VDI Zentrum Ressourceneffizienz

On behalf of:

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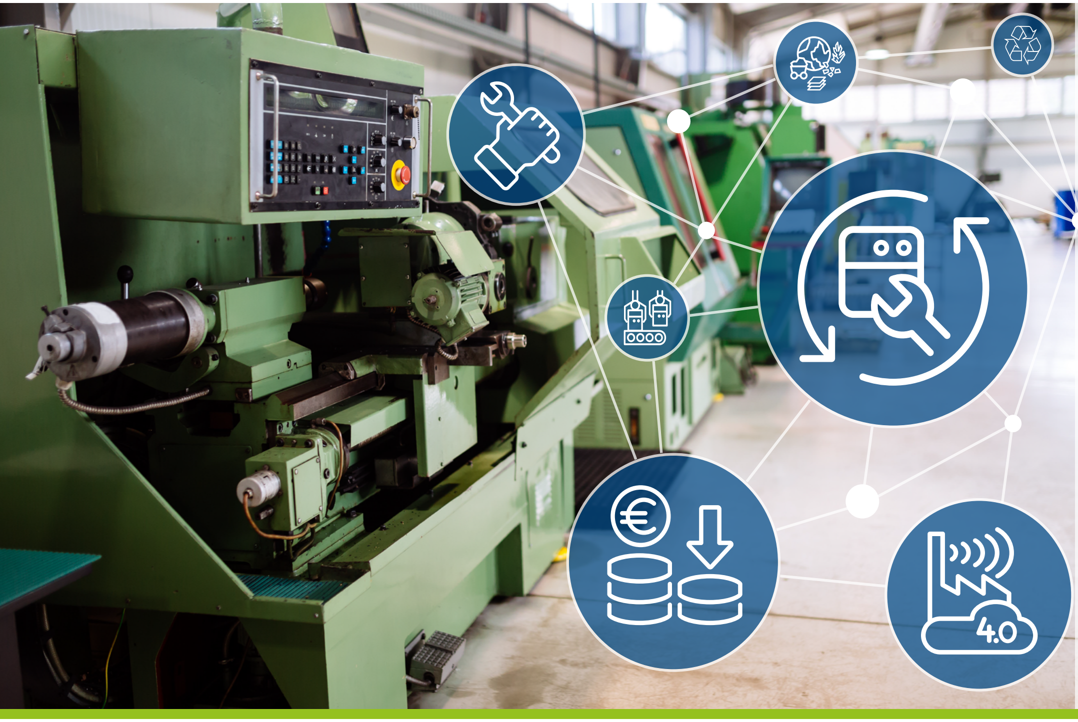
Nuclear Safety and Consumer Protection

Ecological and Economic Assessment of Resource Use

Industry 4.0 retrofit measures on machine tools



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Study: Ecological and Economic Assessment of Resource Use – Industry 4.0 retrofit measures on machine tools

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Ecological and Economic Assessment of Resource Use

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LIST OF ABBREVIATIONS

ADP	Abiotic Depletion Potential (abiotic resource consumption)
AP	Acidification Potential
AW	Anti-Wear (additives in CL)
BDEW	Bundesverband der Energie- und Wasserwirtschaft e.V. (Federal Association of the Energy and Water Industry)
CL	Cooling Lubricant
CNC	Computerised Numerical Control (machine tool)
CO_2	carbon dioxide
CPS	Cyber Physical Systems
CPPS	Cyber-Physical Production Systems
DIN	Deutsches Institut für Normung e.V. German Standards Institute)
EoL	End of Life
EP	Eutrophication Potential/ Extreme Pressure (additives in CL)
FCL	Flood Cooling Lubrication
GWP	Global Warming Potential
HMI	Human-Machine Interaction
HMI-C	Human-Machine Interaction Communication
HRC	Hardness test according to Rockwell
IPCC	Intergovernmental Panel on Climate Change

IWF	Institute for Machine Tools and Manufacturing Technology
KEA	Kumulierter Energieaufwand (Cumulative Energy Demand)
KRA	Kumulierter Rohstoffaufwand (Cumulative raw material demand)
MQL	Minimum Quantity Lubrication
MQTT	Message Queuing Telemetry Transport (open network protocol for machine-to-machine communication)
MT	Machine Tool
NC	Numerical Control
Nwm CL	Non-water-miscible Cooling Lubricants
ODP	Ozone Depletion Potential
PM	Particulate Matter (dust particles)
PM10	Particulate Matter < 10 µm
POCP	Photochemical Ozone Creation Potential
SC	Supply Criticality
SME	Small and medium-sized enterprises
VDI	Verein Deutscher Ingenieure e.V. (Association of German Engineers)
VDI ZRE	VDI Zentrum Resource Efficiency GmbH (VDI Centre Resource Efficiency)
VDMA	Verband Deutscher Maschinen- und Anlagenbauer e.V. (Association of German Machine and Systems Engineers)

WEEE	Waste Electrical and Electronic Equipment
Wm CL	Water-miscible Cooling Lubricants

SYNOPSIS

Machining processes such as turning, drilling, milling and grinding are an essential part of industrial manufacturing process chains. From an economic and ecological point of view, grinding as a typical finishing process is of particular importance, because products have already experienced a high added value up until this step of the process. Manufacturing companies therefore strive to avoid scrap during the grinding process.

The grinding heat generated by the grinding contact requires cooling lubrication to protect the tool from wear and to reduce wastage, in the interests of process safety. However, the technical advantages of cooling lubricants (CL) are countered by environmental disadvantages, especially with regard to conventional CL when considering the entire life cycle.[1] Not only the CL as such, but also the usual flood cooling lubrication (FCL) during grinding is problematic, as it is associated with a high peripheral demand and energy-intensive operation. The ecological performance of the FCL can be significantly increased through energy and material efficiency measures, but this requires process monitoring, which is carried out for older machines using retrofit measures from the Industry 4.0 sector.

Retrofit in the context of Industry 4.0 refers to the modernisation of existing plants or equipment by means of extension or the retrofitting of sensors and communication interfaces and their integration into a networked production environment. Goals of a retrofit can include extending the service life of the production plant, increasing the production volume or reducing the production-related environmental effects. For machining production, especially in small and medium-sized companies, this results in a wide range of options for the modernisation of conventional machine tools.

The aim of the study is a comparative ecological assessment and an economic analysis of selected Industry 4.0 retrofit measures for machining production on the basis of a reference component. After an initial introduction of Industry 4.0 using the cyber-physical model presentation of a production system (CPPS), a machine tool is retrofitted for experimental purposes. The focus is

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[1] **Cf. VDI Zentrum Ressourceneffizienz GmbH (2017b).**

on a software and hardware solution that is as easy to implement and cost-effective as possible, in order to address a wide spectrum of applications and, in particular, small and medium-sized enterprises in the manufacturing industry. In many cases, they do not yet have enough experience and knowledge regarding the opportunities, challenges and implementation of such retrofit measures.

The project is carried out in four steps:

- research regarding basics and state-of-the-art technology for manufacturing processes and machine tools, Industry 4.0, CPPS and retrofit stages,
- definition and description of the spatial and temporal study framework, selection of a reference component and the functional unit,
- ecological and economic assessment of the various retrofit measures in terms of the concept and reference system,
- evaluation of results, summary and conclusions.

The technical production system limitations of the study relate to the machine tool, the peripheral systems and the CPPS. The system limitations as well as the considered phases of the product lifecycle are shown in Figure 1.

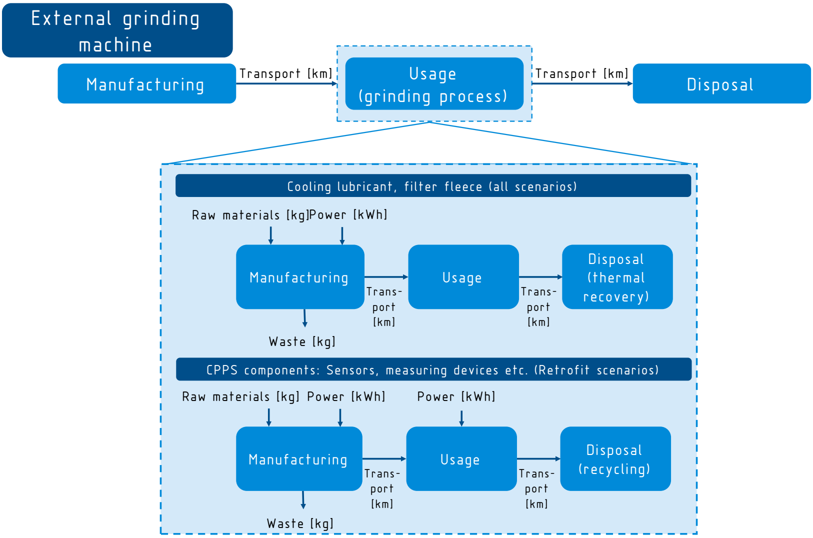

Figure 1: System limitations of the considered scenarios (ecological and economic evaluation)

The CPPS is based on four components: the physical level (I), data acquisition and processing (II), the virtual level (III) and decision support incl. control and regulation (IV). These constituent elements extend an existing machine environment to a CPPS, constituting the reference scenario for ecological and economic evaluation. As a retrofit scenario, three measures are introduced into the reference system that relate to the following retrofit strategies.

- Oscillation and vibration retrofit

Suitable sensors for vibration measurement are fitted close to the process that is to be observed and the data thereby acquired is processed by a backend system. Data processing is process-oriented and requires just a few installation steps that can be implemented by SMEs. The potential here is the improvement of component qualities, the optimised operation of the system or the prediction of failures.

- Energy retrofit

The installation of an energy retrofit comprises the overall measurement of all energy supplies of the plant and their monitoring. Methodological knowledge such as the energy value stream or energy breakdown analyses are generally applied to convert a significant basis of data into insights and process improvements. This can lead, for example, to optimised process chains or energetically efficient operating states.[2]

- Condition monitoring retrofit

Condition monitoring does not only include the measurement of vibration data but also the overall coverage of the environmental data of the plant, so that a digital image, a so-called digital shadow, can be created[3] [4]. This implementation requires sensors (for example, tool force measurements or large-scale temperature and humidity measurement), the introduction of which is highly complex. In addition, networking is necessary for the optimal recording of data-based states, in order to be able to e.g. predict failures.

The retrofit measures of the comparison scenario result in a customised sensor strategy that is implemented within the physical level of the CPPS. As a result, the scenarios can be compared and solutions can be created within the CPPS to improve the basic system. This basis of transparency results in improvement measures for the system, which in this example relate to the CL supply of the process. Based on the observations and comparisons of the data situation, it is evident that processing within the process without a CL supply can lead to considerable energy savings. This is due to the performance ratio between the CL system and the machine. However, the prerequisite for processing without a CL feed is based on the assumption that the process can continue to be guaranteed without any quality compromises (see chapter 5.1.3). In Figure 2 the difference between the energy consumption in the reference scenario and the retrofit scenario is illustrated.

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[2] Cf. VDMA (2020).

[3] Cf. Engels, G. (2020).

[4] Cf. Anisic, Z.; Lalic, B. und Gracanin, D. (2020).

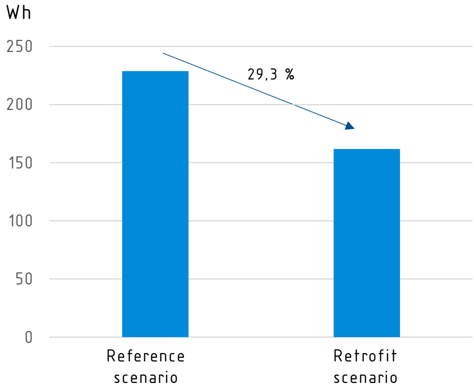

Figure 2: Improving the energy efficiency of the system

This more efficient processing is generated verifiably by the retrofit. The striven for quality, which can be assessed primarily through the oscillation and vibration retrofit, is still within the required tolerance range, despite the saving. In this case, the condition monitoring retrofit also contributes to the confirmation of the result, but if observed for a longer period would allow further conclusions to be drawn about the process or component quality. This retrofit scenario could conceivably harbour possible potential in relation to predictive maintenance or in-process monitoring of the component. This retrofit scenario provides the framework for an ecological and economic assessment of the used hardware and CPPS as a retrofit method.

The definition of a functional unit is required for the balance sheet comparison. A functional unit generally refers to the quantified benefit of a producing system that is used as a comparison unit. For the present case, a standard test with the following data was selected, which was used as a basis according to the literature for a grinding production system[5] (see Table 1):

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[5] Cf. Winter, M.; Thiede, S. und Herrmann, C. (2015).

Table 1: Functional unit related to a production scenario of a single machine

Size	Unit	Value
Working days per year	Days/year	250
Shifts per day	-	1
Shift duration per day	h/day	8
Operating time per year	%	80
Productive machine utilisation	h	1,600
Chipping quantity per reference workpiece	cm³/piece	1.4
Cutting time per reference workpiece	min/piece	1.6388
Quantity produced per year	**pcs./year**	**58,579**
Chipping volume per year	**cm³/year**	**82,010**

The natural resources expenditure (energy, raw materials, water, soil) required for the implementation of the retrofit measures is taken into account over the entire lifecycle of the machine tool. The ecological assessment was carried out using environmental indicators for the individual resource groups, as shown in Table 2. This also shows the overall results for all indicators.

The economic assessment includes manufacturing and transport costs, as well as utilisation costs (in this case exclusively electricity consumption) and disposal costs. If these cost components are compared and added up, electricity costs at 52.0% account for the highest proportion of costs in the reference scenario, while manufacturing and transport costs amount to 40.6% and disposal costs are 5.8%. In the retrofit scenario, due to the additionally required sensors, computers and servers, the manufacturing and transport costs are 53.8%, making up the highest proportion, while the electricity costs are only 40.4% and the disposal costs are 5.8%.

Table 2: Results of the ecological assessment (per functional unit)

Effect indicator	Reference unit	Reference scenario	Retrofit scenario
Global warming potential	Kg CO_2equivalent	11,352.9	9,436.5
Cumulative energy demand (KEA) (exhaustive + regenerative)	MJ	20,5243.6	16,9249.5
Cumulative resource expenditure (KRA) (biotic + energy raw materials + metal raw materials + mineral raw materials, stones and earths)	kg	4148.9	4581.0
Water consumption	kg	60,992.2	51,265.7
Land use, (agricultural land + residential land)	m^2*a	402.9	344.1

In total, the higher investments of the retrofit measures (€742.32/a, costs in relation to the functional unit) are only partially compensated for by savings in power consumption (€451.59/a) and in the disposal phase (€61.22/a) over the assumed service life of the machine tool of a further 15 years. There remains a balance of additional costs of €229.51/a for the retrofit measure. The overall overview of the cost allocation is shown by Table 3.

Table 3: Cost allocation of manufacturing (including transport), use and disposal – comparison of reference and retrofit scenario

Scenario	Manufacturing and transport costs in €/a	Cost of power consumption (usage phase) in €/a	Disposal Costs in €/a	Total costs in €/a
Reference scenario	1,912.43	2,445.75	346.50	4,704.67
Retrofit scenario	2,654.75	1,994.16	285.28	4,934.18
Cost difference in the retrofit scenario	742.32	-451.59	-61.22	229.51

The results of the study are summarised in Table 4 and divided into a scale system with “++” as the best and “- -” as the worst indicator value.

Table 4: Overall comparison of the criteria for the reference and retrofit scenarios – including a sensitivity analysis regarding increased power consumption – referring to the functional unit

Effect indicator	Reference scenario	Retrofit scenario	Sensitivity analysis with increased CPPS power consumption
Global warming potential	-	++	+
Cumulative energy demand (KEA)	-	++	+
Cumulative resource expenditure (KRA)	++	-	-
Water consumption	-	++	+
Land use	-	++	+
Total costs	+	o	-

The results of this study show that the individual indicators predominantly support the introduction of the considered retrofit measures. With the exception of cumulative resource expenditure, retrofit measures lead to an improvement in the impact on the environment. If the power consumption of the CPPS units increases by 50% (assuming a sensitivity analysis), the advantage of retrofitting measures is slightly reduced compared to the normal situation.

However, under the given assumptions, the additional costs of the retrofit measures are not fully amortised over the lifecycle of the investment. However, due to the lack of information on maintenance and upkeep, the study could not take into account that the retrofit measures could potentially extend the service life of the plant. Similarly, a significant increase in the electricity price in the future, or the assumption that small enterprises still face a higher electricity price – similar to that for private households – could relativise the unprofitability of the investment from a corporate perspective. Furthermore, the product diversity, as well as the product quality, can be increased through technical retrofit measures. The initial acquisition of measuring technology is also the starting point for further measures that can be used to identify and therefore make use of economic and ecological potential.

Where an increased use of retrofit measures is socially beneficial from an efficiency and environmental point of view, such investments should be supported by the state in order to create an incentive for the company during the remaining lifecycle of the plant, regardless of uncertainty regarding economic profitability: On the one hand, SMEs are provided with teaching and learning environments for sustainable production. On the other hand, there should be an interest in this on the part of the government, because the appropriate implementation of the measures can tap into environmental potential and thereby contribute to the achievement of the CO_2 targets. At the same time, such retrofit measures should be supported by accompanying measures such as targeted information, scientific monitoring and documentation of good practice examples from different fields of application.

1 BACKGROUND AND OBJECTIVES

The digital networking of people, machines and processes in the industrial sector (Industry 4.0) offers the opportunity to increase the resource efficiency potential and thereby contribute to the conservation of resources. Material and energy savings can be realised based on raising productivity, reducing throughput times and increasing flexibility. The use of information and communication technologies as part of Industry 4.0 enables the collection and analysis of production data, in some cases in real time. This leads to the creation of a high level of information transparency, which records material-structure-process-property relationships and decentrally derives measures for process optimisation. Possible process improvements can be implemented directly in production.

Implementation can be achieved, for example, with retrofit measures. Retrofit refers to the modernisation of existing plants or equipment. In the context of Industry 4.0, this means extending or retrofitting sensors and communication interfaces and integrating them into a networked production environment. The additional data thus available can lead to specific improvements in the production process after analysis and evaluation. A variety of measures or improvements can be the aim of retrofitting, such as extending the service life of the plants, increasing the production volume or improving ecological and economic aspects through material and energy savings. An energy-saving retrofit could include the use of more energy-efficient motors or the installation of frequency inverters for the operationally optimised control of the motor[6]. In the field of machining, especially in small and medium-sized enterprises (SMEs), there are retrofit options for the modernisation of conventional machine tools.

On the other hand, the production of new parts and components as well as their use also incurs costs (e.g. energy costs) and resource outlay. This may result in further environmental pollution. In addition, when considering a retrofit measure, the costs must also be explicitly taken into account, as these represent a significant part of the economic perspective of a retrofit.[7]

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[6] Cf. VDMA (2020).

[7] Cf. Kruk, R. (2011).

A further challenge is how to achieve the optimal combination of operating conditions to minimise environmental impact and at the same time costs, while maintaining or increasing the quality of the product being processed. SMEs, in particular, often lack the knowledge and experience to implement retrofit measures in the context of Industry 4.0 and the opportunities it presents. In order to support decision-making, the influence of a retrofit measure in the field of Industry 4.0 is therefore analysed not only from an ecological but also from the economic point of view of the company.

