Gesellschaft für Tribologie e.V.

Tribology in Germany

Wear protection and sustainability as cross-sectional challenges

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Inhalt

About this study

Compared to the CO_2 issue, the public discourse perceives sustainable resources as only secondary in importance. Everyone is talking about global warming but the term sustainability remains vague. Tribology has made significant contributions in both areas, offering huge potentials for both reducing CO_2 emissions and saving resources. Therefore, an easily comprehensible presentation of these important options is absolutely essential.

Whereas the study "Tribology in Germany – Cross-sectional technology for the reduction of CO_2 emissions and the conservation of resources", published by the Gesellschaft für Tribologie e.V. in 2019, presented the interaction between the reduction of friction and CO_2 emissions, the following study focuses on the contribution of wear protection for sustainability – a topic which has not made inroads into the public discourse. All findings are based on the 17 sustainability development goals (SDG) published by the United Nations in fall 2015.

Both a technology and science, tribology is based on a broad and solid industrial foundation. It is the objective of this study to present how tribological research and development can improve sustainability through wear protection, condition monitoring, maintenance, repair and recycling, thus contributing to resource conservation and increased material efficiency. Those affect the use of materials across all industrial sectors, consumer products and are not limited to mobility. As an interdisciplinary key technology, tribology will reduce excess CO_2 emissions by 2040 or 2050. In the medium term, friction reductions will contribute to saving 8-13% of primary energy, whereas wear protection and condition monitoring offer similar, not yet exact quantifiable contributions for the reduction of CO_2 emissions because the extended service life of machines and their components generates less material consumption ultimately reducing CO_2 emissions related to extraction and conversion of raw materials. This study illustrates the selected solution approaches based on the technologies available.

Brief summary of the GfT tribology study 2021 “Wear protection and sustainability“

TRIBOLOGY, the science of friction, lubrication and wear, is a cross-sectional technology of economic importance, inseparably combining wear protection and sustainability as well as the correlation between CO_2 emissions and friction. A basic technology, it enables material efficiency and resources conservation through products with a longer life-cycle requiring less material thus ultimately reducing CO_2 emissions. Wear is the irreversible loss of surface material under mechanical sollicitations resulting in functional failure.

Compared to the easily comprehensible correlation between “CO_2 and friction“, the interaction between „wear protection and sustainability“ is more complex: firstly because there are so many aspects to sustainability and secondly because the impact is mostly indirect.

Sustainability and tribology

In future modern society, sustainability will be one of the most important global goals. Wear protection will extend service life and functionality of the components integrated in a machine thus requiring fewer replacement machines for production and handling operations, reducing materials, primary energy and work required for the production ultimately lowering emissions. In the technosphere of a circular economy, this will enable a more intensive use of materials in consumer products.

Lower wear extending the product life cycle subsequently decouples material consumption from economic growth.

Global warming dominates the public discourse, whereas resources have currently faded to the background. In the year 2017, the human material footprint increased to 92.1 gigatons of mass with an additional 8.6 gigatons of recyclates, of which 15.047 gigatons were fossil resources and 24.062 gigatons were biomasses. The global combustible fossil CO_2 emissions in 2019 amounted to 33.3 gigatons. The total of 37.9 gigatons of CO_2 includes non-combustible industrial processes, e.g. in the cement or brick production. Material consumption also generates CO_2 emissions.

The remaining potential resource pool allowing to apply tribological measures to extend service life amounts to > 17.6 gigatons of consumed resources annually. Improved wear protection extending service life and condition monitoring is currently difficult to estimate since the saved tonnages cannot so far be quantified and directly allocated to applications and end-uses with tribosystems or being affected by tribosystems. This requires further research.

A hypothetically doubled service life would save 8.8 gigatons of resources annually and amount to a CO_2 equivalent of similar magnitude.

Forecasts assume an increase in the material footprint of 167 gigatons (OECD) or respectively 190 gigatons (UNEP-IRP) by 2060. Repairability extends the life cycle of worn goods.

Measures increasing service life by improving wear protection, using tribotronics and condition monitoring for improved material efficiency and resource preservation are just as significant as friction reduction to lower CO_2 emissions contributing to energy efficiency. Where sustainability is concerned, industry and science share different viewpoints and constantly changing definitions. The sustainability strategy of the German government of 2017 is based on the three guiding principles of sustainability “economy-social-environment“, also known as the three dimensions of sustainability. They are further subdivided into the 17 sustainable development goals (SDG) defined by the United Nations in 2015, essence and benefit for global sustainability. Tribology affects minimum six of the 17 sustainable development goals.

Wear protection increases resource efficiency and thus drives sustainable development goals forward. The economic significance of wear must not be underestimated.

“Wedges“ are working bases to stabilize the CO_2 content in the atmosphere and the global surface temperature and they help achieving the climate targets. Depending on the principle, they consist of 7, 12 or 31 wedges all not taking the contributions of tribology into consideration. The share of friction losses in global CO_2 emissions of 37.9 gigatons of CO_2 in 2019 amounts to 7.58 to 11.4 gigatons of CO_2 with a long-term reduction potential of 2.66 to 4.93 gigatons of CO_2 annually or minimum one wedge accordingly. Estimating the contribution of improved wear protection and modern condition monitoring for extended service life cycles is not really possible because the savings in tonnages of resources were so far not quantified.

Sustainable development goals of the United Nations directly related to tribology

Corrosion and tribology both act on the interfaces of two contacting surfaces. The simultaneous occurrence of both phenomena is called tribocorrosion. Corrosion and wear cause irreversible material and functional losses. The economic saving potential from measures of wear and corrosion protection is between 1.5% and 3% of the Gross National Product. The material volume saved by extended service life cycles lowers CO_2 emissions, material consumption and waste.

Tribology contributes to CO_2 reductions in dimensions of several wedges or >11 gigatons of CO_2, respectively >29% of the globally emitted 37.9 gigatons of CO_2 equivalents by:

a. primary energy savings through friction reduction and

b. the preservation of resources due to longer life cycles.

Sustainability and lubricants

The purely technical and highly functional formulations of lubricants are intended to meet the complex requirements of the industry's specifications in varying stringency. Although lubricants are further developed to meet functionality requirements, they are also subject of a socio-political discourse demanding to improve the eco-toxicological properties as well as scrutinizing and optimizing property profiles according to sustainability criteria. In 1990, the first environmentally compatible lubricants were marketed. Even 30 years later, they never achieved a market penetration of more than 3% to 4%. The eco-toxicological criteria restrict the selection of suitable base oils and additives. The main reason for the small market share was not the performance of the sustainable alternative, but the higher raw material price. The most important regulations for environmentally acceptable lubricants (EAL) are:

c. European ecolabel according to EC/2018/1702 (3rd Amendment),

d. b. Second issuance of U.S. Vessel General Permit (VGP2013 or next as VIDA) and

e. c. Biolubricants compliant with EN16807.

