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Ecological and economic Assessment of Resource Use

Cleaning Technologies in industrial Production

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Ecological and Economic Assessment of Resource Expenditure

Cleaning Technologies in industrial Production

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LIST OF ABBREVIATIONS

a	Year
BGR	Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe)
CML	Institute of Environmental Sciences Leiden (Centrum voor Milieukunde Leiden)
CO_2	Carbon dioxide
DERA	German Mineral Resources Agency (Deutsche Rohstoffagentur)
DIN	German Institute for Standardisation (Deutsches Institut für Normung e. V.)
SCS	Single-chamber cleaning system
ELCD	European Reference Life Cycle Database
EN	European Standard
eq	Equivalent
FU	Functional unit
g	gram
GCEL	Global Coal Exit List
G_i	Weighting factor
GWP	Global warming potential
h	hour
HHI	Herfindahl-Hirschman Index
I_0	Investment expenditure
IGCV	Fraunhofer Institute for Foundry, Composite and Processing Technology (Fraunhofer-Institut für Gießerei-, Composite- und Verarbeitungstechnik)

ISO	International Organisation for Standardisation
IVV	Fraunhofer Institute for Process Engineering and Packaging (Fraunhofer-Institut für Verfahrenstechnik und Verpackung)
IZT	Institute for Future Studies and Technology Assessment gGmbH (Institut für Zukunftsstudien und Technologiebewertung gGmbH)
CED	Cumulative energy demand
kg	kilogram
kHz	kilohertz
K_j	Correction factor
SMEs	Small and medium-sized enterprises
CRMD	Cumulative raw material demand
LCA	Life-cycle assessment
m^2	square metre
m^3	cubic metre
MCS	Multi-chamber cleaning system
MJ	megajoule
mm	millimetre
N	Useful life
Nm^3	Standard cubic metres
U	Revolution
VDA	Association of the Automotive Industry (Verband der Automobilindustrie e. V.)
VDI	Association of German Engineers (Verein Deutscher Ingenieure e.V.)
FD water	Fully demineralised water

W	watt
WGI	World Governance Indicator
VDI ZRE	VDI Center Resource Efficiency GmbH (VDI Zentrum Ressourceneffizienz GmbH)
µm	micrometre

ABSTRACT

The cleanliness requirements and the associated residual dirt requirements have risen sharply in the field of industrial parts production in recent years. This forces companies to see the cleaning process no longer as a low-priority part of the manufacturing chain, but rather as a processing step that creates value. In this context, resource efficiency potentials can be tapped, which reduce material and energy consumption and lead to cost savings at the same time.

In most cases, increasing resource efficiency fails due to insufficient knowledge about the factors that influence the process. In order to avoid compromising cleaning quality, obsolete but well-established systems are often operated until either it is no longer possible to service them or media can no longer be used because of hazardous substances regulations.

The aim of the study is to show especially SMEs what influence the choice of the cleaning process and the adjustable process parameters can have on material and energy consumption. The results of the study should thus provide an impetus for an in-depth analysis of the cleaning process step and raise awareness of the potential to save resources through optimised cleaning technology and process management.

The subject of the study is the comparison of a single-chamber and a multi-chamber ultrasonic cleaning system. Ultrasonic cleaning is a fast, reliable and economical method, especially after machining work, for removing both contaminants that form films, such as coolants, release agents and polishing pastes, and particles or chips. For these reasons, ultrasonically assisted wet-chemical cleaning processes are widely used in various industries. In addition to the ultrasonic frequency, the choice of system technology and the loading or capacity utilisation of the system are crucial for cleanliness.[1] Taking a drive sealing ring[2] from a contaminated state after a lapping process to a state of defined cleanliness represents the basis of the ecological and eco-

1 See Schulz, D. (2012), pp. 44-47.

2 Component made of metallic chilled cast iron, which is used to retain lubricants in a large number of different machines and vehicles.

nomic evaluation of the two cleaning technologies, as the cleaning task selected. This is a "cradle-to-grave" assessment, i.e. all phases of the life cycle from raw material extraction to disposal of the cleaning system are taken into account.

For the ecological assessment, the method of life-cycle assessment according to the ISO standard guideline DIN EN ISO 14040/14044 is used. The four impact categories described in the guidelines VDI 4800 Part 1, VDI 4800 Part 2 and VDI 4600 Cumulative Energy Demand (CED), Cumulative Raw Material Demand (CRMD), Water Consumption and Land Use are examined. In addition, the greenhouse gas potential is determined and an analysis of the raw material criticality in accordance with VDI 4800 Part 2 is carried out. Static cost accounting is used for economic assessment.

The study is structured as follows: Following the introduction, chapter 2 briefly explains the motivation for the study. Chapter 3 first provides an overview of cleaning technology. Subsequently, the parameters for observation of wet-chemical ultrasonic cleaning are defined, based on data on the relevance of individual cleaning technologies.

After a brief overview of the methods of life-cycle assessment, raw material criticality and cost evaluation, the reference use case is defined and specified in chapter 4 based on a real component. The functional unit was determined to be a “clean component” and defined as follows:

"The cleaning of a component up to a fluorescence intensity at the edge of detectability and a filter clogging after particle extraction between 0.5 and 1.5%, combined with the requirement that at most one particle larger than 400 microns may be present."

Then the system boundaries and the relevant energy and material flows are defined. Subsequently, production scenarios and process parameters are defined. The observation parameters include the cleaning technologies single-chamber cleaning system and multi-chamber cleaning system using the principle of aqueous ultrasonic cleaning. In order to be able to evaluate the dependency of the assessment of process parameters, two combinations were identified for each system, which lead to a similar component cleanliness despite process parameter variations. Most of the datasets collected have been generated based on real experiments. With the help of these and other background data, the life-cycle assessment model based on GaBi software from thinkstep is developed in chapter 4. Chapter 6 presents the results of the ecological and economic evaluation in detail. It becomes clear that the scenarios of the operating parameter combinations have significantly less influence on the results than the capacity utilisation of the systems.

The results of the ecological and economic evaluation can essentially be reduced to one key statement: by far the most influential factor on resource efficiency is the capacity utilisation of the system, if all system boundaries are complied with and the objective of “delivering a component that meets the cleanliness requirements” is fulfilled.

1 INTRODUCTION

In the field of industrial parts production, the cleanliness requirements and the corresponding residual contamination requirements have increased sharply in recent years. Companies are thus forced to consider the cleaning process as a processing step that creates value and to carry out optimisations or to consider new system concepts. This opens up opportunities to exploit resource efficiency potential and thereby reduce material, energy and thus costs in operation.

In view of ever stricter requirements, the system manufacturers are therefore working on solutions that can achieve higher levels of cleanliness in a dependable, economical and environmentally friendly manner. On the one hand, extensive basic research is required in this context. On the other hand, technical solutions must be developed from the results obtained which can be integrated into systems at marketable costs. There is therefore a large demand for innovative, environmentally sound and economical cleaning methods.

Industrial cleaning systems are used to prepare technical components for further processing. The main task of industrial parts cleaning is to ensure adequate part cleanliness that meets the requirements of the subsequent process. In this process, auxiliary and operating substances (grease, oil, etc.) required in the previous processing steps are primarily removed to allow high-quality painting, for example, or surface finishing of the components. Residues of oils, greases, salts and other substances would otherwise significantly compromise or prevent wet coating and adhesion of these layers on the metallic substrate. Furthermore, particulate contaminants hinder the functional reliability of products in end use. Particles adhering to the surface, such as chips, abraded particles or blasting agents, can lead to blockages or increased wear. Here it is the requirements of the vehicle industry, in particular, which are causing increasing demands for suitable cleaning methods and systems.

In this context, system manufacturers and users alike are responsible for designing and adjusting the cleaning process in such a way that the components can be cleaned in a way that saves resources and assures quality. This requires knowledge of the parameters influencing the cleaning result and their interactions. The requirements of the cleaning results are crucial in determining the method and the cleaning effort applied.

2 MOTIVATION AND OBJECTIVE FOR THE STUDY

Although the perception of the importance of the cleaning process step has improved progressively in recent years, it can still be seen across sectors that it is subordinate to others in the production process chain. The complexities and existing research issues, e.g. how other parameters in the context of ultrasonic cleaning influence the chain of action of the ultrasound, continue to deter especially SMEs from focusing on this process step. Combined with the increasing demands on technical cleanliness, process engineering measures that lead to a reduction of operating costs through material and energy savings are being implemented only slowly.

Increasing the material and energy efficiency of cleaning processes often fails because of insufficient knowledge of the variables that affect it. Often in industrial production outdated but well-established systems are operated beyond their specified service life or until cleaning media are no longer usable due to hazardous substance regulations. When acquiring new system technology, the user then has to choose a manufacturer from the large market of cleaning technology. In turn, these usually only cover small areas of the spectrum of available cleaning technology and are thus limited to certain processes from the outset. In addition to the technological range of services, investment expenditure and operating costs are usually the key criteria here, while the environmental effects and resource efficiency are often not considered due to a lack of information.

The aim of the study is therefore to show especially SMEs what influence the choice of the cleaning process and the adjustable process parameters can have on resource efficiency and company costs. The results of the study can thus provide a decisive impetus for an in-depth analysis of the cleaning process step and raise awareness of the potential to save costs and resources through optimised cleaning technology and process management.

In summary, the study has the following objectives:

- An application-related basis for decision-making with regard to economic and ecological parameters for procurement of new cleaning technologies and for optimisation of process management

- Transparent presentation of economic and ecological indicators along the life cycle of cleaning technologies (phase of system production, utilisation phase, end-of-life phase)

- Fluctuation of the economic and ecological indicators along a defined process window and identification of the process parameters responsible for this

3 SELECTION AND CHARACTERISATION OF THE CLEANING TECHNOLOGY

3.1 Overview of cleaning technologies

Cleaning is defined as the “removal of unwanted substances (contaminants) from the surface of workpieces to a required, agreed or possible degree”[3]. Furthermore, "the achievable degree of cleanliness (...) depends on the cleaning method as well as on the type and nature of the contamination”[4].

Classification according to cleaning objective

Cleaning can be classified by considering the objective of cleaning: cleaning, descaling, de-rusting, stripping, degreasing, dedusting, removing soot, sterilizing, disinfecting and decontaminating.[5] The last three cleaning objectives are for biological or radioactive contaminants and have less relevance for general technical applications in the manufacturing sector.

Classification according to type of cleaning procedure

Furthermore, the cleaning processes specified in DIN 8592 are assigned to separation processes in the main group of production processes and are divided into subgroups according to the type of process. A detailed overview of this classification according to the type of procedure is given in Figure 1 and reflects the entire scope of solutions for the design of cleaning processes.

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[3] DIN 8592:2003-09, p. 3.

[4] DIN 8592:2003-09, p. 3.

[5] See DIN 8592:2003-09, p. 6.

Group 3.6 cleaning procedures					
3.6.1	3.6.2	3.6.3	3.6.4	3.6.5	3.6.6
Blast cleaning	Mechanical cleaning	Fluid blasting	Solvent cleaning	Chemical cleaning	Thermal cleaning
gfla	Wipe off	Washing rinsing	Flaking	Pickling	Evaporating
Wet air pressure blasting	Brushing, sweeping	Blowing off	Stripping	Lye stripping	Burning off
Wet abrasive blasting	Scratching, scraping	Vaccuming		Chemically transforming	Thermally decomposing
Hydraulic fluid cleaning	Abrasive cleaning	Ultrasonic cleaning			Purification annealing
Steam cleaning	Beating				
Spin cleaning line	Beating				

Figure 1: Overview of cleaning procedures[6]

In the case of **blast cleaning** (3.6.1), blasting agents are the tool accelerated to strike the surface of the workpiece being processed (blasting material). Contamination is removed during the process by abrasion. Air (compressed air jets), an impeller (airless blast cleaning) and water (wet blasting) can be used to accelerate the blasting agent. As the blasting agent itself, mineral, organic or metallic substances are often used.[7]

With **mechanical cleaning** (3.6.2) contaminants are removed by the effect of objects (cleaning tools) or their movement. In addition to wiping, brushing, sweeping, scratching, scraping, grinding and knocking out, this also includes other methods, such as vibration cleaning or vibratory finishing.[8]

Fluidic cleaning (3.6.3) is based on the effect of moving fluids (e.g. air or water), which can bring about removal of contaminants. In wet cleaning processes, cleaning media are often added to enhance the way in which the binding energies of contaminants dissolve and thus improve the cleaning action.

[6] See DIN 8592:2003-09, p. 7.

[7] See Schweinstieg, S. (2012), p. 23.

[8] See Motschmann, S. (2010).

In addition to water-based cleaning agents, solvents are also used for cleaning purposes. These can be divided into hydrocarbons, oxygen-containing hydrocarbons (alcohols) and chlorinated hydrocarbons.[9] The associated process is referred to as **solvent cleaning** (3.6.4).[10]

In the case of **chemical cleaning** (3.6.5), acids, alkalis or chemicals that cause a targeted chemical reaction are used for cleaning purposes. The mechanisms by which they have an effect vary significantly depending on the substance used, so that a uniform description of the method is not possible.

In **thermal cleaning** (3.6.6), the impurities are vaporised, chemically converted or decomposed by high temperatures. The high temperatures are generated by different methods, such as the use of ovens, laser radiation or the direct application of flames or hot media.[11]

Classification according to cleaning process groups

In industrial applications, the cleaning technologies listed are frequently combined with one another. Alongside the classification in Figure 2, there is also a practice-based subdivision into the process groups of blasting processes, mechanical processes, thermal processes, wet processes, special processes and other processes.[12]

While the groups blasting processes, mechanical processes and thermal processes correspond to the properties described above (3.6.1, 3.6.2, 3.6.6), the **group of wet processes** primarily includes fluidic cleaning (3.6.3) and links this through the use of different cleaning media with the characteristics of chemical cleaning (3.6.5) and solvent cleaning (3.6.4). Thus, the use of wet processes covers a wide range of industrial cleaning tasks. Special processes include, for example, plasma cleaning, laser beam and electron beam cleaning, while vacuum distillation and chemical stripping, for instance, fall under other methods.

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9 See Schweinstieg, S. (2012), p. 27.

10 The work of Kreisel, G.; Wilbert, H.-P.; Goldhan, G. (1998) created a comparative life-cycle assessment of various cleaning media that can be used to better understand the environmental effects of cleaning media.

11 See Künne, B. and Richard, T. (2015).

12 See Bilz, M. et al. (2012), p. 7.

3.2 Selection of practice-based cleaning technologies

3.2.1 Selection of the cleaning process type

Cleaning processes are always required when the cleanliness of parts and components does not meet the requirements of the subsequent process or the end use. Based on the market and trend analysis in industrial parts cleaning - carried out by the Fraunhofer Cleaning Technology Alliance - the users of cleaning technology processes are predominantly found in the automotive, metal and mechanical engineering sectors.[13] These industries are characterised by the use and processing of metallic materials. Processing of metals in most cases requires the use of secondary production materials which, together with particulate contamination, leave residues on the component surfaces and create stubborn dirt. In combination with the often complex geometrical shape of the components, these contaminants are often removed by wet-chemical cleaning processes. This is also reflected in a market share for wet process of 59% of users, sub-divided into solvent-based and aqueous cleaning processes. The latter offer a wider range of applications in terms of cleaning objectives and are the most frequently used with a share of 65%.[14] In particular, ultrasonic, spray cleaning and flooding methods increase the mechanical cleaning effect in the process. The widespread use of aqueous immersion methods with support from **ultrasound and flooding** in manufacturing companies is an indication of the high practical relevance of the procedures.

Ultrasonic cleaning

Ultrasonic cleaning is a process in which ultrasound is introduced by means of a vibration generator mounted in the cleaning basin, which is disseminated in the form of longitudinal vibrations in the cleaning agent. Under the influence of a local sound field in the negative pressure phase, cavities are created in liquids, which are referred to as cavitation bubbles (Figure 3).

[13] See Bilz, M. et al. (2012), p. 7.

[14] See Bilz, M. et al. (2012), p. 21.

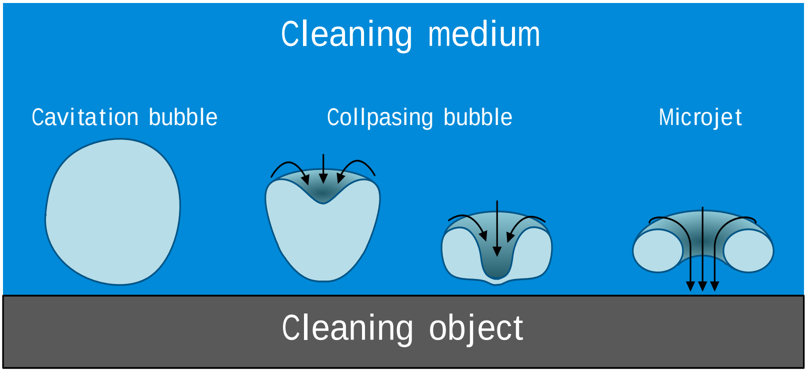

Figure 2: Schematic representation of a collapsing cavitation bubble[15]

The cavitation bubble tends to form at interfaces that have an uneven surface. Dirt on component surfaces is usually distributed unevenly in their structure and thus provides optimal cavitation formation properties.[16] Short, high implosion pressures caused by the contaminants remove particles and film contaminants from the surface of the component and these are transported away from the surface, supported by a liquid [17]jet, and dissolved or dispersed in the cleaner. Ultrasound-based methods are already widely used in the field of industrial component cleaning. However, the design of system technology is usually based not on a scientific analysis of the operating principle and its boundary conditions, but on subjective experience of the system manufacturers.

Flooding

Flooding, also referred to as pressure flooding, denotes a closed immersion process in which the mechanical cleaning effect is enhanced by nozzle systems below the bath surface. The cleaning liquid is sucked in via a pump and pushed back into the bath at a pressure of 5 to 20 bar[18]. In addition to the high turbulence, which is generated by the prevailing pump pressures, the component is set in relative motion during the cleaning process by rotating

[15] See Gülich, J. (2010), p.263.
[16] See Kahlen, I. (2012).
[17] See VDI Technologiezentrum (2000).
[18] See Haase, B. (1996), p. 78.

or pivoting movements of the basket, resulting in constantly changing dynamic pressure conditions. The pressure gradients range from the overpressure to the negative pressure range (suction). The cleaning effect created by these constant flow reversals is highly suitable for cleaning cavities, deep holes and undercuts.

3.2.2 Selection of cleaning system type

Automated systems for **wet chemical cleaning processes** typically differ in the number and equipment of the process chambers in which the components are cleaned. Decisive factors for the design of such systems, in addition to economic and ecological aspects, include: contamination, cleaning object and target cleanliness. There are two basic process alternatives for cleaning systems that are intended to meet increased requirements for technical cleanliness, which differ according to the number of process chambers.

Single-chamber cleaning systems

Single-chamber cleaning systems consist of a process chamber which, after the items to be cleaned have been inserted, is partially or completely filled with cleaning fluid and/or flushing medium (Figure 3). Single-chamber cleaning systems are usually equipped with the technology for ultrasonic and flooding procedures. The process chamber is filled via separate rinsing and cleaning tanks, while the cleaning object remains in the chamber throughout the entire process. This type of system is therefore primarily suitable for batch operation.

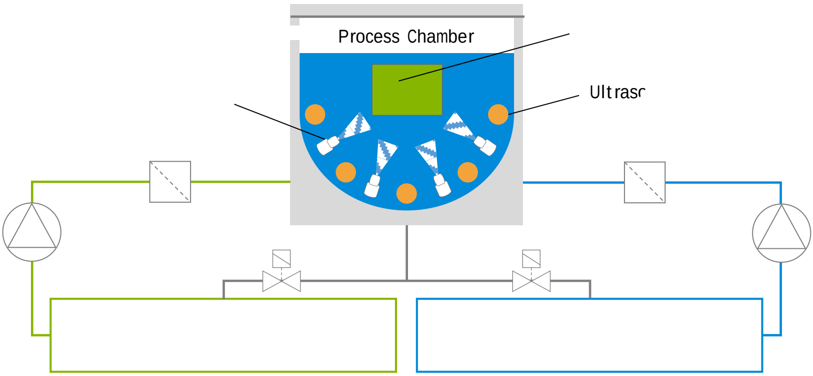

Figure 3: **Schematic diagram of a single-chamber cleaning system**

Multi-chamber cleaning systems

In contrast to single-chamber cleaning systems, multi-chamber cleaning systems bring the items to be cleaned to the cleaning medium. There are typically three to six open process chambers available that already contain the respective cleaning or rinsing medium (Figure 4). These are combined within a closed structure. In the individual process chambers, ultrasound is usually used as a mechanical cleaning component. Instead of flooding, the system uses simple circulation of the medium with a very low flow rate in the foreground, which serves to treat the medium in the form of filtration and oil separation. The items to be cleaned are moved from one chamber to the next, reducing the amount of residual contamination on the component at each step if the system is operated properly. Continuous treatment of the cleaning and rinsing media makes it possible to operate such a system as a continuous line.

