessing examined here is extremely positive: the environmental impact in the basic scenario is more than 90% lower than that associated with manufacture of new goods in all considered impact categories. In particular, this is due to the continued use of components that, from an ecological standpoint, are very costly. It is also thanks to the limited need to replace components and the efficient reprocessing process. The environmental impacts of reprocessing are also significantly lower in the considered sensitivity analyses. Even in the worst-case consideration for reprocessing, greenhouse gas emissions are still 89% lower than those generated by the manufacture of new goods.

A similar picture can be seen for raw material criticality. Most of the critical resources found in the product are used in the electronics and battery, followed by the manufacture of the casing and mechanics. As both the electronics and the casing and mechanics are reused as part of reprocessing, raw material criticality for reprocessing is much lower. The covers and batteries are replaced for heavy reprocessing, and critical raw materials are therefore used here. For simple reprocessing, however, no components are replaced and the process thus requires no additional critical raw materials.

Lorenz offers a refund for the return of water meters. The amount of this refund depends of the condition of the water meter and the subsequent reprocessing steps required. The calculation of manufacturing costs shows that the way in which the refund amount is chosen ensures that the overall reprocessing costs are almost identical regardless of the extent of reprocessing. The costs for reprocessing equate to around 50% of the manufacturing costs for new goods which, from an economic standpoint, is very advantageous for Lorenz.

Reprocessing is also advantageous for the customer: the refund provided upon return of the water meter also reduces costs for the customer. These savings can correspond to around one third of the price of a new meter depending on the returned meter's condition. The customer therefore no longer just pays for the physical water meter but instead also receives a refund following the plannable period of use. This reduction in costs for a product represents a shift towards a business model where the customer only pays for the provision of the necessary service (product-to-service or product-service system), namely the calibrated recording of water flow quantities in this case.

The comparative evaluation shows that the reprocessing of water meters is advantageous in all considered frameworks. Lorenz is able to profit from lower costs for reprocessing. There is also a reduced dependency on suppliers as the water meters are returned by the customer. The reduced raw material criticality involved with reprocessing reduces the risks associated with purchasing. From a society standpoint, reprocessing must also be rated very positively due to the significant reduction in the environmental impact. Reprocessing is also proven to be very advantageous for the customer as it ensures the same performance as guaranteed by a new product (namely the calibrated recording of water flow quantities) at effectively lower costs.

6 FINDINGS AND RECOMMENDATIONS

6.1 Findings

As shown within the scope of this study, remanufacturing offers huge potential if systematically developed and implemented. In principle, products and business models must be reimagined, redeveloped and implemented for remanufacturing to allow the business to tap into the economic and ecological benefits (cf. chapter 3.1.1).

As shown in chapter 2, four main aspects must be fulfilled:

- Product design compatible with a closed-loop system
- Suitable collection and return systems
- Adapted, innovative business models
- Additional internal and external aspects

On a technical level, a product's design determines whether, how and to what extent it can be reprocessed. This includes aspects such as modularity, ease of disassembly, longevity and clear identifiability of product variants and materials used. If these points are fulfilled, a product is well suited for reprocessing. If this is not the case, the product design should be re-examined to facilitate reprocessing.

Products for reprocessing must be available to companies, however. A suitable collection and return system is essential here. For example, information on the whereabouts of the products must be available, and the expense involved with collection should be as low as possible in relation to the product value. A plannable inventory (e.g. by way of contractually agreed use periods) and good storability also help to ensure the availability of products for reprocessing. If there is no established collection and return system in place, it is recommended that businesses systematically develop a suitable system or, if possible, make use of a compatible, established collection and return system.

Although the function of reprocessed products is, in most cases, identical to the function of newly manufactured products, there are some differences with regard to the business model. To start with, the cost structure for reprocessing is different as the process steps for manufacturing become redundant while new costs for the return and reprocessing arise. It is also possible that the positioning and pricing of the product must be adjusted, depending on how the customer perceives the quality and the value of the relevant reprocessed product. Competition on the market also plays a role here. This aspect can only be partially influenced by the company itself.

Further aspects include, for example, legal frameworks for the collection or recirculation of products or liability and warranty risks arising from reprocessed products. The availability of qualified employees for reprocessing also falls within this category. These points cannot be influenced directly by the company itself and are typically a result of the relevant framework conditions in place. However, adjustment of these framework conditions by political actors could lead to an improved starting situation.

The potential of remanufacturing is confirmed through the growing revenue and employee numbers (cf. chapter 2.2). Another aspect relates to the increased control over the value chain for businesses: if products are returned and reprocessed, the dependency on (often globally interconnected) supply chains decreases as a large portion of components and parts can be reused. This can make the value chain more resilient in particular during difficult periods of international trade caused as a result of price fluctuations, protectionism and tariffs, environmental disasters or, as most recently experienced, the COVID-19 pandemic.