Objectives

The aim of the study is a comparative ecological and economic assessment of the machining production of a reference component. For this purpose, various production scenarios with and without retrofitting a machine tool are analysed by means of retrofitting measures. It shows the ecological and economic effects the choice of production methods can have for a wide range of applications. The main target groups of the study are small and medium-sized enterprises (SMEs) in the manufacturing industry, manufacturing companies in the mechanical and plant engineering sector, consultants and research institutes. They are to be supported in their decisions regarding the chosen manufacturing process. The study also serves as a source of information for initiatives and associations, as well as federal, state and representative bodies.

After an analysis of the state of the art, the reference component is selected for the subsequent evaluation, taking into account various aspects (e.g. functional unit, system limitation, data availability, machine usage time, framework conditions). This is divided into an overall ecological assessment, which considers energy and raw material requirements as well as CO_2 emissions, land requirements and supply-critical raw materials, among other things, and an economic analysis, in which investment and ongoing costs from different lifecycle phases are analysed. It is also examined whether the investments of the retrofit components fully amortise under the conditions considered. The ecological assessment is carried out according to VDI 4800-1[8] and VDI 4800-2[9] as well as VDI 4600[10] and DIN EN ISO 14040[11]/44[12].

Answers to the following research questions will be developed:

- What advantages and disadvantages or obstacles result from the implementation of retrofit measures in the field of Industry 4.0, in particular with regard to increasing the resource efficiency of the production process?
- What expenditure on raw materials, energy, water and land must be paid for the production of the reference products (including and excluding retrofitting measures), taking into account the entire lifecycle?
- Which supply-critical raw materials are used or saved in the manufacture of the reference products (including and excluding retrofitting measures)?
- What greenhouse gas emissions, expressed in CO_2equivalents, are emitted in each manufacturing scenario?
- What are the costs for the production scenarios under consideration?

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[8] VDI 4800-1:2016-02.

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

[10] VDI 4600-1:2015-08.

[11] DIN EN ISO 14040:2006.

[12] DIN EN ISO 14044:2006.

2 STRUCTURE OF THE STUDY

The study is carried out in four steps (cf. Figure 3):

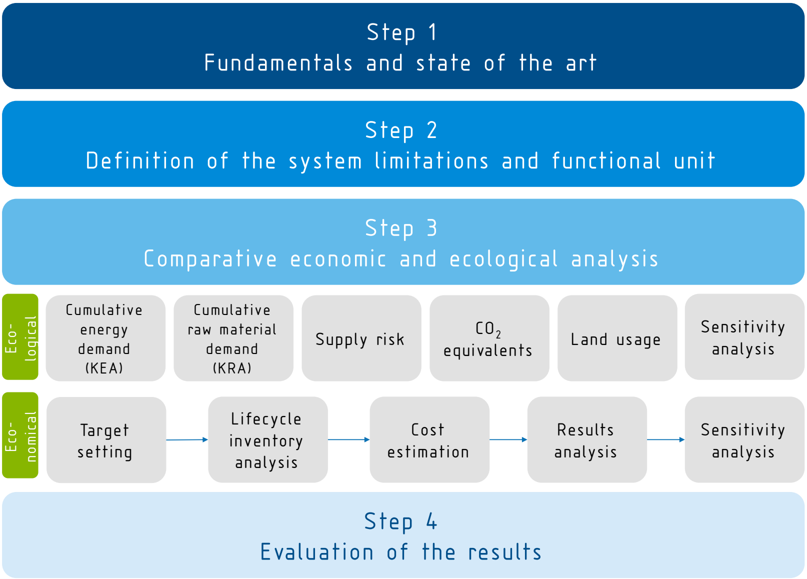

Figure 3: Structure of the study

First, machine tools are presented as representative manufacturing processes for the sustainability efforts of the metal processing industry and Industry 4.0 is described on the basis of the CPPS. This is followed by a classification of Industry 4.0 retrofit measures. The second step involves the definition and description of the spatial and temporal investigation framework (process configuration and observation period), the determination of a reference component and the derivation of the functional unit. In the third step, the ecological and economic evaluation of the various retrofit measures is carried out with regard to the compiled concept and the reference system, including a scaling framework.

To conclude, the results are evaluated in the fourth step, the core results are summarised and conclusions are drawn.

3 SUSTAINABLE SETUP OF METALWORKING PROCESSES

3.1 Metal processing

3.1.1 Manufacturing processes and machine tools

According to DIN 8580, separation is one of the six main groups of manufacturing processes in addition to primary shaping, forming, joining, coating and changing material properties[13]. The subgrouped separation processes of dividing, cutting with geometrically defined or undefined cutting edges, removal, disassembly and cleaning are an essential component of industrial manufacturing process chains. In particular, machining processes according to DIN 8589[14] are very common and are further divided into processes with geometrically defined cutting edges such as turning, drilling and milling, as well as processes with geometrically undefined cutting edges such as grinding, honing and lapping. At machine level, the above-mentioned procedures are implemented by using machine tools (MT).

According to DIN 69651, a machine tool is a “mechanised and more or less automated manufacturing device that generates a predetermined shape on the workpiece or a change in a predetermined shape on a workpiece by means of relative movement between the workpiece and the tool”[15]. Machine tools for procedures such as turning, milling, drilling and grinding machines are widely used. Main manufacturing groups and a selection of common machine tools for separating processes are shown in Figure 4. Grinding processes are particularly important in manufacturing process chains, as they are usually used at the end of the process chains.

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[13] Cf. DIN 8580:2003.

[14] Cf. DIN 8589:2003.

[15] DIN 69651:1981.

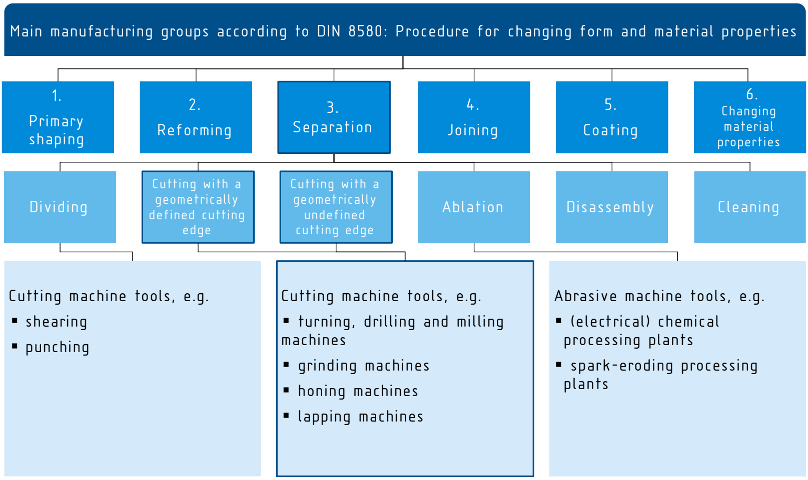

Figure 4: Main groups of manufacturing processes and machine tools[16]

3.1.2 Grinding and cooling lubricants

Grinding methods are used for machining with geometrically undefined cutting edges[17]. In these, a large number of stochastically distributed sanding elements penetrate the component to be machined. In addition to material pairing, grinding processes are defined by the input setting parameters. These include the delivery (traversing distance), the feed speed (traversing speed) and the cutting speed (peripheral speed of the grinding wheel) as the most important parameters. The combination of these parameters largely determines the production result of the grinding process.

The heat generated during grinding requires cooling lubrication in order to protect the tool and to reduce scrap by increasing process reliability. Conventionally, cooling lubricants (CL) are used for this purpose[18], which on the one hand dissipate heat through cooling and on the other hand prevent heat generation through lubrication. The technical advantages of CL are partially

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[16] In reference to DIN 8580:2003 and DIN 8589:2003.

[17] Cf. DIN 8589:2003.

[18] Cf. Brinksmeier, E.; Meyer, D.; Huesmann-Cordes, A. G. und Herrmann, C. (2015).

counteracted by negative influences on the environment, especially with regard to conventional CL over the entire lifecycle.[19]

Conventional CL are mineral oil-based (non-water miscible CL) or emulsions with a mineral oil content and have correspondingly high environmental impacts. The CL used are usually routed into circuits and have a high peripheral requirement. Pumps, filter systems and extraction systems are the most energy-intensive systems in the peripheral systems. In particular, the operation of high-pressure CL pumps can be consumption-intensive[20]. This high energy requirement is associated with high operating costs, which are often due to oversized CL applications. An example shows that the same technical performance is achieved with fewer resources when measures are taken to optimise the nozzle design[21]. Overall, the use of CL represents a technological necessity for companies when grinding, but at the same time it is associated with a greater cost and environmental impact.

3.2 Overall consideration of manufacturing processes

3.2.1 Material and energy flows in productionsystems

Manufacturing processes are part of a production system and are used to deliver products using materials and energy. For the sustainable setup of individual processes, an overall view is required, which considers all flows in and out of the production system, enables a derivation of measures and thereby provides the basis for an evaluation. It is not only a single machine tool that must be taken into account here, but the combination of these to form a process chain.

In the context of production, a machine tool is one of many machines whose processes as a whole result in the manufacturing process chain. Figure 5 shows an overall view of processes and process chains. The main material flow goes through the processes one after the other until the last process, in which the final product is finally manufactured. The individual process steps each have their specific resource requirements, which depend on the current

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[19] Cf. Herrmann, C.; Madanchi, N.; Winter, M.; Öhlschläger, G.; Greßmann, A.; Zettl, E.; Schwengers, K. und Lange, U. (2017).

[20] Cf. Denkena, B.; Helmecke, P. und Hülsemeyer, L. (2014).

[21] Cf. Madanchi, N.; Winter, M.; Thiede, S. und Herrmann, C. (2017).

machine status. In addition, the processes have specific process, downtime and repair times that significantly influence the productivity of the overall process. Energy flows are supplied in various forms such as electricity, compressed air or steam. The outgoing resource flows are waste materials and scrap. For example, the energy supplied to the processes is converted into thermal energy as the starting product. The process chain is also supported by technical building equipment systems. These include, for example, air conditioning and ventilation systems, which again require resources such as oil and gas[22]. A grinding process is a single operation in the entire manufacturing process chain and has process-specific material and energy flows, including the material and energy flows of the peripheral systems.

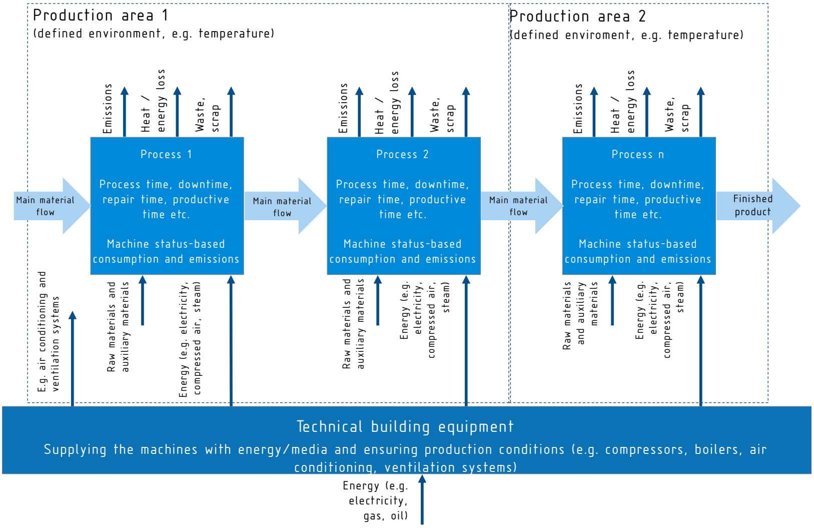

Figure 5: Overall consideration of process chains[23]

3.2.2 Material and energy flows in grinding processes

In addition to energy and grinding discs, CL is also required for the actual grinding process. The peripheral systems of the CL circuit must be taken into

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[22] Cf. Thiede, S.; Seow, Y.; Andersson, J. und Johansson, B. (2013).

[23] Based on Thiede, S.; Seow, Y.; Andersson, J. and Johansson, B. (2013).

consideration as significant material and energy consumers[24]. On the one hand, the pump and filter system of the CL must be mentioned, which in turn must also be supplied with energy and the CL fluids. A further raw material is, for example, belt filter material, which is used up during the process. The CL and chipping residue nebulised in the process are suctioned in as emissions from the exhaust air system with further energy expenditure and incur waste. Figure 6 shows such a constellation of important material and energy flows from grinding processes.

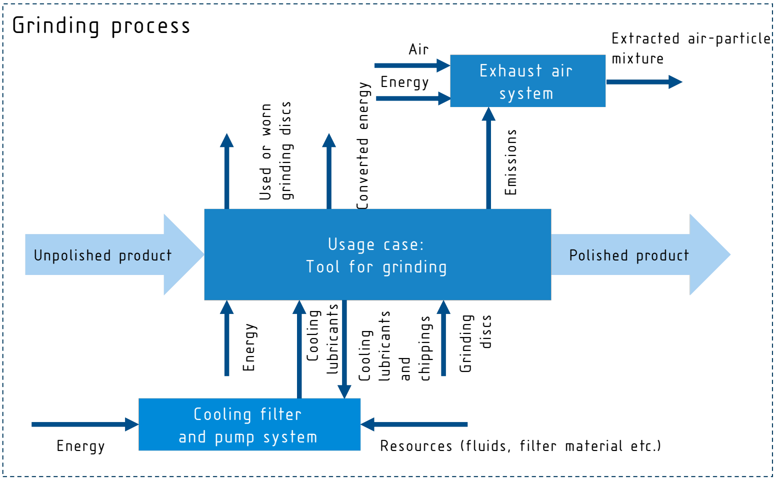

Figure 6: Important material and energy flows in grinding processes[25]

A quantitative breakdown of consumers is required to identify potential energy savings. Figure 7 shows an example of the energy distribution of a grinding machine in which the energy flows for the exhaust air system and for the CL system were taken into account[26]. The example shows a consumption of 45% in relation to the total energy consumption of the grinding system, with 29% for the CL system and 16% for the exhaust air system. In addition to the basic energy requirement of the grinding machine (35%), the

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[24] Cf. Madanchi, N.; Thiede, S.; Gutowski, T. und Herrmann, C. (2019).

[25] Based on Madanchi, N.; Thiede, S.; Gutowski, T. and Herrmann, C. (2019).

[26] Cf. Madanchi, N. (2022).

spindle with 12% and the grinding process with 8% constitute the other consumers that are difficult to make more efficient. Efforts to increase the energy efficiency of peripheral systems therefore have particularly great potential.

Figure 7: Example of energy components of a grinding system[27]

3.3 Approaches to environmentally sustainable grinding

A reliable evaluation of efficiency-enhancing measures and the resulting outcomes must take into account all system changes in order to quantify problem-shifting effects. The CL supply is an example of this. In addition to the respective CL types, various approaches to the CL feed strategy are conceivable. While common flood cooling lubrication (FCL) has technical advantages due to good cooling and lubrication conditions, it is also associated with a high peripheral demand and a potential risk to the environment and health. A further disadvantage is the aging of water-based CL and the associated regular CL change. Aging, however, is unproblematic in the case of minimum quantity lubrication (MQL), in which volume flows are reduced to a minimum. With the MQL there is no circulation, which on the one hand has the advantage of peripheral savings, but at the same time has the disadvantage of fluid loss, because unlike in the circulation system, the fluid is not returned to the circuit after use but is disposed of together with the resulting chippings.

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[27] **Based on Madanchi, N. (2022).**

However, the risk potential for human health and the environment is reduced in the case of MQL compared to FCL. In dry machining, CL and therefore all CL-related peripherals are completely dispensed with. However, the disadvantages here are poor process performance and consequently higher reject rates, as well as increased tool wear,[28] which in turn have a negative impact on ecological and economic performance. A further approach to environmentally sustainable grinding is the substitution of conventional, mineral oil-containing CL with organically based alternatives. Although the disposal of these CL is less critical, a shorter shelf life of the CL leads to more frequent CL changes.

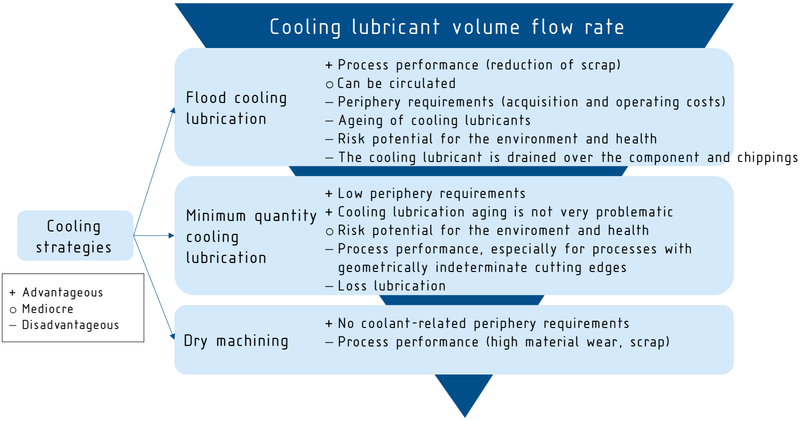

Figure 8: Advantages and disadvantages of common CL feed strategies[29]

As the most proven CL strategy for grinding processes, the FCL is still the most common feed strategy, which is why opportunities for demand-oriented process control are provided here. This means that a reduced CL pressure can, on the one hand, save pump power and CL loss through suction, while on the other hand the CL reduction may lead to technical performance deficits.

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[28] Cf. Arafat, R.; Madanchi, N.; Thiede, S.; Herrmann, C. und Skerlos, S. J. (2021).

[29] Based on Arafat, R.; Madanchi, N.; Thiede, S.; Herrmann, C. and Skerlos, S. J. (2021).

The resulting potential excess rejection of workpieces, as well as increased machine and tool wear, counteract the savings.

A reduction in performance by the CL extraction system is also associated with energy savings. However, if the exhaust system has a drastically reduced performance or is completely shut down, the risk of fires and health risks for machine-operating employees due to the inadequate extraction of aerosols increases. Appropriate approaches for the more sustainable setup of the FCL in conventional grinding processes are summarised in Table 5 , whereby problem-shifting effects were taken into account.

As mentioned above, an overall ecological and economic assessment must take into account all material and energy flows of the process or process chain. The stated examples, meanwhile, show that the evaluation of sustainable setup approaches is complex, not least because the approaches always have negative effects.

To quantify potential savings, process monitoring through data collection is essential. Tools from Industry 4.0 are widely used for this purpose, which will be discussed in more detail in the next section.

Table 5: Example approaches to the sustainable design of FCL in grinding processes

Approach	Sample literature	Possible positive effects	Possible negative effects
Substitution of FCL with MQL	Campitelli, A. et al. (2019)[30]; Arafat, R. et al. (2021)[31]	Partial saving of CL-related peripherals such as pump and filtration systems and their operation → Lower peripheral waste, lower energy consumption	Increase in scrap, increased tool wear, increased machine wear, greater risk of corrosion, higher CL waste, need for additional cooling peripherals
Dry machining instead of FCL	Kitzig, H. et al. (2014)[32]; Tawakoli, T. et al. (2007)[33]	Saving on all CL-related peripherals → no peripheral waste, better environmental performance	Poor process performance (especially during grinding) → scrap rate and tool wear are greater
Substitution of oil-based CL with organically based fluid	Venkatesh, K. et al (2018)[34]; Dettmer, T. (2006)[35]	Improved environmental performance, cost savings through waste utilisation	Reduced CL durability → More frequent CL changes, more waste, greater CL maintenance requirements
Requirements regulation or omission of the supplied CL	Wittmann, M (2007)[36]	Lower energy consumption of the pump system, reduced CL waste due to suction, less pump wear, saving of filtration material	Increase in scrap, increased tool wear, greater machine wear, higher risk of corrosion
Reduction or shutdown of the CL suction	Madanchi, N. (2015)[37]	Lower energy consumption of the suction system, reduced CL waste due to extraction, less wear of the suction system	Danger due to leakage of CL mist into electronic parts, increased fire hazard due to oil aerosol, greater health hazard due to aerosol formation

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[30] Cf. Campitelli, A.; Cristóbal, J.; Fischer, J.; Becker, B. und Schebek, L. (2019).