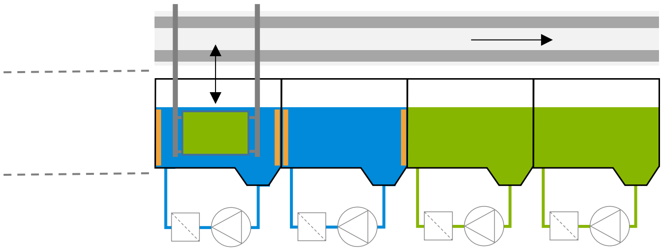

Figure 4: **Schematic diagram of a multi-chamber cleaning system with converter**

Comparison of single-chamber and multi-chamber cleaning systems

Both system types have advantages and disadvantages that have an impact on the economic and ecological balance of operations (Table 1). Due to the structural differences of both systems already mentioned, there is also a difference in the process sequence of the cleaning. While the process of the multi-chamber cleaning system is dictated by the sequence of the chambers, the sequence of process steps for the single-chamber cleaning system is determined by the plant control system, thereby providing increased process flexibility. The individual process steps are variable with regard to the operating variables and are selected so that the requirements of the cleaning task are met.

Table 1: **Comparison of the characteristics of the system types**

Characteristics	Single-chamber system	Multi-chamber cleaning system
Achievable technical cleanliness	Good	Very good
Flexibility (process adaptation)	Very good	Good
Component throughput	Low	High
Space requirements	Low	High
Investment expenditure	Low	High

3.2.3 Factors affecting cleaning

The key interactions in wet chemical cleaning processes are illustrated using the Sinner circle in Figure 5.[19]

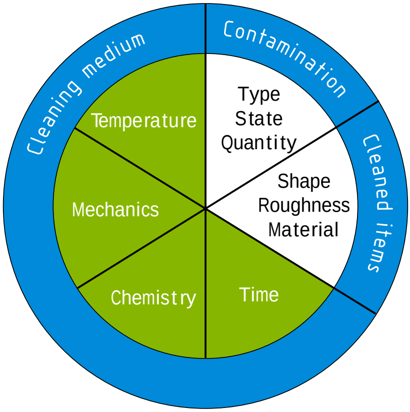

Figure 5: Factors affecting wet chemical cleaning (Sinner circle). [20]

This includes the three components of contamination, cleaning material and cleaning process, the interaction of which is determined by the cleaning system. The effectors introduced in the cleaning process – temperature, chemistry, mechanics, time – form the process parameters that have to be adapted to the given contamination and the items to be cleaned. Interactions between the effectors also occur, so that the process influences can compensate for one another. An exact adaption to the specific application is a prerequisite for successful cleaning and the basis for the cost-effectiveness of the process. This means, for example, that in order to obtain the same cleaning result while shortening the cleaning time, the influence of at least one of the other factors must be increased to compensate. By increasing the temperature or using more chemicals, the cleaning time can be shortened, but the resulting environmental and cost aspects must always be considered. Increasing the cleaning mechanics is also limited in industrial use for reasons of system and process technology. In addition, investment expenditure and operating

[19] See Wildbrett, G. (1996), p. 94.

[20] See Wildbrett, G. (1996), p. 94.

costs are important decision-making principles in the design of the cleaning process. In addition to the perspective of the cleaning process, requirements of the cleaning material must also be taken into account. For example, cleaning products can be impaired by high exposure to ultrasound or temperature.

This demonstrates the complexity of wet processes and the potential of process optimisation. The selection of a suitable method and the accompanying setting of effective parameters is based on specialist knowledge and knowledge of the interactions that occur. A growing awareness of procedural interactions on the part of users of cleaning technologies enables optimisation of process chains.

4 METHODS AND DATA OVERVIEW

4.1 Methods of ecological and economic assessment

4.1.1 Life-cycle assessment method

Life-cycle assessment (LCA) refers to the systematic analysis of potential environmental impacts of products and of processes or services taking into account the entire life cycle, from the cradle to the grave. Especially in the area of process design and optimisation, LCA results can be used e.g. as a decision-making aid for environmentally sound production, use or recycling. The International Organisation for Standardisation (ISO) provides guidelines for the performance of a life-cycle assessment within the framework of the standard DIN EN ISO 14040/14044[21] . This consists of four main phases, as shown in Figure 6.

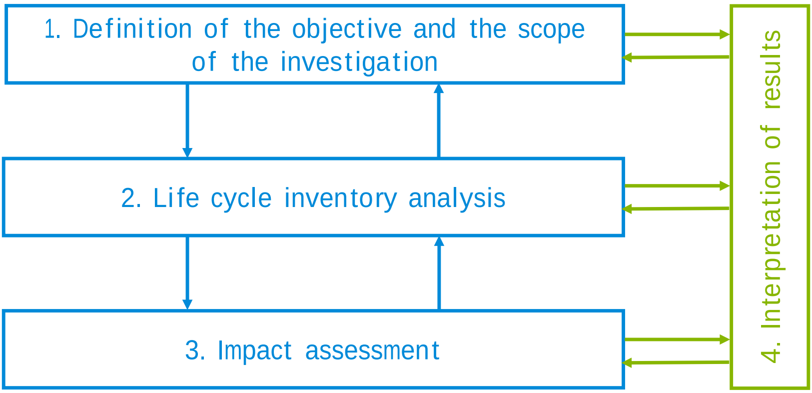

Figure 6: Framework of an LCA according to the DIN standard series DIN EN ISO 14040/14044[21]

These include the determination of the objective and the scope of the investigation, the preparation of the life cycle inventory analysis, the impact assessment and the evaluation and interpretation of the results. As shown in Figure 6, the four main phases build on one another. The results of each individual phase are taken up by the subsequent phases. The LCA is carried

[21] See DIN EN ISO 14044:2006 and DIN EN ISO 14040:2009-11.

out iteratively. This allows adaptation of previous phases to the growing level of knowledge of subsequent phases.

(1) Definition of the objective and the scope of the investigation

This phase defines not only the objective and the scope of the investigation in connection with the system boundaries to be considered, but also the subject of investigation. This is called the functional unit (FU) and represents the reference value for each LCA. All input and output streams and the analyses based on them are aligned or standardises in accordance with the FU. The choice of system limits and the degree of detail depends primarily on the objective. The breadth and depth of an LCA can vary depending on how the objective is defined and has a significant impact on the other three phases of the LCA.

(2) Creation of the life cycle inventory analysis

The life cycle inventory analysis includes data collection and calculation of relevant input/output flows for each process module within the system boundaries. In relation to the provision of data, a distinction can be made between a technical foreground and background system. While energy and material flows in the foreground system are described by technical intermediate products, such as energy or material consumption, the technical background system combines this data with the extracted resources and the emissions released into the environment (air, water, soil). The background data can often be accessed using databases (ProBas, ELCD, GaBi databases, ecoinvent database, PlasticsEurope, etc.). For the foreground system, however, additional literature searches, expert surveys or measurement series are required, depending on the object under investigation. All necessary data are finally summarised in the life cycle inventory analysis, taking into account the functional unit, to give an overall balance. The modelling, i.e. the structure of the energy and material flow model, can be designed with the aid of life-cycle assessment software.

(3) Impact assessment

The impact assessment serves to identify, quantify and assess potential environmental impacts of the system under consideration. The selection of impact categories, the classification and the characterisation are classified as obligatory by the ISO 14040 series, taking into account the selected impact indicator.

Classification is carried out once the impact categories have been determined depending on the environmental effects to be investigated. This step represents the classification of the LCI results into the impact categories. Classification is followed by characterisation, which describes the quantification of environmental impacts. The life cycle inventory analysis results of the various impact categories are weighted accordingly using characterisation factors and aggregated into one impact indicator each. The calculation of the characterisation factors depends on the environmental impact model setup for each individual impact indicator. Further aggregation of the different impact categories is not possible due to the different environmental effects or physical principles at work.

(4) Interpretation and evaluation of the results

The impact assessment is followed by the evaluation of the results. This includes an interpretation and critical discussion of the results from the impact assessment, taking into account the defined objective and the investigation framework. Sensitivity analyses are used to investigate the effects of data uncertainties. If there is an effect, the data must be collected more accurately. Using parameter and scenario analyses, different production scenarios can also be presented and analysed. Based on the evaluation, conclusions, recommendations and decision-making tools are formulated.

The present study looks at a total of five impact indicators relevant to the environmental assessment. These include the cumulative energy demand (CED), the cumulative raw material demand (CRMD), the consumption of blue water, the land use and the greenhouse gas potential.

Cumulative energy demand (CED)

Calculation of the cumulative energy demand (CED) is based on VDI guideline 4600 "Cumulative energy demand (KEA); Terms, definitions, methods of calculation"[22]. This is defined as the sum of the primary energy provided along the life cycle of the functional unit. The term primary energy stands for the energy that is taken from the environment and fed into a technical system here. In a broader sense, the consumption of renewable and non-renewable energy resources is recorded. In addition to the resources of oil and natural gas, these include renewable energies such as wind and solar energy. The cumulative energy consumption impact indicator is given in the unit MJ /FU, whereby the primary energy assessment is based on the calorific values (upper heating values). Basically, a distinction can be made between the two categories CED renewable and CED exhaustible.

CED renewable covers all primary energy consumption in the form of renewable energy and substance carriers. The use of primary energy in the form of exhaustible energy and substance carriers, however, is covered by the category CED exhaustible. These include both fossil and nuclear primary energy demand.

Cumulative raw material demand (CRMD)

The cumulative raw material demand (CRMD) is determined in accordance with VDI Guideline 4800 Part 2 "Resource efficiency – Evaluation of raw material demand"[23] and describes the total quantities of raw materials used or required per functional unit. The raw materials water and air are not taken into account. The cumulative raw material demand (CRMD) is given in kg/FU and can be subdivided into the following four categories:

- The category $CRMD_{eneregetic}$ covers all energy resources used
- The category $CRMD_{metallic}$, on the other hand, covers all mineral raw materials used for the production of metals

[22] See VDI 4600:2012-01.
[23] See VDI 4800 Part 2:2018-03.

- $CRMD_{construction\ and\ industrial\ minerals}$ comprises the remaining mineral raw materials which are not included in the indicator $CRMD_{metallic}$

- The biotic raw materials consumed are assigned to the category $CRMD_{biotic}$

Blue water consumption

The blue water consumption includes the consumption of surface and groundwater. It does not take into account the consumption of rainwater. The virtual or latent water consumption is calculated. The unit of blue water consumption is defined as m^3/FU.

Land use

Land use takes into account the use of different types of land over a given period. Land is one of the natural resources and can be subdivided into arable, pasture, forestry, building, traffic or landfill sites. Land use is specified in the unit m^2*a/FU.

In order to assess land use, the land is assigned to the categories agricultural and residential estate areas in this study.

Global warming potential

The global warming potential (GWP for short) contributes to all life-cycle assessment results that cause global warming. These include, for example, the greenhouse gases methane, nitrous oxide and carbon dioxide. The greenhouse effect of a substance is given relative to the global warming potential of carbon dioxide (CO_2). The corresponding unit is kg CO_2- equivalent/FU. The indicator values GWP_{100} are taken into account in the present study. These represent the contribution of a substance to the greenhouse effect, averaged over a period of one hundred years. The calculation of the global warming potential is based on the environmental impact model CML 2001 January 2016.

4.1.2 Method of raw material criticality

For assessment of raw material criticality, a criticality analysis according to VDI 4800 Part 2 “Resource efficiency – Evaluation of raw material demand”[24] is carried out. The criticality dimension of supply risk is considered. This takes into account the potential supply risks of a raw material. The supply risk comprises three categories, consisting of 13 indicators. An overview of the indicators is given in Table 2.

Table 2: Categories, criteria and indicators of the criticality dimension of supply risk[25]

Categories	Criteria	Indicator
Geological, technical and structural criteria	Static range	Ratio of reserves to global annual production
	Co-product/by-product dependency	Level of companionality
	Recycling	Spread of functional end-of-life recycling technologies
	Logistic constraints	Economic viability of storage and transport
	Constraints due to natural disasters	Geographical distribution of natural deposits/growing regions
Geopolitical and regulatory criteria	Country concentration of reserves	Herfindahl-Hirschmann Index of reserves
	Country concentration of production	Herfindahl-Hirschmann Index of country concentration of production
	Geopolitical risks of global production	Political country risk
	Regulatory situation for raw material projects	Regulatory country risk
Economic criteria	Company concentration of global production	Herfindahl-Hirschmann Index of companies
	Global demand impetus	Level of demand growth
	Substitutability	Technical and economic feasibility of substitutions in main applications
	Raw material price fluctuations	Annualised price volatility

The indicators are determined for the respective raw material to be assessed and then allocated to the classes in the value range 0; 0.3; 0.7 or 1. Classification is carried out in accordance with the specifications of VDI Guideline 4800 Part 2. The individual indicator values are summarised below to provide an overall criticality. For this purpose, the method of degressive addition

[24] See VDI 4800 Part 2:2018-03.

[25] See VDI 4800 Part 2:2018-03, pp. 14 et seqq.

is used. The indicator values for the supply risk per raw material are sorted in descending order of size. For each indicator, a weighting factor G_i is determined according to equation (4.1) and multiplied by the respective indicator value. The index i stands for the order rank of an indicator value.

$$G_i = \frac{2^{(i-1)}}{3^i} \tag{4.1}$$

To standardise the weighted indicator values, they are multiplied by the correction factor K_j. This is calculated using equation (4.2). The index j describes the number of indicator values which are taken into account for the criticality evaluation.

$$K_j = \frac{1}{\sum_{i=1}^{j} G_i} \tag{4.2}$$

The sum of the standardised and weighted indicator values results in an aggregated total criticality for the supply risk per raw material.

For the sake of clarity, a detailed description of how the indicators and the data base are determined is provided in section 6.2 in the context of the criticality assessment.

4.1.3 Method of static cost evaluation

The economic assessment is carried out on the basis of a cost comparison calculation. The annual additional costs per component resulting from cleaning are determined for both cleaning systems under consideration.

The cost comparison calculation is based on the method of static cost evaluation.[26] The total annual costs result from the annual operating costs (B_a) and servicing of debts (e.g. interest on loans). The operating costs include personnel, material, energy, maintenance, set-up and tooling costs. Rental costs were also considered. Details on the calculation of operating costs are provided in section 4.6. Servicing of debt, in turn, consists of the recovery and the interest portion. The recovery portion $\left(\frac{I_0}{N}\right)$ stands for the depreciation of the initial investment expenditure I_0 over the useful life N. The interest

[26] See Grob, H. L. (2015); p. 22.

share, however, is composed of the average capital tied up multiplied by the imputed interest rate i. In the case of investment appraisal, annual repayments at the end of the relevant operating year are often taken as the starting point.[27] For this reason, a discrete cost reduction is assumed, which is shown schematically in Figure 7. A reduction in value by a residual amount is not taken into account in the study.

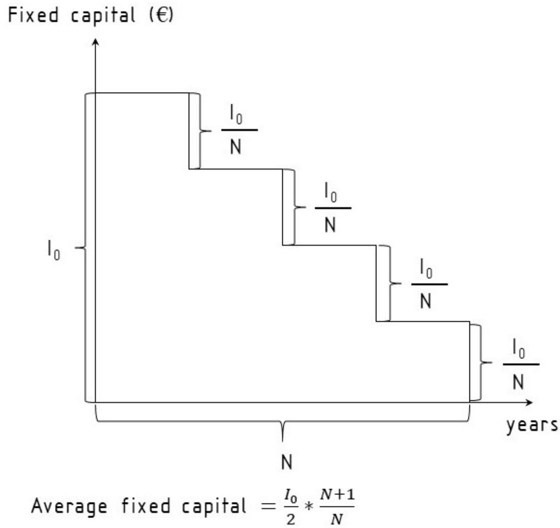

Figure 7: Discrete capital reduction[28]

The following equation is applied to the static cost evaluation, taking into account a discrete capital reduction:[29]

$$K_a = B_a + \frac{I_0}{N} + \frac{I_0}{2} * \frac{N+1}{N} * i \tag{4.3}$$

[27] See Poggensee, K. (2015); pp. 40 et seqq.
[28] Based on Poggensee, K. (2015); p. 49.
[29] See Poggensee, K. (2015); p. 52.

K_a: Annual total cost
B_a: Annual operating costs
I_0: Initial investment costs
N: Useful life
i: Imputed interest rate

4.2 Definition of the reference use case

In order to strengthen the general validity and meaningfulness of the study, great importance should be placed on market needs and practical relevance when defining both the reference application and the cleaning technology to be investigated. In addition, the availability of data in the selection of cleaning technologies must be taken into account when carrying out a reliable and transparent ecological and economic analysis. The following reference use case was therefore chosen.

Reference use case

Real, **industrially manufactured components (drive sealing rings) (a)** with filmic and particulate contamination are cleaned in both a **single-chamber and a multi-chamber system (b)** using an aqueous cleaning process with ultrasonic and spray cleaning methods from a **defined ACTUAL component state** to a **defined TARGET component state (c)**. The cleaning medium used for both system types is a neutral cleaner.

(a) Reference component

With regard to these aspects, a **real, industrially manufactured component was selected as the reference test** object. These are chilled cast metal drive sealing rings, used to retain lubricants in a variety of different machines and vehicles. The sealing rings, shown in Figure 8, have an outer diameter of 119 mm and a weight of 240 g. To ensure functional reliability, high demands are placed on dimensional tolerances and the quality of the material surface of the components. This is achieved in a processing step involving a lapping process using a lapping paste. This manufacturing process leaves oily, sometimes slightly dried layers on the component surface, consisting of lapping oil, abrasive grains and abraded base material. The **film and particulate contamination** is a problem for further processing and ultimate fulfilment of the drive sealing rings' function, and must therefore be removed by a cleaning process to a defined degree.

Figure 8: Drive sealing rings

(b) Single chamber and multi-chamber system

As described in section 3.2, an **aqueous cleaning process** with ultrasonic and spray cleaning and a slightly alkaline or pH-neutral cleaning medium is suitable for this cleaning task. In particular with regard to the industrial and market relevance of this method, a comparison between a **multi-chamber and single-chamber cleaning system** is selected as the reference use case. For reasons of system and data availability for a test procedure within a selected reference scenario, the study draws on two corresponding test systems[30] in the technical centre of the research institutes involved. Based on the structural and technical differences between the two systems outlined in section 3.2.2, there are also different process sequences for the cleaning. While the process for a multi-chamber cleaning system is determined by the sequence of chambers, the order of the process steps for the single-chamber cleaning system is set by the plant control system (Figure 9).

[30] Single-chamber cleaning system of the Fraunhofer IVV and multi-chamber cleaning system of the Fraunhofer IGCV, each designed on production scale.

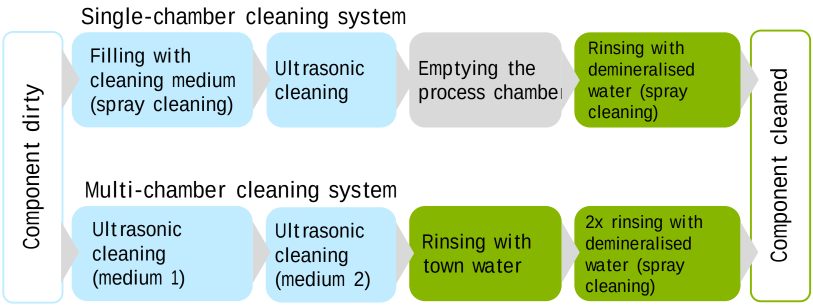

Figure 9: Cleaning process sequence

The individual process steps are variable with regard to the operating variables and are selected so that the requirements of the cleaning task are met. In Table 3, the two systems considered for this study are compared in terms of their characteristic values.

Table 3: Characteristic values of the cleaning systems under consideration

Characteristic values	Single-chamber cleaning system	Multi-chamber cleaning system
Year of construction	2016	2017
Cleaning tanks	700 litres	2 pieces, 72 litres each
Rinsing tanks	700 litres	3 pieces, 64 litres each
Footprint	3,600 mm x 2,600 mm	7,000 mm x 4,000 mm
Process chamber	Max. 408 litres	-
Cleaning medium	Neutral cleaner (40 °C to 80 °C)	Neutral cleaner (up to 70 °C)
Flushing medium	Demineralised water (up to 80 °C)	Town and demineralised water (up to 70 °C)
Filter	Bag filter 10 µm fineness	Cartridge filter 10 µm fineness
Max. component dimensions (LxWxH)	500 mm x 400 mm x 500 mm	350 mm x 260 mm x 250 mm
Component weight	Max. 50 kg	Max. 15 kg
Component rotation	up to 10 rpm	10 rpm
Ultrasonic frequency	40 kHz (alternatively 25 kHz)	25, 40, 80, 120 and 150 kHz
Ultrasonic vibrator	5 rod vibrators	3 plate vibrators per cleaning chamber
Max. power density	15.8 W/l	15.6 W/l
Nozzle arrangement	4 registers @ 7 flat jet nozzles	-
Nozzle pressure	4.5 bar	-

Despite differences in the component sizes and weights that can be processed, it is evident that the systems are essentially of a comparable size. In the interests of comparability of limit conditions, theoretical utilisation of individual parameters of the systems to their limits, such as an increase in the number of test pieces for one of the systems or simultaneous use of several washing baskets, was avoided.

The installation area of the systems differs according to the system principle. Potential dimensional restrictions may in practice limit the choice of cleaning technology, but these are not included in the study.