An evaluation system was developed to systematically assess the suitability of products and product groups for remanufacturing (cf. chapter 3.1) based on the four main aspects outlined above. Several criteria, both qualitative and quantitative, were derived for each of the main aspects. The quantitative evaluation is carried out on a scale of -2 to +2. If an aspect is highly conducive to remanufacturing, it is given a score of +2, if it is extremely obstructive, it receives a rating of -2. An overall value is calculated based on the evaluation of the individual aspects, and this overall value represents the product or product group's suitability for remanufacturing. This structured recording and evaluation of aspects helps to identify and address any factors that hinder remanufacturing.

The evaluation of the selected examples highlights significant differences between product groups and, in some cases, within the product group itself. One main takeaway from this evaluation is that a good rating in the individual main aspects (e.g. product design) is not enough for a high remanufacturing potential. Instead, in addition to a suitable product design, high potential requires a functioning collection and return system and functioning business model as well as other aspects such as a positive perception of value on the part of the customer and public.

Particular drivers and obstacles for remanufacturing are derived from the evaluation of the product examples and previous literature research (cf. chapter 4). Aspects that are conducive to remanufacturing include the four main aspects already outlined. A suitable product design with modular structure and easy maintainability, the use of materials compatible with a closed-loop system and the avoidance of toxic substances all increase a product's suitability for remanufacturing. A functioning collection and return system that ensures a plannable availability of used products for reprocessing is also extremely conducive to remanufacturing, as is ease of storage of products and components.

While the product design and introduction of a collection and return system can be relatively well planned internally, developing a functioning business model is often a challenge. The business model depends on factors such as product design and the return of products and can often only be devised once these elements are in place. At the same time, however, a reverse logistics system, for example, cannot be easily financed without a functioning business model. The development of business models must therefore be taken into account right from the start, and ideally this should influence the product design and the related return system structure.

Further aspects that can only partly be influenced by the individual businesses include: value perception among the public, availability of qualified employees or high salaries. There is therefore a certain dependency on conducive framework conditions that is prominent in this area. Where these are not present, a business can often only push for improvement to the framework conditions, for example through political actors and associations.

The four previously outlined main aspects are also applicable for the factors preventing suitability for remanufacturing. High integration and miniaturisation at the component level are not conducive to the separation and dismantling required for remanufacturing. This often also goes hand in hand with small material flows, meaning separation is technically possible but in many cases not cost-efficient. While, in principle, miniaturisation and dematerialisation does improve resource efficiency, it is, in many cases, detrimental to recirculation. The high level of integration often means that the lifespan of the entire product is determined by the component with the shortest lifespan as disassembly and repair is not feasible. A wide variety of materials leads to a collection system that mixes materials which, in turn, results in the need for a more extensive sorting process. Hard-to-calculate return quantities also make planning inventories and processing capacities more difficult. This increases the logistical challenges involved and makes it difficult to identify the returned parts. Due to the lack of established structures for reverse logistics, insufficient storage capacities for returned products, a lack of qualified specialist staff and often low costs for the manufacture of new goods, staying clear of remanufacturing can be seen as an easier, more cost-efficient solution for many businesses than devising a corresponding viable business model. Another aspect can be the perception within society and by customers. Many products are seen as status symbols. Reprocessed products can lack the allure and thus symbolic nature of new products. In many different areas, businesses and society also lack knowledge of the advantages of remanufacturing and its potential to provide products that are identical in function at often lower costs and reduce environmental impacts. The appreciation of reprocessed products as high-quality and ecologically and economically advantageous options must be supported by a fundamental change in values.

The life cycle analysis outlined in chapter 5 using Lorenz as an example shows the design possibilities in a positive light. Product design and collection/return systems were systematically combined with a business model with each geared towards the other, and these are then continuously improved and optimised. While most companies on the market do not deem the reprocessing of water meters to be worthwhile (cf. chapter 3.3.6), Lorenz has managed to carve out a market for reprocessed products through product analysis, collaboration with its customers and long-term investment. A large portion of the product, such as the casing and mechanics, can continue to be used long beyond the set calibration period (and thus beyond the actual lifespan of the water meter). The product design is adapted through the use of efficient electronics which, in turn, reduces the probability of replacement being required. As the electronics have the largest environmental impact out of the components used, this represents a targeted investment into an environmentally friendly product design. By reusing many components, Lorenz is able to significantly reduce the environmental impact in comparison to that associated with the manufacture of new goods. In the basic scenario, this equates to a 90% reduction for all evaluated environmental indicators. This value is consistent across all sensitivity analyses – even in the worst-case consideration for reprocessing, greenhouse gas emissions are still 89% lower than those generated by the manufacture of new goods.