Lubricants based on biomasses or renewable raw materials benefit from the same functional profile as petrochemical products, but with distinctly better environmental balance. Sustainable lubricants based on the 17 SDGs of the United Nations feature the following benefits:

» Friction reductions lower CO_2 emissions (energy efficiency).

» Extended oil change intervals reduce waste and the consumption of resources.

» Base oils and additives based on renewable raw materials lower the consumption of resources on CO_2-neutral basis (solutions: esters, polyalkylene glycols and bio-olefines).

» Fast bio-degradability combined with low toxicity for flora, fauna and life.

» Complete waste oil collection with a material recycling concept.

Various lubrication classes can add more functionalities, such as bio-no-tox properties, and offer sustainability to their existing premium attributes.

The term “tribology“

In 1966, Sir Peter Jost, first established the term “tribology”. The original English definition states:

> *„Tribology is the science and technology of interacting surfaces in relative motion and of related subjects and practices“*

Friction, wear and lubrication, the key elements of tribology, aim to control the use of friction, to reduce wear over a long service life and to remove motion resistance and wear by means of lubrication. Solutions for the challenges posed by tribology require a holistic system analysis with an interdisciplinary conception.

The term “wear”

In 1969, the International Research Group on Wear of Engineering Materials of the OECD defined wear as:

> *“The progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface.”*

This is consistent with the definition of “wear“ in DIN 50320.

> *„Wear is the progressive loss of material from the surface of a body caused by mechanical impact, i.e. contact and relative motion of a solid, liquid or gaseous contrary compound.“*

Notes:

a. The surface stress on a solid body impacted through contact or relative motion of a solid, liquid or gaseous counterbody is described as tribological stress.

b. Wear is characterized by the occurrence of loosened small particles (wear particles) as well as changes in the substance and shape of the tribologically stressed surface areas.

c. Wear occurring in technical processes is usually unwanted, i.e. it diminishes the value. In exceptional cases, such as run-in processes, wear can be desirable. Machining as value-creating technological process on the workpiece to be manufactured are not considered as wear, although tribological processes occur on the interface area between workpiece and tool.

[1] OECD = Organisation for Economic Co-operation and Development, www.oecd.org

1. Point of Departure

In the past, monetary criteria were crucial for long service life and wear protection, while today primary energy savings, environmental aspects and material consumption play an equally important role. On the one hand, manufacturers develop more efficient equipment thus saving energy costs for the consumer and thereby contributing to the reduction of CO_2 emissions. Sophisticated wear protection, on the other hand, safeguards the longevity of the end user's investment and avoids reinvestments, even if the existing machinery performance is suboptimal in terms of energy consumption.

In the public discourse, the issue of resources is secondary to the CO_2 issue. Economic constraints and ecological legislation are closely linked to each other through the use of resources thus creating a balance between energy and material efficiency and the resource conservation . Here, a distinction should be made between worn and obsolete. It must be verified case-by-case whether further use of an older vehicle may conserve more resources, even if a new vehicle features less fuel consumption and the customer switched to a more fuel-efficient vehicle.

Ultimately, lower fuel consumption is beneficial for the vehicle owner or operator. Fuel savings bring about economic benefits. Here, the balance between the resource consumption of the new investment, energy savings and productivity gain is of great significance. On the other side of this efficiency equation, wear protection is equally important both for comprehensive sustainability efforts as well as for the return-on-invest for the end user, because durability/wear protection and resource use for the manufacture of equipment both depend directly on CO_2 emissions and other pollutant emissions.

2. Definition of Sustainability

Sustainability has its origin in the forestry industry of the 18th century. Ever since, no term has evolved more by the socio-political climate debate in recent decades than sustainability. Today's definition approaches not only imply the protection of natural resources but also take the long-term existence of the reference objects humans and nature into account.

The World Commission on Environment and Development (WCED) of the United Nations published the following definition of sustainability under the title "Our Common Future":

> *„Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."*
>
> *(World Commission on Environment and Development 1987, S.41)*

This definition approach suggests that socio-cultural, ecological and economical resources are to be consumed and utilized only to an extent that still allows to make them available in equal quality and quantity to further generations. The fact that large quantities of resources are irreversibly consumed one way or another, even if used up ecologically and/or sustainably, receives only little attention in the public discourse.

Definition approaches shifting from economic to ecologic valuations effect change of the economy framework. The global population growth, combined with the pursuit of a comfortable lifestyle, inevitably increases the consumption of resources and primary energy, if no countermeasures are taken. Around the world, sustainability is regarded differently, in varying intensity and based on different needs. To date, there is no global and uniform understanding of sustainability, neither in essence nor in benefits.

When related to wear protection in this context, tribology coincides with sustainability as cross-sectional challenge. Although wear protection and sustainability are extremely popular terms, the cross-sectional challenges they impose cannot be met 100% at the same time (see also Chapter 6 "Zero wear)".

[2] The conservation of resources is measured over the total raw material productivity.

In general, three strategies can be selected for sustainability:

» the efficiency strategy,
» the consistency strategy, and
» the sufficiency strategy.

The *consistency strategy* is about the compatibility of anthropogenic material and energy flows with nature, in the sense that preferably no waste is generated unable to be “digested“ by nature. Effective recycling management, renewable raw materials and regenerative resources are the supporting pillars of the consistency strategy.

Companies using the *sufficiency strategy* define the socially and environmentally compatible ceilings for economic activities but let go from “always-wanting-more“ from the beginning. In order to follow the principles of sustainability, research and development, production and utilization of all products improvements and inventions must meet the criteria of environmental compatibility. This also includes the resource-saving extraction of basic materials and their conversion.

Where *efficiency strategy* is concerned, the consumption of energy and resources as well as transport/mobility flows must be decoupled from economic growth. At the same time, efforts should be taken to more than compensate for the rising demand for energy, resources and transport/mobility with gains in efficiency and operating life – here, tribology makes a substantial contribution.

The excessive exploitation of natural resources will be followed by unavoidable declines in economic growth. That is why, when assessing prosperity, the depreciation of natural capital must be taken into account. If we use up too much natural capital[3] for the economic production of today, we will not have enough for the product of the future.