Drying of the components is not considered in this reference use case. The reason for this is the simple geometric structure of the drive sealing rings and the cleaning media temperatures necessary for cleaning. After the final rinsing process, the components are still hot and dry under ambient conditions within the process times considered, which is why additional drying in the reference scenario is not necessary. However, this approach means that ambient conditions must be kept constant. It is assumed that during the cleaning process the ambient temperature is 20 °C ± 3 K and the relative humidity is 55% ± 10%. Likewise, the drive sealing rings are brought up to temperature in these conditions to exclude temperature-related influences on the cleaning.

(c) Transition from ACTUAL component state to TARGET component state

In order to define the degree or success of cleaning, the cleaning is considered to be a transition from an ACTUAL component state to a TARGET component state (see also section 4.3). The ACTUAL state is determined by the input contamination of the drive sealing rings. This input contamination is subject to certain fluctuations in industrial practice due to the large number of influencing or disruptive factors within the production process chain. Comparability of the cleaning technologies is usually achieved by falling below a defined limit of component cleanliness generated in the process. This limit value can take a variety of forms in practice, especially in view of the requirements of the subsequent process steps. Examples of this in relation to film contamination include gravimetric data such as grams per square metre or milligrams per component, but also permissible residual layer thicknesses or the presence of fluorescent residues, or an intensity and/or area-based limit value. With regard to particulate impurities, information such as maximum particle size, maximum number within certain particle size classes, filter clogging of an analytical membrane or its gravimetric evaluation are typical requirements, supported by VDA volume 19 part 1. Variations in the range of input impurities are addressed during process selection and parameterisation by checks.

4.3 Definition of the functional unit

For a reliable interpretation of ecological and economic indicators of the selected cleaning technologies, it must be ensured that only a comparison of concrete products, defined by a comparable benefit and comparable boundary conditions, takes place. Specifically, this means that the technologies must have the same function, e.g. the degree of cleaning for a defined type of contamination and meet a specified component geometry. It must also be possible to maintain the function defined in the context of the study even if the process parameters vary. The functional unit (FU) represents this benchmark in the LCA. All quantified input and output flows of the system have reference to this unit. This allows comparison of different processes or products. The defined functional unit applies to both the ecological and the economic assessment and is defined as follows:

Functional unit

The cleaning of a component in accordance with section 4.2 up to a fluorescence intensity at the edge of detectability and filter clogging following particle extraction between 0.5 and 1.5%, combined with the requirement that at most one particle larger than 400 microns may be present. This applies to the following boundary conditions.

In the context of the present study, a **function-based functional unit** has been chosen, and therefore the technologies to be assessed must be of concrete benefit. In this case, this involves cleaning of the reference component selected in section 4.2, taking into account the framework conditions of the **degree of contamination and degree of cleaning**. In order to determine the benefit, fixed target parameters were defined for both framework conditions, the degree of contamination and the degree of cleaning, on which the data collection of energy and material flows is based (section 4.5). The state "cleaned" is specified by a defined level of technical cleanliness with regard to film and particulate impurities. In the context of both the ecological and the economic assessment of the two cleaning technologies under investigation, simply failing to reach a limit value for component cleanliness does not provide a reliable data base, since, for example, the consumption of resources is usually closely linked to the cleanliness achieved.

Requirements of the functional unit: Degree of contamination

To establish comparability, on the one hand a reduction in fluctuations on the input variables side is required. In the reference use case, the component removal has been defined in this connection: all 54 test components were simultaneously lapped on a system at the supplying manufacturing company within a process step following on directly from the production process chain and placed in separate airtight packaging on site. After a storage period of 14 days, these were each taken out about one hour before the experiment and positioned in the basket carrier which was used for both cleaning systems. For statistical verification, the layer thickness or distribution of the filmic contamination was also assessed for a subset of the contaminated components by measurement of the fluorescence on site. Information on the measurement environment and excerpts of the records can be found in Appendix C.

Requirements of the functional unit: Degree of cleaning

On the other hand, an interval to be achieved rather than a cleanliness threshold was defined. In simple terms, the components cannot reach the state “clean” within the scope of the comparison, since this cannot be quantified in any meaningful way in the context of the experiments. However, the auxiliary processing material in the use case brings certain challenges: the capacity for removal of the film components by the cleaning technology used is much higher than that of the particulate components. A meaningful definition of an interval for the film component, the base oil of the lapping paste, within the detection limits of common measuring methods using fluorescence therefore results in the presence of particulate residues to an impractical degree. In addition to losing any realistic reference to the requirements of subsequent processes, the limits of correct quantifiability are exceeded for the evaluation methods using the standard approaches of VDA Volume 19 Part 1.

Due to this divergence, the following definition and prioritisation is used with regard to the level of technical cleanliness that can be achieved as precisely as possible:

Film contamination

Based on laser-induced fluorescence, a spatially resolved measurement is carried out. The cleanliness objective is to achieve the limit of detectability as closely as possible for the film contamination present for a given parameterisation of the test system with a high degree of sensitivity (see Appendix C).

Particulate contamination

The measurement method is based on VDA Volume 19 Part 1. Remaining particles are extracted in a rinsing cabinet with a solvent and collected through a filter membrane. The flushing protocol was based on a performed decay measurement involving

- 5000 ml spraying of component (500 ml/min) and
- 1000 ml re-spraying of the rinsing cabinet (500 ml/min).

The filter membrane obtained in this way is then analysed with regard to particle size and type and the visible clogging of the filter membrane (see Appendix D). Due to the very small size of the lapping grains anticipated and the associated high number of very small particle classes, the filter is then evaluated visually with regard to particle clogging. The goal here is to achieve filter clogging greater than 0.5% and less than 1.5%. This is combined with the requirement that at most one particle larger than 400 µm may be present per component.

4.4 Definition of process parameters and production scenarios

4.4.1 Process parameters

The cleaning technologies presented and selected in section 3.2 must be capable of meeting the stated requirements of component cleanliness for the reference use case presented (section 4.2) and the functional unit (section 4.3). As a lever for this, the parameters shown in Table 4 are available:

Table 4: Extract of parameters in wet chemical cleaning processes

Category	Parameter
Movement	Rotational speed, lifting height, stroke
Ultrasound	Frequency, power
Temperature	Temperature of cleaner, temperature of flushing medium
Spraying	Pressure, nozzle, geometry, spacing
Media	Type of cleaner, concentration of cleaner, degassing, volume flow circulation
Bath care	Filtration, service life
Component carrier	Alignment, position, fixing
Times	Cleaning time, ultrasonic cleaning time, rinsing time
Interlinking	Program sequence

Based on a typical configuration for the application, a baseline scenario was developed which can be configured in the same way in as many aspects of both cleaning technologies as possible and achieves the cleanliness specifications. On the basis of a statistically planned test series, the following results were obtained (Table 5).

Table 5: Baseline scenario “60 °C”: Low temperature, high mechanical impact

Parameter	Single-chamber system (SCS)	Multi-chamber system (MCS)
Rotational speed	5 rpm	10 rpm
Frequency	40 kHz	40 kHz
Power	11 W/l	15 W/l
Temperature of cleaner	60 °C	60 °C
Temperature of flushing medium	60 °C	60 °C
Pressure	4 bar	-
Type of cleaner	Olschner Optimal 9.1SP-N	Olschner Optimal 9.1SP-N
Type of flushing medium	FD water	FD water
Concentration of cleaner	3%	3%
Cleaning time[31]	570 s	570 s
of which ultrasound	90 s	300 s
Flushing time	60 s spraying	2x 90 s 1x 60 s immersion

Starting from the lowest temperature for effective use of the cleaner (60 °C for spray cleaning), parameters with a relatively high ultrasonic power were used to bring the cleaning results into the required cleanliness range (Figure 10, Appendix C, Appendix D).

[31] Includes auxiliary times such as emptying or draining the chamber.

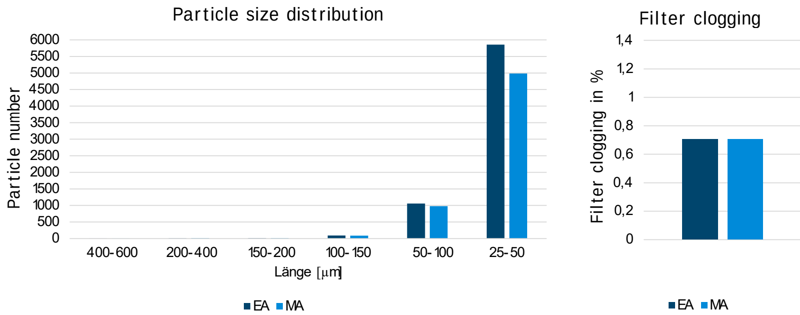

Figure 10: Evaluation of component cleanliness for the baseline scenario according to VDA 19.1

The influences of individual process parameters on the component cleanliness to be achieved vary greatly. As shown in Figure 5, cleaning time, ultrasonic power as a lever for the component mechanics, the cleaning medium and the temperature have a significant effect on the achievable technical cleanliness. In theory, the parameters can be changed to compensate for one another with a comparable starting situation and the same cleanliness results. Comparable cleanliness results do not necessarily have a comparable effect with regard to the use of resources, however. In addition to the assessment of the cleaning technologies with a similar constellation of parameters, a further comparison of similar cleaning performance is therefore of particular interest. This makes it possible to determine, in particular, whether the effect of changing the parameters within a cleaning technology is a more important factor than the choice of technology itself.

With regard to the consumption of resources during system operation, it can already be assumed, in view of the connected load, that the heating elements for controlling the temperature of the media represent a significant lever. Based on a medium temperature of 70 °C, a second operating parameter scenario (Table 6) was therefore developed, which can also achieve technical cleanliness in the required range for a component.

Table 6: Scenario “70 °C”: High temperature, low mechanical impact

Parameter	Single-chamber system (SCS)	Multi-chamber system (MCS
Rotational speed	5 rpm	10 rpm
Frequency	40 kHz	40 kHz
Power	7.4 W/l	7.5 W/l
Temperature of cleaner	70 °C	70 °C
Temperature of flushing medium	70 °C	70 °C
Pressure	3 bar	-
Type of cleaner	Olschner Optimal 9.1SP-N	Olschner Optimal 9.1SP-N
Type of flushing medium	FD water	FD water
Concentration of cleaner,	3%	3%
Cleaning time[32]	560 s	570 s
of which ultrasound	60 s	300 s
Flushing time	60 s spraying	2x 90 s 1x 60 s immersion

This parameterisation results in technical cleanliness for the component as shown in Figure 11.

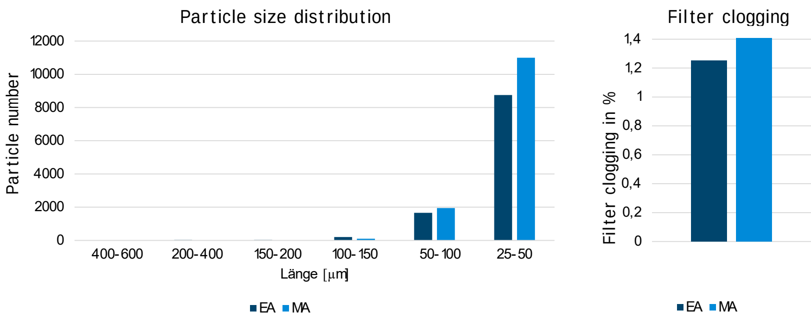

Figure 11: Assessment of component cleanliness in the “70 °C” scenario in accordance with VDA 19.1

The two parameter combinations “60 °C” and “70 °C” produce comparable cleanliness results on both systems. The focus is on comparability within the framework of the functional unit, in order to put the subsequent assessment on a solid footing. In addition, both systems are in principle capable of achieving higher cleanliness requirements. As a reference, an additional scenario was developed for the multi-chamber cleaning system, which achieves the best possible, "optimal" cleaning result (Figure 12) by exhausting the parameters to the limit for a temperature of 60 °C.

[32] Including auxiliary times such as emptying or draining the chamber.

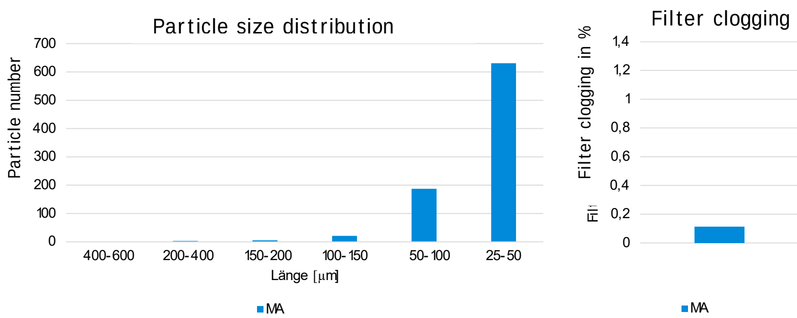

Figure 12: Evaluation of the component cleanliness in the “60 °C optima” scenario according to VDA 19.1

In comparison to the baseline scenario “60 °C”, a second cleaning step was integrated in particular. Both cleaning steps are implemented over a period of three minutes each with ultrasonic support of the frequencies 25 kHz and 40 kHz (bath 1) as well as 80 kHz and 150 kHz (bath 2). By reducing the rinsing steps to two of 45 s and one of 30 s, the total duration of the cleaning process has even been reduced to eight minutes.

4.4.2 Production scenarios

In addition to the operating and process parameters, the utilization scenario for the system in the context of production (section 4.5.2) has a major impact on the economic and ecological assessment of the cleaning technologies. It is based on the assumption of a common useful life for the cleaning technology of 20 years. As far as capacity utilisation of the system over this period is concerned, the baseline scenario assumes two-shift operation on five days a week. Since the capacity utilisation is assumed to have a large influence, a total of four variations with the extremes 24/7 and half a day a week are included in the analysis. The components that are introduced into the system per washing basket and cycle can vary between three and five components. In addition to the operating and process parameters set out in section 4.4.1, the range of scenarios offers flexibility in terms of the recycling route. There is a choice as to whether an oil separator should be included in the media disposal system. Figure 13 is a graphical representation of all the scenarios with their basic characteristics.

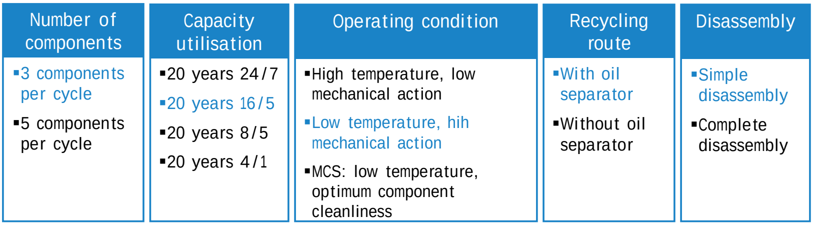

Figure 13: Graphical representation of the range of scenarios

4.5 Definition of system boundaries and data collection of relevant energy and material flows

In the first step of the life-cycle assessment (Figure 6), the system boundaries relevant for the assessment are defined in addition to the functional unit. Building on this, the associated energy and material flows are determined, and subsequently quantified accordingly.

Both the economic and the ecological assessment cover three phases of system manufacture, use and end-of-life phase, as shown in Figure 14.

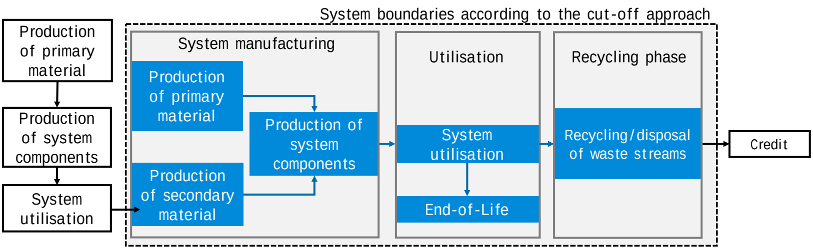

Figure 14: Definition of system boundaries

For each of these phases, the corresponding energy and material flows were determined, which are only shown in the following sections for each phase in the interests of clarity. The economic and ecological assessment is subject to the site-specific system boundary of Germany. If no country-specific modelling data were available at the time of the assessment, European input data were used. Transport processes were not considered.

A "cut-off approach" was used to create the life-cycle assessment model (Figure 14). Here, the focus is not on recycling at the end of the life of a product. Instead, the use of secondary material is taken into account in the system manufacturing phase[33]. For this reason any credit due from recycling is not included in the assessment. An exception is the material flow "water". The material and energy flows of the phases of system manufacturing, utilisation and end-of-life phase are shown below.

4.5.1 System manufacturing

An overview of the energy and material flows in system manufacturing is shown in Figure 15.

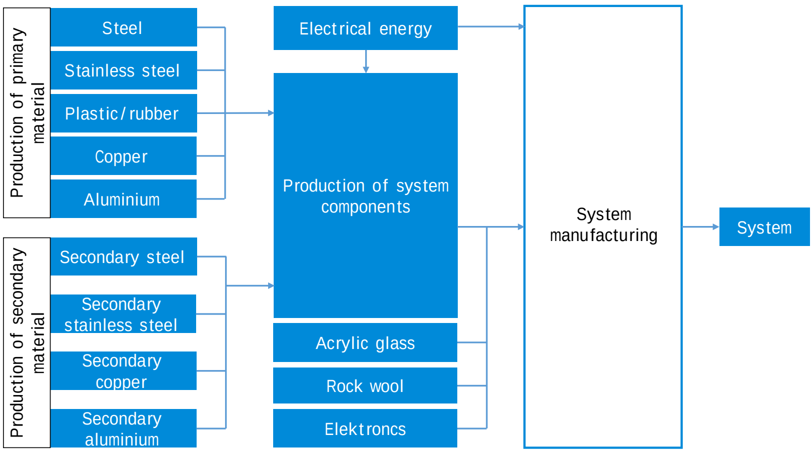

Figure 15: Material and energy flows of the system manufacturing

The relevant input materials and system components resulting from them were identified for the system manufacturing phase on the basis of the available parts lists for the two cleaning systems. Especially important are different metals. These include steel, stainless steel, copper and aluminium. Also relevant are the input variables plastic/rubber, acrylic glass, rock wool and electronic components. Since a cut-off approach has been chosen, the use of secondary material is also considered. For the electrical energy required to manufacture the system components and the system itself, the German elec-

[33] See Paul, S. and Wiesen, K. (2016), pp. 2 et seq.

tricity mix was used. The manufactured system constitutes the output variable for the system manufacturing subsystem. The energy and material flows in system manufacturing always relate to one system.

Based on the parts lists, it was also possible to determine the weight proportions of the material and component groups for the single-chamber and multi-chamber cleaning system. Since corrosive liquids are used within the cleaning systems, all elements which are in contact or may come into contact with them are made of stainless steel. Individual assemblies, where the likelihood of corrosion is less, are mostly made of aluminium or coated steel. With a share of 77% to almost 83% of the total weight, however, the stainless steel components predominate in the case of both systems.

Table 7: Material costs for manufacturing the single-chamber and multi-chamber cleaning systems

Material and component group	Weight	Proportion of total weight
Single-chamber cleaning system		
Stainless steel	3849.8 kg	82.8%
Steel	644.2 kg	13.9%
Aluminium	45.0 kg	1.0%
Copper	20.0 kg	0.4%
Plastic/rubber	10.0 kg	0.2%
Electronic components	80.0 kg	1.7%
Multi-chamber cleaning system		
Stainless steel	1569 kg	77.0%
Steel	200 kg	9.9%
Electronic components	108 kg	5.3%
Acrylic glass	100 kg	4.9%
Copper	30 kg	1.5%
Plastic/rubber	18 kg	1.4%

4.5.2 Utilisation phase

The utilisation phase depicts the cleaning process. A subdivision into several sub-steps was not carried out because the cleaning represents a self-contained process. Figure 16 shows an overview of the energy and material flows of the utilisation phase.

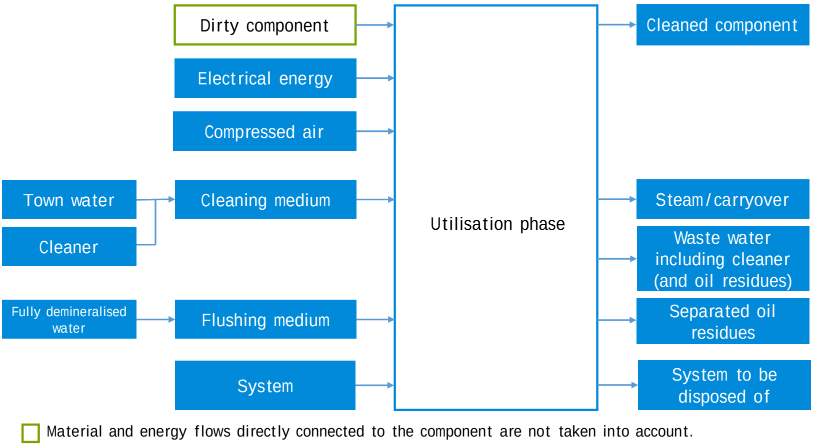

Figure 16: Material and energy flows for the utilisation phase

For both cleaning technologies, electrical energy, compressed air, town water, demineralised water and cleaner are needed. The German electricity mix is also used for the electrical energy in the utilisation phase. In addition to electrical energy, process heat can be used to heat cleaning systems in principle. This approach is usually used in large paint shops, but is not included in the present case.