The results of the life cycle assessment, raw material criticality analysis and cost analysis all show the significant advantages of remanufacturing. This was possible through the assessing the basic conditions of the product life cycle, such as the guarantee of the product's function, attractive pricing and steady ability to supply as well as the positive orientation towards potential, for example through cooperation with suppliers, customers and logistics. The customer is offered a product with equivalent function which comes at a lower cost than the purchase price for new goods due to the provided refund and which is more environmentally friendly.

6.2 Recommended actions

It is clear that the biggest challenges for remanufacturing lie in the complexity of the topic. A product design compatible with a closed-loop system alone is not enough. There must also be collection and return systems in place, suitable business models must be developed, and the framework conditions must be right or at least show potential. Comprehensive analysis and planning is therefore required before remanufacturing is introduced. Only on this basis can products, collection systems and business models be systematically developed, identified and applied in consideration of the given framework conditions.

Analysis of the four main aspects outlined is recommended for analysing the status quo. The evaluation matrix shown in 3 is a suitable tool for this purpose. The combination of quantitative and qualitative evaluation makes it possible to identify weak points and challenges for current or future products and business models in advance. This also provides a basis for identifying potential for developing products and business models compatible with a closed-loop system.

Only once this evaluation has been completed should a business begin to develop recyclable products and circular economy-based business models, taking into account the entire life cycle. Derived from chapter 4.3, Figure 20 shows the recommended process flow. Integrating all life cycle phases within the company can help to systematically support product development, allowing businesses to review products specifically for their compatibility with a circular model. A life cycle analysis looks at a product including all of the upstream and downstream value-added steps. In doing so, businesses can avoid overlooking or overstating potential challenges at the end of a product's lifespan – in this case, for reprocessing. The life cycle model can also be applied to economic analyses. This, in turn, allows businesses to evaluate aspects that fall outside of the typical limits of operations-related considerations but will play a role in the future (e.g. CO_2-based control mechanisms). These analyses can help a company to objectively identify any weak points in their product systems. The relevant indicators for these analyses are the typical impact categories from life cycle assessments. As part of the further development of products and business model, parameters are identified which influence the weak points and simulate the resulting effects of any adjustment to these parameters on the system as a whole. Through extensive consideration of the environmental impacts as part of a life cycle analysis, companies are able to gain a comprehensive overview of both ecological and economic aspects of product variants. Suitable product variants are then transferred into real conditions with methods of solution finding and creativity promotion and critically scrutinised from different standpoints. The aim here is to identify the most promising approaches and devise business models for these. Life cycle and weak-point analyses can be carried out by every company as this process is fully internal.

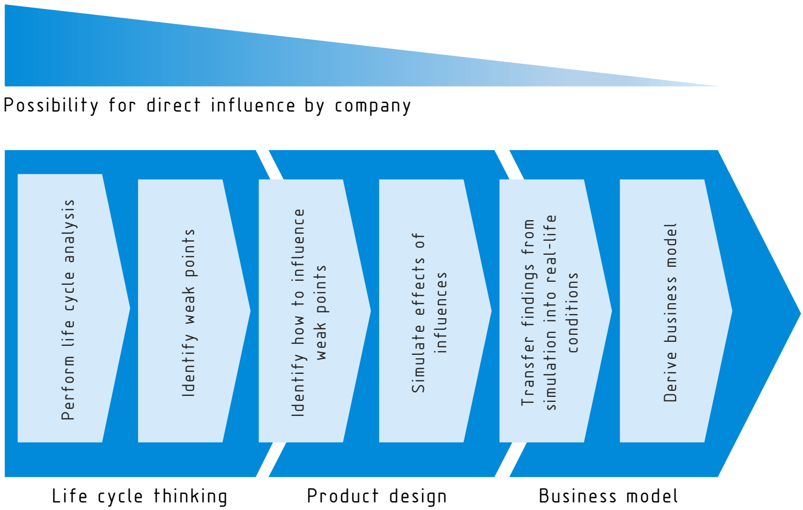

Figure 20: Development of products and business models compatible with closed-loop systems

The possibilities over which an individual company has influence typically become scarcer throughout this process. Before adapting products and value chains, external factors such as compatibility with previous product generations or products already used by the customer must often already be taken into account early on as part of the product design phase or during the manufacturing stage. The development of a business model is heavily influenced by the product design and resulting collection and return system. These must therefore be taken into consideration. General market trends, the customer's willingness to pay, the range of competitor products or costs associated with upstream/downstream process steps (purchase of components, logistics costs, disposal costs), for example, can all have an impact.

Other factors that are very difficult to influence from a company standpoint include the perception of reprocessed products by the customer and society as a whole, legal frameworks (e.g. pertaining to warranty and disposal) and the availability of qualified employees. Policymakers and associations are crucial here for establishing frameworks that are conducive to remanufacturing.