[31] Cf. Arafat, R.; Madanchi, N.; Thiede, S.; Herrmann, C. und Skerlos, S. J. (2021).

[32] Cf. Kitzig, H.; Jandaghi, N.; Azarhoushang, B. und Vesali, A. (2014).

[33] Cf. Tawakoli, T.; Westkaemper, E. und Rabiey, M. (2007).

[34] Cf. Venkatesh, K.; Sriram, G.; Sai Raj Pavan, S. und Suresh, S. (2018).

[35] Cf. Dettmer, T. (2006).

[36] Cf. Wittmann, M. (2007).

[37] Cf. Madanchi, N.; Winter, M. und Herrmann, C. (2015).

4 INDUSTRY 4.0 RETROFIT FOR MACHINE TOOLS

The possible measures for the sustainable operation of grinding processes offer a process-orientated improvement for use with CL, but also show the challenges and possible negative effects of the approaches. Due to the direct intervention and the various strategies for the development of the process, one can reckon on not clearly defined uncertainties. These process uncertainties represent new challenges in the field of process monitoring in order to continue to ensure high productivity and quality. Technical monitoring and process optimisation using Industry 4.0 retrofits can be applied in this context. Over the course of this, however, it also emerges that the sustainability of a system does not arise from the digitisation of processes but from the measures proposed on the basis of decision support. Nevertheless, digitisation using Industry 4.0 solutions is a suitable tool for developing such measures and approaches.

In general, digitisation in production is referred to as “Industry 4.0”. This refers to the fourth industrial revolution and was introduced by the high-tech strategy of the German Federal Government in 2012[38]. The fourth industrial revolution focuses on technologies such as product customisation, a high degree of flexibility and efficient production. The main focus is on the networking of all human and machine operators across production processes, as well as the digitisation and real-time processing of data. This poses risks and challenges for small and medium-sized enterprises (SMEs), but also for large-scale industry, to bring older machines in line with the current times.[39] Against the background of Industry 4.0, the material-structure-process-property relationship can be recorded by creating a high level of information transparency, measures for process optimisation can be derived decentrally and then communicated to the machine-operating employees via assistance systems or used for direct plant control.[40] The optimisation strategies may pursue various objectives, such as reducing energy and material requirements while ensuring high process reliability. The consideration of machines and systems as a cyber-physical production system (CPPS) therefore forms

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[38] Cf. Forschungsunion Wirtschaft und Wissenschaft (2012).

[39] Cf. Roth, A. (2016).

[40] Cf. Monostori, L. (2014).

a possible framework for the implementation of Industry 4.0 measures, which is becoming increasingly important[41].

4.1 Cyber-physical production systems

4.1.1 Model presentation

Fundamentally, CPPS are based on cyber-physical systems (CPS) and the resulting interfaces. Communication is established between physical and cyber components of a system and the production environment. CPS are used to create technical software networks between sensory hardware and data structures, as well as models and simulations. In principle, CPPS are to be regarded as "human-centred", so that the human being remains at the centre of the operation and interaction. Human-Machine Interaction Communication (HMI-C) is therefore the basic prerequisite for the formation of a CPPS, as it enables the machine operator to set or maintain an improved operating condition. [42] [43]

In this context, CPPS should be seen as a methodology for setting up Industry 4.0 systems, which can be used to map the complex interactions between physical and virtual components by means of data-driven or mechanistic models. Based on these interactions, relationships can be reproduced more easily and conclusions drawn more quickly.

CPPS also provide the ability to run through the development stages of Industry 4.0 applications developed by Schuh et al. and map the entire spectrum. In Figure 9 these stages of development are presented. Through the interaction of the physical and virtual world within the CPPS, it is possible to reflect both the stages of digitisation (computerisation, connectivity) and the important stages of Industry 4.0 in this context. Visibility and transparency are key elements for the initial use of CPPS, especially when there is little experience with Industry 4.0 solutions in the application environment. The final stages of predictability and adaptability point above all to the virtual

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[41] **Cf. Danelon Lopes, L. C. und Neumann, C. (2021).**

[42] **Cf. Monostori, L. (2014).**

[43] **Cf. Thiede, S. (2018).**

level of CPPS, which has no limits in terms of the introduction of modelling and simulations.

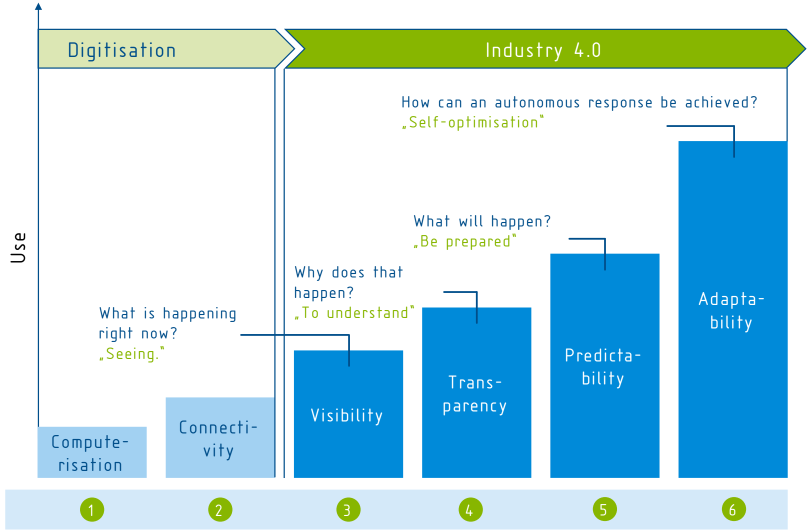

Figure 9: Industry 4.0 development stages[44] [45]

CPPS are basically real-time capable, which can generate advantages especially with regard to the adaptability of a system or retrofit measures. However, this capability can only be realised if the CPPS and the surrounding structures and controls have sufficiently low latency to the production system.

4.1.2 Constituent system components

The basic model presentation of CPPS and its classification in the context of Industry 4.0 were carried out in the previous section. In general, however, it is also necessary to delineate the individual components into the constituent components (see Figure 10). On the physical level (I), CPPS, when abstracted on machine tools as in the use case listed, refers to all the physical components of a machine environment. These include the machine tool itself, the

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[44] Cf. Schuh, G.; Anderl, R. und Dumitrescu, R.; Krüger, A.; ten Hompel, M.

[45] Based on FIR e. V. at RWTH Aachen University.

peripherals as well as the sensors and hardware to be introduced for implementing the CPPS. The implementation of various technical devices and new technologies creates a larger ecological backpack[46].

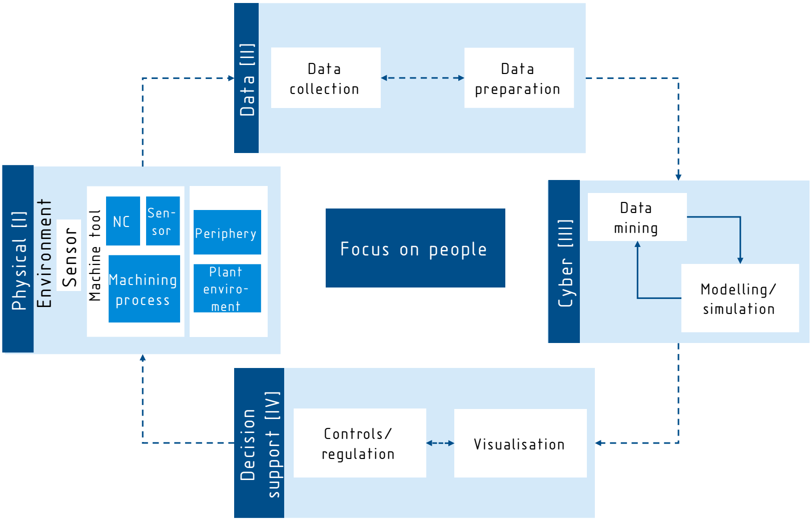

Figure 10: Cyber-physical production system[47] [48]

This initially negative effect is always counteracted by the efficiency gains that the system brings with it, so that the physical plane as a system component is always associated with an increased negative influence in a first iteration. The sensors used are geared to the respective application, which can range from a process-orientated perspective to factory classification of the machine.

Data collection and processing (II) refers to the data generated by the physical layer. Production database systems are used, which are specially developed for this application. These are based on various basic systems (MySQL,

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[46] Cf. Thiede, S. (2018).

[47] Based on Thiede, S. (2018).

[48] Cf. Thiede, S.; Juraschek, M. und Herrmann, C. (2016).

RDS, SQL-Server and many more). The accompanying processing of the data includes a pre-selection and cleaning of the respective data records.

On the cyber level (III), this data is then used to make targeted statements about the physical components and to allow conclusions to be drawn about the system. Modelling and simulation serve as a data-based improvement of the process. Various conclusions about the existing system are conceivable, which can be localised for highly process-related aspects (quality, speed, travel paths etc.) as well as service-orientated structures of the machine system[49].

On the cyber level, a distinction can be made between data-driven and mechanistic models. Real-time-capable solutions are possible, which mainly follow data-driven approaches. Appropriate modelling or methods for implementing such systems refer, for example, to Random Forest Regression[50], Neural Networks[51] or Linear Regression[52].

The solutions and results that are developed can be recorded and visualised under the last section of the cycle, Decision Support (IV). A CPPS is to be understood as a highly iterative process, which can achieve an increase in efficiency through the individual sub-areas and an extended connection between the processes and properties or parameters[53]. The intervention into process structures is possible by means of the appropriate hardware and software at the control end of the system, but often requires in-depth intervention in machine control systems. At the heart of the CPPS there is still the human being as a factor of the system. Due to the usage-orientated design of the CPPS, the focus is always on setting up the components to be simple and easy-to-use, as well as on the reference to methods and models. The system itself must remain tangible, which also gives decision support a special role in this context.[54] [55]

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[49] Cf. Mennenga, M.; Rogall, C.; Yang, C.-J.; Wölper, J.; Herrmann, C. und Thiede, S. (2020).

[50] Cf. Lee, J.; Noh, S. D.; Kim, H.-J. und Kang, Y.-S. (2018).

[51] Cf. Kumar, R.; Patil, O.; Nath S, K.; Sangwan, K. S. und Kumar, R. (2021).

[52] Cf. Suvarna, M.; Yap, K. S.; Yang, W.; Li, J.; Ng, Y. T. und Wang, X. (2021).

[53] Cf. Tao, F.; Qi, Q.; Wang, L. und Nee, A. (2019).

[54] Cf. Kumar, R.; Rogall, C.; Thiede, S.; Herrmann, C. und Sangwan, K. S. (2021).

[55] Cf. Thiede, S. (2018).

4.2 Industry 4.0 retrofit

Retrofit in relation to industry refers to the modernisation or extension of machines, plants or resources under the premise that a positive effect is always brought about by the change[56]. Positive effects can be, for example, an increase in efficiency or the prolongation of the service life. In the traditional sense, retrofits refer to the replacement of machine parts or their digitisation.[57] Extensions to the original retrofit definition relate to Industry 4.0 and are often referred to as “smart retrofit” due to the advanced degree of digitisation of systems[58] [59]. The basic idea here is to transfer the ideas of Industry 4.0 to existing systems or processes with the smallest possible time and cost expenditure[60]. The general digital transformation of companies plays a special role in these challenges, as this is how the value chains and processes of companies influence the everyday and production conditions to a particular extent. Implementing and integrating digital technology or new technologies into existing environments can be seen as a necessary change. Particularly in the context of more efficient production, the goals of Industry 4.0 correlate significantly with retrofit measures. Retrofit measures can always be seen as enablers for Industry 4.0.[61]

In order to make full use of the capability of retrofit measures to initialise digitisation and Industry 4.0, the VDMA provides a retrofit level structure from which requirements can be converted into possible retrofitting actions (Figure 11).

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[56] Cf. VDMA (2020).

[57] Cf. VDMA (2020).

[58] Cf. Hamrol, A.; Ciszak, O.; Legutko, S. und Jurczyk, M. (2018).

[59] Cf. Al-Maeeni, S. S. H.; Kuhnhen, C.; Engel, B. und Schiller, M. (2020).

[60] Cf. Hamrol, A.; Ciszak, O.; Legutko, S. und Jurczyk, M. (2018).

[61] Cf. VDMA (2020).

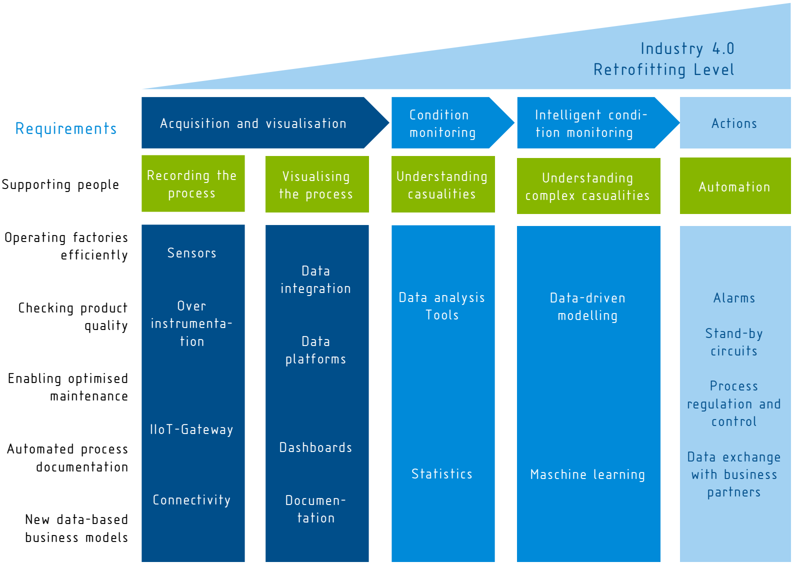

Figure 11: Retrofit level of industry 4.0[62]

Using the level model, retrofit measures can be identified with little technical effort and know-how (Figure 11, shown in dark blue) and developed up to an increased retrofit complexity (Figure 11, shown in blue and light blue). The model is primarily used to identify the current status of the company in order to be able to draw on this to identify possible improvement potential.[63] It uses classic Industry 4.0 measures and is based on data-driven analysis methods on the more complex levels.

The so-called smart services for machines and plants can be mentioned as an extension of this structure. These comprise not only the retrofit levels, but also the communication between systems and the extension of the Industry 4.0 retrofitting for the provision or application of services. Due to the wide availability of data, specific services can be offered using analysis methods (see section 4.1.2), which are directly adapted to the target group.

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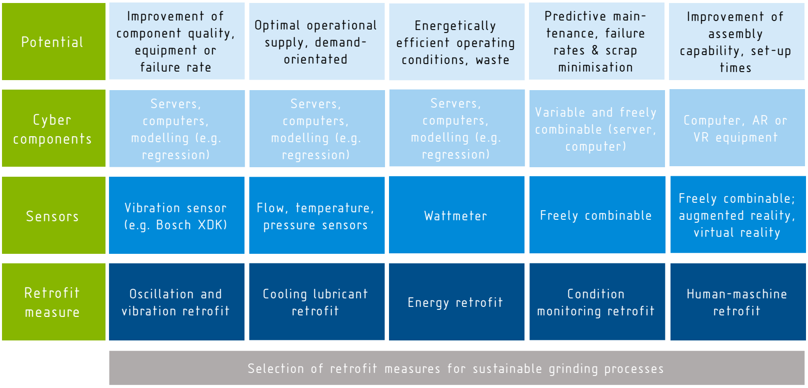
[62] Cf. VDMA (2020).

[63] Cf. VDMA (2020).

4.3 Retrofit measures for sustainable grinding processes

Based on the presented level structures and models, already known retrofit measures are now introduced (see Figure 12). These serve as orientation or development of a specific application case in the field of machine tools.



Potential	Improvement of component quality, equipment or failure rate	Optimal operational supply, demand-orientated	Energetically efficient operating conditions, waste	Predictive maintenance, failure rates & scrap minimisation	Improvement of assembly capability, set-up times
Cyber components	Servers, computers, modelling (e.g. regression)	Servers, computers, modelling (e.g. regression)	Servers, computers, modelling (e.g. regression)	Variable and freely combinable (server, computer)	Computer, AR or VR equipment
Sensors	Vibration sensor (e.g. Bosch XDK)	Flow, temperature, pressure sensors	Wattmeter	Freely combinable	Freely combinable; augmented reality, virtual reality
Retrofit measure	Oscillation and vibration retrofit	Cooling lubricant retrofit	Energy retrofit	Condition monitoring retrofit	Human-maschine retrofit

Selection of retrofit measures for sustainable grinding processes

Figure 12: Classification of retrofit measures within the sample scenarios

These proposed retrofit measures are classified as overarching solutions which can be achieved on the basis of e.g. the level structure Figure 11. The possible actions in a retrofit, such as data-driven modelling or the use of machine learning, do not serve as a result of the retrofit in this case but merely as a means of implementing and achieving the goal. The following are some examples of retrofit measures taking Industry 4.0 into account:

- Oscillation and vibration retrofit

The vibration measurement is already specified as a retrofit in approaches[64]. Here, suitable sensors for vibration measurement are explicitly attached close to the process to be considered and processed by a backend system. Data processing is process-orientated and requires just a few steps that can be implemented by SMEs. The potential here is to improve component qualities, optimise the operation of the system and predict failures.

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[64] Cf. VDMA (2020).

- Cooling lubricant retrofit

In the area of CL supply, enormous energy-related, as well as general ecological improvements have already been achieved[65]. A CL retrofit includes, for example, the measurement of flow rates, as well as general temperature control and pressures in processes. An intelligent process adaptation is also necessary in order to be able to incorporate any findings directly into the process. The advantages of retrofitting measures for the CL are primarily in the area of the optimal operational supply of CL and the reduction of the CO_2footprint. As explained in section 3, these forms of retrofitting offer particularly high potential due to the great influence of CL on the value creation of a product.

- Energy retrofit

The installation of an energy retrofit comprises the overall measurement of all energy supplies of the plant and their monitoring. Methodological knowledge such as the energy value stream or energy breakdown analyses are generally applied to transform a significant basis of data into insights and improvements in the process. This can lead e.g. to optimised process chains or energetically efficient operating states.[66]

- Condition monitoring retrofit

Condition monitoring does not only include the measurement of vibration data, but rather the overall coverage of the environmental data of the system, so that a digital image, a so-called digital shadow, can be created[67] [68]. This implementation requires complex sensors and their networking to optimally record data-based states, in order to be able to predict failures, for example.