Economic reasoning, however, does not contradict the ecological approach. Sustainability is a core principle of resource utilization. Resources not generating added-value cost money in a future world of scarce and thereby more expensive raw materials. This constitutes the regulatory approach of economy.

The 2017 sustainability strategy of the German government is based on three guiding principles or three dimensions of sustainability[4] „Economy-Social-Environment“ which break down the 17 global sustainability goals [1] of the United Nations of 2015 (Agenda 2030) into 169 indicators.

3. Contribution of Tribology for Sustainability

3.1. Sustainable development goals of the United Nations

Tribology affects seven of the 17 sustainability development goals (**Sustainable Development Goals = SDG**) and several of the targets, whereby wear protection directly covers SDG-targets 8, #9 and #12 [1]:

> *„Ensure sustainable consumption and production patterns.“*

Table 1 outlines the direct and indirect effects of tribology on the 17 sustainable develop¬ment goals and presents specific proposals. Resource efficiency should not be limited to the optimization of production processes according to SDG #12. Leaner production processes may reduce the share of production waste, the life cycle approach, however, offers more potentials to protect and save resources during the service life of manufactured products. Here, tribology can make a tremendous impact through wear protection:

[3] This is the value for net losses of natural resources, such as minerals, fossil fuels, forests and similar sources for material and energy inputs in our economy.

[4] Equity market valuations can also include sustainability considerations. The Dow Jones Sustainability Index (DJSI World or ”green“ stock index) was established in 1999 and serves as benchmark for investors integrating sustainability aspects and socio-ecological criteria into their portfolios.

Table 1: The effects of tribology on the 17 global sustainability goals in the United Nations Agenda 2030 of October 2015.

Global goal	Target	Attributes and contributions
#3: Ensure **healthy lives** and promote well-being **for all at all ages**	#3.9: Substantially reduce the number of deaths and illnesses from hazardous chemicals and **air, water and soil pollution and contamination**	Biolubricants: Reduction of particulate emissions using more wear-resistant materials. Hard thin-film coatings replacing Chrom^{VI+}
#6: Ensure availability and *sustainable management of water* and sanitation for all	#6.3: …. improving water quality by reducing pollution, **eliminating dumping and minimizing release of hazardous chemicals and materials**, (…) and substantially increasing recycling and safe reuse globally	Biolubricants
#7: Ensure access to **affordable, reliable, sustainable and modern energy** for all	#7.2: By 2030, increase substantially the share of **renewable energy in the global energy mix**	Energy efficiency, long-life transmissions and bearings in wind turbines, exhaust heat recovery systems
	#7.3: By 2030, double the global **rate of improvement in energy efficiency**	Energy efficiency through the reduction of friction effects the reduction of CO2 emissions, longer wind turbine service life cycles
#8: Promote **sustained, inclusive and sustainable economic growth**, full and productive employment and decent work for all	#8.4: BImprove progressively, through 2030, global **resource efficiency in consumption and production** and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-Year Framework of Programmes on **Sustainable Consumption and Production,** ….	Resource efficiency through wear protection; adaptive condition monitoring, tribotronics Increasing the productivity of construction machinery through efficient hydraulic fluids.
#9: Build resilient infrastructure, promote inclusive and **sustainable industrialization and foster innovation**	#9.4: By 2030, upgrade infrastructure and retrofit industries to make them **sustainable**, with **increased resource-use efficiency** and **greater adoption of clean and environmentally sound technologies and industrial processes**, with all countries taking action in accordance with their respective capabilities	Wear protection = material efficiency and resource conservation plus reduction of fine dust due to fewer wear particles
#12: Ensure **sustainable consumption and production patterns**	#12.2: By 2030, achieve the **sustainable management and efficient use of natural resources.**	Lubricants and additives based on renewable raw materials
	#12.4: By 2020, achieve the **environmentally sound management of chemicals and all wastes** throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their re**lease to air, water and soil** in order to minimize their adverse impacts on human health and the environment .	Bio-lubricants, low-wear braking systems and tires, reprocessing of tribosystems
	#12.5: By 2030, substantially reduce **waste generation through prevention, reduction**, recycling and reuse .	Wear protection = long-life technology and extended service life cycles reduce the amount of waste, re-raffinates – second refining of used oil
	#12.6: **Encourage** companies, especially large and transnational companies, **to adopt sustainable practices** and to integrate sustainability information into their reporting cycle .	
#13: Take urgent action **to combat climate change and its impacts**		Energy efficiency through the reduction of friction effects the reduction of CO_2 emissions, lubricants from renewable or recycled resources

„Using products longer saves resources of any kind“.

Biolubricants meet the expectations of SDGs #3, #6 und #12. The tonnage of lubricants corresponds to about 1% of the fuel volume. That is why, where available, lubricants consisting of base oils and additives synthesized from biomasses, are optimally suitable for the use of resources made of renewable raw materials. This approach coincides with the SDG target #12.2 „sustainable management and efficient use of natural resources“.

3.2. Material footprint

Between 2000 and 2010, the material footprint of mankind[5], calculated as overall global raw material extraction, rose from 48.5 to 69.3 gigatons worldwide and attained 92.1 gigatons 2017 (Table 2) [2,3], tendency increasing. 15.013 gigatons thereof accounted to fossil energy sources and 22.909 gigatons to biomasses[6]. Biomasses can be classified as CO_2-neutral. Recycling economy adds another 8.65 gigatons. The total raw material extraction of the 28 EU member states in 2017 amounted to 7.189 gigatons.

Table 2: Global raw material extraction in 2017

Extractions by material category	Gigatons
Metal ores	9.120
Fossil energy sources	15.047
Mineral raw materials (non-metallic)	43.834
Biomasses of any type	24.062
Total	**92.063**
plus cycled materials	8.600

The OECD study “Global Material Resources Outlook to 2060“ [3] estimates that the global material consumption of 92.1 gigatons in 2017 will rise to 167 gigatons in 2060. The International Resource Panel of UNEP [2] even expects an increase to 190 gigatons. The application of known sustainability strategies will limit the increase to about 143 gigatons. Non-metallic minerals (building materials), such as sand, gravel and limestone etc. will then amount to more than 50% of the total material input.

Overall, there is a global material consumption or flow of 100.6 Gigatons including recycling [4], subdivided in 47.7 gigatons of long-life products and 52.9 gigatons of short-lived products (see Table 3). A portion of these extracted gigatons are non-recyclable and non-renewable materials, such as 15.047 Gigatons of fossil energy sources combusted in transportation/mobility or power generation. An unknown share of biomasses can either be recycled or their life cycle can be extended.