A fact-based decision to adjust framework conditions can be made after following the recommended process: using a life cycle analysis, businesses can provide quantitative evidence on the advantages of remanufacturing, helping policymakers to make fact-based decisions. This can be achieved, for example, through financial and regulatory frameworks for promoting a circular and sustainable economy, such as the European Union's Green Deal (cf. chapter 2.1.3). The information gained can be used to design and draft detailed guidelines at the European and national level based on credible, comprehensible data. This basis can also be used to support a shift in values through support for public information and educational campaigns, thus helping to increase acceptance of reprocessed products and spreading awareness that remanufacturing brings with it both ecological and economic advantages, as shown in chapter 5. Ultimately, such a shift in values is a decisive factor for a successful transition towards a circular economy. Once recyclability, resource efficiency and sustainability become central deciding criteria within the public mind, demand for reprocessed products will grow. If this, in turn, is supported through financial and regulatory frameworks, it is easier for businesses to develop products and business models geared towards a circular economy and position themselves successfully on the market.

The core message can be summarised as the following three recommended actions that apply equally for industrial actors, policymakers and the public domain:

Information

The knowledge and understanding of the advantages and disadvantages of remanufacturing must be gained based on the entire life cycle. The resulting findings must be disseminated in order to initiate a continued rethinking. This applies for industry (identification of new profitable business models) and policymakers (value perception, demand, promotion) in equal measure. Levers and measures, however, will differ depending on the relevant motivators within industry and politics, see the section on collaboration.

Innovation

The interplay between technical measures (design and logistics) and business models for remanufacturing can occur automatically. Potential approaches (based on life cycle concepts) were outlined as part of the study. However, innovation is not a sure-fire ticket to a circular economy. In this respect, external constraints (e.g. through the state and policy) must be supported from an industry point of view so as to ensure that innovation is pursued in the right direction. This includes, for example, aspects of the Green Deal such as fiscal measures (incorporating the internalisation of external environmental impacts), incentive systems, criteria for public procurement, indicators for the achievement of objectives and suitable criteria and programmes for research funding.

Collaboration

Operating in life cycles always involves collaboration. From an industry standpoint and in relation to the product life cycle, this involves all actors associated with the product as part of its life cycle. For manufacturers, this includes internal actors such as the various company units (sales, development, marketing, purchasing) as well as external actors (suppliers, users or disposal contractors). For internal actors, this, on the one hand, means considering the entire life cycle as part of development and planning and working together with various units such as procurement, production and sales (e.g. through mutual incentivisation for an overall optimum). On the other hand, internal actors must also coordinate with external actors, e.g. with customers, suppliers, logistics specialists as well as with local communities and the public domain. Information brokerage and innovations are available to these actors as tools. Policymakers should seek collaboration, e.g. through collaboration platforms (research, markets, public procurement, society), or establish cross-ministry agreements on programmes and measures. A marketable circular economy not only helps to establish optimal boundary conditions for individual actors, it also requires collaboration from all actors to optimise systems.

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APPENDIX - ECOLOGICAL RESULTS

Table 24: Ecological results: Reprocessing

Impact category	1 - Simple reprocessing	2 - Heavy reprocessing	3 - Best case	4 - Worst case	5 - TE biogas	6 - TE off-load	7 - Long transport routes
Water consumption	0.38013	1.47375	0.43842	1.48949	0.81427	0.65262	0.66927
Settlement areas	0.00002	0.00077	0.00003	0.00077	0.00020	0.00020	0.00020
Agricultural areas	0.00882	0.01339	0.03042	0.01427	0.03401	0.00996	0.01085
Metals, minerals	0.52095	1.14232	0.02722	1.14433	0.66994	0.65824	0.67830
Energy resources	0.05462	0.15445	0.00642	0.16161	0.07345	0.07242	0.08674
CED, exhaustible	1.51585	4.96768	0.25552	5.26953	2.10245	2.06443	2.68065
CED, regenerative	0.59536	0.97863	1.73906	0.99620	1.47373	0.69059	0.70875
Global warming potential	0.11420	0.37520	0.02896	0.39775	0.16786	0.16004	0.20165

Table 25: Ecological results: New goods

Impact category	3 - Best case	5 - TE biogas	6 - TE off-load	7 - Long transport routes
Water consumption	20.29	20.30	20.14	20.16
Settlement areas	0.01	0.01	0.01	0.01
Agricultural areas	0.17	0.14	0.12	0.12
Metals, minerals	39.46	40.65	40.64	40.66
Energy resources	1.39	1.49	1.49	1.50
CED, exhaustible	46.42	48.87	48.83	49.60
CED, regenerative	12.34	10.29	9.51	9.53
Global warming potential	3.68	3.85	3.84	3.89

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