A cleaning and a rinsing medium are used. The former is composed of town water and cleaner, while the flushing medium consists entirely of demineralised water. The production of demineralised water is considered within the ecological assessment separately to the city water supply. The cleaner concentration in this context is 3%; the cleaner used is Olschner Optimal 9.1SP-N[34]. This is suitable for spray and ultrasonic cleaning to remove oils, greases and polishing pastes.

Another material flow is the contaminated component. Energy and material flows directly connected to the component, e.g. in the context of component

[34] Data on the composition of the cleaner was provided by Bernd Olschner GmbH and is part of the system boundaries.

manufacturing, are not part of the defined system boundary. All energy and material flows refer to the functional unit of a cleaned component.

A comprehensive and exact database is required for a meaningful assessment of the utilisation phase in particular. Due to the combination of high electrical loads and a long service life for the cleaning systems, this phase is expected to have an enormous impact on the ecological and economic parameters. In the context of data collection for the utilisation phase, assumptions as well as literature and database values are therefore largely avoided and real measurements from the cleaning technologies under investigation are used. For this purpose, the systems were equipped with extensive measuring technology to determine the energy, water and compressed air consumption. For example, several mobile network analysers[35] were used to measure electrical energy consumption. In order to comply with the system limits or to ensure comparability, differential measurements had to be carried out as part of the data collection. For example, a demineralised water system is integrated into the multi-chamber cleaning system, while the single-chamber cleaning system is connected to a central demineralised water supply. The water consumption exceeding the planned new media usage (see section 4.5.3) was calculated by the adjustment of filling levels. Tests without components or baskets allowed further differentiation of displaced and vaporised amounts of the media. The compressed air consumption was determined by means of a flow sensor system fitted in front of the general supply to the system for determination of the standard volume flow[36].

Unlike many other production facilities, such as machining centres, which allow relatively rapid changes in state, cleaning systems are characterised by a certain inertia, especially in the wet chemical field. For instance, a change in state from standby (media temperature at room temperature) to a cleaning process (based on 70 °C medium temperature) takes place in this specific example over a period of two to three hours. This energy-intensive change of state, like others, occurs with varying frequency depending on the usage scenario. The detection of energy and material flows therefore cannot take place only in the steady states on the basis of the operating parameter

[35] Type “PQ-Box 100” from A. Eberle GmbH & Co. KG.

[36] Type Flowtherm NT in conjunction with measuring tube “TA DI 27.2” from Höntzsch GmbH.

scenarios. To record the overall usage scenarios, measurement data for various changes of state and stationary states is therefore essential. This was recorded in test series for both cleaning technologies and systems using measuring equipment. In addition, of course, the cleaning processes themselves were recorded over a representative period of time[37]. An overview of recorded measurement series can be found in Table 8. Appendix E shows examples of measurement data for the single-chamber cleaning system in the 60 °C scenario. With the exception of the cleaning process for optimum component cleanliness in the multi-chamber cleaning system, all states were recorded for both cleaning technologies.

Table 8: System states for recording both cleaning technologies using measurement equipment

System state	Description
Heating up to 60 °C	Heating of all baths from room temperature to 60 °C
Heating up to 70 °C	Heating of all baths from room temperature to 70 °C
Temperature held at 60 °C	Keeping all baths at 60 °C
Temperature held at 70 °C	Keeping all baths at 70 °C
Night lowering	Keeping all baths at 35 °C
Idle state	Stand-by mode of the system (heaters, recirculation systems & kinematics inactive)
Component movements	Targeted sequential activation of the kinematics of the system (linear axes, rotary motors, pumps, etc.)
Cleaning 60 °C	Cleaning process with low temperature and high mechanical action
Cleaning 70 °C	Cleaning process with high temperature and low mechanical action
Cleaning 60 °C “optimal”	Low temperature cleaning and optimisations for outstanding component cleanliness

Times, temperatures as well as energy and compressed air requirements were determined for all of these states. In addition, a measurement of the evaporation and displacement was carried out for the above system states. The collected data serves as a basis for calculating the total energy and material flows of the scenarios, taking into account the type of system utilisation.

4.5.3 Recycling phase

The recycling phase can be subdivided into two areas: recovery of the waste streams from the cleaning process itself and the recycling of the system to be disposed of at the end of its maximum useful life. The material and energy

[37] Approx. five to ten consecutive cleaning cycles until a steady state was reached.

flows of the recycling phases are shown in Figure 17. Due to the selected system limits (cut-off approach), possible recovered materials are not taken into account in the system disposal (Figure 14).

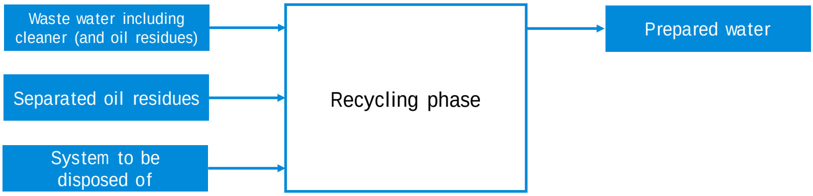

Figure 17: Material and energy flows of the recycling phase.

The composition of the waste water depends on the cleaning system. If an oil separator is installed, oily contamination residues are separated out. Ideally, the waste water is therefore only water and cleaner. In systems without an oil separator, waste water is generated which is contaminated with both cleaners and oil. In both cases, the water used is recycled. The maximum capacity of the respective cleaning and rinsing basins can be used to determine the amount of demineralised water, town water and cleaners used and thus the amount of waste water per system. Taking into account a cleaner concentration of 3%, 1360 litres of waste water, containing 20.4 litres of cleaner are therefore produced for the single-chamber cleaning system. For the multi-chamber cleaning system, on the other hand, 285.84 litres of waste water including 2.16 litres of cleaner are produced. Cleaning and rinsing media are replaced every eight weeks in the multi-chamber cleaning system, regardless of the system utilisation, while the change cycle for the single-chamber cleaning system is twelve weeks. Due to the higher capacity of the cleaning system here, longer time intervals can be used. The maximum contamination per component is 1 g.[38] The amount of oil residues is accordingly also about 1 g/FU.

In addition to the recovery of the waste streams, the disposal of the cleaning systems at the end of their maximum useful life is considered. This includes dismantling of the cleaning system and sorting according to the material

[38] **Weight difference between uncleaned and cleaned component.**

components. System disposal is considered exclusively for the economic assessment. This is ignored in terms of the ecological assessment as the systems are dismantled by hand[39]. The costs taken into account for this can be found in section 4.6.3. In total, the parameter variations for the recycling phase listed in Table 9 were defined; the parameter selection “Dismantling and disposal” applies only to the economic assessment.

Table 9: Definition of parameter variations – recycling phase

Parameter	Parameter variation
Recycling route	with oil separator
	without oil separator
Disassembly and disposal	Simple disassembly
	Complete disassembly

4.6 Data collection of cost items

For the data collection of the cost items, public databases, literature searches, industrial data and the internal databases of the Fraunhofer IGCV and the Fraunhofer IVV were used. The calculation of the cost items depends on the process parameters defined in section 4.4 and is described below for the three phases of plant production, utilisation and recycling.

4.6.1 System manufacturing

The costs of system manufacturing are represented by the cost factor “investment expenditure”. This is included in the calculation in the form of an annual depreciation. In static cost accounting, this is a linear amortisation over the useful life. This is 20 years for both systems. Table 10 shows an overview of the cost factors of the system manufacturing phase:

Table 10: Cost items for system manufacturing

Cost item	Single-chamber system (SCS)	Multi-chamber system (MCS)
Investment expenditure[40]	€113,000	€183,534

[39] See Scholpp GmbH.

[40] The investment expenditure is internal data from the Fraunhofer IGCV and the Fraunhofer IVV and includes the purchase price as well as the transport, installation and commissioning costs.

The cost of system manufacturing per component is calculated taking account of the investment expenditure per system as follows:

$$Costs\ per\ component_{System\ manufacturing} = \frac{I_0}{N * B_N} \qquad (4.4)$$

I_0: Investment expenditure in €
N: Useful life in years
B_N: Number of cleaned components per year

The number of cleaned components per year B_N is calculated as a function of the process parameters "Type of plant utilisation" and "Number of components":

$$B_N = \frac{S * h_S * T}{t_{Cycle}} * B_{Cycle} * 52 \qquad (4.5)$$

B_N: Number of cleaned components per year
S: Number of shifts per day
h_S: Hours per shift
T: Working days a week
t_{cycle}: Duration of each cleaning cycle in hours
B_{cycle}: Number of components per cleaning cycle

In the context of static cost assessment, interest costs are also incurred, which are calculated using a discrete capital reduction according to equation 4.6

$$Interest\ costs = \frac{I_0}{2} * \frac{N+1}{N} * i \qquad (4.6)$$

I_0: Initial investment costs
N: Useful life
i: Imputed interest rate

The imputed interest rate for the calculation year 2019 was used as the imputed interest rate. This is 5.74% and is based on the average issuing yield of fixed income securities of domestic public issuers over the past fifty years (1968 to 2017)[41].

4.6.2 Utilisation phase

The cost factors of the utilisation phase can be subdivided into system, personnel, energy and material costs. System costs include the cost factors of

[41] **See gpaNRW (2019).**

maintenance costs, set-up costs and tool costs, while energy costs are subdivided into compressed air costs and electricity costs. An overview of the cost items used for the calculation can be found in Table 11.

Table 11: Cost items for utilisation phase

Cost item	Single-chamber system (SCS)	Multi-chamber system (MCS)
System costs		
Maintenance [42]	€500/a	€1,450/a
Set-up costs [42]	€1,459/a	€0/a
Tool costs [42]	€10/a	€0/a
Personnel costs		
Standard personnel cost rate [43]	€30/h	
Night personnel cost rate 43	€38/h	
Proportional consideration 42	25%/h	
Energy costs		
Electrical energy [44]	€0.19/kWh	
Compressed air [45]	€0.019/Nm^3	
Material costs		
Cleaner [42]	€7.35 / l	
Water [46]	€1.72/m^3	
Rental costs		
Surface area [42]	10 m^2	28 m^2
Rent per month [47]	€5.5/m^2	

The set-up costs for the single-chamber cleaning system refer to the ultrasonic oscillator of the system. In the case of different cleaning tasks, where different frequencies are necessary, set-up times of four hours per month are applied. The system costs are calculated as follows:

$$Costs_{System} = \frac{(K_I+K_R+K_W)}{B_N} \tag{4.7}$$

K_I: Maintenance costs per year
K_R: Set-up costs per year
K_W: Tool costs per year
B_N: Number of cleaned components per year

The personnel costs are calculated on the basis of the applicable tariffs of IG Metall from April 2018 (43). The metal-electric sector was used, with person-

[42] Internal data from the Fraunhofer IGCV and the Fraunhofer IVV.
[43] See Table 12.
[44] See Federal Association of the Energy and Water Industry (BDEW) (2019), p. 24.
[45] See Festo AG & Co. KG (2014), p. 2.
[46] See Federal Office of Statistics (Destatis) (2018b); Database Germany 2016.
[47] See City of Augsburg (2014); Database for production areas/outskirts of the city/city centre/max.

nel costs referring to salary grade 6 of level B. This applies to those employees with at least three years of relevant vocational training including an additional subject-specific qualification. It is assumed that one employee is employed 25% of each shift on the cleaning system. A distinction is made between the standard and night personnel cost rates.

Table 12: Calculation of cost rates

Cost item	Personnel costs
Annual remuneration [48]	€40,344/a
13th monthly income (45%) [48]	€1,513/a
Performance bonus (14%) [48]	€5,648/a
Pension insurance (9.30%) [49]	€3,752/a
Statutory health insurance (7.30%) [50]	€2,945/a
Unemployment insurance (1.25%) [51]	€504/a
Long-term care insurance (1.53%) [52]	€615/a
Working hours per week [53]	35 h
Standard personnel cost rate	**30/h**
Additional night costs (25%) [48]	€8/h
Night personnel cost rate	**38/h**

The night personnel cost rate is applies to the period from 8 p.m. to 6 a.m. The following shift times apply - 1st shift: 6 a.m. to 2 p.m., 2nd shift: 2 pm to 10 pm and 3rd shift: 10 p.m. to 6 a.m. The total personnel costs per component are determined as follows:

$$Costs_{Personnel} = \frac{(PK_{Standard} * h_{Standard} + PK_{Night} * h_{Night}) * T) * 52}{B_N} \tag{4.8}$$

$PK_{Standard}$: Standard personnel cost rate
PK_{Night}: Night personnel cost rate
$h_{Standard}$: Number of standard working hours per day (from 6 am to 8 pm)
$h_{Special}$: Number of night working hours per day (from 8 pm to 6 am)
T: Working days a week
B_N: Number of cleaned components per year

The cost items energy, material and rent are also collected for each scenario for each year and divided by the number of cleaned components. The corresponding quantities for energy and material were presented in section 4.5.

48 See IG Metall (2019).
49 See German Social Code (SGB VI) (2018), § 287 SGB VI.
50 See Federal Ministry of Health (2018).
51 See Federal Ministry of Justice and Consumer Protection (2019).
52 See German Social Code (SGB XI) (2018), § 55 SGB XI.
53 See IG Metall (2017).

$$Costs_{Energy/Materiel/Rent} = \int_{i=1}^{n} \frac{m_i * p_i}{B_N} \tag{4.9}$$

m_i: Amount of the cost factor i per year
p_i: Price of the cost factor i per year
B_N: Number of cleaned components per year

Adding up all the cost items gives the additional costs per component in the utilisation phase.

4.6.3 Recycling phase

In contrast to the ecological assessment, the evaluation of costs not only considered recovery of the waste streams, but also recycling of the system itself. A list of the cost items is given in Table 13.

Table 13: Cost items for recycling phase

Cost item	Single-chamber system (SCS)	Multi-chamber system (MCS)
Recycling waste streams		
Liquid hazardous waste [54]	€0.16/l (plus €50/transport, toll, consignment note)	
Waste water charge [55]	€2.4/m³	
Change cycle of the cleaning and rinsing medium	twelve weeks	eight weeks
Recycling of cleaning system		
Simple disassembly [56]	€2,350	€3,820
Complete disassembly [56]	€2,870	€4,370

Waste water, which contains only the cleaner and no oily residues from the lapping oil, may take the standard recycling route of waste water disposal. If the cleaning system in question has an oil separator, the current waste water charge can be applied for the disposal of the rinsing and cleaning medium. The waste water residues which are separated by the oil separator during the cleaning process, however, take the special disposal route. In the case of the multi-chamber cleaning system, the cleaning and rinsing media are changed every eight weeks. Due to the larger capacity of the basins, a change cycle of twelve weeks can be assumed for the single-chamber cleaning system. The €50 additional costs for special waste disposal for transport, tolls and consignment note are incurred per collection and are based on the respective change cycle of the media. In the case of the single-chamber cleaning system, the additional costs are therefore incurred about seven times a

[54] Cost estimate provided by industrial partner (industrial partner is subject to secrecy) (as of 2019).
[55] See Federal Office of Statistics (Destatis) (2018b); Database Germany 2016.
[56] Cost calculation provided by Scholpp GmbH (as of 2019).

year and in the case of the multi-chamber cleaning system about four times a year. If no oil separator is used, the entire rinsing and cleaning medium is disposed of as special waste. The costs of disposal of the waste streams are calculated each year and then divided by the corresponding number of cleaned components.

$$Costs_{Recycling\ of\ waste\ streams} = \frac{\left(m_{Special} * p_{Special} + m_{Standard} * p_{Standard} + \frac{p_{Additional} * 52}{Cycle}\right)}{B_N} \tag{4.10}$$

$m_{Special}$: Amount of oily waste water in litres
$m_{Standard}$: Price for special disposal of waste water in €/litre
$p_{Special}$: Price for standard disposal of waste water in €/litre
$p_{Standard}$: Price for disposal of wastewater in €/litre
$p_{Additional}$: Additional costs for special disposal of waste water in €/collection
Cycle: Change cycle for the cleaning and rinsing medium in weeks
B_N: Number of components per year

Scholpp GmbH was consulted for an estimate of the disposal costs for the cleaning systems, by means of which an individual cost calculation was made on the basis of empirical values for both systems. Included here are the costs for disassembly and removal of the system and handover to the customer in clean condition. For preparation of the cost estimate, the systems must be assessed individually. In addition to the degree of disassembly required or desired, the local conditions in the respective factory hall must also be taken into account. These can have a significant impact on the total cost. Scholpp has therefore estimated the dismantling costs for simple and for full disassembly. “Simple disassembly” is carried out when the system to be disposed of is positioned in an easily accessible location. For example, if the system is not located in a ground-floor, easily accessible production hall, this increases the complexity of disassembly. This in turn has an impact on the costs. Complex disassembly is called “full disassembly”. Not included are the disposal costs and possible scrap proceeds. The disposal proceeds are always based on the daily updated prices. However, these often coincide with the expenses that cause disposal, which is why they are not included in the static cost accounting. The additional costs per component for utilisation of the systems are calculated analogously to the costs of the system manufacturing phase.

$$Costs_{Recycling\ of\ system} = \frac{V_{System}}{N * B_N} \tag{4.11}$$

V_{System}: Recovery costs for the system at the end of its useful life
N: Useful life in years
B_N: Number of cleaned components per year

5 DESCRIPTION OF THE ECOLOGICAL AND ECONOMIC BALANCE MODEL

5.1 LCA model

On the basis of the energy and material flows presented in chapter 4, the datasets generated from them and the background data used, the LCA model was created using the software GaBi (Ganzheitliche Bilanzierung, LCE) (Version 8.7.0.18) from the company thinkstep.

The life-cycle assessment model consists of a main plan, which is subdivided into three sub-plans according to the life cycle phases (Figure 18).

In the system manufacturing sub-plan, the energy and material flows are modelled and linked to the corresponding background data required for the production of a system. Due to the different material compositions and quantities, a subplan has been created for both the single-chamber and the multi-chamber cleaning systems.

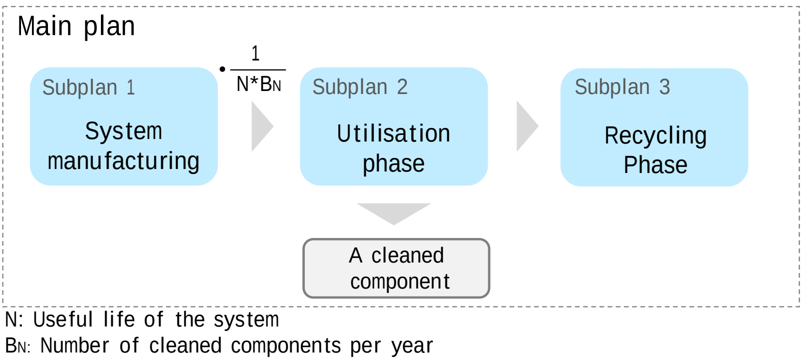

Figure 18: Structure of the LCA

The “utilisation phase” sub-plan took into account all the energy and material flows needed to clean a component, the FU. A proportion of the environmental effects of the system are included (Figure 18) by dividing these by the number of components that are cleaned within the service life (see factor $1/(N{*}B_N)$).

The energy and material flows in the utilisation phase are set up according to parameters in order to reflect the production scenarios defined in section 4.4.

The “disposal phase" sub-plan contains the energy and material flows for two different recycling routes. Depending on whether the cleaning system has an oil separator or not, the waste water is disposed of or treated by means of the standard or special recycling route. The corresponding energy and material flows are related to the FU, a cleaned component.

5.2 Cost calculation model

To carry out the static cost calculation, an Excel tool was set up in which the individual cost items were stored as a basis for the data. The cost factors were determined by means of public databases, literature searches, and on the basis of industrial and internal data from the Fraunhofer IGCV and the Fraunhofer IVV (Table 10 to Table 13), as explained in section 4.6. This, the imputed interest rate i and the useful life N form the background data for the calculation tool. The input data consists of the data collected in section 4.5 relating to the material and energy flows for SCS and MCS and the process parameters “number of components”, “type of system utilisation” “recycling route”, “dismantling and disposal”. The material and energy flows vary according to the selected operating scenario for the cleaning system. Table 14 shows a detailed list of the input data required for the cost calculation model.

Table 14: Input data for the cost calculation model

Input parameter	Unit
Number of shifts	Number
Hours per shift	h
Working days a week	d
Number of components per basket	Number
Number of baskets per wash	Number
Time per wash cycle	h
Electrical energy per wash cycle	kWh
Compressed air requirement per wash cycle	Nm^3/h
Compressed air requirement for night reduction	Nm^3/h
Compressed air requirement for heating up	Nm^3/h
Time per heating process	h
Electrical energy per heating process	kWh
Output in night operation	kW
Quantity of cleaner	l/change
Amount of water	l/change
Change of medium	Weeks
Displacement/evaporation per cycle	l/cycle
Amount of oil residues from oil separator	g/component
Disassembly and disposal of the system	[1] Simple disassembly; [2] Full disassembly

Parameterised modelling uses the method of static cost calculation to calculate the costs of system manufacturing, the utilisation phase and the recycling phase, and the interest costs per component depending on the input data. The utilisation phase includes the cost items system, personnel, energy, material and rental costs.