Table 3: Consumption of recyclable resources to improve life by means of tribological measures

Type of use	Recyclable	Renewable
Short-lived products	13.816 gigatons	24.062 gigatons (biomasses)
Long-life products	47.646 gigatons	–

From the materials annually entering the world economy, the majority of 52.925 gigatons is converted into short-lived products, such as biomasses, textiles or fossil energy sources whose utilization period usually ends after one year or latest after two years. The remaining 47.646 gigatons of materials are used in products of a longer life, i.e. mainly in buildings, for infrastructure, household, machinery and capital goods, but also electronic products.

As long as they are in use, buildings, infrastructure and capital goods made of minerals and ores are classified by society as resource stocks or CO_2 assets. Such materials are currently not available as secondary resources. Therefore, it is of paramount importance that tribological measures also maximize the friction efficiency and life cycle of buildings, roads as well as household, machinery and equipment. Subsequently, at the end of the life cycle, such equipment, machinery and products should be completely recycled. The potential resource pool, allowing tribological meas-

[5] The “material footprint” describes the amount of raw materials obtained that are used to meet the final demand. It is a measure of the stress to which the environment is exposed in order for the economy to grow and the material needs of people to be met.

[6] Water and solar power as well as geothermal energy generate mostly direct „green“ electric power and are to be considered separately from material and renewable resources, such as biomasses.

ure to extend the life cycle, would amount to about > 61.4 gigatons of used resources annually minus the 43.8 Gigatons of non-metallic minerals (building materials, sand, gravel and limestone, etc.) not affected by tribology [3].

» The remaining potential resource pool allowing measures to extend the life cycle amounts to about > 17.6 gigatons of used resources annually and the equivalent of to be specified CO_2 emissions (see Table 6).

Streams, as for catalyzers, packaging, building construction and civil engineering, are not related to tribology. It requires further research and investigations to assign the material streams going into applications forming tribosystems or into applications affected by tribosystems. However, buildings also include components with tribosystems, such as pumps and fans of HVAC (heating, ventilation, and air conditioning) systems. Roads, including pavements and surfaces as well as rail infrastructure, are all subject to massive wear. The consumption of material inevitably produces CO_2 emissions (see Table 6). Here, it becomes apparent why wear protection extending life cycles is just as important for improved material efficiency and resource conservation as the reduction of friction is for CO_2 emissions and ultimately for energy efficiency [5].

Wear protection is important because technical products are not regenerative like bio-systems, although the materials they are made of can be recycled. Wear protection, i.e. anti-corrosive properties, allow for more durable products enabling better resource efficiency reducing the generation of waste and the need for more material. Wear protection strongly delays replacements due to wear and thus minimizes both consumption and waste volumes. Eventually, wear protection increases resource efficiency and drives sustainability goals forward. Improved product design using the benefits of wear protection provides a systematic approach to keep products and materials in the life cycle and thereby adding economic and ecologic value.

Another aspect of wear protection is the reduction of wear particles and fine dust (see "Zero wear" and chapter 8.1) which serves sustainability goal no. 3 of the United Nations. "Ensure healthy lives and promote well-being for all at all ages" and particularly target 3.9 „Substantially reduce (...) air, water and soil pollution and contamination". The European Union has adopted the framework of the United Nations 17 global sustainability goals of 2015 but explicitly states the "exposure to suspended particulate matter". Biolubricants definitely contribute to the goal of the United Nations for a "Pollution-free planet" [6] considering SDGs #3 and #12.4, but also SDG #6.

3.3. The "Wedges" approach for the reduction of CO_2 emissions

The "Wedges" approach [7] was introduced by Robert Socolow und Stephen Pacala, two Professors of the University of Princeton. It postulates the following: greenhouse emissions shall be stabilized on the 2004 level (when the KYOTO-Protocol became effective) for the following 50 years starting in 2005, and the climate goal of 500 ppm CO_2 released into in the atmosphere and a surface temperature of 2°C shall not be exceeded. The authors called each axis to minimize emissions a "wedge". They identified seven wedges for alternative technologies with 15 possible options for the reduction of the carbon emission rate by one gigaton of carbon annually and 3.67 gigatons of CO_2 annually until 2054. Supposedly, only the wedge "Energy efficiency and savings" under the option "Efficient vehicles" is applicable for tribology. In 2004, they suggested to increase the range from 30 miles per gallon (= 7,84 L/100 km) to 60 miles per gallon (= 3,92 L/100km) compared to U.S. EPA which states a fleet consumption for new vehicles in 2019 of 25.5 mpg (9,22 L/100 km). A later study, conducted by Steve J. Davis et al. [8] of the University of California, suggested that the number of wedges should be increased to 31 (12 previously unnoticed, 9 additional ones to further stabilize emissions and 10 more to exit emissions) in order to still achieve the climate goals, because future growth and potentially even more CO_2 emissions due to a growing population and more prosperity, should be avoided. All these studies, however, did not have tribology on "their radar".

Extraction and conversion of raw materials inevitably generates CO_2. However, reducing material demand and waste generation by extending the product life cycle, by improving wear resistance and reducing friction should be included in the wedge approach.

The share of friction losses of global primary energy consumption and global CO_2 emissions of 33.3, respectively 37.9 gigatons (see footnote 8) lies between 24 and 33%, or 7.99 and 12.5 gigatons CO_2 [5] with a long-term reduction potential of 2.66-4.93 gigatons CO_2 corresponding to one “wedge“.

The contribution of extended service life due to improved wear protection and modern condition monitoring can currently not be determined because saved tonnages of resources cannot be quantified. When hypothetically assuming life cycle extension due to various tribological measures, the resource pool is halved from 17.7 gigatons to 8.8 gigatons of annually consumed resources. Based on a rather conservative equivalent of 1 ton of CO_2 per ton of metal/plastic (see Table 6), tribological measures for wear protection contribute to CO_2 reductions with several “wedges“.

4. Macro-Economic Importance of Tribology

Particularly abrasive and adhesive wear mechanisms cause economic losses, i.e. irrever-sible material losses on tribosystems. In studies of the 1980s [9-16], economic significance of “wear“ was restricted to downtimes, costs for maintenance and replacements but also to the reduction of import dependencies. Saving energy and resources, increasing material efficiency and reducing CO_2 emissions were not considered from an ecological point of view.

4.1. Economic considerations

Table 4 summarizes the range of the wear-induced share of the Gross Domestic Product and other variables. By order of the national planning commission of the German Democratic Republic (GDR), the Commission for Lubrication Technology projected in 1961, a conservative savings potential of one Billion Mark [9], due to wear and damage, amounting to about 1.25% of the Gross Domestic Product[7], if scheduled lubrication intervals were established. The Commission for Lubrication Technology even assumed “Billions of damage, if lubrication was neglected“ [10].