- Human-machine retrofit

The human-machine interaction (HMI) is regarded as a necessary instrument of Industry 4.0, since the human being as a factor is still at the centre of the

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[65] **Cf. Winter, M. (2016).**

[66] **Cf. VDMA (2020).**

[67] **Cf. Engels, G. (2020).**

[68] **Cf. Anisic, Z.; Lalic, B. und Gracanin, D. (2020).**

considerations[69]. An HMI retrofit requires tools such as the development of augmented or virtual reality applications that, in this specific case, support the user in carrying out optimum operating conditions or maintenance. Accordingly, extensive, complex sensor technology is also required for the HMI retrofit in order to be able to make the statements required for the HMI based on data.

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[69] **Cf. Roth, A. (2016).**

5 COMPARATIVE ECOLOGICAL AND ECONOMIC ASSESSMENT

5.1 Study framework

As part of the study, Industry 4.0 retrofit measures as a tool for reducing the environmental impact of grinding processes are to be evaluated ecologically and economically in order to highlight the advantages for their industrial application in a simple and comprehensible manner. The procedure and the test setup are chosen in such a way that they serve as a blueprint for industrial implementation.

As an economically and ecologically relevant application case at the end of process chains and therefore value chains, external cylindrical grinding is chosen as the machining process. A machine whose age of 15 is representative of machines in German machine parks is also used. A hardened workpiece made of 100Cr6 is used as a reference component as typical bearing steel. The grinding of hardened steels is conventionally carried out with corundum, which is why a corundum grinding wheel is used as a machining tool. For all test cases, the same conditions of true running are required, which sufficiently compensate for tool wear. The machining CL is a non-water miscible, mineral oil-based CL. Necessary peripheral systems for operating the CL circuit are exhaust air systems as well as filtration and supply systems. The CL supply in particular offers potential savings due to mostly oversized pump systems, which are often not recognised due to a lack of data transparency. This study therefore takes peripheral systems into account.

On the basis of the described retrofit measures and possibilities, three different types of retrofitting are compared within the context of this study and presented as a production framework under as real as possible conditions. Due to the lack of energy transparency of the plant and the great economic and ecological impact, the first retrofit measure to be used is an energy retrofit. The aim here is to map the power consumption of the system on the virtual level in order to reveal waste and potential. The energetic mapping supports the demand-orientated operation of the grinding machine. In order to be able to describe the grinding process optimally, an oscillation and vibration retrofit is also carried out. This supports the assurance of component quality and allows conclusions to be drawn about the adaptation of the process, depending on the improvement measure that is carried out on the basis of the data. Furthermore, the aim is to make the machine condition more transparent and easier to plan. For this reason, a condition monitoring retrofit is used. The energy, oscillation and vibration retrofit is to be understood as part of condition monitoring. The latter can therefore be considered to be combinable and feasible in various stages. The detailed explanation of these retrofits is given in Chapter 5.1.3 in connection with ecological evaluation and economic analysis.

5.1.1 System limitations

The technical production system boundary of the study relate to the machine tool, the peripheral systems and the CPPS. Figure 13 shows the delimitation of the study area and the production environment.

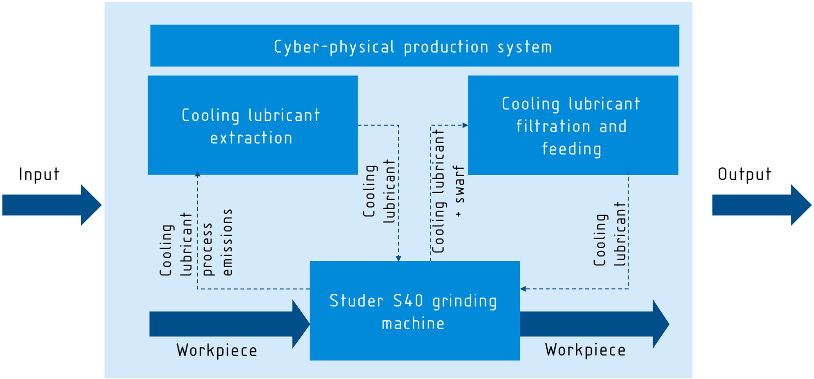

Figure 13: System boundaries in technical production application[70]

In the following, the individual aspects of the machine environment are examined in more detail and defined on the basis of the principles set out in the previous chapters. The machine tool and the process itself are first explained. This is followed by the peripheral aspects of the system and the process properties in order to define the CPPS in the final step.

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[70] Based on Madanchi, N.; Kurle, D.; Winter, M.; Thiede, S. und Herrmann, C. (2015).

The environmental assessment takes an overall cradle-to-grave approach that relates to the environment shown in Figure 13 and takes into account all the resources required in the scenarios described. The lifecycle phases of raw material extraction, product manufacture, use (incl. maintenance) and disposal, as well as the most important transport processes between these lifecycle phases are taken into consideration (see Figure 14). The calculation of the environmental impact of the grinding machine over its lifecycle is not the subject of the investigation. This does not apply to the inputs and outputs that occur during the grinding process during the remaining life of the machine (for example electricity, raw materials for cooling lubricants and filter fleece, production waste), as these will vary depending on the presence of the retrofit measures. The retrofit scenarios consider the entire lifecycle of the required CPPS components.

- **Raw material extraction:** All raw materials used to manufacture the CPPS components and the products required for the operation and maintenance of the grinding machine (such as cooling lubricants and filter fleece) are included in the balance sheet for this lifecycle phase.

- **Product manufacturing:** In this lifecycle phase, all material and energy inputs are recorded, which are required for the composition of the raw materials into usable components or products.

- **Use (incl. maintenance):** With regard to the usage phase, the power requirement is recorded as input, which is necessary for the operation of the grinding machine with or without the retrofit measure.

- **Disposal:** Based on the WEEE Directive (2012/19/EU), it is assumed that old electronic equipment is disposed of properly and are fed into existing recycling streams. Thermal recycling is assumed as the usual disposal method for the used cooling lubricants and fleeces used in filtration.

- **Transport processes:** In the context of ecological assessment, the two most important transport processes are also taken into account: firstly, the transport of the products used (CPPS components, cooling lubricants, filter fleece) from the respective factory gate of the production to the site of use (business-to-consumer logistics), and secondly, the transport of the same products from the site of use to the respective disposal facilities (recycling and waste incineration plant).

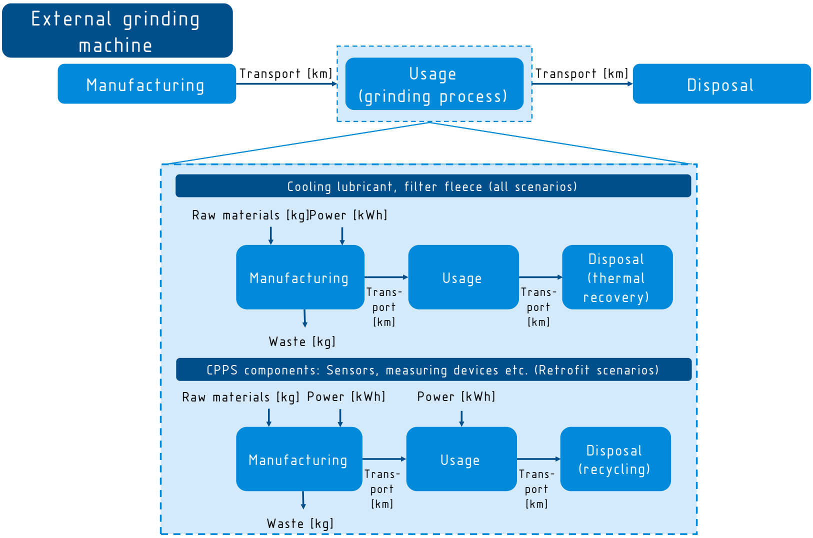

Figure 14: System limitations of the considered scenarios (ecological and economic evaluation)

5.1.1.1 Reference machine

A machine tool from the machine park that does not contain any digitised extensions is chosen as the reference machine and is suitable for retrofitting measures due to its age (built in 2007) and could therefore be a comparable machine for the Germany-wide trend. The reference machine is the external cylindrical grinding machine Studer S40 including the cooling lubricant system (see chapter 5.1.1.2). Figure 15 shows an external image of the grinding machine for illustration purposes.

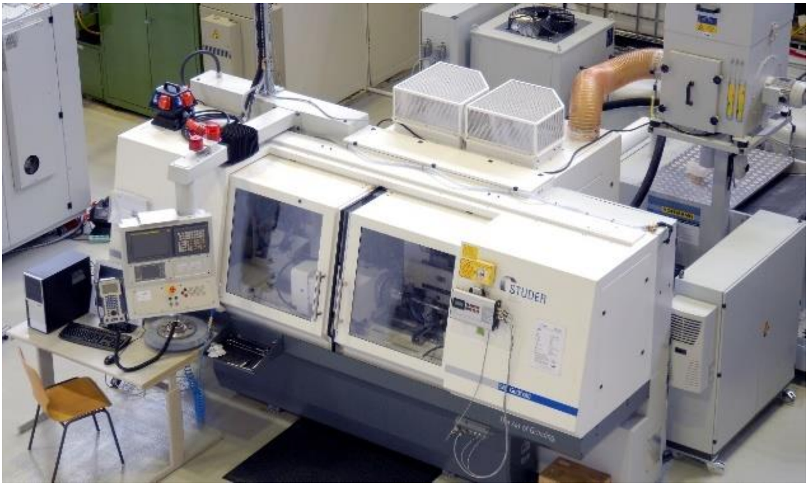

Figure 15: Reference machine Studer S40[71]

For general machine data, see Table 6. The grinding machine is called a “CNC universal cylindrical grinding machine”, proves its versatility through the four spindle drives (one grinding dresser and three tool spindles) and enables external and internal grinding. The Studer S40 also offers the option for high-speed machining, which may be necessary or helpful in special applications. However, since special process and product conditions must be met for this purpose, only standard machining by the machine – external cylindrical grinding at conventional speeds (spindle 2) – is taken into account in the reference system of the study.

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[71] **H. Engel, IMF/TU Braunschweig.**

Table 6: Reference machine specifications[72]

Specification	Studer S40 data
Dimensions (footprint, L, W, H)	4717 mm/2095 mm/1745 mm
Spindle 1	15 kW power with cutting speeds of up to 140 m/s with a grinding wheel diameter of 500 mm
Spindle 2	9 kW power with cutting speeds of up to 50 m/s with a grinding wheel diameter of 500 mm
Spindle 3 (internal grinding spindle)	Cutting speeds in the range 24000-42000 1/min.
Model (CL)	Set up for cooling lubricants or oils (currently operated with oil) and controlled by Hoffmann filter system
Model (exhaust air)	Exhaust air filtration is handled via the Hoffmann filter system, as an external vapour separator

5.1.1.2 Peripheral systems

The peripheral equipment of the reference system relates to the cooling lubricant and exhaust air filtration for the grinding machine. Both systems represent necessary extensions to the reference machine, whereby an overall removal of the additional systems is not possible.

Figure 16 shows on the left the exhaust air filtration and on the right the CL filtration system including the belt filter and the supply pumps, as well as the lifting pump.

The main tasks of the CL filtration system are the feeding and/or discharge of the cooling lubricant in direct connection with the grinding machine and the filtration of the CL, which in this case is oil and is described in chapter 5.1.1.4, via a filter belt. A pump system is integrated into the filter system for the supply of the cooling lubricant, comprising three machine supply pumps and a recirculation (lifting) pump. Not all supply pumps are activated at all times, but only the pump necessary for processing. In high-speed machining, as already mentioned in the previous chapter, increased consumption and expenditure are to be expected. The supply and discharge pumps cannot be regulated.

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[72] IMF/TU Braunschweig and Fritz Studer AG.

Figure 16: Peripheral systems of the reference system (left: exhaust air, right: CL filtration)[73]

Figure 17 shows the corresponding relationships and connections within the peripheral system. CL filtration is operated with electrical energy and releases de-oiled chippings with residual moisture as waste. Depending on the processing, the machine tool receives the cooling lubricant from the supply pumps and returns the used CL incl. chippings that are in the fluid via the return flow.

The CL suction or exhaust air filtration of the reference system is directly connected to the grinding machine in order to be able to extract any process air from the machine interior. The extraction is operated by a fan motor. The filtration of the exhaust air is achieved by means of a three-stage process. First, a demister is used to pre-separate the material and then the pre-filtration takes place. As the third step, a fine filtration through a particulate filter cassette is necessary so that clean air can be separated from the filter.

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[73] **H. Engel, IMF/TU Braunschweig.**

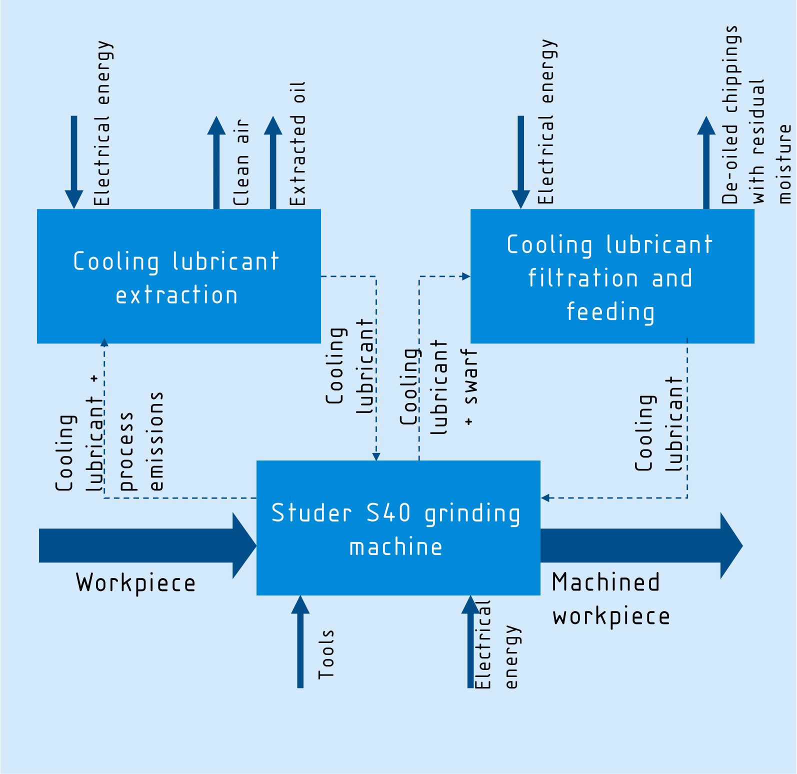

Figure 17: Relationship between the peripheral systems and the reference machine[74]

As shown in Figure 17, the exhaust system is supplied with electrical energy and releases this clean air to the environment. In addition, a certain amount of oil is suctioned during processing, which amounts to approximately 0.1 grams per second[75]. Through the CL supply to the machine, CL emissions, process and processing emissions are released within the processing, which can be cleaned through the suction. Due to the legal directives on workplace limit values when working with cooling lubricants, the exhaust air filtration or the extraction system cannot just be shut down completely.[76] The installed

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[74] In Anlehnung an Madanchi, N.; Kurle, D.; Winter, M.; Thiede, S. und Herrmann, C. (2015).

[75] Cf. Madanchi, N.; Winter, M. und Herrmann, C. (2015).

[76] Cf. Deutsche Gesetzliche Unfallversicherung.

extraction system achieves an extraction capacity of approx. 40 m^3/min[77] and therefore exceeds any requirements.

5.1.1.3 Reference workpiece and process parameters

A well-known and widespread application for grinding processes is the external cylindrical grinding of bearing rings. Therefore, a ring made of 100Cr6 with a hardness of 62 HRC is used as a reference component for the study. The initial diameter of the rings is 150 mm with an internal diameter of 50 mm and a workpiece width of 10 mm. Processing is carried out in reverse rotation (Figure 18).

Reference workpiece: 100Cr6 ring

- Hardness: HRC 62
- Initial outer diameter: od = 150 mm
- Internal diameter: id = 50 mm
- Workpiece width: w = 10 mm
- Processing in reverse rotation

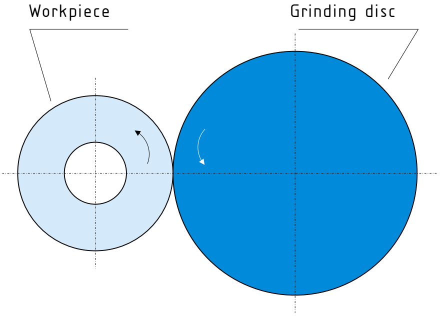

Figure 18: Initial dimensions of the reference workpiece

The process parameters for grinding represent a standard test under real production conditions. The parameters are not within a machine limitation range and are shown in Table 7.

Table 7: Process parameters of the grinding process

Grinding parameters	Unit	Value
Chipping volume	mm^3	1,400
Cutting speed	m/s	35
Workpiece speed	m/s	0.3475
Feed speed	mm/min	0.207 (roughing) to 0.0155 (fine finishing)

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[77] **Cf. Hoffmann Maschinen- und Apparatebau GmbH.**

5.1.1.4 Reference cooling lubricant

Water-based CL (emulsions) and mineral oil-based, non-water miscible CL are common in the industry. Mineral oil-based CL provide high corrosion protection and usually have a longer service life than water-based CL. On the other hand, however, there are high acquisition costs and environmental impacts. In order to depict a cost-relevant and emission-relevant practical case, a mineral oil-based CL with versatile application possibilities for steel processing is used in this study. The used CL Berucut SCO 310 by the company Bechem contains Extreme Pressure (EP) and Anti-Wear (AW)-additives and is therefore representative of commercially available CL. The exact composition of the CL is not known and the formula is not disclosed by the manufacturer, which is why for the CL experience or estimated values are referred to. The lack of a database on additive packages or its deficiency was evaluated as insufficient in a study on the ecological and economic evaluation of CL, which is why additive packages are often not taken into account in the balance sheet[78].

5.1.1.5 Retrofit measures for building up a CPPS

The cyber-physical measurement system results from a basic cyber-physical production system, as explained in section 4.1. The system, which was explicitly implemented in conjunction with the reference machine, is therefore based on the correlation between the physical and cyber levels of a CPPS. The retrofit of the reference grinding machine is carried out taking into account the process conditions and the selected retrofit measures. Due to this, various sensors and process recording are necessary. Figure 19 shows the structure of the CPPS, taking into account the measurement technique and the relationships between the individual areas. Various process scenarios are therefore conceivable for the development of such a CPPS in connection with extended sensor technology. In this case, the sensor technology comes directly from the retrofit measures and is specified based on the selection. However, it is conceivable that this pre-selection cannot be carried out in the industry, as no retrofit measures are selected but clear objectives (e.g. in-

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[78] **Cf. VDI Zentrum Ressourceneffizienz GmbH (2017b).**

crease in energy efficiency) are set. For these cases, there are further selections and methods in the literature that allow an application to build a CPPS.[79]

On the physical level (I), the reference machine (incl. exhaust air filtration) and the CL system are basic physical objects of operation in the CPPS. In addition, the corresponding power measurements are integrated for the energy retrofit, which record the CL system performance as well as the reference machine performance. The sensor nodes shown (Bosch XDK) are introduced into the process for the condition monitoring retrofit. These are able to monitor various environmental conditions, such as temperature, humidity, acceleration, gyroscopic location, noise etc. For the oscillation and vibration retrofit, an acceleration measurement is integrated, which is realised using the Beckhoff ELM3602 terminal and the connected piezoelectric vibration transducer.

The sensors provide the necessary data to implement data collection in Area II of the CPPS and to process it in the following step. The spatial arrangement and the technical aids necessary for recording are explained in more detail below.