6 ECOLOGICAL AND ECONOMIC ASSESSMENT

6.1 Ecological assessment

The ecological assessment includes an evaluation of the baseline scenario (section 4.4) and completion of a parameter analysis. Based on the results of all environmental indicators, a scenario with the lowest environmental impact “min” scenario) and a scenario with the highest environmental impact (“max” scenario) were selected for presentation and discussion of the results. An overview of all the parameter settings considered can be found in section 4.4.2 and in Figure 13. Figure 19 shows the resulting minimum and maximum scenarios of ecological assessment.

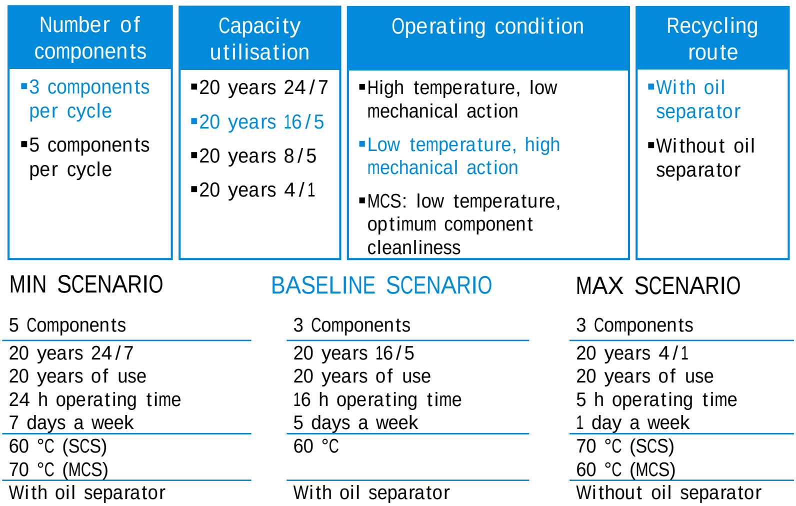

Figure 19: Ecological assessment - parameter selection for scenario analysis

The environmental indicators cumulative energy demand (CED), cumulative raw material demand (CRMD), blue water consumption, land use and the global warming potential (GWP) were investigated for a single-chamber (SCS) and a multi-chamber cleaning system (MCS). A detailed overview of the LCA results of the parameter analysis is available in Appendix A.

6.1.1 Cumulative energy demand

The calculation of the cumulative energy demand took place according to VDI Guideline 4600 “Cumulative energy demand (KEA); Terms, definitions, methods of calculation”[57]. Figure 20 shows the total energy demand for the **baseline scenario** of the single-chamber and multi-chamber cleaning systems, divided into CED renewable and CED exhaustible.

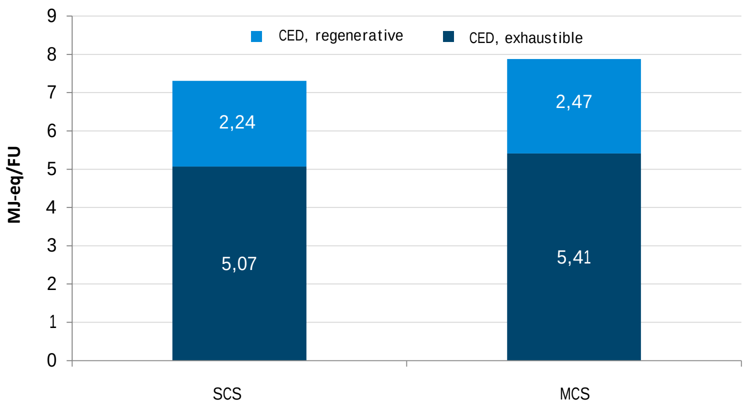

Figure 20: Cumulative energy demand (CED) per functional unit (FU) for the entire life cycle (baseline scenario)

CED regenerative and CED exhaustible have a comparatively higher value for the multi-chamber cleaning system. The difference from the single-chamber cleaning system is 9.3% (CED regenerative) and 6.3% (CED exhaustible), in both cases the energy consumption in the utilisation phase being the main influencing factor. Although the multi-chamber cleaning system itself has a lower energy consumption during cleaning, the power requirement for maintaining the lower temperature outside of the operating times is significantly higher. In the baseline scenario (16/5), this situation means that the pro-rata power consumption per cleaned component in the MCS is higher than in the SCS, which also has an effect on the cumulative energy demand. In Figure 21 the cumulative energy demand is also subdivided according to the life cycle phases.

[57] See VDI 4600:2012-01.

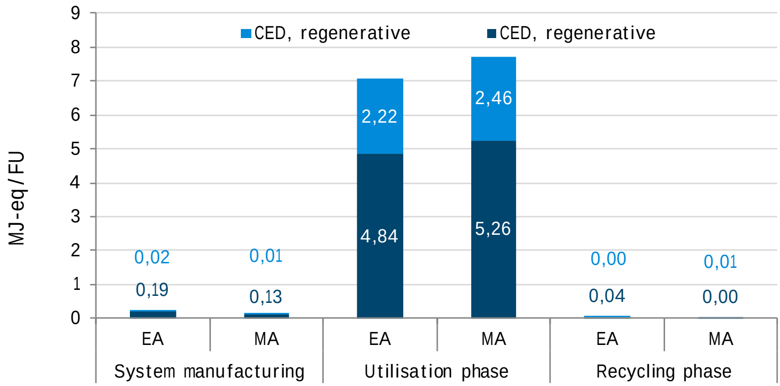

Figure 21: Cumulative energy demand (CED) per functional unit (FU), sub-divided by life cycle phases (baseline scenario)

Due to the high number of cleaned components per useful life (SCS: 63,737 and MCS: 59,038 components per year), neither the system manufacturing phase with an average share of 2.3% nor the recycling phase with an average share of 0.4% has a significant influence on the total energy consumption over the entire life cycle. The influence of the utilisation phase clearly predominates. On average, this accounts for a share of the total energy expenditure of 97%. A parameter analysis was used to determine the influence of different production parameters on the baseline scenario (0% line in Figure 22). A positive percentage change corresponds to an increase in the cumulative energy demand.

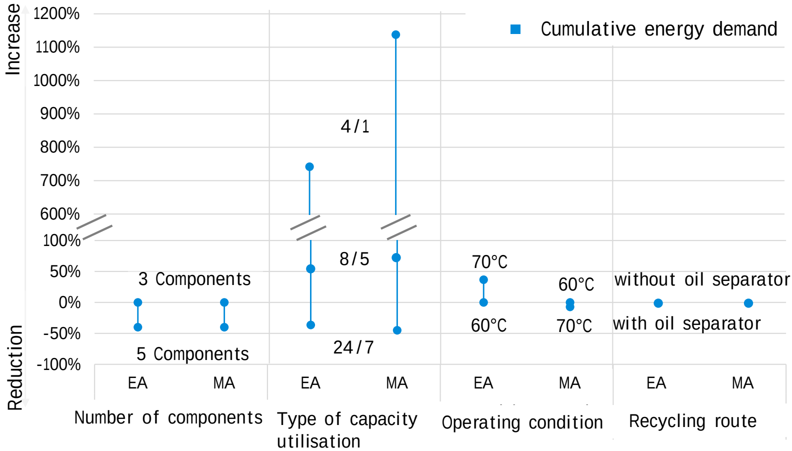

Figure 22: Cumulative energy demand CED) per functional unit (FU), parameter analysis (baseline scenario)

The type of system utilisation has the greatest influence on the primary energy demand. This mainly depends on the energy used to heat up the system, which must be done every day, except for continuous operation, as well as the energy used to maintain the reduced temperature outside the operating hours. With lower system utilisation, these environmental effects are distributed over a smaller number of cleaned components. Furthermore, the power consumption for maintaining the reduced temperature in the multi-chamber cleaning system plays a bigger part than it does in the single-chamber cleaning system. Continuous operation (24/7, no night temperature reduction) therefore leads to a higher reduction potential in the multi-chamber cleaning system.

By cleaning several components at a time (three instead of five), the CED can be reduced by an average of 41%. The reason for this is, among other things, the fact that the energy and material flow in the utilisation phase are almost entirely independent of the number of components cleaned simultaneously and are therefore distributed over several components. Increasing the operating temperature while reducing the mechanical impact, however, leads to a 37% higher primary energy consumption in the SCS. By contrast, the operating status of the MCS has hardly any influence. Nor does the use of an oil separator lead to a significant change in the cumulative energy demand.

All parameters that led to a reduction were brought together in a "min" scenario. In the same way, the "max" scenario includes all production settings that caused an increase. Figure 23 shows the maximum fluctuation range of the cumulative energy demand. The horizontal bar corresponds to the environmental effects of the baseline scenario.

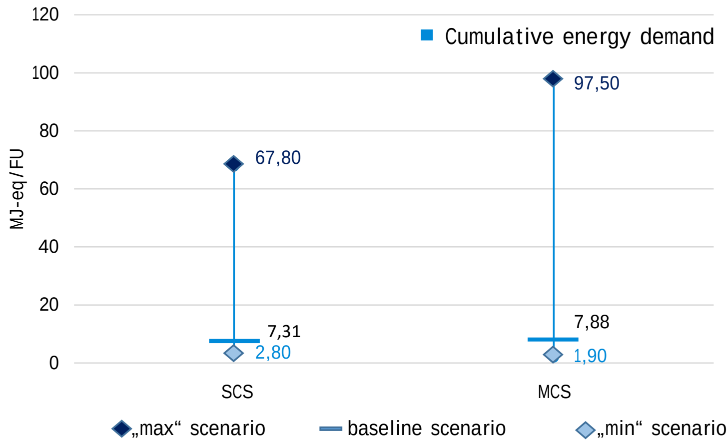

Figure 23: Cumulative energy demand (CED) per functional unit (FU), scenario analysis (baseline scenario, "min" scenario, "max" scenario)

The "min" scenario allows a 62% reduction in the cumulative energy demand per FU compared to the baseline scenario for the single-chamber cleaning system. With regard to a multi-chamber cleaning system, the primary energy demand can be reduced by 75% to 1.9 MJ-eq per cleaned component and is thus lower than the CED of the single-chamber cleaning system. If the scenario "max" is chosen, an average increase of 982% of the baseline scenario occurs.

6.1.2 Cumulative raw material demand

The calculation of the cumulative raw material demand was carried out in accordance with VDI Guideline 4800 Part 2 "Resource efficiency - Evaluation of raw material demand"[58]. Figure 24 shows the total raw material consumption of the single-chamber and multi-chamber cleaning system for the baseline scenario defined in section 4.4.

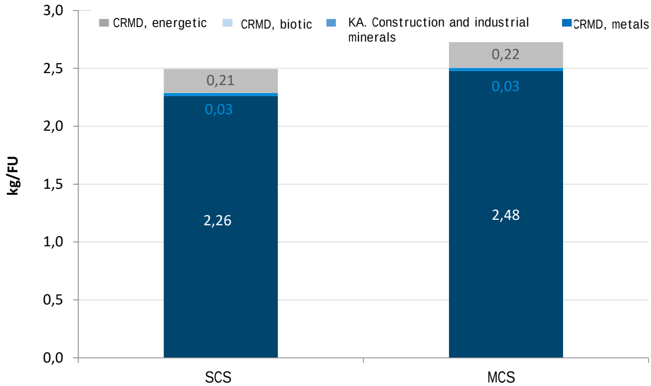

Figure 24: Cumulative raw material demand (CRMD) per functional unit (FU) for the entire life cycle (baseline scenario)

CRMD $_{\text{biotic}}$ and CRMD $_{\text{Construction and industrial minerals}}$ have a negligible impact on total raw material consumption, whereas CRMD $_{\text{metallic}}$ predominates. This applies to both the single-chamber and the multi-chamber cleaning system, with the cumulative raw material demand for the former being about 8.4% lower. To demonstrate the relevance of the individual life cycle phases, the cumulative raw material demand is divided in Figure 25 according to the phases system manufacturing, utilisation and recycling phases.

[58] See VDI 4800 Part 2:2018-03.

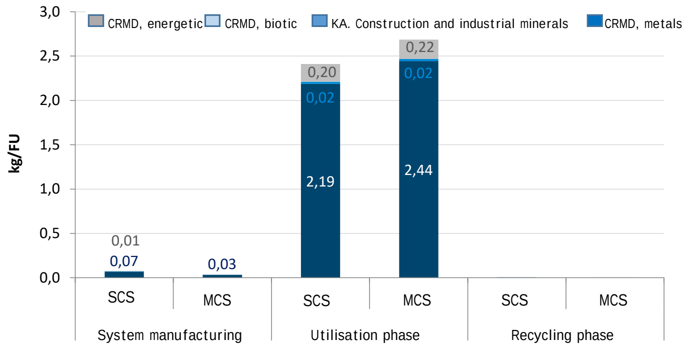

Figure 25: Cumulative raw material demand (CRMD) per functional unit (FU), subdivided according to life cycle phases (baseline scenario)

As with the CED, the utilisation phase predominates in terms of cumulative raw material demand with an average share of 97.6%. The impact of system manufacturing on the CRMD, with an average share of 2.3%, is just as negligible as the impact of the recycling phase. A parameter analysis was used to determine the influence of different production parameters on the baseline scenario (0% line in Figure 26). A positive percentage change corresponds to an increase in cumulative raw material demand.

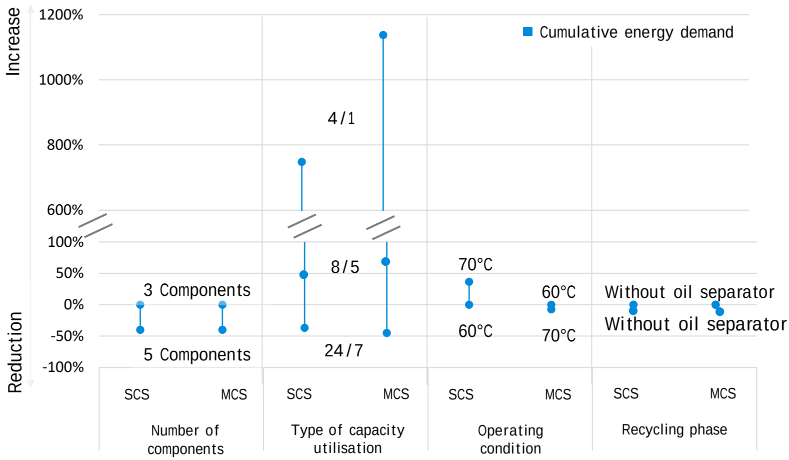

Figure 26: Cumulative raw material demand (CRMD) per functional unit (FU), parameter analysis (baseline scenario)

If the system is in continuous operation (24/7), there is a reduction in the total raw material consumption by an average of 41% compared to the baseline scenario. If the plant is operated in single shift operation (8/5) or even half a shift per week (4/1), the CRMD increases by up to 748% for SCS and 1137% for MCS compared to the baseline scenario. This is due to the fact that, with a low system utilisation, the environmental pollution caused by heating the plant and maintaining the reduced temperature outside the operating times is distributed over a smaller number of cleaned components. If five components are cleaned per cycle instead of three, the cumulative raw material demand for both cleaning systems can be reduced on average by about 40% compared to the baseline scenario. By contrast, a change in the operating state for the single-chamber cleaning system to a higher process temperature of 70 °C with a simultaneous lower mechanical action leads to an increase in the CRMD of 37% compared to the baseline scenario. The change in the operating state in the case of multi-chamber cleaning system has a negligible impact, however. Likewise, the use of an oil separator does not lead to any significant changes in the CRMD.

The scenarios “min” and “max” result in the maximum fluctuation ranges shown in Figure 27. The horizontal bar corresponds to the environmental effects of the baseline scenario.

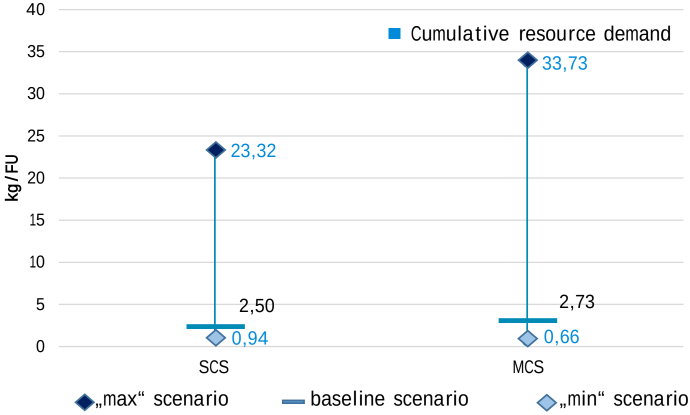

Figure 27: Cumulative raw material demand (CRMD) per functional unit (FU), scenario analysis (baseline scenario, “min” scenario, “max” scenario)

The “min” scenario leads to an overall reduction in cumulative raw material demand of 62% (SCS) and 75% (MCS) respectively. By contrast, the scenario “max” results in an increase in environmental impact of 800% for the single-chamber cleaning system and 1130% for the multi-chamber cleaning system.

6.1.3 Water consumption

Water consumption was assessed according to the definition of blue water consumption. Actual consumption was considered. This includes only the proportion of water that cannot be recycled. For this reason and despite the cut-off approach, recovery of the water in the course of treatment is taken into account, which is why the recycling phase can have negative values for blue water consumption. Figure 28 shows an overview of the water consumption for the single-chamber and multi-chamber cleaning system.

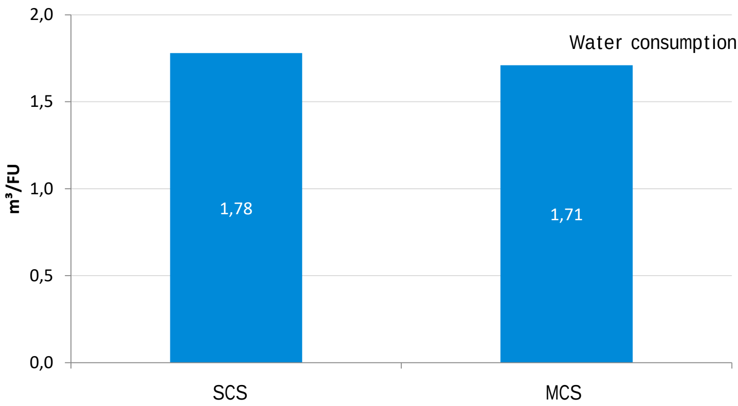

Figure 28: Water consumption per functional unit (FU) for the entire life cycle (baseline scenario)

In contrast to the CED and CRMD, the multi-chamber cleaning system has a lower value in terms of water consumption than the single-chamber cleaning system. There is a difference of 0.07 m^3/FU. This corresponds to a percentage deviation of about 4%. The reason for this is the lower capacity of the cleaning and rinsing basins. Figure 29 also shows water consumption, subdivided according to the individual life cycle phases.

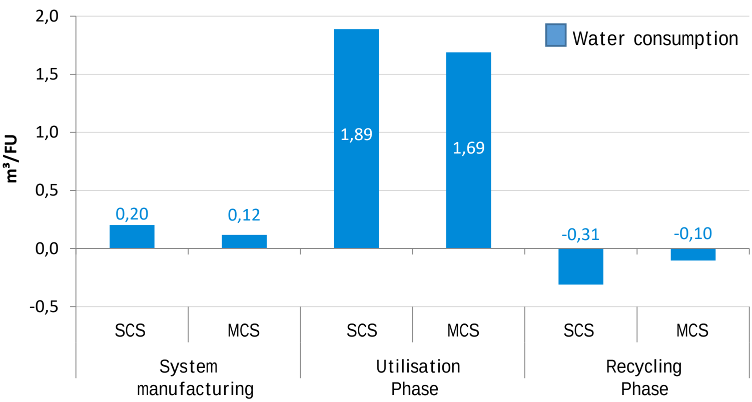

Figure 29: Water consumption per functional unit (FU), subdivided according to life cycle phases (baseline scenario)

An average of 9% of the water is consumed in system manufacturing, while the utilisation phase accounts for an average of 103%. In the recycling phase, on the other hand, an average of 12% can be recovered. This reduces the actual water consumption over the entire life cycle. The parameter analysis based on the defined baseline scenario shows the dependence of water consumption on various parameter variations (Figure 30; 0% line corresponds to the base scenario). A positive percentage change corresponds to an increase in blue water consumption.

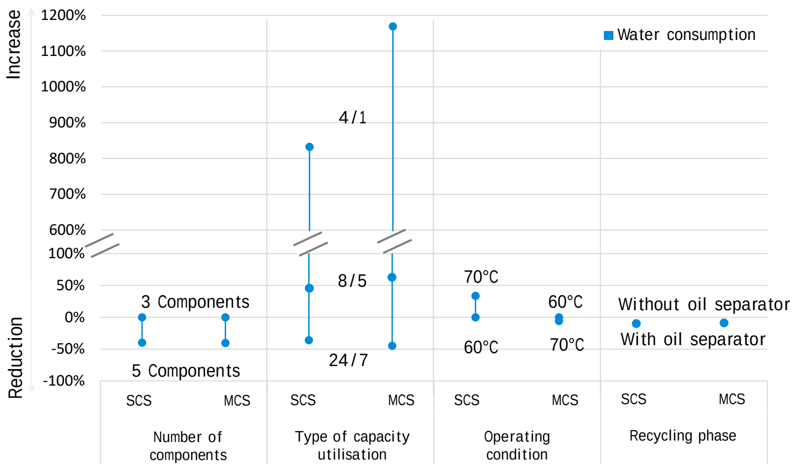

Figure 30: Water consumption per functional unit (FU), parameter analysis (baseline scenario)

The greatest influence on the water consumption is utilisation of the system. If system utilisation is low, consumption can only be distributed over a small number of components, since the frequency of the water change is largely independent of system utilisation. If five rather than three components are cleaned at the same time, the water consumption per FU will decrease on average by 40% compared to the baseline scenario. If, on the other hand, system utilisation drops to one shift per day (8/5) or even to half a shift per week (4/1), the water consumption per FU increases considerably. Compared to the baseline scenario, an increase of up to 833% for SCS and up to 1169% for MCS is possible. While variation in the operating state for MCS shows only a small effect, with the SCS a higher operating temperature of 70 °C leads to an increase in water consumption of 34% compared to the baseline scenario. By contrast, use of an oil separator does not have any significant influence on water consumption.