Therefore, lubrication technology made inroads in GDR legislation [11,12] and was adopted by university curricula.

The Materials Group of United States Office of Technology Assessment (O.T.A.) quantified the cost for maintenance and repair [13,14] for automobiles, aircrafts and railroad, thus “transporta-

Table 5: Consumption of economic and ecologic resources due to wear

Studies	Considered year	Expenditures for the consequences of wear, maintenance, repairs [%]	Reference value
Savings potentials			
German Democratic Republic (GDR)	1960	>1.25	Gross Domestic Product
China (only industry[#])	2006	1.55	Gross Domestic Product
Total expenditures			
United States*	1976	>2.4	Gross Domestic Product
Federal Republic of Germany (FRG)	1980	11.8	Gross Domestic Product
Canada (only Industry)	1982	0.9	Gross Domestic Product
Finland [16]	1997	15.2	Sales revenues of mining industry
Mining industry [16]	*2014*	*6.2*	*Global primary energy consumption*

*O.T.A. of U.S. Congress, only for automobiles, aviation and railroad = transportation; [#]eight industrial branches

[2] The Gross Domestic Product of the GDR in 1960 amounted to 79.4 Billion Mark.

tion“ alone, to 46.8 Billion US-$ or 2.4% of the Gross Domestic Product and projected a savings potentials of 25-30%.

In 1982, the Federal Republic of Germany spent 102 Billion Euros (200 Billion German Marks) for maintenance and repair caused by wear [15] or 11.8% of the Gross Domestic Product (GDP) of the Federal Republic of Germany in 1982 of 860 Billion Euros. In Finland, the maintenance costs in the mining industry in 1997 amounted to 15.2% of the annual sales revenues [16].

According to Holmberg et al. [17], frictional or tribological contacts consumed 23% of global primary energy which are subdivided into 20 absolute percent to overcome friction and about 3 absolute percent for the maintenance of worn parts. The share of energy losses caused by industrial wear was calculated based on data of the mining industry [16] and constitutes an upper limit since the mining industry is very wear-intensive. The mining industry is a fundamental part of the world economy and a significant CO_2 emitter. In this energetic approach, repair or wear contributes to a 3% share of the global primary energy consumption, and, under consideration of renewable energy resources, to a share of 14% (IEA, 2018) and a 2.5% share of global CO_2 emissions[8] or of currently about 827 Million tons of CO_2.

A two-year study of the Chinese Tribology Institution (CTI) [18] quantified the macro-economic significance of tribology in China. Based on savings potentials in eight representative industries (metallurgy, energy, railroad, automotive, petrochemical, agriculture and shipping) the study yielded conservatively estimated savings of 41.4 Billion US-Dollars annually at the prices of 2006 which would correspond to savings of 1.55% in the Chinese Gross Domestic Product (2006 of 2.774 Billion US-Dollars) [18,19]. Knowledge deficiencies and lack of awareness were identified as causes for the economic damage. In China, tribology is also not included in the university curriculum.

Table 5 summarizes the effective ratio between friction and wear for various quantities. For 1982, the National Research Council of Canada (NRC) [20] calculated the economic damage caused by friction and wear to 5,1 Billion Can-$ or 1.3 % of the Gross Domestic Product (GDP) of which 3.9 Billion Can-$ could be attributed to wear-related damage and 1.12 Billion Can-$ to friction losses, thus a cost ratio between friction and wear of about 1:3. The calculations of NRC applied only to industrial activities without considering individual transport/mobility and private consumption.

Holmberg et al. [16] came up with comparable results for the mining industry where predominantly unlubricated and abrasively stressed machinery is in operation. When switching from an economic to an energetic approach, the friction and wear ratio in the consumption of resources is more than reversed (see Table 5). Consequently, the reduction of friction when using primary energy is of great significance for the reduction of CO_2 emissions.

The global mining industry‘s consumption of primary energy is an estimated 6.2% [18] of the total global energy consumption or a calculated 2.05 gigatons of CO_2. The share of the mining in-

Table 5: The interrelation of loss quantities friction and wear

Authors	**Considered year**	**Regarded quantity**	**Ratio between**	
			Friction	**Wear**
National Research Council of Canada (NRC) [9]	1982	Costs (in the industry)	1	3
Holmberg et al. [18]	1997	Kosten (Abrasion)	1	2,2
Holmberg et al. [17]	2014	Primärenergie (global)	7,66	1

[8] Emissions are composed of different volumes. In 2018, global CO_2 emissions caused by oil, gas and coal (without international aviation) amounted to 33.3-33.9 gigatons of CO_2. Taking industrial, non-combustible processes into account, such as in the production of building materials (cement, bricks), global CO_2 emissions attained 37.9 gigatons in 2018. In 2018, total global greenhouse emissions amounted to about 51.8 gigatons of CO_2 equivalents (U.N. Emissions Gap Report 2019). The gap to CO_2 emissions results from anthropogenic, non-CO_2 greenhouse gas emissions (CH_4, N_2O, SF_6, FKW, NF_3). Emissions from agriculture, land use change and forestry included, mankind emitted 55.3 gigatons of CO_2 equivalents of greenhouse gases.

dustry of the global primary energy consumption, including other basic materials, amounts to about 9% [17] composed of overcoming friction and wear or about 2.98 gigatons of CO_2.

Approximately 38-43% of the energy consumed by the mining industry is used to overcome friction because many tribosystems (friction points) can only be operated unlubricated. Additionally, 25% of the primary energy is used to refurbish worn parts and keep spare parts and equipment in stock which may be spontaneously required due to wear-induced failure, ultimately resulting in a 1.6% share of the global primary energy consumption.