In the third area (III) of the CPPS, the data is modelled and evaluated. This is done from a process point of view and by means of a direct comparison of the individual processes. From this evaluation, measures can be derived that are mapped via the visualisation in Area IV, the Decision Support, and therefore have an influence in turn on the physical reference system (Area I). In the usage case, these measures are created by analysing the existing data. The exact scenario procedure can be found in Chapter 5.1.3.

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[79] **Cf. Rogall, C.; Mennenga, M.; Herrmann, C. und Thiede, S. (2022).**

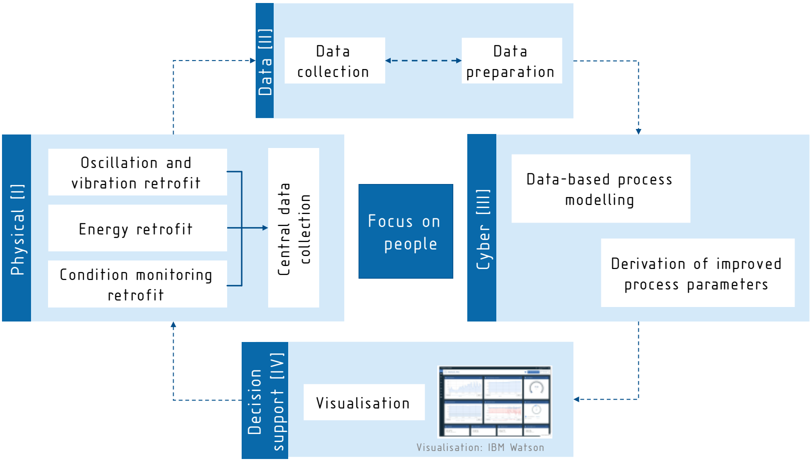
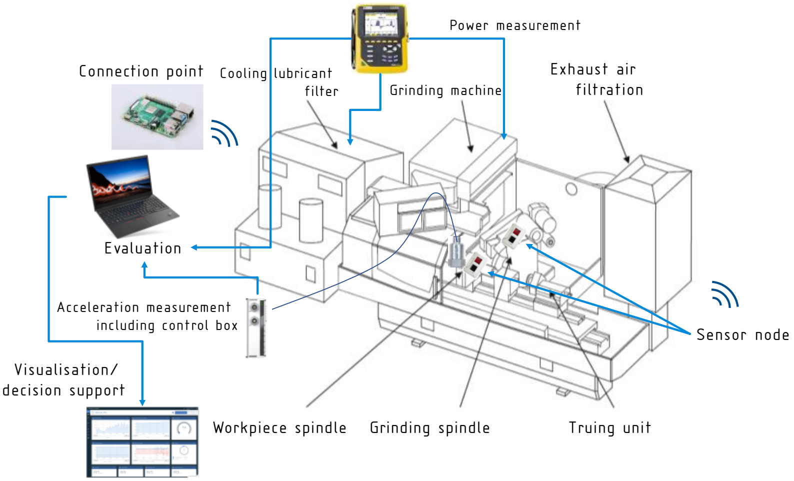


Figure 19: The cyber-physical production system of the reference system

The schematic arrangement within the space and the data collection are shown in Figure 20. The power measurement is connected to the cooling lubricant filtration and the grinding machine, while the latter also records the output of the exhaust air filtration. The acceleration measurement takes place above the workpiece spindle so that the vibrations introduced into the workpiece can be calculated. The sensor nodes are mounted both above the workpiece spindle and on the tool spindle in order to be able to record the environmental factors for condition monitoring.

For data processing, a Raspberry Pi is affixed near the machine and sensors. WLAN for communication and MQTT, as an established Internet of Things protocol, are provided for data collection. In addition, there is a computer for the evaluation and recording of the further data sets. The entire setup therefore offers an easy transfer to other applications or machines, is not integrated into the machine and can therefore be dismantled and uninstalled at any time. The sensor system also operates in the field of “low-cost sensor technology”, so that it is associated with low costs compared to finished industrial solutions.



Power measurement: Chauvin-Arnoux.at CA8336
Acceleration sensor: mmf.de / Beckhoff.com
Sensor node: developer.bosch.com
Notebook: lenovo.com
Raspberry: raspberrypi.com/products
Visualisation: IBM Watson

Figure 20: Schematic representation of the reference system[80]

5.1.2 Functional unit

The definition of a functional unit is required for the balance sheet comparison. According to DIN EN ISO 14044:2006, the functional unit of a system describes a quantified benefit of a producing system that is used as a comparison unit. In this case, a chipping volume of 1.4 cm^3 with a processing time of 1.6388 min is selected as the standard test for the machining of a single component.

In order to depict a production scenario, data from a grinding production system from the literature is used as a basis[81]. In the scenario, the production machine is operated in a single-shift system 250 working days a year at a

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[80] Based on Winter, M. (2016).

[81] Cf. Winter, M.; Thiede, S. und Herrmann, C. (2015).

productive utilisation rate of 80% (Table 8). This results in a productive machine utilisation of 1,600 hours per year, taking into account an eight-hour shift.

Table 8: Functional unit related to a production scenario of a single machine

Size	Unit	Value
Working days per year	Days/year	250
Shifts per day	-	1
Shift duration per day	h/day	8
Operating time per year	%	80
Productive machine utilisation	h	1,600
Chipping quantity per reference workpiece	cm^3/piece	1.4
Cutting time per reference workpiece	min/piece	1.6388
Number of units produced per year	**pcs./year**	**58,579**
Chipping volume per year	**cm^3/year**	**82,010**

The functional unit is either a produced number of 58,579 components or a machined volume of 82,010 cm^3 per year according to the aforementioned scenario. For the final balancing of various scenarios, the required data is inventoried in the following.

5.1.3 Scenario description for the test procedure

Based on the retrofit package of measures described above, which includes energy, condition monitoring, oscillation and vibration retrofit, the basic results and findings of the test procedure are presented below. In order to generate suitable values that allow an economic and ecological evaluation of the retrofit, reference tests are carried out in the machine environment shown, which can be traced back to the production scenario from chapter 5.1.2 as a comparable functional unit.

Within the experiment, a reference scenario is considered, which is compared with different retrofit measures with associated ecological sustainability goals (see Table 9).

Table 9: Comparison of the reference and retrofit scenarios

Reference scenario	Retrofit measure 1	Retrofit measure 2	Retrofit measure 3
Conventional grinding process	Energy retrofit	Oscillation and vibration retrofit	Condition monitoring retrofit
Sustainability goal	Minimising energy waste	Improvement of component quality in connection with an energy-optimised operating state	Overall monitoring of the system - energetic - qualitative

The selected retrofit scenario contains a conglomerate of three retrofit measures (energy, oscillation and vibration, as well as condition monitoring retrofit). With the help of these retrofit measures, it is possible to realise a wide range of improvement potential in the reference system, whether of process or technical origin. Initially, no automatic improvement of the overall system can be expected, even with the help of the introduced CPPS. The initial added value of the retrofit measures lies exclusively in the creation of transparency within the process (analysis of the actual state). Only in the subsequent steps and the analysis of the data at the cyber level of the CPPS is the modelling and simulation of possible improvements possible.

In addition, exemplary improvements that correspond to realistic scenarios are derived from the transparent data state of the machine and used for economic and ecological evaluation in order to be able to establish a comparability of reference and retrofit scenarios. Therefore, this study argues on the basis of the aforementioned transparency and generates a concrete application case, which, however, remains transferable to the wide variety of variants of the market and the company. In this case, the improvements that result from the CPPS data collection and are generated by the cyber layer are not automated in the usage case. In the explicit case, this is due to the further involvement of the human being in the process.

Especially in this respect, increased complexity by automating improvements and data processing is a hindrance to the transfer of the solution and would minimise the know-how and influence of the employees in the process. Therefore, in this specific case, implementation of measures is only possible on the basis of recommendations for action by Decision Support.

The various retrofit scenarios provide process data that enables the strategies described in chapter 3.3 for the increase in material and energy efficiencies to be implemented . The specific data as well as simple approaches for preparing it and deriving decision support are described below.

Energy retrofit

The approach for this ecological and economic comparison and its evaluation for retrofit measures in the Industry 4.0 context is provided by the performance measurement of the facility. Through a real-time analysis of the energy demand, energy-driven process optimisation can be carried out in the area of production planning and machine design, as well as during operation itself. For this purpose, both the CL system and the grinding machine itself were measured. Figure 21 shows an example of the setup of a power measurement over time for the specified grinding machine. The start and end points of the process can be clearly interpreted from the performance of the system.

Significant points within the machining process can also be highlighted. The figure shows that the machine has a peak power of approximately 3 kW, whereas for the machining process it is approximately 2 kW. If the areas below the curves are now depicted on this diagram, the measured power per unit of time can be seen, allowing the energy requirement of the system to be calculated.

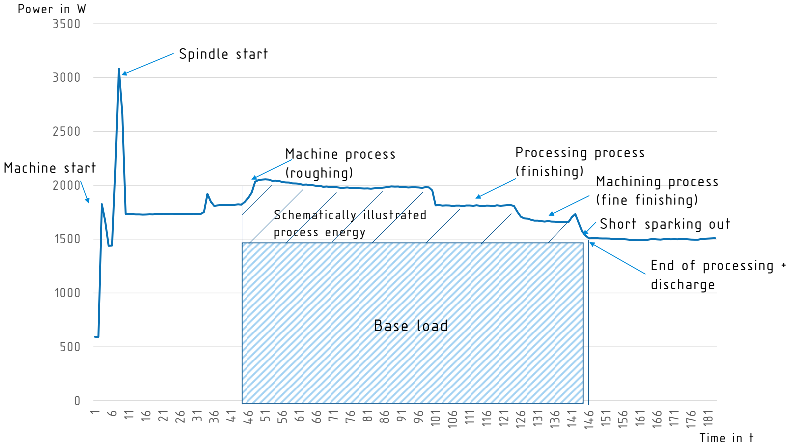

Figure 21: Example of recording the performance of the reference system

By means of more complex preparation and presentation forms, it is possible to convert these power recordings into a so-called “Energy Breakdown”, in which the different energy areas of the plant can be highlighted. Figure 21 Shows an approach to such an energy breakdown to compare the system's base load with the process energy. Even at this point, without the need to carry out more complex modelling or calculations, it is clear that the machine's base load is significantly higher than the process performance.

If, taking this consideration into account, the overall performance of the system (grinding machine and CL system) is compared, a comparison can be created from the individual process sections, which is visualised in Figure 22. The energy requirement for the machine (blue) compared to that of the CL system (orange) results in a significantly higher overall consumption than when considering the individual performance of the machining process. However, this higher energy requirement is primarily due to the power consumption of the CL system within the process.

Explicitly calculated, the total demand consists of a 78% share of the CL system and only 22% of the demand of the grinding machine. This comparison in the environment of the reference system allows the conclusion that the CL consumption in particular in the machining process has a high potential for savings in terms of the power input (cf. chapter 5.1.1.2). In the next classification stage, this finding is primarily related to roughing, which is responsible for approx. 87% of the energy requirement (based on the 78% total share).

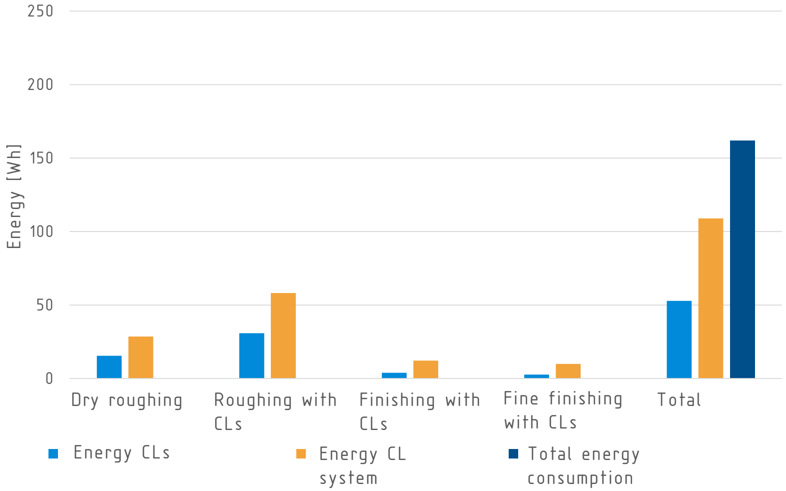

Figure 22: Comparison of the energy requirements of the reference system

As a result of this energetic analysis, the following considerations are included for the reference and retrofit scenarios, which are used respectively for ecological and economic evaluation.

- **Reference scenario:** Conventional grinding process according to the machine manufacturer's guidelines with standardised cutting parameters (chipping volume 1.4 cm^3, cutting speed 35 m/s).

- **Retrofit scenario:** Exemplary improvement of the overall machining process. Recording of process and environmental data through the introduction of sensory and information technology elements. The analysis of this data allows the implementation of appropriate measures to achieve the sustainability goals. The machine will be converted from its basic state (delivery condition in 2007) to a comparable Industry 4.0 scenario. Based on the findings, roughing is partly carried out with and without a CL feed in order to relieve the performance of the overall system. The cutting parameters are not changed compared to the conventional process. Compared to the overall process, one third of the roughing is carried out without CL.

The power requirements of the retrofit scenario are shown in Figure 23. It can be seen here that dry machining achieves a considerable reduction in demand, so that the power consumption of the CL system is adjusted to the performance of the machine.

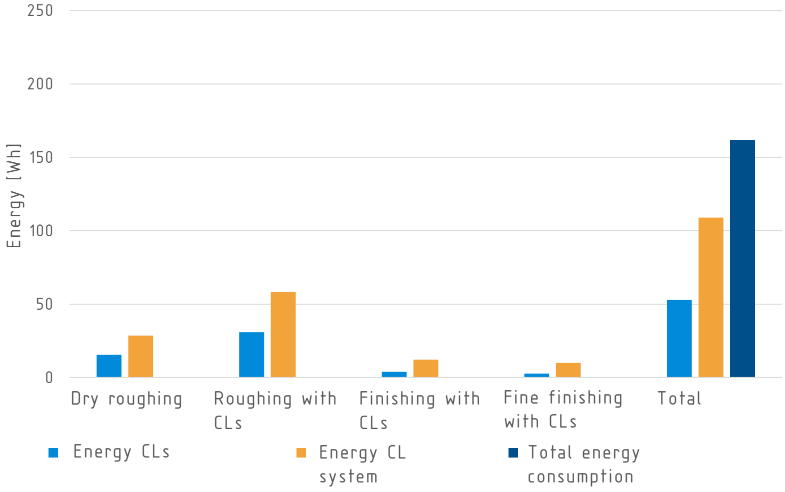

Figure 23: Retrofit scenario energy requirements per process step

The overall comparison of the two scenarios also shows the savings very clearly. Figure 24 shows this comparison. It can be seen that the savings of the retrofit scenario compared to the reference scenario are approximately 29.3%, which corresponds to the equivalent of 67 Wh of energy consumption.

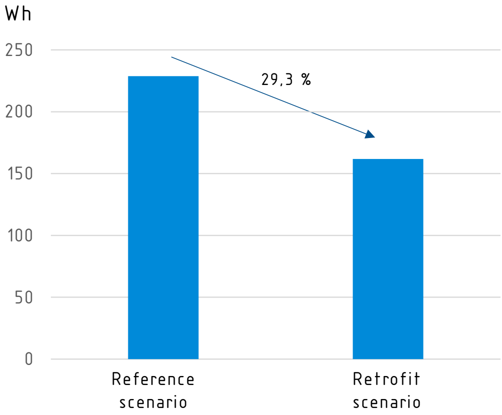

Figure 24: Improvement of energy demand through retrofit

Oscillation and vibration retrofit

The aim of the oscillation and vibration retrofit in this application is to monitor the quality of the component and process. For example, the machine status with respect to the tool can also be recorded. In any case, this type of retrofit can also be used as a stand-alone solution and does not necessarily require the energy retrofit to be introduced. In this application case, the retrofit measures are considered as building on each other.

The oscillations and vibrations recorded reflect the quality of the workpiece due to the process structure (see chapter 5.1.1.5). For an example of this consideration, see Figure 25.

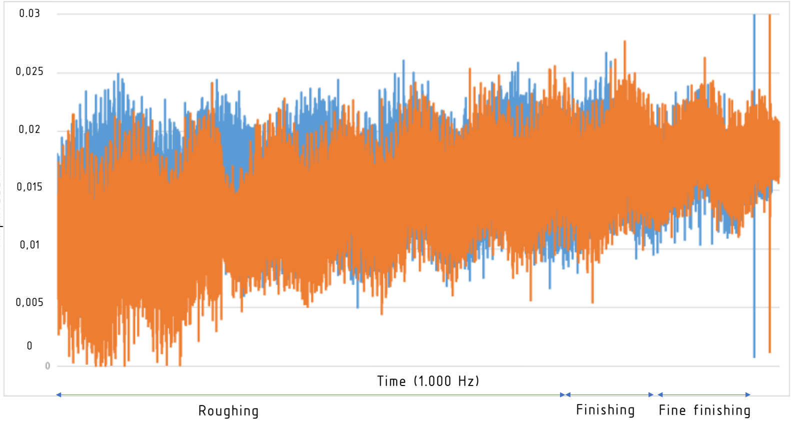

Figure 25: Vibrations in the reference scenario (blue) and retrofit scenario (orange)

Here you can see the individual process steps as well as the deflections during processing. In particular in further application cases, the oscillation and vibration retrofit can be used to make extended statements about the quality and properties of the workpieces. Using long-term measurement campaigns, the values for machine vibrations, workpiece holders or tool vibrations can be evaluated, for example, by means of machine learning approaches, and the amount of data can facilitate detailed statements for predictive operation of the system. In this application case, the absolute values of the oscillation and vibration analysis are more useful in that it is a case-by-case comparison between two scenarios (see Table 10).

Table 10: Comparison values for the oscillation and vibration retrofit

Process step	Reference scenario	Retrofit scenario	Percentage deviation of amplitude
Dry roughing		0.0259	
Roughing with CL	0.0224	0.0232	3.57%
Finishing	0.0142	0.0152	6.81%
Fine finishing	0.0129	0.0123	-4.24%

The deviation between the two processes is at most approx. 6.8% and is within the quality limits of grinding for this application. These values and quality limitations can vary depending on the application and are very specific. The uniform increase in roughness is also visible, which allows a direct correlation with the amplitude to be established. Nevertheless, the deviations in surface qualities are within a similar percentage framework (Table 11). When considering the absolute values for the $_{\mathrm{Ra}}$or$_{\mathrm{Rz}}$values (mean roughness index or roughness depth) of the surface, the persistently very good quality of the component with and without retrofitting measures is evident. The degrees of roughness vary within the tolerance range and therefore correspond to the industrial standard. The vibration can therefore be used as proof of the quality of the component.

Table 11: Comparison of surface quality

Reference scenario	Retrofit scenario	Deviation in %
1.359 µm (Rz)	1.443 µm (Rz)	6.18% (Rz)
0.176 µm (Ra)	0.181 µm (Ra)	2.84% (Ra)

The oscillation and vibration retrofit can therefore also be carried out as a stand-alone retrofit and is helpful for the early detection of surface defects or quality deviations. Nevertheless, the comparison between the limit comparison of energy and quality is considered to be much more effective in order to achieve a multi-paradigm improvement.