The maximum fluctuation ranges for the blue water consumption are shown in Figure 31. The horizontal bars correspond to the environmental effects of the baseline scenario.

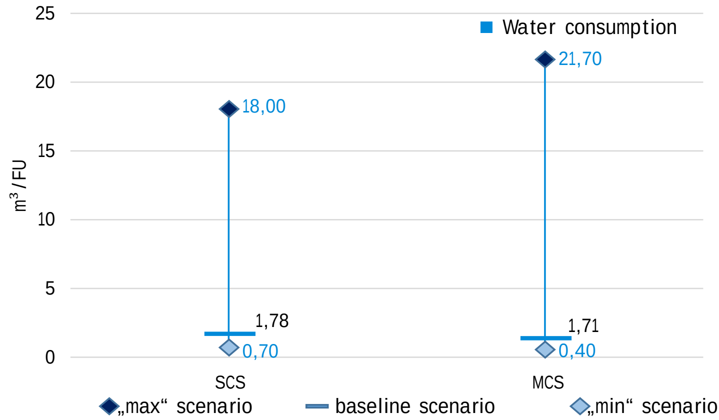

Figure 31: Water consumption per functional unit (FU), scenario analysis, (baseline scenario, "min" scenario, "max" scenario)

The maximum reduction in water consumption from the baseline scenario is 62% (SCS) or 75% (MCS). The overall increase in the "max" scenario is 911% (ECS) and 1169% (MCS) respectively.

6.1.4 Land use

For the assessment of land use, the area required for the provision of raw materials was taken into account. The classification of different types of land as settlement areas and agricultural areas was carried out as described in section 4.1.1. Land use over the entire life cycle is shown in Figure 32 for the single-chamber and multi-chamber cleaning systems.

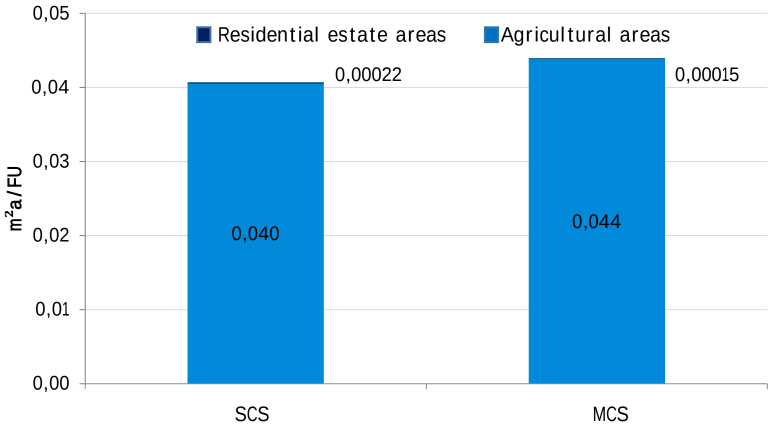

Figure 32: Land use per functional unit (FU) for the entire life cycle (baseline scenario)

Land use is dominated by the impact of the use of agricultural land. The SCS also has a slightly lower demand, with a difference from the multi-chamber cleaning system of about 0.004 m^2 a/FU. This corresponds to a percentage deviation of 9%. For clarification, a differentiation was made in the life cycle phases of system manufacturing, utilisation and recycling phase (Figure 33).

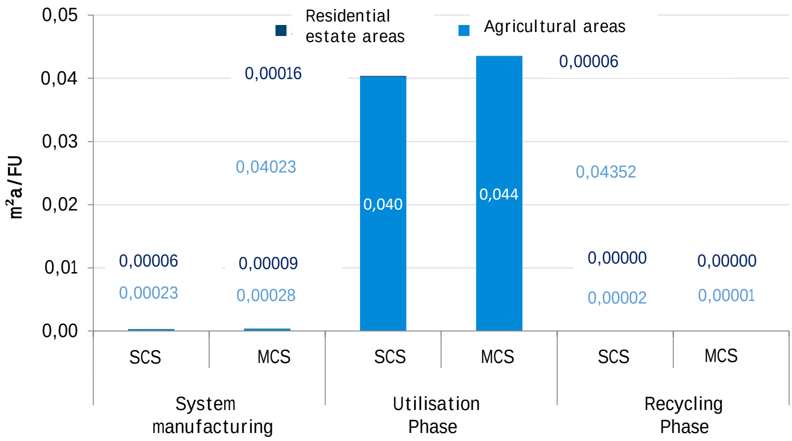

Figure 33: Land use per functional unit (FU), subdivided according to life cycle phases (baseline scenario)

The impact of the recycling phase is negligible in terms of land use with an average of 0.04%. The same applies to system manufacturing, which contributes an average of 0.8% to total land use. By contrast, the utilisation phase accounts for approximately 99% in each case. The main factors affecting land use were determined by means of a parameter analysis. The results are shown in Figure 34, where the 0% line represents the baseline scenario and a positive percentage change represents an increase in land use.

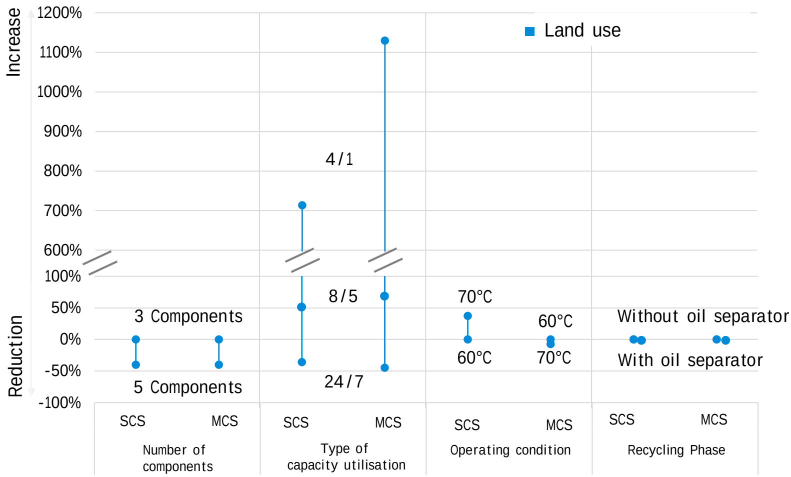

Figure 34: Land use per functional unit (FU), parameter analysis (baseline scenario)

The type of system utilisation also has a considerable influence on land use. In a similar way to the environmental indicators CED and CRMD, the environmental effects are distributed over a small number of cleaned components at low system utilisation.

If five components are cleaned instead of three per cycle, land use per cleaned component can be reduced by an average of 40% compared to the baseline scenario. On the other hand, a reduction in system utilisation results in a significant increase in land use per FU. If the cleaning system operates for only one shift per day (8/5) or half a shift per week (4/1), land use will increase by up to 714% for SCS and up to 1130% for MCS compared to the baseline scenario.

If the operating state of the SCS is changed to a higher operating temperature with low mechanical action (operating state “70 °C”), this results in an increase in land use of 37% in relation to the base scenario. In contrast, a change in the operating state of the MCS only results in a small variation in land use compared to the base scenario. At the same time, the use of an oil separator has no significant effect on the environmental impact per FU for both systems.

The maximum fluctuation range which results from a combination of the parameters investigated is shown in Figure 35. The horizontal bar corresponds to the environmental effects of the baseline scenario.

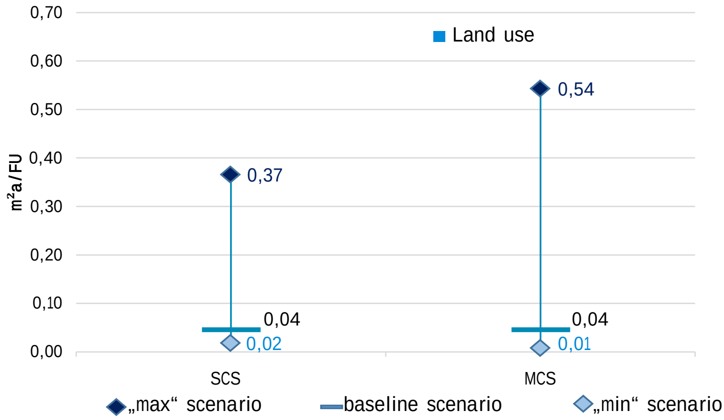

Figure 35: Land use per functional unit (FU), scenario analysis, (baseline scenario, "min" scenario, "max" scenario)

For the "min" scenario, there is an overall reduction in land use compared to the baseline scenario of 62% (SCS) and 76% (MCS). The "max" scenario shows an increase of 835% (SCS) and 1137% (MCS) respectively compared to the baseline scenario.

6.1.5 Global warming potential

Calculation of the global warming potential is based on the CML 2001 method (as of January 2016). In Figure 36, the global warming potential GWP 100 for the single-chamber and multi-chamber cleaning systems is shown for the entire life cycle.

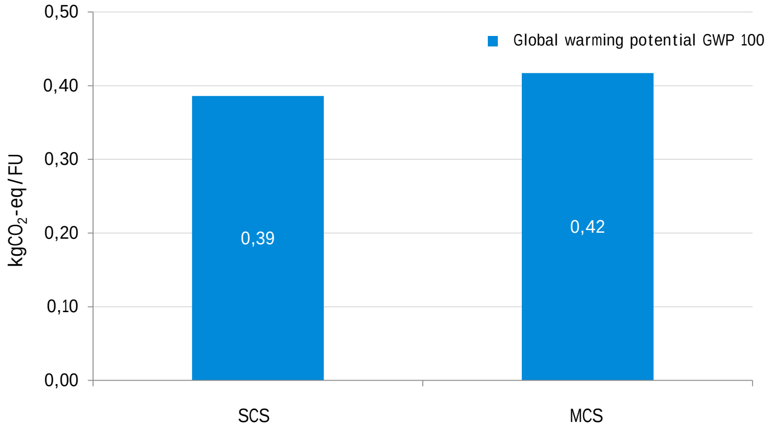

Figure 36: Global warming potential GWP100 per functional unit (FU) for the whole life cycle

The global warming potential of the single-chamber cleaning system is 0.03 kg CO_2-eq/FU higher than the multi-chamber cleaning system. The difference corresponds to a percentage deviation of around 7%. Figure 37 shows an analysis of the global warming potential, subdivided according to the life cycle phases of system manufacturing, utilisation and recycling.

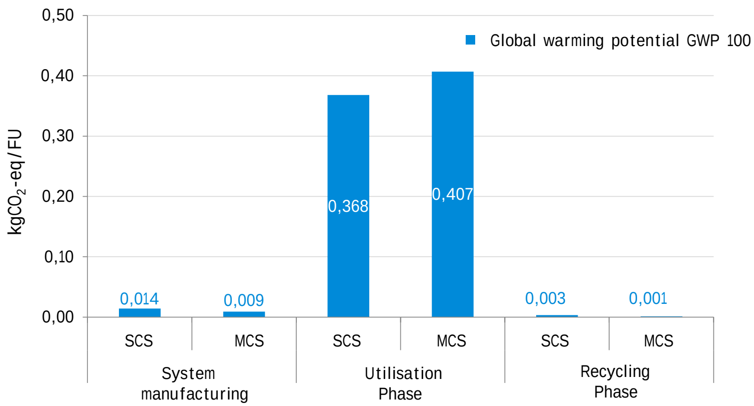

Figure 37: Global warming potential GWP100 per functional unit (FU), subdivided by life cycle phases

System manufacturing accounts for 3.7% (SCS) and 2.2% (MCS) of the total global warming potential, while the utilisation phase accounts for 95.3%

(SCS) and 97.6% (MCS) respectively. By contrast, the impact of the recycling phase is extremely low with respect to global warming potential at 0.9% (SCS) and 0.3% (MCS). The results of the following parameter and scenario analyses show the influence of individual (Figure 38) and combined (Figure 39) parameter variations on the total global warming potential per functional unit. In Figure 38, the 0% line represents the baseline scenario; parameters leading to an increase in global warming potential result in a positive percentage change in global warming potential.

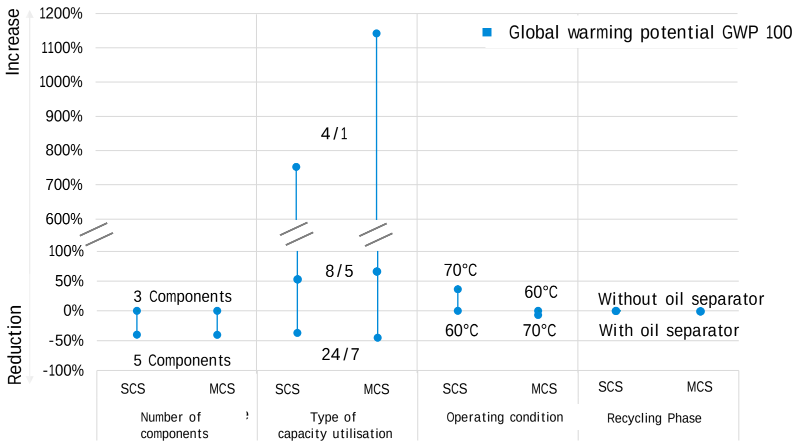

Figure 38: Global warming potential GWP100 per functional unit (FU), parameter analysis (baseline scenario)

As with the previous impact categories, system manufacturing has the greatest impact on global warming potential. If system utilisation is low, the environmental impact per component is distributed over a smaller number of components. This is mainly due to the energy used to heat up the system, which must be done every day unless the system is in continuous operation, and the energy consumption to maintain the reduced temperature outside operating hours.

Increasing the number of components per cleaning cycle from three to five reduces the global warming potential by about 40% compared to the baseline scenario. On the other hand, if system utilisation decreases, this leads to an increase in environmental impact of up to 752% (SCS) or 1142% (MCS) respectively.

Variation of the operating state has a significant effect on the single-chamber cleaning system only. In the case of a higher operating temperature with a simultaneously lower mechanical impact per FU, the global warming potential increases by 36% compared to the baseline scenario.

By contrast, the use of an oil separator has negligible effects on the global warming potential per cleaned component.

Figure 39 shows the maximum fluctuation range of the global warming potential.

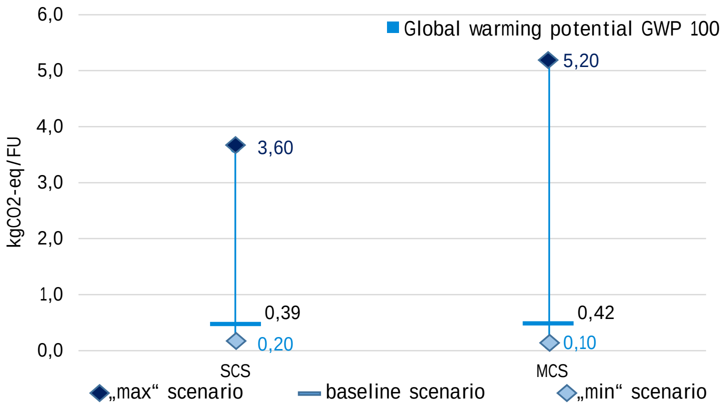

Figure 39: Global warming potential GWP 100 per functional unit (FU), scenario analysis, (baseline scenario, "min" scenario, "max" scenario).

The "min" scenarios leads to a decrease in the global warming potential per functional unit of 62% (SCS) or 75% (MCS). The "max" scenario, however, results in an 838% increase over the baseline scenario for the single-chamber cleaning system and 1142% for the multi-chamber cleaning system.

6.1.6 Comparison of the results of the ecological assessment

In order to be able to compare the single-chamber and multi-chamber cleaning systems for the baseline scenario clearly for all environmental indicators considered, the results of the ecological assessment for each indicator were standardised to the indicator value for the single-chamber cleaning system (Figure 40).

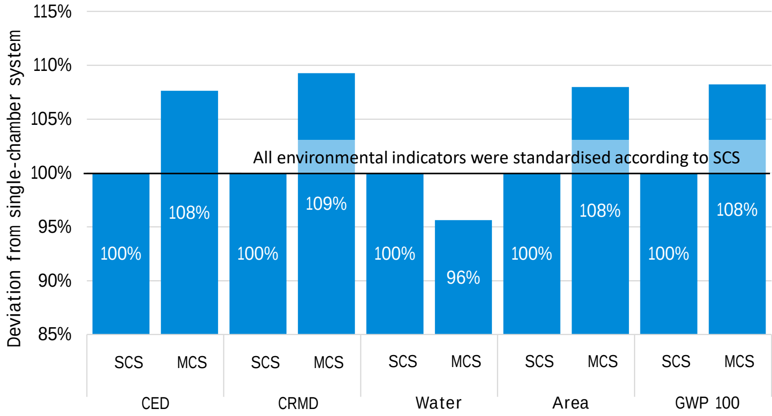

Figure 40: Ecological evaluation results standardised to SCS - baseline scenario

Figure 41 shows that the multi-chamber-cleaning system has a higher environmental impact for the environmental effects considered, with the exception of water consumption. The difference to the single-chamber cleaning system is 8 to 9%, depending on the environmental indicator. The reason for this is the proportionately higher energy consumption of the multi-chamber cleaning system per FU. This is mainly caused by a higher power requirement during the night temperature reduction. By contrast, the single-chamber cleaning system has a higher water consumption compared to the multi-chamber cleaning system due to the larger capacity of the cleaning and rinsing basins.

Figure 41 and Figure 42 show a comparison of the fluctuation ranges (min/max) for all environmental impacts. For a clear presentation, the environmental indicators of both scenarios were standardised according to the baseline scenario for the SCS and MCS respectively. The comparison of the "min" scenario with the baseline scenario shows that a greater reduction of the environmental impact is possible for the multi-chamber cleaning system. For example, CED for SCS accounts for only 38% of the environmental impact per FU of the baseline scenario. This results in a reduction of CED by 62%.

This also applies to the other environmental indicators. In general, a reduction of around 75% can be achieved for the multi-chamber cleaning system, while the single-chamber cleaning system offers a reduction of 62% compared to the baseline scenario.

In the case of the “min” scenario, the multi-chamber cleaning system consequently has lower environmental impacts. The reason for this is the type of energy consumption of the two systems. If continuous system utilisation (24/7) is chosen, the total energy consumption is determined solely by the energy requirements of the cleaning process. While the single-chamber cleaning system has a lower energy requirement in terms of night temperature reduction, its energy consumption in relation to the heating phase and the cleaning process itself is higher than the multi-chamber cleaning system. Since the impact categories considered are primarily influenced by the electricity demands, lower environmental impact can be achieved in the “min” scenario for the multi-chamber cleaning system than for the single-chamber cleaning system.

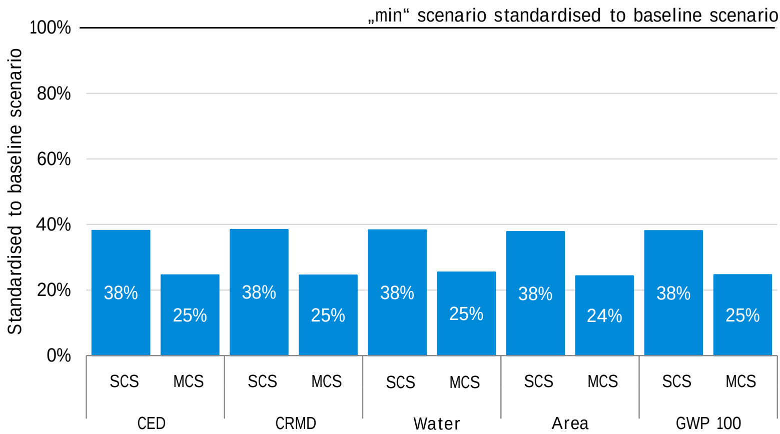

Figure 41: Results of the ecological scenario analysis for the “min” scenario, standardised to the baseline scenario

Figure 42 illustrates, however, that in comparison to the “min” scenario, the "max" scenario results in a significant increase in environmental impacts for all environmental indicators. The reason for this is primarily a very low system utilisation (4/1), which has a greater influence on the multi-chamber cleaning system than on the single-chamber cleaning system. This is due to the higher energy consumption during the night temperature reduction, which, in the case of a system utilisation of half a shift per week, dominates the total energy demand per FU.