The surface properties corrosion and tribology are interconnected via tribocorrosion and overlap. Both are responsible for irreversible material and functional losses. The study *Economic Effects of Metallic Corrosion* in the USA [21] estimated the costs for metallic corrosion for the US-economy. The study conducted by the Battelle Columbus Laboratories and the National Institute of Standards and Technology (NIST) determined additional costs in 1975 of 82 Billion US-$ and 4.9% of the Gross Domestic Product or 382 Billion US-$ converted to the prices of 2018. Presumably, 60% of this amount could not be prevented, whereas the 40% or 33 Billion US-$ or 154 Billion US-$ converted to 2018 prices, attributed to knowledge gaps in surface technology, metallurgy and electro-chemistry, could have been avoided. The 4.9% share of corrosion damage of the US Gross Domestic Product of 20.5 Trillion US-$ in 2018 even amounts to 1,000 Billion US-$. Between 1999 and 2001, CC Technologies contracted by the Federal Highway Administration (FHWA) and the National Association of Corrosion Engineers (NACE), calculated costs generated by corrosion damage. The total direct costs generated by corrosion for infrastructure, supply, transport, production and manufacture and for government authorities were projected on a national scale. The study (U.S. Corrosion Costs Study) came to the conclusion that directs costs from corrosion damage for the US-economy amounted to about 278 Billion US-Dollar annually [22] corresponding to 3.1 % of the Gross Domestic Product. The Chinese Society for Corrosion and Protection quantified their damage induced by corrosion in 2014 to 3.37% of the Gross Domestic Product [23].

4.2. Consumption of resources

In their final use as fuels, both fossil and CO_2 neutral energy resources eventually release into the atmosphere. Apart from resources consumed by vehicles and industrial machines, waste is generated after their shutdown which needs to be collected, processed and recycled or residuals thereof must be stored using more resources which previously generated CO_2 … and the cycle continues.

In the public discourse of the CO_2 issue, technical products are only perceived from an ecological perspective if they are "right in front of your nose (tank-to-wheel)". The question of how many resources are required for their generation and the recycling aspect remain unconsidered. The "cradle-to-grave" approach which includes manufacture, use and durability and disposal/recycling provides more serious considerations.

A long life cycle ensures that equipment functions over a longer time period and does not require frequent replacement. A long, low-maintenance service life saves material and monetary resources incurring for replacements and new purchases.

The broad public awareness perceives vehicles or machines only when they are in use and overlooks the consumption of metallic resources, primary energy and water required for their manufacture and disposal. Point of departure is the "procurement" of the hardware consuming material and energy resources. Consequently, ecological valuations must consider the production and aim for a long life cycle. This approach applies for all types of equipment and machines globally used in all industrial sectors, power generation and by consumers.

4.3. CO_2 emissions from the extraction of primary metals

Tribosystems are composed of materials. In 2018, fossil CO_2 emissions reached 37.9 gigatons worldwide [24]. The global metallic material footprint in 2017 amounted to 9.120 gigatons of mass as reported by the U.N. Resources Outlook 2019 [2, p. 43;25] or 10.1 gigatons as of the circularity Gap Report 2020 [4, p. 18]. Extracting metals required for manufacturing tribosystems of machine elements generates process emissions which consist of consumed cumulative energy and raw materials during the extraction phase. Both produce CO_2 emissions and CO_2 equivalents. Table 6 outlines the emitted and average CO_2 equivalents for selected metals. The CO_2 equivalents for selected metals and raw materials are multiplied with the global consumption of each materials with its CO_2 emissions during mining, smelting and processing. The sum of 6.492 gigatons of consumed materials will not significantly increase with the addition of missing elements from the periodic table.

Additionally, CO_2 emissions are generated by industrial, non-combustible processes, such as the production of cement and bricks (see footnote 8). On the other hand, metallurgy makes great efforts to reduce CO_2 emissions through new and optimized processes. About 50% of the steel produced is used by the building industry and infrastructure. The OECD [3] presumes that by 2060 the inevitable increased consumption of metal materials (Al, Cu, Fe, Mn, Ni, Cu, Pb, Zn) and mineral resources will raise global CO_2 emissions to a share of 21%. Improved wear and corrosion protection extending life cycles, thus reducing raw material consumption, will contribute to the reduction of CO_2 emissions.

From the CO_2 equivalents for selected metals and basic materials in Table 6, a conservative approach assumes minimum one ton of $CO_{2eq.}$ per ton of metal/basic material.

Table 6: Average CO_2 emissions from the primary production of one ton of primary metal [26,27,28,29,30,31]

Primary metal	CO_2 equivalent [ton metal]	Global production 2018 in thousand tons	Calculated CO_2 emissions from primary production in thousand tons
Titanium	45	7,200	324,000
Nickel	42	2,330	97,860
Chrome	25	12,300	307,500
Magnesium	20-26	1,100	>22,000
Aluminum	14 (EU27)	64,800	907,200
Zink	9.8	13,400	131,320
Molybdenum	3.4-14.8	259	881-3,788
Copper*	5.5-9.5	23,600	129,800-224,200
Plastics+	~3.4	360,000	~1,224,000
Steel (iron)	>1.8	1,808,000	>3,254,400
Cement	0.6-1.3	4,200,000	2,520,000-5,460,000
Total		6,492,989	8,797,773-11,956,368
Germany 2019[9]	–	–	684,000
Global CO_2 Emissions 2018[9]	–	–	37,900,000

* From concentrates, open pit mining, +plastics = thermoplastics, polyurethane, thermosets, elastomers, adhesives, coatings and sealants as well as polypropylene fibers.

[9] In 2018, greenhouse gas emissions in Germany amounted to 858,3 megatons of CO_2 equivalents or 755.3 megatons of CO_2 (about 88%) and 888.3 megatons of CO2 equivalents taking aviation into account. In 2019 greenhouse gas emissions decreased to 805 megatons of CO_2 equivalents (without aviation) and 683.8 megatons CO_2. See footnote 8.

5. Zero Wear as an Opportunity to Boost Sustainability

In relation to resource consumption and future reduction of CO_2 emissions, „service life/durability/life cycle are rather diffuse. “Zero wear“ or “no wear“ can be considered as hostile to technology, transformation and progress. On the occasion of a wear conference in 1938 (!) held by the Association of German Engineers (VDI), the following statement was made [32]:

> *“Tribology should never aim to sustain technically and economically obsolete machinery and operating equipment. Therefore, only the short-sighted would strive to develop a non-wearing material …“ (1938)*

In this interesting consideration, it must be distinguished between worn[10] and becoming obsolete[11]. An obsolete good must be replaced whereas a worn good in operation only increases resource consumption. This presumes repairability and availability of spare parts. Consequently, sustainable wear protection or repair should not extend the life of obsolete goods but modernize the overall system to prevent obsolescence.

The overall concept of the circular economy includes upstream product design, the development of services to increase product life [33] and periodic modernizations reducing the consumption of natural resources. In the transition to a CO_2-neutral society, we must increasingly deal with „lost assets[12]“ from an economic perspective, i.e. decide whether obsolete goods can be modernized.