Condition monitoring retrofit

In this case, the required condition monitoring retrofit (see vibration measurement) only contributes to confirmation of the contents. This is mainly due to the duration of the scenario under consideration and the scope of this study. Despite all this, it is possible to achieve or discover even more significant savings potential due to a sophisticated data analysis in the long term by incorporating condition monitoring into the grinding process. Since condition monitoring is always a long-term operation, only options and expected savings or process improvements can be stated in this case. In the case of vibration monitoring, these can refer, for example, to bearing wear, make predictive maintenance possible or ensure consistent quality over long process runtimes. The environmental data such as temperature or humidity (for example XDK) are also used explicitly to determine environmental values and to compare them with the primary data such as energy or vibrations.

The comparisons and juxtapositions presented here are based to a large extent on experience with the process and the transparency created by the retrofit scenario. Nevertheless, further potential is possible through the in-depth application of the cyber level as well as a decision support concept within the CPPS. An extension of data analysis using additional analysis methods (e.g. statistical analysis, deep analysis or analysis of interdependencies between variables) is conceivable and feasible. Appropriate methods for this could refer to further trend analyses, Fast-Fourier transformations or traditional regressions, which can already be implemented with the resulting data sets using suitable software. For example, on the basis of this data, artificial intelligence (AI) can be learned, taking into account the operating states, which means that the AI is in a position to detect anomalies in the future.

Thanks to further expert knowledge, AI can even make a statement about the system condition or errors by correlating the different measurement data and locations. The described CPPS and this application case for the scenario procedure show the beginning of such a series of analyses and thus only a fraction of the possibilities for improvements to the corresponding reference system. Starting with the resulting transparency, which has been described in detail in this report, long-term improvements to the system can be achieved on the basis of the three retrofit measures in the scenario and under the assumption of possible further test and production runs for data generation.

Predictive maintenance of tools or the CL system, demand-orientated supply of cooling lubricants and exhaust air filtration at machine tools, or in-process management of component quality using oscillation and vibration absorption are conceivable. These additional modelling and data analyses can be directly integrated into machine operation by means of a suitable decision support system, which also includes the control of the relevant physical plants.

In this context, a CL regulation system for the machine feed could be an intervention stage that can improve material and energy requirements in the long term. The extent of intervention also describes the degree of automation of the resulting system, whereby depending on the effort involved, it is also possible to present the action options in a decision support system on the machine level and to carry out manual intervention in the supply or the machine programme for subsequent production runs. The scenario described here can therefore only represent the beginning of a retrofit measure and must be understood as a system to be extended in order to make the full potential of the facility usable.

5.1.4 Inventory of the required data

The data inventoried for the environmental and economic assessment are explained below and summarised in Table 12 for the two scenarios.

Machine operating age: In all three scenarios, an external cylindrical grinding machine that has been in operation for 15 years is considered.

Machine lifespan: In all scenarios, it is assumed that the grinding machine can be used for another 15 years and therefore achieves a normal service life of a total of 30 years. However, it is often hypothesised that retrofit measures can extend the life of the grinding machine by monitoring condition parameters and thereby bring ecological benefits. The extent of the service life extension is determined by the interaction determined by several factors (e.g. machine type, throughput rate, maintenance frequency, costs of new purchases compared to the costs of spare parts, etc.), so that there is no specific information in the specialist literature on how much longer a grinding machine equipped with retrofit measures can be operated. In order to take the extension of lifespan into account in the ecological assessment even so, sensitivity scenarios could be defined in principle, which are also based on an extended lifespan. However, this could not be done during this investigation as the maintenance and upkeep of the equipment could not be taken into account due to lack of information.

Table 12: Inventory of the data within the scenarios

	Reference scenario	Retrofit scenario
	Grinding process without parameter adjustment and retrofit measure (conventional)	Grinding process with vibration and energy retrofit
Grinding machine (current)	15 years old + assumption: another 15 years (realistic)	
Description of the process	Roughness depth (Rz): 1.359 µm; centre roughness (Ra): 0.176 µm	Roughness depth (Rz): 1.443 µm; centre roughness (Ra): 0.181 µm
Cooling lubricant (CL) input [kg, transport km]	1,720 kg transport: Hagen > Braunschweig (285 km)	
Total losses CL [kg]	582.42	414.20
Filter fleece [kg]	1.87	1.33
Energy consumption: Machine + filter [kWh]	13,401.3	9,474.9
Energy measuring devices [pcs.]	none	2 (entire service life; 1 replacement if necessary)
Acceleration sensor [pcs.]	none	1 terminal + control box (Lifetime: 15 years) + 3 sensors (lifetime: 2 years)
Sensor nodes [pcs.]	none	2 (Lifetime: 2 years)
Computer, monitor, keyboard, mouse [pcs.]	none	1 (lifetime: 5.8 years)
Server, monitor, keyboard, mouse [pcs.]	none	1 (Lifetime: 6 years)

CPPS components: Depending on the scenario, different CPPS components are required. Some of these components have a shorter service life than the grinding machine, so they need to be replaced (several times) during the remaining service life.

Cooling lubricant, electricity, filter fleece: The properties of the CL and the chippings are found in Table 13 and are necessary for calculating the values in

Table 14: Experimental values for lifecycle parameters of the grinding process

. The quantities of cooling lubricant, electrical energy and filter fleece required for the grinding process were determined during tests (see

Table 14: Experimental values for lifecycle parameters of the grinding process

).

Table 13: Properties of the cooling lubricant and chippings

Physical size	Unit of measure	Value
Density of the cooling lubricant	kg/l	0.86
Volume of cooling lubricant	l	2000
Mass of the cooling lubricant	kg	1720
Material density (100Cr6)	g/cm³	7.83
Chipping volume	cm³	1.4
Chipping mass	g	10.962

The calculations of the amount of cooling lubricant in the exhaust air and on the chippings are assumptions based on information in the literature[82] [83].

Parameter	Unit of measure	Scenario 1: Grinding process without retrofit	Scenario 2: Grinding process with retrofit
Runtime without CL	s	-	28.40096618
Runtime with CL	s	98.32943571	69.92846953
Power consumption of machine	Wh	51.32181923	52.81936719
Power consumption filters	Wh	177.453607	108.9270891
CL in the exhaust air	g	9.832943571	6.992846953
CL on the chippings	g	0.10962	0.077957926
Filter fleece	g	x	x*(69,92487/98,32944)
Total power consumption	Wh	228.7754262	161.7464563
Use of CL	g	1720000	1720000
CL output	g	1719990.057	1719992.929

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[82] Cf. Madanchi, N.; Winter, M. und Herrmann, C. (2015).

[83] Cf. Herrmann, C.; Madanchi, N.; Winter, M.; Öhlschläger, G.; Greßmann, A.; Zettl, E.; Schwengers, K. und Lange, U. (2017).

The residual moisture content of oil is assumed to be 1% of the chipping volume[84]. The oil mass lost by the exhaust system is estimated at 0.1 g/s, based on literature values[85]. The exact input values are calculated in accordance with the production scenario (see Table 8) in the context of work package 3.

Table 14: Experimental values for lifecycle parameters of the grinding process

Water consumption: Water is not used as a process input in any of the three scenarios in the usage phase (i.e. in the grinding process). However, water is taken into account in the data sets used for the model and is therefore not excluded from the study.

Direct emissions (water, soil, air): Direct emissions to the environmental compartments water, soil and air could not be identified.

5.2 Ecological assessment: Quantification of the life cycle inventory analysis

Inventory information and data were compiled using the commercial databases ecoinvent V3.7.1 and the free database "PROBAS" to define the subject-specific balance of ecological assessment[86][87]. Relevant literature has been used for the assumptions regarding the energy requirements of the CPPS components (these sources are described in the following sections). In accordance with VDI guidelines VDI 4600 and VDI 4800-2, credits for potentially avoided emissions due to recycling materials and credits for energy recovery after combustion are not taken into account.

The overall lifecycle analysis is divided into three phases:

- **Manufacturing:** KSS, filter fleece, CPPS components,
- **Usage:** Power consumption for the grinding process,

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[84] Cf. Herrmann, C.; Madanchi, N.; Winter, M.; Öhlschläger, G.; Greßmann, A.; Zettl, E.; Schwengers, K. und Lange, U. (2017).

[85] Cf. Madanchi, N.; Winter, M. und Herrmann, C. (2015).

[86] Cf. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E. und Weidema, B. (2016).

[87] Cf. PROBAS Database (25th. January 2022).

- **Disposal:** Waste treatment of materials used for grinding process and retrofitting measures.

5.2.1 Power consumption

The power consumption of the external grinding machine was measured in the tests for both scenarios (IWF). The power consumption of the CPPS components is described in the following subchapters with reference to the respective usage phase.

5.2.2 Cooling Lubricant

The lubricating oil is a non-water miscible mineral oil-based cooling lubricant. These types of lubricants are generally composed of the following components[88]: 85-90% mineral oils (base oils), 5-8% synthetic/natural ester oils, 5-15% high-pressure additives (org. sulphur compounds, org. phosphorus compounds, chlorinated paraffins), < 4% anionic surfactants, antioxidants, oil mist inhibitors.

However, the specific formulations of CL are kept secret by the manufacturer. The exact formulations of mineral oil-based, non-water miscible cooling lubricants used in the grinding process are generally subject to trade secrecy. In particular, this includes additive packages, as already explained in section 5.1.1.4. Reliable data is available for the base oil upstream chains, but only to a limited extent for the other materials[89].

Based on the expected LCA dimension of mineral oil-based cooling lubricants, relevant LCA studies were evaluated in order to make assumptions about the components and their percentages. The assumptions are based on the LCA studies on cooling lubricants listed in Table 15. Although this literature screening may be useful for an initial overview of background information, accurate information about the composition could only be kept general in this study.

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[88] Cf. Alex, M. (2010).

[89] Cf. Hansen, A et al. (2005).

Table 15: LCA studies on cooling lubricants (abbreviations*)

Authorship	Base oils	Applications	Examined phase of life	Area of investigation	Effect category
Dettmer (2006)[90]	Mineral oil, rapeseed oil, palm oil, animal fat, used cooking fat	Nwm CL EP additives: sulphurous fatty oils, sulphurous hydrocarbons AW additives: phosphorus, phosphorus-sulphure compound	Raw material chain, production phase, usage phase, end-of-life	1,000 machined workpieces (174 kg ground ball hubs)	GWP, AP, ODP, KEA, POCP, PM, ADP
William-Olsson (2020)[91]	Mineral oil (petroleum), rapeseed oil, olive oil, sunflower oil, pentaerythritol	Phenol-based antioxidant additives	Crude oil extraction, refining, manufacturing, use, end-of-life)	Production of 100 piston drums	GWP, Human and freshwater toxicity, EP
Herrmann et al. (2007a, b)[92][93]	Mineral oil, vegetable oils	Nwm CL Variocut G500, chlorine-free palmitic acid ethylhexyl ester	LCA, no specification	Machining of metals	GWP, AP, ODP, PM, POCP, ADP, KEA
Oemeta (2016)[94]	Mineral oil	Nwm CL	Extraction, production, use and disposal Cradle to Grave	Process chain for crankshaft production (milling, turning, deep drilling, grinding)	GWP, AP, EP, ADP
TUBS/ IMF (2011)	Mineral oil	Wm CL no additive specification	Raw material extraction, production, use, disposal	Number of workpieces to be machined in a specific machining procedure	ADP, GWP, AP, EP
Gonzáles-Reyes et al. (2020)[95]	Mineral oil, synthetic oil, biodegradable oil (ester)	no further explanation	Extraction, production, transport, use, recycling	Water and wind energy	Energy (kWh/l), emissions (kg CO_2/l)

* Nwm CL: Non-water-miscible cooling lubricants; Wm CL: Water-miscible cooling lubricants; ADP: Abiotic Depletion Potential; AP: Acidification Potential; KEA: Cumulative Energy Demand; EP: Eutrophication Potential; GWP: Global Warming Potential; KRA: Cumulative Raw Material Demand; ODP: Ozone Depletion Potential; PM: Particulate Matter; POCP: Photochemical Ozone Creation Potential

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[90] Cf. Dettmer, T. (2006).

[91] Cf. William-Olsson (2020).

Since it is very difficult to obtain information about the reduced amount of additives, a generic mineral oil-based product is considered using the ecoinvent database to model a representative CL. The treatment and disposal of CL by incineration are taken into account. The literature considered in this context refers to the year 2011[96] (lower calorific value 34.7 MJ/kg KSS).

5.2.3 Filter fleece

Filter fleece is used in both scenarios for the filtration of the cooling lubricant. The required quantity was determined in the tests for a reference workpiece and calculated in the production scenario for the functional unit. In the retrofit scenario, approximately 29% less filter fleece was required compared to the reference scenario (corresponds to about 0.5 kg of savings per year). This model is based on a filter fleece made of polyester (spunbonded fabric) with a surface weight of 25 g/m^2.

5.2.4 Sensors

In the retrofit scenario, the manufacturing, use and disposal of four different sensor devices, for which common sample products were identified, were considered in the lifecycle assessment.

The weight and material composition of the sensor devices (cf. Table 16) were estimated to model the manufacturing phase, with the help of technical product data sheets and product webpages. Further assumptions are made due to the incompleteness of the available data. For example, the power analyser was assumed to be a smaller laptop and its weight was adjusted in the model. Except for the inputs listed in Table 16, no further consumptions or production steps (e.g. processing of raw materials or similar) were considered within the orientating LCA.

For the usage phase of the sensor devices, the power consumption was identified as the only parameter relevant to the lifecycle assessment. Based on

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[92] Cf. Herrmann, C.; Hesselbach, J.; Bock, R.; Zein, A.; Öhlschläger, G. und Dettmer, T. (2007a).

[93] Cf. Herrmann, C.; Hesselbach, J.; Bock, R. und Dettmer, T. (2007b).

[94] Cf. Oemeta (2016).

[95] Cf. González-Reyes, G. A.; Bayo-Besteiro, S.; Vich Llobet, J. und Añel, J. A. (2020).

[96] Cf. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E. und Weidema, B. (2016).

expert estimation, a total power consumption of 120 kWh per year (based on 1,600 operating hours in the production scenario) was assumed for these four CPPS components. The total annual power consumption of the sensors therefore accounts for about 56% of the computer's power consumption and 11% of the server's power consumption, which is less significant compared to the other two CPPS components.

Table 16: Assumptions for the material composition of the sensor devices

	Product weight (kg)	Material/sub-component	Weight percentage	Source
Power analyser	1.9	Laptop	100 %	https://docs.rs-online.com/e33b/A700000007015170.pdf
Sensor terminal	0.35	Metal casing made of zinc	75 %	https://www.beckhoff.com/de-de/produkte/i-o/ethercat-klemmen/elmxxxx-messtechnik/elm3602-0002.html
		PCB with LED	25 %	
Industrial acceleration sensors	0.07	Stainless steel housing	71 %	https://www.mmf.de/industrieaufnehmer.htm#ks74-80
		Polyamide connectors	29 %	
Sensor node	0.054	Polycarbonate housing	40 %	https://www.bosch-connectivity.com/media/downloads/xdk_node_110_combined_datasheet.pdf
		PCB with LED	40 %	
		Rechargeable lithium-ion battery	20 %	

The disposal of the sensor components was modelled in accordance with the WEEE Directive of the European Union (2012/19/EU), which requires adding old electronic equipment to existing recycling streams, by means of an appropriate recycling process. This represents a global average for the recycling of waste electrical equipment.

5.2.5 Computers/servers

Literature data was used to model the computers and servers required. A composition based on assumptions in the ecoinvent database was found in the literature. A computer (desktop computer) or server is modelled as a product that includes, among others, a graphics card, network card, hard disk, printed circuit boards, RAM, battery and other materials (e.g. metals, plastics, packaging). All of these materials were taken into consideration, as were the mouse, keyboard and LCD monitor.

The usage phase of computers and servers was modelled using literature data regarding average consumption rates in Europe. In particular, the energy requirements for computers (215 kWh/a) and servers (1,117 kWh/a) were modelled taking into account a VDI ZRE study[97]. The lifespan of computers (5.8 years) and servers (6 years) was defined using average data from various sources[98] [99].

For the waste management of computers, servers and peripheral devices, thermal recovery is assumed, taking into account pre-mechanical treatment and residual material treatment[100].

5.3 Economic evaluation: Selection and quantification of cost items

5.3.1 Selection of the cost items

The economic analysis is intended to provide a decision-making basis for SMEs in particular, since there is a tendency for a greater requirement for retrofitting measures here compared to larger companies, especially for craft businesses and workshops, which often still use machines of older years of construction. The focus of the economic evaluation is therefore primarily on the costs of the CL users, i.e. small or medium-sized companies in the metal processing industry. In this case, however, the costs are generally relevant over the entire lifecycle of the two scenarios, since in the retrofit scenario, the additional measures involved differ components from all cost categories in different directions and amounts from those of the reference scenario.

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[97] Cf. VDI Zentrum Ressourceneffizienz GmbH (2017a).

[98] Cf. Yao, M. A.; Higgs, T. G.; Cullen, M. J.; Stewart, S. und Brady, T. A. (2010).

[99] Cf. European Commission, D. E. (2012).

[100] Cf. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E. und Weidema, B. (2016).

For this reason, the following cost items are accounted for in the economic valuation within the usage phase:

- Production costs of the cooling lubricant (use for regular replacement and replacement requirements due to losses) and the filter fleece,
- transport costs for cooling lubricant and filter fleece between manufacture and use,
- utilisation costs in the form of the consumption of electrical energy by the machine and filter in both scenarios and additionally for computers and sensor devices in the retrofit scenario,
- Disposal of CL and filter fleece in both scenarios and additionally for computers and sensor devices in the retrofit scenario.

The transport activities between manufacture and use only play a minor role as a cost factor. They are therefore not shown as a separate category in the following, but are allocated to the manufacturing costs.

However, additional application-related costs that do not allow for any differences between the two scenarios in the underlying functional unit are not considered. Since the Berucut SCO 310 was based on the use of a non-water miscible CL, the water consumption does not play a role in the operation from a cost point of view.

5.3.2 Quantification of selected cost items

The costs are accounted for using realistic average values. For the cost estimates, data was collected either from ecoinvent or primarily publicly available data, such as average market prices on internet portals, as well as own estimates.

(1) Procurement costs for the cooling lubricant Berucut SCO 310

The non-water-miscible cooling lubricant Berucut SCO 310, manufactured by the company BECHEM, is offered in the containers of a 180 kg barrel at

€1.94/kg and a 18 kg can at €2.13/kg[101]. Due to the extent of the annual use of 926.42 kg CL in relation to the functional unit, the following assumes sourcing in the larger unit of volume of the 180 kg drums.

(2) Procurement costs for the filter fleece

The use or consumption of the filter fleece can vary depending on the mode of operation and the type or quantity of chipping and is therefore not fixed. The ground components and the final use of CL also play a major role in this.

Based on the experience gained from their own use at the IWF at TU Braunschweig, a roll of filter fleece is used from the company LANTOR made of 100% polyester with the quality SB401, which has a material weight of 3.75 kg with dimensions of 1,000 mm x 150 m. This roll is purchased from the IWF at a price of €147.56. In the reference scenario, this roll can cover the quantity required for two years (117,158 parts). This results in a price of €73.78 per year or €39.45 per kg of filter fleece for the reference scenario.

In the retrofit scenario, it is assumed that an equivalent proportion of fleece is saved in 28.8% of the time by grinding without CL. Accordingly, instead of 1.87 kg, only 1.33 kg of filter fleece is consumed; consequently, the same roll of filter fleece would not last for two years, but for 2.81 years of production.