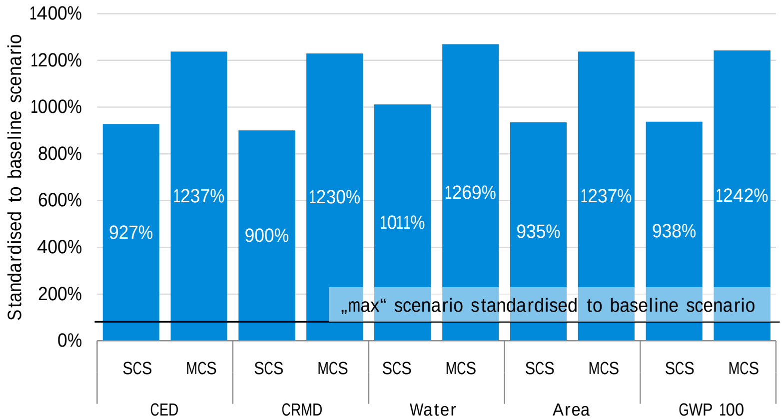

Figure 42: Results of the ecological scenario analysis for the "max" scenario, standardised to the baseline scenario

6.2 Raw material criticality - supply risk

For assessment of raw material criticality, a criticality analysis according to VDI 4800 Part 2 "Resource efficiency - Evaluation of raw material demand"[59] was carried out. Here, the raw materials which play a major role in system manufacturing were taken into account. These include steel and stainless steel with the most frequently used alloy elements (chromium, nickel, molybdenum, tungsten, vanadium, silicon, manganese, phosphate, titanium and niobium)[60], and the metals aluminium and copper. In view of the use of some plastic elements, such as seals, the fossil resource crude oil was also considered. Furthermore, the ecological assessment shows that the utilisation phase or the electricity demand plays a central part in the resulting environmental impacts. The energy raw materials coal, natural gas and uranium are therefore also a focus of the criticality assessment. The cleaner used

[59] See VDI 4800 Part 2:2018-03.

[60] See Informationsstelle Edelstahl Rostfrei.

is not relevant in terms either of quantity or of the ecological and economic assessment, and therefore its constituents have not been considered here. In order to understand the assessment, a brief explanation of the supply risk indicators is provided first.

(1) Geological, technical and structural criteria

Static range

The static range represents the relationship between the available global reserves and the annual production of the raw material:

$$Static\ range = \frac{\text{Global reserves}}{\text{Annual production of the raw material}} \tag{6.1}$$

The term reserve refers to the subset of geological resources the mining of which is economically and technologically feasible at a given time. To calculate the static range of the metallic raw materials, the raw material data of the US Geological Survey was used. In each case, the annual production and the reserve availability as of 2018 were taken into account[61]. For the remaining raw materials, the database of the World Energy Council was used (as of 2016)[62].

Combined production/auxillary production

If a raw material is obtained as a by-product or co-product, there is a dependence on the supply of or demand for the main product. For this reason, a classification is made according to the "degree of combined/secondary production”. The database for the assessment was provided by a study on raw material criticality by the Institute for Future Studies and Technology Assessment (IZT)[63]. VDI standard values were taken into account and expert knowledge was also used.

[61] See U.S. Geological Survey (USGS) (2019).

[62] See World Energy Council (2016).

[63] See Institute for Future Studies and Technology Assessment (IZT) (2011).

Recycling

The criterion of recycling considers the material recycling of end-of-life waste. If established recycling technologies are available, natural resources can be saved and the entire supply of raw materials can be extended by secondary raw materials. The more established recycling technologies are available and the lower the degree of downcycling, the more positive the impact is on raw material criticality. Material recycling is not possible in the case of fossil fuels, which is why they have been set to indicator 1 (recycling not established). The database for the assessment of the remaining raw materials was provided by a study on raw material criticality by of the Institute for Future Studies and Technology Assessment (IZT).

Logistic constraints

The parameter "economic efficiency of storage and transport" takes into account the transport distances, trade links and shelf life of a raw material. The database was derived from default values in the VDI guideline and on expert estimates. The classification of uranium took into account the risk of radioactive radiation.

Constraints due to natural events

This indicator relates mainly to biotic raw materials, the availability of some of which can be affected significantly by natural events (e.g. drought, flood and pest infestation). Susceptibility to natural events is low for the extraction and mining of mineral and fossil resources. For this reason, the VDI guideline uses a default value of 0 here.

(2) Geopolitical and regulatory criteria

Country concentration of reserves

If there is a high distribution of reserves across several countries, there is less risk of exploitation of existing market power. The country risk for the reserves was determined using the Herfindahl Hirschmann Index (HHI). This is defined as the sum of the squared share values x_i of all market participants n.

$$HHI = \sum_{i=1}^{n} \left(\frac{x_i}{\sum_{i=1}^{n} x_i} \right)^2 \tag{6.2}$$

The calculation must include at least 80% of the total reserves. The basis for the calculation was the same database as used for the static range.

Country concentration of production

The indicator "Country Concentration of Production" also serves to assess the distribution of market power. The Herfindahl-Hirschmann Index (HHI) was also used as the calculation method, using the databases for the “static range” and the “country concentration of reserves”.

Geopolitical risks of global production

The political stability of a country can significantly affect access to raw materials. This includes, in particular, countries in which there are ongoing political and military conflicts. The political risk was calculated on the basis of the indicators “voice and accountability” and “political stability and absence of violence”. Both indicators are included in the assessment for the entirety (at least 80%) of all mining and exporting countries. Both of these are compiled annually by the World Bank as part of the World Governance Indicators (WGI) for a total of 215 countries. The data was based on the year 2017[64].

Regulatory situation of raw material projects

In addition to political stability, the availability of raw materials is also influenced by the economic, fiscal and environmental conditions of the mining and exporting countries. The regulatory situation of commodity projects is taken into account in the criticality assessment by the indicator “regulatory country risk”. The four World Bank indicators “rule of law”, “regulatory quality”, “control of corruption” and “government effectiveness” of at least 80% of the raw material mining and exporting countries were used for the calculation. The database was also for the reference year 2017[64].

(3) Economic criteria

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[64] See World Bank Group (2019).

Company concentration of global production

Raw material prices and supply can be influenced significantly by companies, which is why a low concentration of companies has a critical impact on supply risk. In line with the country concentration of reserves and production, the corporate concentration of global production is also calculated using the Herfindahl-Hirschmann Index (HHI). The database for determination of the corporate concentration of the raw materials iron, uranium and coal was the information on the annual production volume of the World Steel Association (as of 2017)[65], the database of the World Nuclear Association (as of 2017)[66] and the Global Coal Exit List (GCEL) (as of 2018)[67]. For the metallic raw materials, the corresponding values were taken from the DERA raw material information in the category “Concentration of companies”[68] and from the raw material economic profile of the Federal Institute for Geosciences and Natural Resources (BGR)[69]. For the raw materials crude oil and natural gas, however, the standard values according to the VDI guideline are taken as the basis.

Global demand impetus

Innovative technological leaps or changes in technology can bring about a disruptive increase in demand. In the wake of a strong increase in demand, the risk of price increases rises depending on whether a simultaneous expansion of production can be achieved. Any resulting influence on raw material criticality is taken into account by the indicator “level of demand growth”. As far as possible, standard values according to the underlying VDI guidelines were used for the evaluation of raw material criticality, supported by experts' estimates.

Substitutability

Functional substitution of raw materials may be feasible from a technological and functional point of view, but entails high costs. For this reason, the sub-

65 See World Steel Association (2017).
66 See World Nuclear Association (2019).
67 See Urgewald.
68 See German Mineral Resources Agency (DERA) (2014).
69 See Federal Institute for Geosciences and Natural Resources (BGR).

stitutability of a raw material is evaluated in the context of resource-criticality by means of categories. The classification ranges from complete substitutability without major effort or performance losses through to technically and/or economically unacceptable substitution. For the assessment of raw material criticality, standard values according to the VDI guideline or expert estimates were used, in the same way as the indicator “level of demand growth”.

Raw material price fluctuations

The fluctuation ranges within a given period of raw material prices are calculated using the “annualised price volatility” indicator. In this case, the period from February 2018 to January 2019 was taken into account. “Annualised price volatility” for the raw materials coal, natural gas, uranium and iron was determined on the basis of the present daily closing prices[70]. For the other raw materials, the values of the Volatility Monitor 2019 of the German Mineral Resources Agency (DERA)[71] were used.

(4) Summary

The results of the raw material criticality assessment for the supply risk are shown in Table 15. The criticality values of the individual indicators and the aggregated total criticality are shown. For a better overview, the raw materials are arranged in descending order of total criticality.

70 See finanzen.net.

71 See German Mineral Resources Agency (DERA) (2019).

Table 15: Assessment of the criticality dimension supply risk

		Geopolitical, technical and structural indicators					Geopolitical and regulatory indicators				Economic indicators				
Raw material/element	Scope of application	Ratio of reserves to annual global production	Degree of combinised/secondary production	Degree of dissemination of functional EoL recycling technologies	Cost-effectiveness of storage and transport	Extent of distribution of natural resources/cultivation areas	Herfindahl-Hirschmann-index of reserves	Herfindahl-Hirschmann-index of country	Political country risk	Regulatory country risk	Herfindahl-Hirschmann-index of companies	Degree of increase in demand	Substitutability	Annualised price volatility	Aggregation (degressive addition)
Vanadium	Alloy element	0	1	0,7	0	0	1	1	0,7	0,7	0,3	0,3	0,3	1	0,92
Chrome	Alloy element	1	0	0,3	0	0	1	1	0,7	0,3	0,3	0,3	1	0,7	0,91
Cobalt	Alloy element	0,7	0,7	0,7	0	0	1	1	0,7	0,7	0,3	0,3	1	1	0,89
Tungsten	Alloy element	0,7	0	0,3	0	0	1	1	0,7	0,3	1	0,3	0,7	0,3	0,88
Molybdenum	Alloy element	0,3	0	0,7	0	0	1	1	0,7	0,3	0,7	0	0,7	0,7	0,84
Phosphate	Alloy element	0	0	0,7	0	0	1	1	0,7	0,3	0,7	0,3	1	0,3	0,81
Uran	Power generation	1	0	1	0,7	0	0,3	1	0,7	0,7	0,3	0,3	0,3	0	0,81
Niobium	Alloy element	0	0,3	0,7	0	0	1	1	0	0	1	0	0,7	0,7	0,79
Manganese	Alloy element	0,7	0	0,3	0	0	0,7	0,7	0,7	0,7	0,3	0	1	1	0,76
Nickel	Alloy element	0,7	0,3	0,3	0	0	0,7	0,3	0,7	0,3	0	0,3	1	0,7	0,75
Silicon	Alloy element	0	0	0,7	0	0	0,3	1	0,7	0,3	1	0	0,7	0,3	0,71
Iron	Steel/stainless Steel	0,3	0	0,3	0	0	0,7	0,7	0,7	0,7	0	0	0,7	0	0,63
Aluminium	Aluminium metal	0	0	0,3	0	0	0,7	0,7	0,7	0,7	0,3	0	0,7	0,7	0,63
Copper	Copper metal, electronics	0,7	0,3	0,3	0	0	0,3	0,7	0,7	0,3	0,3	0,3	0,7	0,7	0,62
Natural gas	Power generation	0,7	0,3	1	0,3	0	0,3	0,3	0,7	0,7	0,3	0,7	0	0	0,62
Coal	Power generation	0	0	1	0	0	0,3	1	0,7	0,3	0,3	0,3	0	0	0,59
Crude oil	Plastic manufacturing	0,3	0	0,3	0,3	0	0,3	0,3	0,7	0,3	0,3	0,7	0	1	0,52
Titanium	Alloy element	0	0	0,3	0	0	0,7	0,3	0,7	0,3	0,3	0	0,3	1	0,51

- Data is calculated and sources are known and referenced
- Default value specified by guideline
- Expert estimate

Based on aggregate total criticality, the raw materials vanadium, chromium, cobalt and tungsten are the most critical, followed by molybdenum, phosphate and uranium. With the exception of uranium, these are alloy components of steel and stainless steel metals. Above all, chromium is used very frequently and in higher concentrations. Depending on the alloy, it may contain over 28% chromium[72]. The use of coal and natural gas as fossil energy sources and the use of crude oil for the production of plastic, however, is considered to be uncritical in terms of raw material criticality.

If the individual indicator values are considered, it can be seen that, above all, the “country concentration of reserves” and the “country concentration of annual production” are to be regarded as critical or highly critical for the majority of the raw materials considered, with a criticality value of 0.7 or 1. This also applies to the “political country risk”, since all raw materials, with the exception of niobium, have a criticality of 0.7. By contrast, the “regulatory country risk” and the “company concentration of global production” have only a moderate criticality value of 0.3 for a large number of raw materials. In the case of metallic raw materials, the “logistic constraints” and the “constraints due to natural events” are also non-critical. In the case of natural gas, crude oil and uranium, on the other hand, the “logistic constraints” is not negligible. In particular, transport and storage of uranium are classified as critical due to the risk of radioactive radiation and the associated costs.

In summary, it can be stated that, in contrast to the ecological assessment, it is the system manufacturing that plays the central role in terms of the criticality assessment. This is due to the use of steel and stainless steel with the corresponding alloy elements. The use of copper and aluminium and the use of crude oil for the production of plastics, however, can be classified as relatively uncritical. This also applies to the use of the raw materials coal and natural gas for power generation, which is required in the utilisation phase for cleaning of the components.

[72] See Informationsstelle Edelstahl Rostfrei (ISER).

6.3 Economic assessment

The economic assessment includes an evaluation of the baseline scenario, a parameter analysis and a scenario analysis in the same way as in the ecological assessment. For the scenario analysis, a minimum and a maximum cost scenario were defined. However, this does not correspond to the minimum and maximum environmental scenario, as it was based on the results of the ecological parameter analysis. In the case of the economic assessment, the scenario analysis is based on the economic parameter analysis. The method of "static cost evaluation" (section 4.1.3) was used for the evaluation.

6.3.1 Static cost evaluation

Using the "static cost assessment" method, the additional costs per component incurred during cleaning were determined for a useful life of 20 years. Due to different cycle times, the total cost of the single-chamber cleaning system (ten minutes and 59 seconds) can be reduced to 63,737 components, the total cost of the multi-chamber cleaning system (twelve minutes and 41 seconds) to only 59,038 components. Table 16 shows the results of the cost evaluation for the baseline scenario for the single-chamber cleaning system and multi-chamber cleaning system as defined in section 4.4.

Table 16: Static cost assessment - baseline scenario

Cost factor	Single-chamber system		Multi-chamber system	
	€/FU	Proportion	€/FU	Proportion
System manufacturing				
Depreciation costs	€0.09	9.12%	€0.16	13.60%
Subtotal	€0.09	9.12%	€0.16	13.60%
Utilisation phase				
System costs	€0.03	3.18%	€0.02	2.15%
Maintenance costs	€0.01	0.81%	€0.02	2.15%
Set-up costs	€0.02	1.36%	€0.00	0.00%
Tool costs	€0.00	0.02%	€0.00	0.00%
Personnel costs	€0.51	52.64%	€0.55	48.32%
Energy costs	€0.21	21.8%	€0.23	19.73%
Electrical energy	€0.17	17.67%	€0.19	16.22%
Compressed air	€0.04	4.13%	€0.04	3.51%
Material costs	€0.06	6.14%	€0.05	4.47%
Costs of cleaner	€0.06	6.09%	€0.05	4.43%
Costs of water	€0.00	0.05%	€0.00	0.04%
Rental costs	€0.01	1.04%	€0.03	2.74%
Rental costs	€0.01	1.04%	€0.03	2.74%
Subtotal	€0.82	84.80%	€0.88	77.42%
Recycling phase				
Disassembly and disposal	€0.00	0.19%	€0.00	0.28%
Cost of waste water disposal	€0.00	0.39%	€0.01	0.50%
Subtotal	€0.01	0.58%	€0.01	0.78%
Interest costs				
Imputed interest costs	€0.05	5.50%	€0.09	8.20%
Subtotal	€0.05	5.50%	€0.09	8.20%
Total	€0.97	100.00%	€1.14	100.00%

Overall, the total costs are dominated by the utilisation phase. On average, this accounts for a share of 80%. The costs of the utilisation phase are in turn mainly caused by personnel and energy costs. Around 50% of the total costs are for personnel and around 20% for energy. In comparison, the costs per component resulting from the utilisation phase are negligible.

The cleaning costs per component are about 17.5% higher for the multi-chamber cleaning system than for the single-chamber cleaning system. This corresponds to an absolute amount of €0.17. However, the single-chamber cleaning system has lower investment expenditure, personnel and rental costs. The lower personnel and energy costs for the single-chamber cleaning system are primarily due to the different cycle times of the systems. The equipment and material costs for the single-chamber cleaning system, however, are comparatively higher. Depending on the system, the material costs per component amount to between 4.5 and 6% and are made up of almost

100% of the cleaning costs. The reason for the higher material costs of the SCS is the higher capacity of the cleaning basin. With an identical detergent concentration of 3%, the cleaning medium of the single-chamber cleaning system contains approximately 90% more cleaner. In the economic assessment, however, it was considered that, due to the larger capacity of the basin, the rinsing and cleaning medium only needs to be changed every twelve weeks instead of every eight weeks. This in turn has a positive effect on the material costs of the single-chamber cleaning system, which is why the difference between the systems is minimal.

6.3.2 Parameter analysis

For the parameter analysis of the economic assessment, the number of components that can be cleaned at the same time, the type of system utilisation, the operating status and the type of waste water treatment in the system were analysed in the same way as in the ecological assessment. In addition, two different options for disassembly and disposal of the system were considered. Figure 43 shows the results of the parameter analysis for the single-chamber and multi-chamber cleaning systems. In each case, the change in the cleaning costs per component compared to the baseline scenario (0% line) is shown.

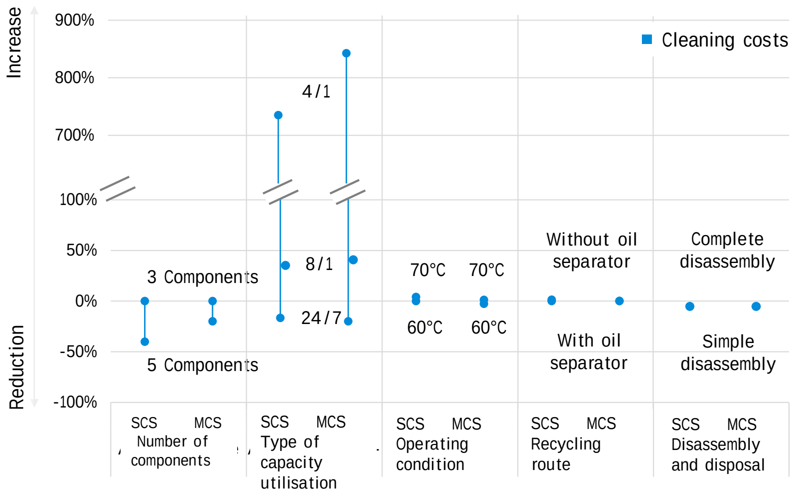

Figure 43: **Static cost evaluation - parameter analysis**

In a similar way to the ecological assessment, the type of system utilisation also has a considerable impact on the costs of cleaning. If utilisation is lower, the energy costs of the night temperature reduction and the material costs (cleaner) in particular are distributed over just a few components.

Increasing the number of components per cleaning cycle can reduce the cost per component by an average of 40% compared to the baseline scenario. If, on the other hand, system utilisation changes to one shift per day or even half a shift per week, the total cost per component increases by up to 735% (SCS) or 843% (MCS) compared to the base scenario. An increase in the operating temperature with a simultaneous reduction of the mechanical action leads on average to 3% higher costs. If the parameter variation “60 °$C_{optimal}$” is applied to the MCS, the costs can be reduced by 2.6% due to shorter cycle times (12 minutes, 19 seconds) and lower energy consumption during the cleaning process.

With regard to the recycling phase, although higher cost rates are used for full disassembly and a system without an oil separator (Table 17), this has no significant impact on the cleaning costs per component.

Based on the results of the parameter analysis, a minimum (min) and maximum (max) cost scenario were defined in addition to the baseline scenario. An overview of the parameter variations for all three scenarios can be seen in Table 17.

Table 17: Static cost evaluation – parameter selection for scenario analysis

Parameter	"Min" scenario	Baseline scenario	"Max" scenario
Number of components per cleaning cycle	5 components	3 components	3 components
Type of plant utilisation	20 years 24/7 20 years of useful life 24 h operating time 7 days a week	20 years 16/5 20 years of useful life 16 h operating time 5 days a week	20 years 4/1 20 years of useful life 4 hour operating time 1 day a week
Operating condition	60 °C (SCS) 60 $°C_{optimal}$ (MCS)	60 °C	70 °C
Recycling route	with oil separator	with oil separator	without oil separator
Disassembly and disposal	Simple disassembly	Simple disassembly	Complete disassembly

The cleaning costs were calculated using the static cost assessment for the "min" and "max" scenarios and compared to the baseline scenario. This does not correspond to the minimum and maximum environmental scenario, as it was based on the results of the ecological parameter analysis. In the case of the economic assessment, however, the scenario analysis is based on the economic parameter analysis. REF _Ref7088237 \h Figure 44 shows the results of the scenario analysis, i.e. the maximum fluctuation range of the cleaning costs.