Article 23 Section 2 No. 1 of the German Waste Management and Recycling Act calls for product responsibility as a factor of sustainability, that products must be “reusable and technically durable“. Consequently, political demands for minimum requirements to the manufacturers have intensified, particularly for the “longest possible product durability“ of consumer products, both as a basic design principle to save resources and as subject of federal sustainability control. The topic of life cycle extensions of worn goods also includes repairability or “easy-to-dismantle-design“. Original equipment manufacturers perceive zero wear differently than end customers:

- **End user:** Maintenance and downtime determine the operating costs for end users. Environmental protection and new purchases affect their budget.
- **OEMs:** Spare parts, services and accessories contribute largely to the margin of the OEM.
- **Society:** Resource conservation and material efficiency are today’s political and economical drivers.

The solution to this dilemma could be derived from the technological design of the tribosystems:

High or excessive wear resistance of tribomaterials or coatings can be depleted by a significant increase of the PxV-value[13] under sliding, by Hertzian contact pressures under slip-rolling, by increased power densities, and operating temperatures or over life cycles without maintenance. This approach promotes lightweight design and reduces material input and improved resource conservation.

The tribological guiding principles for sustainable product developments in the future are:

Energy efficiency, wear protection, safety, affordability, performance.

- **Energie efficieny.** In recent decades, the development of engine technology was coined by fuel consumption and increasing engine performance, today measured in CO_2 emissions.

[10] Technical wear or physical obsolescence: the material obsolescence is caused by the lack of performance of materials and components but also by extensive or intensive use.

[11] Functional obsolescence, moral wear: rapidly changing technical and functional requirements for a product and obsolescence due to technological progress are causes for functional obsolescence .

[12] “Stranded assets“ are assets that have become prematurely obsolete or are no longer adding value and must therefore be depreciated. They may frequently occur as a result of countermeasures to climate change. Stranded assets require increased capital for new investments.

[13] The PV factor or PxV value is a tribological solicitation quantity. It is the product of bearing contact pressure and surface velocity (pure sliding!).

» **Wear protection.** Wear protection is a synonym for material efficiency and resource conservation. It increases in importance against the backdrop of more drive technologies and types of mobility. End customers and consumers want, need and expect alternative sustainable solutions.

» **Safety.** Safe use of alternative drivelines and energy resources are basic requirements for passengers and operators. They also define the most important development goal – protection against failure of machine elements through tribology and lubrication technology.

» **Affordability.** Apart from the technical functionality, the affordability of an alternative solution is the largest obstacle for global market penetration and defines the technological development for cost reductions.

» **Performance.** Performance or "fit for purpose" is the basic industrial requirement for each new technology.

Various visions and business models, such as "Zeronize" [34] or "Green Tribology" [35] as well as „Upcycling", can be imagined to benefit from „zero wear". "Zeronize" symbolizes efforts to minimize negative and detrimental impacts of energy conversion and/or mobility on the environment. "Green Tribology" expands the classic goals of tribology, e.g. friction reduction, wear protection and lubrication optimization by new attributes, such as energy and material efficiency, resource conservation, emission reduction and environmentally compatible lubricants. "Recycling" is a well-known measure for the reuse of raw materials defined as waste products. Not only in the perception of our society but also in the practical implementation, this term is conceived as a devaluation of raw material quality or "downcycling". In order to achieve a recycling status for the result of waste disposal that corresponds with the same initial functionality of the raw product and usability of the waste product in a new product composite, primary raw materials must be added to the waste product. This translates into an increased expenditure of raw materials and more CO_2 emissions. Disposal of the materials of waste products often requires large amounts of energy to dismantle waste products into their individual constituents.

"Upcycling" is an alternative to reducing excess primary resource consumption and CO_2 emissions required for primary resource production in the recycling process at simultaneous reduction of the CO_2 emissions produced by the downcycling process of the waste disposal. Here, the use of seemingly worthless materials for new products comes into play: old automobile tires turn in to flip-flop soles, wooden pallets serve as slat frames for beds, nylon hoses are recycled as hair ties and glass bottles are used for building construction. In recent decades, upcycling has been a widely used practice in developing countries. Now also industrial nations have raised awareness how upcycling can protect the environment and be beneficial for mankind. Bearing also economic benefits, some industrial outfits have linked upcycling with tribology by re-refining used industrial lubricants to new base oils with distinctly improved viscosity-temperature characteristics. When producing usable base oils, the first refinement of crude oil only yields 2% usable base oils. The yield of new base oils re-refined from used oils amounts to 70% thus saving considerable amounts of CO_2 and material. In addition, 2.7 tons of CO_2 are generated from first refinement to incineration in the production and recycling of industrial lubricants. That is why upcycling of used oils conserves at least the CO_2 emissions generated by the incineration process for lubricant recycling [36].

Admittedly, re-refined base oils must be functionalized with additives which in turn offers potentials for tribological research and development to design the corresponding additives as upcycling products. The upcycling of PTFE materials is a good example. Tribological research found that PTFE secondary material processed into nanoparticles generates less friction in various base oils compared to new PFTE material processed in the same base oils. New and secondary PTFE materials featured comparable wear properties that were better than the base oils without nanoparticle addition [37]. Altogether, these examples prove how tribological knowledge is indispensable for the development of upcycling products.

6. Wear Protection

Worldwide, legislation and supervisory authorities have enforced regulations mostly oriented towards CO_2 emissions to apply sustainability to a wide product spectrum. Vehicles for ground, sea and air transportation, operated with consistent efficiency over their entire life cycle, are an important piece of the puzzle.

It is important to remember that durability and wear protection are inseparably linked to sustainability and that sustainability is one of the most important goals in our society. Products with a longer life cycle better valorize materials, primary energy and labor embedded therein. Within the technosphere of a circular economy, extending the life cycle makes for better use of resources in consumer products.

Increasingly challenging requirements to emissions[14] and fuel consumption have boosted developments, particularly in mobility. Apart from a robust design, condition monitoring design and maintenance concept are integral parts of wear protection. No vehicle can meet the specified emission and fuel consumption requirements without regular and timely fillings with high-performance fluids. High-performance lubricants are one key for increasing the service life and consequently, the sustainability of all types of industrial machines and equipment. Particularly in Germany, lubricants have been recycled in their prescribed interval for decades. Lubrication industry and material technology must continue to develop higher performance products while emphasizing the importance of durability and sustainability.

With a concept called “fill-for-life“ which delivers good lubrication performance over the entire lifecycle of the vehicle, future lubricants and fluids will provide e-mobility with economic benefits. Such technologies must be fit for purpose over the entire vehicle service life while ensuring all the benefits of tribological protection.

Apart from the optimum lubricant, suitable materials and surface treatments, such nitriding, nitrocarburizing, thin-film technology and surface texturing, are among the most important variables when designing a long-life and thereby sustainable tribological system.