(3) Procurement costs for the additional devices in the retrofit scenario

The following price assumptions are used for the devices that are additionally required in the retrofit scenario (Table 17):

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[101] **Data from the IWF at TU Braunschweig, from which Berucut SCO 310 is obtained in 180 kg barrels**

Table 17: Prices for devices in the retrofit scenario

Device	Price in €/ unit	Source
Energy measuring device	4,000	Estimated value, see for example pricing on the RS platform online[102]
Acceleration sensor - sensor terminal	350	Information from the manufacturer Beckhoff New Automation Technology[103]
Acceleration sensor (industrial accelerometers)	210	Information from the manufacturer MMF[104]: https://www.mmf.de/pdf/1-10.pdf
Sensor node	160	Average value, see e.g. Information from specialist dealer Conrad Electronic SE[105]
Computers (without peripheral devices)	1,000	Average of prices on the internet
Servers (without peripheral devices)	600	Average of prices on the internet
Mouse	10	Average of prices on the internet
Keyboard	12	Average of prices on the internet
LCD monitor	170	Average of prices on the internet

(4) Transport costs for cooling lubricant, filter fleece and equipment

For all transport costs between the place of manufacture and the place of use, prices from ecoinvent for the “Transport Lorry” category of €0.156 per tonne kilometer are assumed.

(5) Cost of energy consumption when using CL (machine and filter)

Energy consumption is based on costs of ct. 18.25/kilowatt hour of electricity. In this context, indications for a relevant industrial electricity price in the present case were considered. This is not easy, because according to the websites of providers, such as e-on or Uniper, the price of electricity appears to industrial customers largely as an individual matter of negotiation and is crucially dependent on total electricity consumption; electricity companies enquire about the current electricity tariff and consumption as part of price inquiries -. For example, around 100,000 kWh and 1 million kWh are apparently considered to be threshold values for pricing.

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[102] Cf. RS Online (25th January 2022).

[103] Cf. Beckhoff Automation GmbH & Co. KG (23th January 2022).

[104] Cf. MMF (2021).

[105] Cf. Conrad (25th January 2022).

In individual cases, the purchase price therefore depends decisively on the size of the company and the resulting total electricity consumption. Furthermore, there are very different pricing models that are more or less suitable for certain target groups.

Therefore, an average price for the industry (in which SMEs are also represented) of 18.25 ct/kWh is assumed below; this value is also shown in the statistics portal Statista as industrial electricity price including electricity tax for the year 2021 in Germany. A BDEW source, according to which the average electricity price for industrial electricity as of July was 2020 17.75 ct/kWh including electricity taxes, levies and levies, is consistent with this information.

It should be noted that very small craft businesses may pay the higher rate for private households of up to approx. ct 30/kWh. Consequently, the influence of such an increased price on the overall result can be analysed with regard to the advantages of the retrofit measures.

In the general sensitivity analysis, no changes in electricity prices are assumed, only a percentage variation in the power consumption for the devices in the retrofit scenario, since, unlike the power consumption of the grinding machine and the filter, there are still no reliable empirical values regarding these. However, it is easy to examine how an increase or decrease in the price of electricity affects the relative benefits of both scenarios, or whether there is a critical price of electricity at which a break-even point of retrofit investment is reached.

(6) Costs for the additional energy consumption of the devices for the retrofit measures

The same assumptions regarding the electricity price also apply to the power consumption that the additional devices require for the retrofit measures. Again, an average industry price of 18.25 ct/kWh is assumed to be the default value, as well as the corresponding alternative sensitivity values for SMEs and for the 2030 EU electricity mix. A separate sensitivity analysis addresses the amount of power consumed by all additional devices in the retrofit scenario. A general increase of 50% in this component of power consumption and its effect on the overall result are shown in the results chapter.

(7) Disposal costs

Appropriate average costs for disposal processes from ecoinvent are allocated for the disposal costs. These are shown as specific costs in Table 18.

Table 18: Prices for disposal in the reference scenario and in the retrofit scenario

Device	Price in €/kg	Used category of disposal regarding ecoinvent
Cooling lubricant	0.374	Treatment of waste mineral oil incineration
Filter fleece	0.0092	Fibre and plastic waste treatment, polyester
Energy measuring device	0.272	Mechanical treatment transport WEEE
Acceleration sensor - sensor terminal		
Acceleration sensor (industrial accelerometers)		
Sensor node		
Computers (without peripheral devices)		
Servers (without peripheral devices)		
Mouse		
Keyboard		
LCD monitor		

It should be noted that these costs also include transport costs for average distances to the respective plant. These are used in ecoinvent as standard parameters, which depend on the distribution or the average distances from the respective disposal companies, e.g. waste incineration plants. For “fibre and plastic waste” – the category to which the filter fleece is assigned – this standard distance is approximately 100 kilometres. Transport costs between operation and disposal are therefore not calculated as an additional component, as they are already included in the prices for disposal on a pro rata basis.

In the study by the VDI Centre for Resource Efficiency (2017b)[106], a value of €72.50/m^3 for the CL disposal was assumed to be a gate fee to be paid to the disposal company (i.e. only the acceptance price for waste from disposal companies, without proportional transport costs). From this, the average value of an interval of €45 - 100/ m^3 can be derived from an estimate of 2010.[107] However, this value refers to the volume of a CL emulsion consisting of 95%

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[106] Cf. VDI Zentrum Ressourceneffizienz GmbH (2017b).

[107] Cf. Fischer, P., Itasse, S. (5. Mai 2010).

water. If, as a simplification, a density of 1 g/cm^3 is assumed, the cost corresponds to €72.50/t or €0.0725/kg – that is, only about 20% of the value from ecoinvent. However, this figure is not comparable to the cost rate from ecoinvent, not only because the underlying estimate from eleven years ago is likely to now be out of date: The higher costs of €0.374/kg reported by ecoinvent relate to the combustion of 100 % mineral oil, i.e. the non-water-miscible CL used here. These assumptions appear plausible and consistent with the other data from ecoinvent.

For the economic analysis, a reference to the functional unit is also made by comparing the specific costs presented with the data from the quantity structure (quantities or weight in kg).

6 RESULTS OF THE ECOLOGICAL AND ECONOMIC ASSESSMENT

6.1 Results of the ecological assessment

The implementation of retrofit measures takes into account the cost of natural resources (energy, raw materials, water, soil) over the entire lifecycle of the machine tool. This analysis is carried out using environmental indicators for each resource group. The overall results are shown in Table 19.

Table 19: Results of the ecological assessment (per functional unit)

Impact indicator	Reference unit	Reference scenario	Retrofit scenario
Global warming potential	Kg CO_2equivalent	11,352.9	9,436.5
KEA (exhaustive + regenerative)	MJ	205,243.6	169,249.5
KRA (biotic + energy raw materials + metal raw materials + mineral raw materials, stones and earths)	kg	4,148.9	4581.0
Water consumption	kg	60,992.2	51,265.7
Land use, (agricultural land + residential land)	m^2*a	402.9	344.1

6.1.1 Greenhouse gas potential

Greenhouse gas emissions were calculated using the "EF 2.0 Climate change, total" indicator based on the 2013 report by the[108] Intergovernmental Panel on Climate Change (IPCC). Emissions are expressed in CO_2equivalent emissions. The results of the greenhouse gas potentials for production, use and disposal are listed in Table 20.

Table 20: Greenhouse gas potential, three phases (kg CO_2equivalents)

Impact indicator	Manufacturing		Use		Disposal	
	Reference	Retrofit	Reference	Retrofit	Reference	Retrofit
Global warming potential (kg CO_2-eq.)	1,232.8	1218.8	7820.0	6310.0	2300.1	1907.7

The results show that greenhouse gas emissions are 17% lower in the retrofit scenario over the entire lifecycle than in the reference scenario. This repre-

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[108] Cf. IPCC (2013).

sents a total saving of approximately two tons of CO_2equivalents per functional unit. In both scenarios, the largest share of greenhouse gas emissions can be attributed to the usage phase. While in the reference scenario emissions of about eight tons of CO_2equivalents are generated during the usage phase, the retrofit measures lead to a reduction of emissions to about six tons of CO_2equivalents. This means that the greatest savings are in the usage phase, which is related to the lower power consumption. The emissions associated with the manufacturing phase are approximately the same in both scenarios. In the disposal phase, only a minimal reduction in the retrofit scenario compared to the reference scenario can be achieved, which is due to the lower disposal effort of the cooling lubricant (as lower consumption). The disposal and manufacture of CPPS components account for only 3% of lifecycle-related greenhouse gas emissions over the entire lifecycle. In both scenarios, electricity consumption is considered the main driver of CO_2across all lifecycle phases, accounting for 69% (without measures) and 67% (with appropriate measures) respectively.

6.1.2 Cumulative energy demand (KEA)

The methodology of VDI guideline 4600 “Cumulative energy demand (KEA)” is used for the analysis of the cumulative energy demand[109]. It shows the aggregated results of the manufacturing, use and disposal phases. The KEA is usually specified grouped according to primary energy sources as KEA, regenerative and KEA, exhaustive (see Table 21).

Table 21: Cumulative energy demand, three phases (KEA) (MJ)

Impact indicator	Manufacturing		Use		Disposal		Total	
	Reference	Retrofit	Reference	Retrofit	Reference	Retrofit	Reference	Retrofit
KEA, exhaustive (MJ)	59,350	51325	129000	104000	256	216	188,605.6	155,541.0
KEA, regenerative (MJ)	1,225	1,298	15,400	12,400	13	11	16,637.9	13,708.5

In terms of cumulative energy demand, the picture is similar to that of the greenhouse gas potential: The total cumulative energy demand (exhaustive

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[109] Cf. VDI 4600 (2012:01).

and regenerative) in the retrofit scenario is about 18% lower than in the reference scenario. This is equivalent to a saving of approximately 36 GJ. The proportion of renewable and regenerative energy sources in both scenarios is 92% and 8% respectively. If we look at the distribution of the cumulative energy demand over the different lifecycle phases, it is also apparent that the use phase also plays a key role in this environmental indicator. At around 70%, it represents the lifecycle phase in which the most energy must be used up. The remaining 30% is in the manufacturing phase. The CPPS components at 2-3% account for a marginal share of the total cumulative energy demand.

6.1.3 Cumulative raw material demand (KRA)

The VDI guideline 4800-2 is used to calculate cumulative raw material demand (KRA). The results of this study are summarised in four different types of KRA: Energy raw materials, metal raw materials, mineral raw materials, stones and earth, as well as biotic raw materials. The aggregated results of the manufacturing, use and disposal phase are shown in Table 22.

Table 22: Cumulative raw materials demands (KRA), two scenarios (MY)

Effect indicator	Reference unit	Reference scenario	Retrofit scenario
KRA, energy raw materials	kg	1,279.8	1,071.0
KRA, metal raw materials	kg	511.8	1,249.6
KRA, mineral raw materials, stones and earth	kg	2,355.7	2,258.7
KRA, biotic. Raw material expenditure	kg	1.6	1.7

In contrast to the other environmental indicators considered, the results for cumulative raw material demand show a different picture. Over the entire lifecycle, the retrofit scenario results in a 10% increase in raw material demand, which corresponds to approximately 430 kg of raw material per year. While the proportion of mineral raw materials, stones and earth, as well as biotic raw materials, changed slightly compared to the reference scenario (-4% and + 6% respectively), the differences for the other sub-categories are more pronounced. In the retrofit scenario, cumulative raw material demand for energy raw materials is approximately 16% lower. This is primarily due to the lower cooling lubricant consumption. However, an even more noticeable change can be observed for metal raw materials: Their proportion is 59% higher due to the used CPPS components with various metallic components.

6.1.4 Water consumption

The "ReCiPe 2016 v1.1 Midpoint (H) - Freshwater Consumption" method implemented in GaBi[110] is used for the analysis of water consumption. The results of water consumption for manufacturing, use and disposal are shown in Table 23.

Table 23: Water consumption, three phases (kg)

Impact indicator	Manufacturing		Use		Disposal	
	Reference	Retrofit	Reference	Retrofit	Reference	Retrofit
Water consumption (kg)	11,755	11548	48500	39100	737	618

6.1.5 Land use

For the determination of land use, the corresponding elementary flows were calculated in m^2 and year per functional unit (m^2*a/FE) of the lifecycle assessment modelling according to VDI guideline 4800 page 2. Quantification was carried out using ecoinvent database entries[111]. Here, the category "land use" was used for quantification and temporary use was excluded in accordance with VDI guideline 4800. The aggregated results for manufacturing, use and disposal are shown in Table 24.

Table 24: Three-phase (m^2*a) land use

Impact indicator	Manufacturing		Use		Disposal	
	Reference	Retrofit	Reference	Retrofit	Reference	Retrofit
Land use, agricultural land (m^2*a)	57.2	60.2	286.0	230.0	0.6	0.5
Land use, urban areas (m^2*a)	17.4	19.8	41.1	33.2	0.6	0.5

The retrofit measures also have advantages in terms of land use: Compared to the reference scenario, the retrofit scenario requires a total of approximately 14% less space over the lifecycle. This reduction corresponds to a saving of an area of about 60 m^2 per year. In both scenarios, the most important driver for land use is power consumption or the provision of power.

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[110] Cf. Huijbregts, M. A. J.; Steinmann, Z. J. N.; Elshout, P. M. F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A. und van Zelm, R. (2017).

[111] Cf. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E. und Weidema, B. (2016).

The reduction in land use in the retrofit scenario can be explained by the lower power requirement in the usage phase. 7% of total land use can be attributed to the manufacturing and disposal of CPPS components.

6.1.6 Sensitivity analysis: Worst case of an increased power consumption of 50% for CPPS components in the retrofit scenario

The sensitivity analysis allows the variability and stability of the ecological comparison and the underlying assumptions to be assessed. This analysis also serves as a basis for understanding potential ecological hotspots that could be improved. The sensitivity analyses could influence the presented ecological comparison and the statements regarding the criticality of raw materials. The economic analysis is not affected by this.

As one of the most important processes is the need for electrical energy, a sensitivity analysis is proposed to determine possible effects on all indicators considered. A sensitivity analysis to simulate an increased power consumption of the CPPS components (+ 50%) is shown here (see Table 25, “Variant: Retrofit scenario”).

Table 25: Results of the sensitivity analysis

Effect indicator	Reference scenario	Retrofit scenario	Variant: Retrofit scenario	Relative change
Global warming potential	11,352.9	9,436.5	9855.5	+ 4.4%
KEA (exhaustive + regenerative)	205,243.6	169,249.5	176978.5	+ 4,6 %
KRA (biotic + energy raw materials + metal raw materials + mineral raw materials, stones and earths)	4,148.9	4,581.0	4,680.4	+ 2.2%
Water consumption	60,992.2	51,265.7	5.3862,0	+ 5.1%
Land use, (agricultural land + residential land)	402.9	344.1	361.6	+ 5.1%

As the data on energy requirements are taken from the literature and have not been directly measured, it is considered to be unreliable. However, the results of the sensitivity analysis show that even with an increase in energy demand by 50% of the CPPS components, the aggregated overall results do not change.

6.1.7 Raw material criticality

The methodology from VDI guideline 4800-2 was used for the analysis of the supply risk (see Table 27)[112]. The directive refers to a system of evaluation with a total of 13 indicators, which are in turn divided into three groups. Table 26 shows these indicators. For each indicator, a rating per raw material is given. The rating scale ranges from 0 to 1, and levels of 0.3, 0.5, and 0.7 are presented.

Table 26: Indicators according to VDI 4800-2

Geological, technical and structural indicators	Geopolitical and regulatory indicators	Economic indicators
Ratio of reserves to global annual pro-duction	Herfindahl-Hirschman index of reserves	Herfindahl-Hirschman index of companies
Level of co-production/ by-production	Herfindahl-Hirschman index of country production	Level of demand growth
Spread of functional EoL recycling technologies	Political country risk	Technological and economic feasibility of substitutions in main applications
Economic viability of storage and transport	Regulatory country risk	Annualised price volatility
Geological distribution of natural reserves/growing regions		

The VDI guideline 4800 contains a selection of raw materials. These are assessed on the basis of literature, estimates and expert opinions. Among other raw materials, gold is not included in the VDI guideline 4800. Therefore, based on another VDI study, it is[113] assumed that the missing values for gold are very similar to those for silver. Table values for the mineral oil (mainly based on crude oil) can be found in the VDI guideline 4800 page 2[114] which shows the critical raw materials in both scenarios.

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[112] Cf. VDI 4800-2 (2018:03).

[113] Cf. VDI Zentrum Ressourceneffizienz GmbH (2018).

[114] Cf. VDI 4800-2 (2018:03).

Table 27: Raw material criticality analysis (the rating scale ranges from 0 to 1 and levels of 0.3, 0.5 and 0.7 are presented; source: VDI guideline 4800 page 2[115])

	Raw material/ Element	Aluminium	Chromium	Copper	Iron	Lithium	Manganese	Nickel	Silicon	Silver	Titanium	Zinc	Petroleum
	Average Criticality of raw material	0,3	0,5	0,4	0,4	0,5	0,4	0,4	0,4	0,5	0,4	0,5	0,3
Geological, technical and structural indicators	Ratio of reserves to global annual pro-duction	0,0	1,0	0,7	0,3	0,0	0,7	0,7	0,0	1,0	0,0	1,0	0,3
	Level of co-production/by-production	0,0	0,0	0,3	0,0	0,0	0,0	0,3	0,0	0,7	0,0	0,3	0,0
	Spread of functional EoL recycling technologies	0,3	0,3	0,3	0,3	1,0	0,3	0,3	0,7	0,3	0,3	0,7	0,3
	Economic viability of storage and transport	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,3
	Geological distribution of natural reserves/ growing regions	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Geopolitical and regulatory indicators	Herfindahl-Hirschman-index of reserves	0,7	1,0	0,3	0,3	1,0	0,7	0,3	1,0	0,3	1,0	1,0	0,3
	Herfindahl-Hirschman-index of country production	1,0	1,0	0,7	1,0	1,0	0,7	0,3	1,0	0,3	1,0	1,0	0,3
	Political country risk	0,5	0,7	0,3	0,7	0,3	0,3	0,3	0,7	0,7	0,7	0,7	0,7
	Regulatory country risk	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,7	0,3	0,7	0,3	0,3
Economic indicators	Herfindahl-Hirschman-index of companies	0,3	0,7	0,3	0,3	0,7	0,3	0,3	0,3	0,3	0,3	0,3	0,3
	Level of demand growth	0,0	0,3	0,3	0,0	0,3	0,0	0,3	0,0	0,3	0,0	0,0	0,7
	Technological and economic feasibility of substitutions in main applications	0,7	1,0	0,7	0,7	0,7	1,0	1,0	0,7	0,7	0,3	1,0	0,0
	Annualised price volatility	0,7	0,7	1,0	0,7	0,7	1,0	1,0	0,7	1,0	1,0	1,0	1,0

The average criticality of all raw materials is calculated from the average of all values of the respective criteria (between 0.3 and 0.5). As part of this, it can be concluded that there is a major risk for all raw materials from country production. In addition, two other aspects are associated with risks: the technical feasibility and economic viability of substitutions in major applications and annualised price volatility. Both scenarios use the same raw materials in this analysis. In addition, it should be noted that all of the listed critical raw materials are also present in both scenarios. Therefore, a

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[115] Cf. VDI 4800-2 (2018:03).

comparison of the two scenarios was not required. However, the results of the KRA analysis show that the retrofit scenario showed a higher consumption of critical elements (aluminium oxide, copper, lead, silicon, tin, zinc) which are used in the manufacture of electrical and electronic CPPS components.