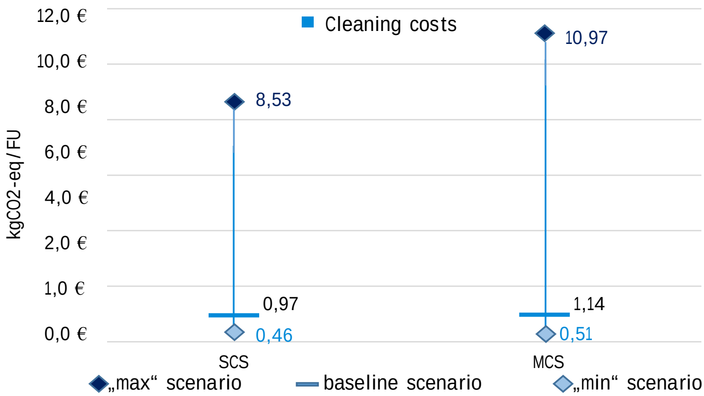

Figure 44: Static cost evaluation - scenario analysis

Compared to the baseline scenario, for the “min” scenario a total cost reduction per component can be achieved of €0.51 to €0.46 (SCS) or €0.64 to €0.51 (MCS). The percentage cost reduction is 52% for the single-chamber cleaning system and 56% for the multi-chamber cleaning system. The cost increase in the case of the “max” scenario amounts to €7.56 (€8.53) or €9.83 (€10.97) per component. This represents an increase of 778% (SCS) or 860% (MCS). A detailed overview of the parameter analysis and scenario analysis can be found in Appendix B.

7 CONCLUSION

In the context of the study, the ecological and economic indicators for determining the resource consumption for two ultrasonic cleaning systems were determined and compared. For the baseline scenario (Figure 13), the single-chamber cleaning system has a lower cumulative energy demand and raw material consumption, lower land use and a lower global warming potential than the multi-chamber cleaning system. The cleaning costs are also slightly lower. Only the water consumption is higher in the single-chamber cleaning system than in the multi-chamber cleaning system. This is due to the higher capacity of the cleaning and rinsing basin.

Furthermore, the influence of various cleaning parameters on resource consumption was surveyed. In particular, system utilisation has had a significant impact on the results of both systems studied. In addition to an increase in the number of components to be cleaned simultaneously in the wash basket, continuous use of the system can lead to a significant reduction in costs and/or environmental impacts of up to 50% compared to the baseline scenario. On the other hand, if the cleaning system is only used to a small extent, the resource utilisation and the cleaning costs incurred during the heating processes or when the reduced temperatures are maintained are distributed over only a few components. From this, three findings can be derived for plant operation and plant dimensions:

- An existing system should always be used with the maximum number of parts that can be accommodated in the basket or workpiece carrier
- Grouping washing jobs together makes sense to reduce heating processes
- A new system design should be adapted in terms of dimensions as accurately as possible to the number of parts to be cleaned

For cleaning systems in small and medium-sized enterprises, flexible use of the systems, for example across several product lines, should be explored continuously in order to achieve optimal utilisation.

The cleaning parameters, the operating condition and the use of an oil separator, on the other hand, have hardly any influence on the use of resources.

Only with the single-chamber cleaning system does a higher operating temperature lead to higher environmental impact (by up to 36%). This is due to the higher energy consumption during the heating processes and during operation. In the multi-chamber cleaning system, the energy consumption is accounted for mainly by maintaining the reduced temperature (at night), so that a higher operating temperature affects the result only slightly. Optimisation of the system parameters (temperature reduction from 70 °C to 60 °C for the multi-chamber cleaning system) has also shown that technical cleanliness can be improved significantly (Figure 10 and Figure 12). As a result, even cleaning costs are reduced by 3% and resource costs by 4% on average, compared to the baseline scenario. This shows that the implementation of higher cleanliness requirements does not always go hand-in-hand with a higher demand for resources as long as this can be achieved by adjusting the parameters of the existing cleaning technology.

A combination of all cleaning parameters in a minimum and maximum scenario has shown that with a high plant utilization, the multi-chamber cleaning system leads to lower environmental impacts. In a three-shift operation with seven days per week, no night temperature reduction is required. However, the power requirement for this is significantly higher for the multi-chamber cleaning system than for the single-chamber cleaning system. On the other hand, the energy consumption for the cleaning itself is lower. In continuous operation, therefore, a multi-chamber cleaning system should be used, while in case of low utilisation, the single-chamber cleaning system is preferable.

However, this does not apply to the economic assessment. In contrast to the ecological assessment, the influence of energy consumption is significantly lower here. Rather, the key factor affecting costs is personnel. However, the multi-chamber cleaning system always has higher cleaning costs, regardless of the scenario. This is a consequence of higher investment expenditure and longer cleaning cycles compared to a single-chamber cleaning system. It was not considered that in the multi-chamber cleaning system components can be cleaned continuously, while the single-chamber cleaning system represents a batch process. Multiple cleaning chambers thus have the advantage that during a running cleaning cycle, cleaning of other components can be started. The number of components per cycle increases compared to the single-chamber cleaning system, the influence on the energy and material flows, however, is low. Doubling the number of components per cycle thus leads to a reduction of around 50%. In the case of the baseline scenario, this could reduce cleaning costs by about 40% compared to the single-chamber cleaning system. The multi-chamber cleaning system should therefore be chosen exclusively from an economic point of view, if the advantage of several cleaning chambers can be exploited to the full.

In summary, it should be emphasised that purchasing and operating a cleaning system with low utilisation is unprofitable from both an ecological and an economic point of view. A solution that would be profitable for small and medium-sized companies, at least within the system boundaries considered here, could be commissioning of contract cleaning service providers. These can usually make effective utilisation of system capacities by combining orders. In this case, however, the effect of an essential transport journey for implementing the cleaning process should be taken into account.

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APPENDIX A: LCA RESULTS

Table 18: Ecological assessment - parameter analysis

Absolute values		GWP	CED	CRMD	Water	Surface area
Single-chamber cleaning system SCS						
Base	Base	0.39	7.31	2.49	1.78	0.04
Components	3 components	0.39	7.31	2.49	1.78	0.04
	5 components	0.23	4.39	1.50	1.07	0.02
Plant utilisation	24/7	0.24	4.65	1.57	1.14	0.03
	16/5	0.39	7.31	2.49	1.78	0.04
	8/5	0.60	11.20	3.85	2.77	0.06
	4/1	3.29	61.50	21.15	16.60	0.33
Operating condition	70 °C	0.53	9.99	3.41	2.38	0.06
	60 °C	0.39	7.31	2.49	1.78	0.04
	60 °C optimal					
Recycling route	with oil separator	0.39	7.31	2.49	1.78	0.04
	without oil separator	0.39	7.31	2.49	1.78	0.04
Multi-chamber cleaning system MCS						
Base	Base	0.42	7.88	2.73	1.71	0.04
Components	3 components	0.42	7.88	2.73	1.71	0.04
	5 components	0.25	4.73	1.64	1.02	0.03
Plant utilisation	24/7	0.23	4.35	1.50	0.94	0.02
	16/5	0.42	7.88	2.73	1.71	0.04
	8/5	0.72	13.60	4.70	2.95	0.08
	4/1	5.18	97.50	33.73	21.70	0.54
Operating condition	70 °C	0.39	7.32	2.53	1.61	0.04
	60 °C	0.42	7.88	2.73	1.71	0.04
	60 °C optimal	0.40	7.55	2.61	1.64	0.04
Recycling route	with ÖA	0.42	7.88	2.73	1.71	0.04
	without ÖA	0.42	7.88	2.73	1.71	0.04
Changes in comparison to the base		**GWP**	**CED**	**CRMD**	**Water**	**Surface area**
Single-chamber cleaning system SCS						
Base	Base	0.00%	0.00%	0.00%	0.00%	0.00%
Components	3 components	0.00%	0.00%	0.00%	0.00%	0.00%
	5 components	-39.90%	-39.95%	-40.0%	-39.89%	-40.0%
Plant utilisation	24/7	-36.79%	-36.39%	-36.96%	-35.96%	-35.86%
	16/5	0.00%	0.00%	0.00%	0.00%	0.00%
	8/5	54.15%	53.21%	54.37%	55.62%	52.41%
	4/1	752.33%	741.31%	747.90%	832.58%	713.50%
Operating condition	70 °C	36.27%	36.66%	36.58%	33.71%	37.40%
	60 °C	0.00%	0.00%	0.00%	0.00%	0.00%
	60 °C optimal					
Recycling route	with oil separator	0.00%	0.00%	0.00%	0.00%	0.00%
	without oil separator	0.00%	0.00%	0.00%	0.00%	0.00%
Multi-chamber cleaning system MCS						
Base	Base	0.00%	0.00%	0.00%	0.00%	0.00%
Components	3 components	0.00%	0.00%	0.00%	0.00%	0.00%
	5 components	-40.05%	-39.97%	-40.00%	-40.35%	-40.00%
Plant utilisation	24/7	-44.84%	-44.80%	-44.84%	-44.80%	-44.65%
	16/5	0.00%	0.00%	0.00%	0.00%	0.00%
	8/5	72.42%	72.59%	72.24%	72.51%	71.86%
	4/1	1142.21%	1137.31%	1137.30%	1169.01%	1129.69%
Operating condition	70 °C	-6.95%	-7.11%	-7.35%	-5.85%	-7.15%
	60 °C	0.00%	0.00%	0.00%	0.00%	0.00%
	60 °C optimal	-4.08%	-4.19%	-4.10%	-4.09%	-4.10%
Recycling route	with ÖA	0.00%	0.00%	0.00%	0.00%	0.00%
	without ÖA	0.00%	0.00%	0.00%	0.00%	0.00%

Table 19: Ecological assessment – scenario analysis

Absolute values	GWP	CED	CRMD	Water	Surface area
		Single-chamber cleaning system SCS			
"Min" scenario	0.15	2.79	0.02	0.68	0.94
Baseline scenario	0.39	7.31	0.04	1.78	2.49
"Max" scenario	3.62	67.80	0.37	18.00	23.32
		Multi-chamber cleaning system MCS			
"Min" scenario	0.10	1.94	0.01	0.44	0.66
Baseline scenario	0.42	7.88	0.04	1.71	2.73
"Max" scenario	5.18	97.50	0.54	21.70	33.73

Changes in comparison to the base	GWP	CED	CRMD	Water	Surface area
		Single-chamber cleaning system SCS			
"Min" scenario	-61.92%	-61.83%	-61.51%	-61.69%	-62.18%
Baseline scenario	0.00%	0.00%	0.00%	0.00%	0.00%
"Max" scenario	837.82%	827.50%	800.15%	911.24%	834.78%
		Multi-chamber cleaning system MCS			
"Min" scenario	-75.30%	-75.38%	-75.42%	-74.50%	-75.65%
Baseline scenario	0.00%	0.00%	0.00%	0.00%	0.00%
"Max" scenario	1142.21%	1137.31%	1129.69%	1169.01%	1137.30%

APPENDIX B: RESULTS OF COST EVALUATION

Table 20: Static cost evaluation – parameter analysis

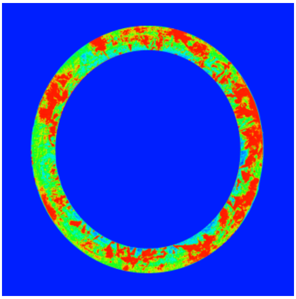
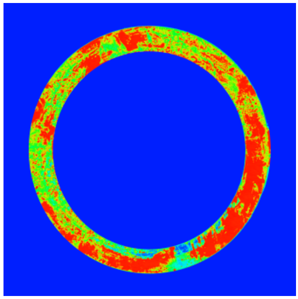
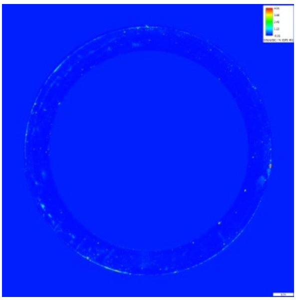
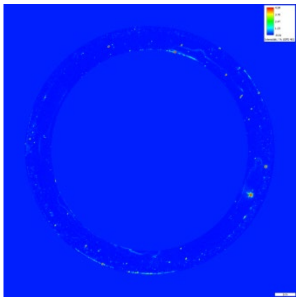
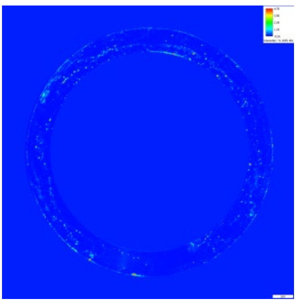
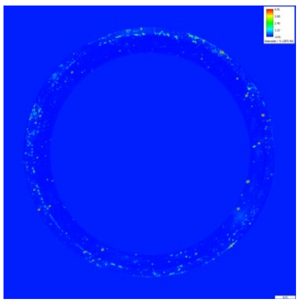
Absolute values		Additional costs per component	
		Single-chamber cleaning system SCS	Multi-chamber cleaning system MCS
Base	Base	€0.00	€0.00
Components	3 components	€0.00	€0.00
	5 components	€-0.39	€-0.46
Plant utilisation	24/7	€0.16	€-0.23
	16/5	€0.00	€0.00
	8/5	€0.36	€0.49
	4/1	€7.14	€9.63
Operating condition	70 °C	€0.04	€0.01
	60 °C	€0.00	€0.00
	60 °C optimal		€-0.03
Recycling route	with oil separator	€0.00	€0.00
	without oil separator	€0.00	€0.00
Disassembly and disposal	Simple disassembly	€0.00	€0.00
	Complete disassembly	€0.00	€0.00
Changes in comparison to the base in percent		**Additional costs per component**	
		Single-chamber cleaning system SCS	Multi-chamber cleaning system MCS
Base	Base	0.00%	0.00%
Components	3 components	0.00%	0.00%
	5 components	-39.99%	-39.99%
Plant utilisation	24/7	-16.59%	-19.86%
	16/5	0.00%	0.00%
	8/5	37.18%	42.96%
	4/1	735.18%	842.63%
Operating condition	70 °C	4.12%	1.20%
	60 °C	0.00%	0.00%
	60 °C optimal		-2.56%
Recycling route	with oil separator	0.00%	0.00%
	without oil separator	1.48%	0.31%
Disassembly and disposal	Simple disassembly	0.00%	0.00%
	Complete disassembly	0.00%	0.04%

Table 21: Static cost evaluation - scenario analysis

Scenario	Additional costs per component	
	Single-chamber cleaning system SCS	Multi-chamber cleaning system MCS
Absolute values		
“Min” scenario	€0.00	€0.00
Baseline scenario	€-0.51	€-0.64
“Max” scenario	€7.56	€9.83
Changes in comparison to the base in percent		
“Min” scenario	0.00%	0.00%
Baseline scenario	-52.99%	-55.69%
“Max” scenario	778.34%	860.19%

APPENDIX C: CLEANLINESS-ANALYSES OF FILM CONTAMINATION BY MEANS OF FLUORESCENCE

Table 22: Overview of the test results regarding film contamination

Process parameters	Images of laser-induced fluorescence	
Samples before cleaning process		
System type	SCS	MCS
"60 °C"		
"70 °C"		

System: F-Scanner (Fraunhofer IPM)
Power: 300 mW; Resolution: 500 µm; Amplification: 80%

APPENDIX D: CLEANLINESS ANALYSES FOR PARTICULATE IMPURITIES ACCORDING TO VDA VOLUME 19.1

Scenario 60 °C multi-chamber cleaning system

Table 23: Extraction, microscopic analysis & statistics 60 °C multi-chamber cleaning system

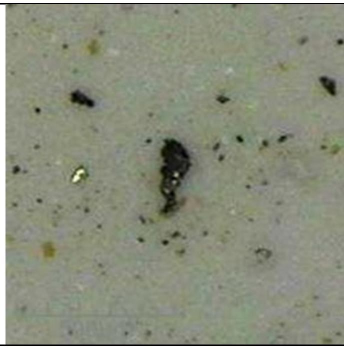
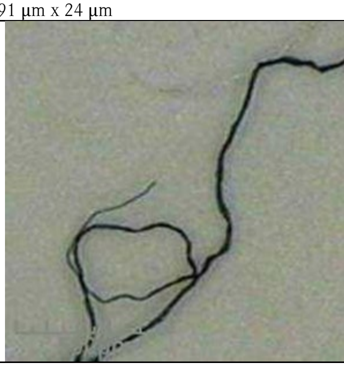
Extraction & gravimetry					
Method:	**Spraying**	**Number of parts:**		**1**	
Flushing liquid:	**Haku 1025-921**	**Filter type:**		**Cellulose 5 µm**	
Quantity [ml]:	**6000 ml**	Weight [mg]:		**n. determined**	
Microscopic analysis					
Scale	X:4.3µm/Pxl Y:4.3 µm/Pxl	Evaluation - Ø [mm]:		44	
Filter clogging	0.70508	Permitted clogging		1.5% (cellulose), 3% (nylon)	
Largest metallic particle		Length [µm]:	236	Width[73] [µm]:	22
Largest non-metallic particle [74]		Length [µm]:	445	Width [µm]:	25
Stretched length of the longest fibre		L_{str} [µm]:	4909	Total [mm]:	24.7

Detailed statistics					
Length	Code	On filter membrane		per component	
[µm]		Total	Metallic	Total	Metallic
> 3000	N	0	0	0.0	0.0
2000...3000	M	0	0	0.0	0.0
1500...2000	L	0	0	0.0	0.0
1000...1500	KL	0	0	0.0	0.0
600...1000	J	0	0	0.0	0.0
400...600	I	1	0	1.0	0.0
200...400	H	11	2	11.0	2.0
150...200	G	14	1	14.0	1.0
100...150	F	88	13	88.0	13.0
50...100	E	980	155	980.0	155.0
25...50	D	4984	401	4984.0	401.0
15...25	C	9378	223	9378.0	223.0
5...15	B	18735	79	18735.0	79.0

[73] Particle widths are always measured in this report as a vertical section.

[74] Counted particles without fibres; fibre criterion: non-metallic, ratio Lstr / surface diameter > 20 and surface diameter ≤ 50 µm.

Table 24: Image material for cleanliness analysis 60 °C multi-chamber cleaning system

	
Largest metallic particle 236 µm x 22 µm	Second largest metallic particle 224 µm x 96 µm
	
Largest non-metallic particle 445 µm x 25 µm	Second largest non-metallic particle 291 µm x 24 µm
	
Filter overview 0.71% clogging in Ø = 44 mm	Longest fibre $Feret_{max}$ = 2036 µm / L_{str} = 4609 µm

Scenario 60 °C single-chamber cleaning system

Table 25: Extraction, microscopic analysis & statistics 60 °C single-chamber cleaning system

Extraction & gravimetry			
Method:	**Spraying**	**Number of parts:**	**1**
Flushing liquid:	**Haku 1025-921**	**Filter type:**	**Cellulose 5 µm**
Quantity [ml]:	**6000 ml**	Weight [mg]:	**n. determined**

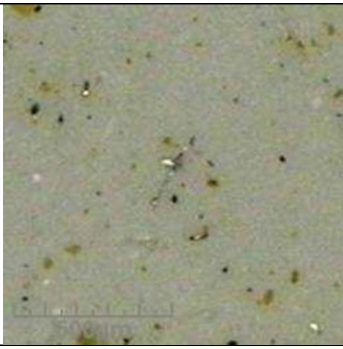
Microscopic analysis					
Scale	X:4.3µm/Pxl Y:4.3 µm/Pxl	Evaluation - Ø [mm]:		44	
Filter clogging	0.704751	Permitted clogging		1.5% (cellulose), 3% (nylon)	
Largest metallic particle		Length [µm]:	269	Width[75] [µm]:	58
Largest non-metallic particle [76]		Length [µm]:	419	Width [µm]:	33
Stretched length of the longest fibre		L_{str} [µm]:	3107	Total [mm]:	16.9

Detailed statistics					
Length	Code	On filter membrane		per component	
[µm]		Total	Metallic	Total	Metallic
> 3000	N	0	0	0.0	0.0
2000...3000	M	0	0	0.0	0.0
1500...2000	L	0	0	0.0	0.0
1000...1500	KL	0	0	0.0	0.0
600...1000	J	0	0	0.0	0.0
400...600	I	1	0	1.0	0.0
200...400	H	8	1	8.0	1.0
150...200	G	13	4	13.0	4.0
100...150	F	93	33	93.0	33.0
50...100	E	1057	274	1057.0	274.0
25...50	D	5860	607	5860.0	607.0
15...25	C	9948	343	9948.0	343.0
5...15	B	19951	125	19951.0	125.0

[75] Particle widths are always measured in this report as a vertical section.

[76] Counted particles without fibres; fibre criterion: non-metallic, ratio Lstr / surface diameter > 20 and surface diameter ≤ 50 µm.

Table 26: Image material cleanliness analysis 60 °C single-chamber cleaning system

	
Largest metallic particle 269 µm x 58 µm	Second largest metallic particle 186 µm x 26 µm
	
Largest non-metallic particle 419 µm x 33 µm	Second largest non-metallic particle 390 µm x 53 µm
	
Filter overview 0.70% clogging in Ø = 44 mm	Longest fibre $Feret_{max}$ = 708 µm / L_{str} = 3107 µm

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Im Auftrag des:
Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit
NATIONALE KLIMASCHUTZ INITIATIVE