6.1.8 Summary

It can be concluded that by implementing retrofit measures, savings are achieved on four out of five environmental indicators considered. The results show that 17% of greenhouse gas emissions, 18% of energy consumption, 16% of water consumption and 14% of land used can be saved over the entire lifecycle. For these environmental indicators, the usage phase – and in particular the power consumption – could be identified as the driver of the impact. At the same time, the greatest potential for savings is harboured by the usage phase, with ecologically advantageous reductions for the four environmental indicators. In the meantime, an opposite change could be observed in the cumulative raw material demand, which in the retrofit scenario was about 10% higher due to the metallic components of the CPPS components.

6.2 Results of the economic evaluation

6.2.1 Manufacturing and transport costs

In the reference scenario, the necessary costs for procuring the CL for applicators are €1,912.43/a, of which €1,871.23/a are the manufacturing costs and €41.20/a are the transport costs. Of these, €1,838.45/a is accounted for by the cooling lubricant and €73.98/a by the filter fleece. In the retrofit scenario, the proportion of components is significantly lower (€1,523.51/a for production and €33.71/a for transport) due to the savings in CL and filter fleece. However, for the devices required in the retrofit scenario, a further €1,097.29/year (production) and €0.23/a transport costs (a total of €1,097.52/a) are added. Of these additional investments, the highest proportion is the annual cost of the energy measuring device at €533.33/a. Overall, the manufacturing and transport costs in the retrofit scenario are therefore 38.8% higher than in the reference scenario. The share of the costs for the components is shown in Table 28:

Table 28: Manufacturing and transport costs of the functional unit in Euro/a.

Product	Manufacturing costs in €	Transport costs between manufacture and use in €	Total costs in €
Reference scenario			
Cooling lubricant use	667.36	15.29	682.65
Cooling lubricant losses	1,129.90	25.89	1,155.79
Filter fleece	73.98	0.01	73.98
Total for reference scenario	1,871.23	41.20	1,912.43
Retrofit scenario			
Cooling lubricant use	667.36	15.29	682.65
Cooling lubricant losses	803.54	18.42	821.96
Filter fleece	52.61	0.00	52.61
Energy measuring device	533.33	0.00	533.33
Acceleration sensor - sensor terminal	23.33	0.00	23.33
Acceleration sensor (industrial accelerometers)	42.00	0.00	42.00
Sensor node	160.00	0.00	160.00
Computers (without peripheral devices)	172.41	0.08	172.49
Servers (without peripheral devices)	100.00	0.07	100.07
Mouse	3.45	0.00	3.45
Keyboard	4.14	0.01	4.15
LCD monitor	58.62	0.07	58.69
Total for retrofit scenario	2.620.80	33.95	2,654.75

6.2.2 Usage costs (power consumption)

The power consumption in the reference scenario is only incurred by the operation of the grinding machine and the filter. A power consumption of 13,401 kWh/a was calculated for this operation. At an average assumed industrial electricity price of ct 18.25/kWh (cf. chapter 6.2.2), the total cost of electricity consumption is €2,445.75 /a.

In the retrofit scenario, the reduced total duration of operation of the grinder and filter to produce the same functional unit over a year can result in a power saving of 29.3% to 9,475 kWh/a. On the other hand, the devices for the retrofit measures consume an additional 1,452 kWh/a, of which the operation of the server accounts for the highest proportion at 1,117 kWh/a. The calculated electricity costs in the retrofit scenario therefore amount to €1,729.17/a for the grinding machine and filter and €264.99/a for the additional devices. The total cost of electricity consumption at €1.994.16/a is therefore reduced by 18.5% compared to the reference scenario. Power consumption and power costs for each component are shown in Table 29.

Table 29: Cost of the power consumption of the functional unit during the usage phase in Euro/a.

Activity/device	Consumption in kWh	Price in €/kWh	Total costs in €
Reference scenario			
Energy consumption of machine and filter/total	13,401	0.1825	2,445.75
Retrofit scenario			
Energy consumption of machine and filter	9,875	0.1825	1,729.17
Energy measuring device	96		17.52
Acceleration sensor - sensor terminal	8		1.46
Acceleration sensor (industrial accelerometers)	8		1.46
Sensor node	8		1.46
Computers (without peripheral devices)	215		39.24
Servers (without peripheral devices)	1,117		203.85
Mouse	Included in the power consumption of the computer and server		n/a
Keyboard			
LCD monitor			
Total energy consumption of the retrofit devices	1,452		264.99
Total for retrofit scenario	10,927	0.1825	1,994.16

6.2.3 Disposal costs

The disposal costs refer to the CL, which is caused both by the regular replacement and new use as well as by the loss contained in the chippings. The costs also include the transport route to the plant, which is assumed to be average. In the reference scenario, the disposal costs amount to €346.50/a, whereby the calculated disposal costs for the filter fleece are negligible at €0.02/a.

In the retrofit scenario, these disposal costs can be reduced to €283.58/a. This is equivalent to a saving of 18.2%. The costs for the disposal of all retrofit devices, the treatment of which has all been assigned to the category “Mechanical Treatment Transport WEEE” from ecoinvent, are €1.70/a. The small additional 0.005% share compared to the disposal costs in the reference scenario is explained by the low weight of the devices in the functional unit. The total waste disposal costs for the retrofit scenario therefore amount to €285.28/a – a saving of 17.7%. The weight shares, specific disposal costs and cost shares of individual components are shown in Table 30.

Table 30: Prices for disposal in the reference scenario and in the retrofit scenario

Device	Quantities to be disposed of in kg/a.	Price for disposal in €/kg (ecoinvent)	Costs of disposal in €/a.
Reference scenario			
Use of cooling lubricant	344.000	0.374	128.66
Cooling lubricant losses	582.421		217.83
Filter fleece	1.875	0.0092	0.02
Total for reference scenario	n/a	n/a	346.50
Retrofit scenario			
Use of cooling lubricant	344.000	0.374	128.66
Cooling lubricant losses	414.198		154.91
Filter fleece	1.333	0.0092	0.01
Energy measuring device	0.253	0.272	0.07
Acceleration sensor - sensor terminal	0.023		0.01
Acceleration sensor (industrial accelerometers)	0.014		0.00
Sensor node	0.054		0.01
Computers (without peripheral devices)	1.948		0.53
Servers (without peripheral devices)	1.883		0.51
Mouse	0.075		0.02
Keyboard	0.250		0.07
LCD monitor	1.759		0.48
Total for retrofit scenario	n/a	n/a	285.28

6.2.4 Total costs from the point of view of the CL user with and without retrofit measures

If you compare and add up the cost components from the chapters 6.2.1, 6.2.2 and 6.2.3, you can see that in the reference scenario, electricity costs account for the highest proportion of costs at 52.0%, followed by manufacturing and transport costs at 40.6%, and disposal costs at 5.8%. In the retrofit scenario, on the other hand, due to the additionally required sensor devices, computers and servers, the production and transport costs account for the highest proportion at 53.8%, while the electricity consumption costs account for only 40.4% and the disposal costs for 5.8%.

Overall, the higher investments of the retrofit measures, which amount to €742.32/a for the functional unit, are only partially offset by the savings in power consumption (€451.59/a) and the savings in the disposal phase (€61.22/a). This leaves a balance of additional costs of €229.51/a for the retrofit measure. The overall overview of the cost distribution is shown in Table 31.

Table 31: Cost allocation of manufacturing (including transport), use and disposal – comparison of reference and retrofit scenario

scenario	Manufacturing and transport costs in €/a	Cost of power consumption (usage phase) in €/a	Disposal costs in €/a	Total costs in €/a
Reference scenario	1,912.43	2,445.75	346.50	4,704.67
Retrofit scenario	2,654.75	1,994.16	285.28	4,934.18
Cost difference in the retrofit scenario	742.32	-451.59	-61.22	229.51

6.2.5 Sensitivity analysis: Worst case of an increased power consumption of 50% for CPPS components in the retrofit scenario

In line with the environmental assessment, it is assumed also here that the power consumption in the retrofit scenario for all CPPS components is 50% higher than the standard assumptions. This does not affect the power consumption for the grinding machine and filter in the retrofit scenario and in the reference scenario. Many years of experience have been gained for this operation, so there is little uncertainty regarding the estimates.

The electricity consumption in the reference scenario remains unchanged at 13,401 kWh/a, which, in view of the electricity price for the industry used at ct. 18.25/kWh, results in a total electricity consumption of €2,445.75/a. In the retrofit scenario, this component of the power consumption is reduced by 29.3% to 9,475 kWh/a. However, the devices for the retrofit measures now use a further 2,178 kWh/a (i.e. 50% more than in the basic assumption), of which the operation of the server takes up the highest proportion with 1,675.5 kWh/a. The electricity costs in the retrofit scenario therefore amount to €1,729.17/a for the grinding machine and filter and €397.49/a for the additional devices. The total electricity consumption (and therefore also the total electricity costs) increases by 6.6% compared to the previous standard case assumption. Overall, the total cost of electricity consumption of €1.994.16/a is still lower than the reference scenario, but now only by 13.0% instead of 18.5%. The electricity consumption and costs of each component for the alternative assumption of a 50% increase in CPPS component power consumption are shown in Table 32.

The assumption that the devices consume more power only affects the costs of the usage phase and tends to shift the result further, albeit insignificantly, to the detriment of the retrofit scenario. In the retrofit scenario, manufacturing and transport costs account for the highest proportion at 52.4%, the share of electricity consumption costs rises to 42.0%, and the share of disposal costs drops slightly to 5.6%.

Table 32: The costs of power consumption of the functional unit during use phase in Euro/a – sensitivity assumption with 50% higher power consumption of CPPS devices in the retrofit scenario

Activity/device	Consumption in kWh	Price in €/kWh	Total costs in €
Reference scenario			
Energy consumption of machine and filter/total	13,401	0.1825	2,445.75
Retrofit scenario			
Energy consumption of machine and filter	9,875	0.1825	1,729.17
Energy measuring device	144		26.28
Acceleration sensor - sensor terminal	12		2.19
Acceleration sensor (industrial accelerometers)	12		2.19
Sensor node	12		2.19
Computers (without peripheral devices)	322.5		58.86
Servers (without peripheral devices)	1,675.5		305.78
Mouse	Included in the power consumption of the computer and server		n/a
Keyboard			
LCD monitor			
Total energy consumption of the retrofit devices	2,178		397.49
Total for retrofit scenario	11,653	0.1825	2,126.65

In total, the savings in electricity consumption fall from €451.59/a to €319.09/a, so that the total surplus cost for the retrofit scenario rises from €229.51/a to €362.00/a. The overall overview of the cost allocation is shown by Table 33.

Table 33: Cost allocation manufacturing (including transport), use, and disposal – comparison of reference and retrofit scenarios with 50% higher power consumption by CPPS devices

scenario	Manufacturing and transport costs in €/a	Cost of power consumption (usage phase) in €/a	Disposal costs in €/a	Total costs
Reference scenario	1,912.43	2,445.75	346.50	4,704.6
Retrofit scenario	2,654.75	2,126.65	285.28	5,066.68
Cost difference in the retrofit scenario	742.32	-319.09	-61.22	362.00

In addition, it should be noted that this assumption only affects a small proportion of electricity consumption and therefore has only a minor effect on the overall result. However, since electricity consumption is in principle an essential component in comparison to the total costs, an increase in the price of electricity (for example for SMEs with low total electricity consumption or in the forecast of a future development of electricity prices) would have a greater impact on the comparison in favour of the retrofit scenario.

7 SUMMARY AND CONCLUSION

7.1 Summary of the results

The aim of the study was to quantify the demand on material, energy, water and land use over the lifecycle of selected retrofit measures in a suitable combination for a typical specified grinding process (external cylindrical grinding as a machining process) using cooling lubricants. The use of supply-critical raw materials was shown, the greenhouse gas potential in CO_2 equivalents was estimated, the relevant cost savings, as well as the additional costs incurred by the retrofit measures were calculated comparatively. The retrofit scenario comprises a grinding process with a conglomerate of energy retrofit, oscillation and vibration retrofit. Alternatively, the functional unit was determined on the basis of the quantity produced (58,579 pieces/year) or on the basis of the chip volume (82,010 cm3/year).

In a sensitivity analysis, contrary to the standard assumptions of the retrofit and reference scenarios, it was assumed that all CPPS components in the retrofit scenario cause a 50% increase in power consumption.

The results of the study are summarised in Table 34 and divided into a scale system with “++” as the best and “- -” as the worst indicator value. Using the intermediate levels “+”, “o” and “-”, the relative performance of the alternatives in the scale system between the best and the worst indicator value is also expressed.

The results of this study show that the individual indicators do not clearly support the introduction of the considered retrofit measures in all cases. However, with the exception of cumulative raw material demand, retrofit measures tend to improve the impact on the environment. If the power consumption of the CPPS units increases by 50%, the benefit of retrofitting measures is slightly reduced.

However, under the given assumptions, the additional costs of the retrofit measures are not fully amortised over the lifecycle of the investment. It was disregarded as a model, however, that the retrofit measures could possibly also extend the service life of the system.

Table 34: Overall comparison of the criteria for the reference and retrofit scenarios, including a sensitivity analysis regarding an increased power consumption in relation to the functional unit

Effect indicator	Reference scenario	Retrofit scenario	Sensitivity analysis with increased CPPS power consumption
Global warming potential	-	++	+
Cumulative energy demand (KEA)	-	++	+
Cumulative resource demand (KRA)	++	-	-
Water consumption	-	++	+
Land use	-	++	+
Total costs	+	o	-

7.2 Conclusions

From a technical point of view, the extension of the machine system by means of the proposed CPPS must be described as positive in principle due to the resulting transparency and the possibility of data collection and evaluation. Especially with older machines and systems, it is often not possible to make in-depth statements beyond the wealth of experience of the technical personnel and to generate the necessary basis of data. The extension of a CPPS, as shown in this study, makes it easier to generate and justify these statements. In addition, the extension of the Industry 4.0 retrofit is an easy and cost-effective possibility, for example by means of further retrofits, since the initial procurement already includes the total proportion for data collection and processing. The entire information technology processing is already built up by the first use of the CPPS and can therefore be easily extended by further data sources (sensor technology). The creation of transparency, which is at the forefront of the two comparative scenarios in the report, is advantageous for the applied extension. The concept shown offers the possibility to reveal further potential through empirical values or data-based analyses. The retrofit measure, considered individually, initially only serves the aforementioned transparency. The further potential and improvements, especially with regard to the use of CL in the grinding process, result from the sustainability strategies described above, which refer to a fundamental efficiency concept and the substitution of conventional CL with organic lubricants, which may require more detailed system monitoring in order to ensure a high process quality and to avoid scrap.

The retrofit scenario, which comprises a total of three retrofit measures, results in a reduction in the use of cooling lubricant in an exemplary application of the grinding process and thus results in an energy saving of 29.3% compared to the reference scenario. Especially during roughing, the retrofitting has shown potential and clearly quantified it. This comparison describes an exemplary usage case and could lead to greater savings potential on an industrial scale. Further improvements, such as predictive maintenance or the vibration-based quality management of workpieces, are also conceivable.

For companies, the potential of retrofitting creates further action and training steps for the retrofit measures. This step-by-step development of the CPPS and the associated retrofit measures can be described as follows.

- Step 1: Transparency

The CPPS was primarily used for the creation of transparency in the usage case. Companies can use the physical level and decision support as visualising elements. Processes can be optimised using simple methodological procedures. Transparency is the first step towards effective use of the cyber level of the CPPS and the associated subsequent development step. The data can be used, for example, to conduct hot spot analyses within the company in order to identify large-scale potential.

- Step 2: Effective use of the cyber components

The cyber components of the CPPS relate to the modelling and simulation of the resulting data collection and processing. It is conceivable to resort to regression approaches or wide-ranging machine learning and thereby to apply data-based optimisation methods. The extended potential of the cyber level is explained within the scenario description and has a variety of application options.

- Step 3: Automation

The automation of the existing components describes the third extension step. By means of existing transparency and advanced modelling of their own system, companies can now also aim for control and regulation within the decision support that affects the components of the physical level, thereby building up a complete CPPS, as described in the literature. The system is regulated on the basis of the findings that arise at the cyber level and are supported by data processing. Nevertheless, even if a high degree of automation is in the foreground in this potential and extension stage, people can still be involved in the processes. Especially due to the resulting know-how and the support by, for example, recommendations for action, a human-machine interaction is absolutely necessary.

With retrofit measures, the ecological assessment shows positive effects in four environmental categories and a negative effect in only one environmental category. On the one hand, the majority of the impact categories (greenhouse gas potential, KRA, water consumption, land use) in the environmental analysis show that retrofit measures reduce the impact on the environment compared to traditional processing. Retrofit measures can achieve savings of between 14% and 18%. The usage phase is the most important phase of the lifecycle for all categories; the impact in the usage phase is determined by the power requirement for the process. The disposal phase, however, generally only has a minimal impact on the overall results.

On the other hand, the effects of retrofitting measures are not beneficial for the indicator of the cumulative raw material demand (KRA). This was to be expected because the material requirement is indeed higher when more resources are used, e.g. electronics with CPPS components. However, the retrofit measures have a higher use of critical elements in the KRA indicator for the production of electrical and electronic CPPS components. This is also important for the indicator of the supply risk. Material criticality has an average value between 0.3 and 0.5.

The results of the sensitivity analysis show that if the energy requirement is increased by 50% of CPPS components, the aggregate overall results for each indicator hardly change (less than 5%).

An evaluation of the costs shows that from the company's point of view, the investment in a retrofit measure leads to a resource saving in the operating phase and to a small extent also during disposal. However, given the assumptions made, in particular the assumption of current electricity prices and the time horizon of the plants, this saving is not profitable for the company. In addition, there is the not inconsiderable additional effort for data acquisition and data evaluation. It should also be noted that the additional power consumption of the retrofit devices is subject to less experience and therefore more uncertainty than the power consumption when operating the grinding machine itself.

A significant increase in the price of electricity in the future, or the realistic assumption that small businesses will continue to pay a higher price of electricity similar to that for private households, could relativise the unprofitability of the investment from a corporate point of view. The possible effect, which is not taken into account in this analysis, that the service life of the entire plant may be extended by a few years by the retrofit measure, or alternatively, that the annual output can be increased compared to the reference scenario during continuous operation, works the opposite way – in favour of the retrofit measure. Where increased use of retrofit measures is socially beneficial from an efficiency and environmental point of view, such investments should be supported by the state in order to create an incentive for the company during the remaining life of the plant, regardless of the uncertainty about the economic profitability. At the same time, it makes sense to accompany retrofit measures with accompanying measures such as targeted information, scientific support and documentation of good practice examples from different fields of application.

Since from an environmental point of view the retrofit measures (apart from the deviating result for the indicator “cumulative raw material demand” (KRA) always appear to be advantageous from an environmental and climate point of view, government support can be justified, possibly also with a targeted new funding programme on a state, German and/or EU level. It would be necessary to examine whether synergies could not be exploited across industries, materials and markets, including in cooperation between SMEs and larger companies.

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