7. Condition Monitoring[15]

Stamping plants used in the automotive industry require large capital investments. If the durability of equipment and tools does not meet the requirements, their replacement uses massive resources and generate costs. Premature failures due to adverse operating conditions or escalating damage must therefore be avoided at all costs. A large turbine in a water power plant, on the other hand, is designed for a life cycle of decades, as long as corrosion and wear conditions are not critical.

The spectrum of usage profiles varies according to customer and time. Consequently, the components of a product never reach their life cycle at the same time. Without condition monitoring a significant potential of service life is wasted as resource consumption. Undetected or unexpected component wear leads to enormous costs and increased risks of accidents and failures. Conventional repair is mainly scheduled as

a. reactive maintenance
   (maintenance after failures) or
b. preventive maintenance
   (maintenance acc. to history data),

whereby

c. predictive maintenance
   (maintenance acc. to real time data)

and failure-oriented maintenance or „fracture maintenance“ will be added as passive strategies. The most important methods of condition monitoring are acoustic emission and lubricant analyses.

[14] Sulfur oxide, nitrogen oxide and particulate emissions from combustion processes (except CO_2) which can be influenced by the fuel composition. Regulations stipulate the sulfur content of fuels, which can be used in such applications and they are therefore subject to legal control. Here, marine shipping must catch up vis-à-vis road transport.

[15] Synonymously used terms are maintenance, repair & overhaul (MRO); reuse, repair, redistribute, refurbish & remanufacture.

For decades, preventive maintenance methods replaced parts whose wear reserve by far was not depleted. This not only incurred costs but also undermined the principle of resource conservation. Predictive maintenance in comparison, determines the remaining life of each main component and thus ensures long-term operability beyond the designed life cycle.

In order to evaluate the condition of the used lubricant, samples are periodically taken and analyzed. As soon as one or several parameters exceed the specified limits, a lubricant change is recommended. Many of the analytic measurement parameters required for the evaluation are measured sensor-based and can be displayed online. As soon as the experienced limits are attained, a lubrication change is recommended. This ensures a finer meshed analysis and not only improves resource conservation through needs-based maintenance but also the detection of trends thus establishing predictive maintenance (acc. to real time data). Various measuring methods (onboard sensor), such as measurement of

a. the sound velocity,
b. the dielectric properties,
c. of the magnetic property,
d. the electric conductivity,
e. the attenuation of piezoelectrically excited surface waves,
f. the adsorption spectrum in the close infrared range or
g. the material fatigue through acoustic emission analyses (vibrations) and also
h. based on usage profile algorithms,

or a combination thereof have been developed to detect specific oil ageing parameters in the lubricant during operation in order to determine the point in time at which accelerated oil ageing begins. Of course, these systems are exposed to adverse conditions, such as contaminated sensor surfaces impairing the measuring stability of those "onboard labs". So far, tribological parameters for the remaining scuffing load capacity or wear resistance have neither been measured in the lab nor onboard. Instead "indirect" analytical material properties were used for the evaluation. It is state-of-the-art to determine friction using the frictional torques of the components or to identify the corresponding changes indirectly by temperature measurement.

In addition to the aforementioned lubricant analysis, structure-borne sound measurement is the most important method for the condition monitoring of components. The use of structure-borne sound measurement allows to detect damage in an early stage thus enabling to prevent escalating damage for example caused by bearing failure in a transmission. High-resolution processes offer early detection of first cracks enabling scheduled repair with short downtimes. Such practices of failure-oriented maintenance are referred to as „failure maintenance".

7.1. Tribotronics

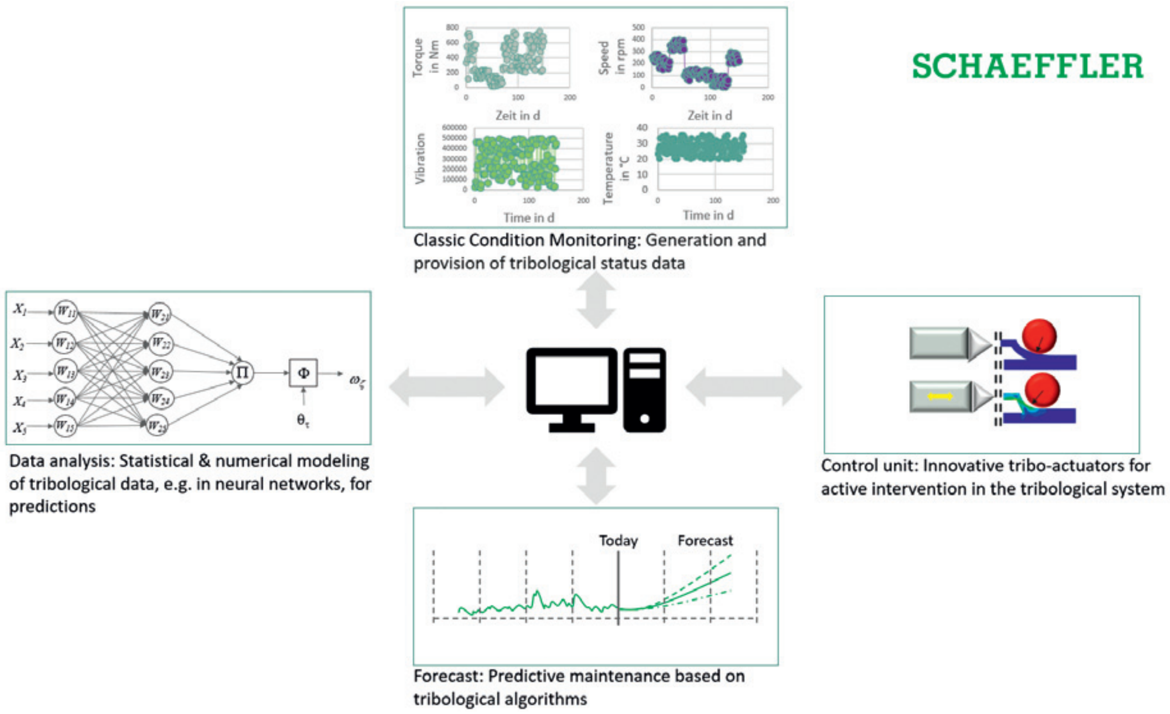
Currently, tribological contacts are designed passively, i.e. the tribosystem cannot be changed during operation. Tribotronics combines tribology and electronics to actively control and monitor tribological systems in real time. Tribotronics not only process the performance parameters measured in real time, such as friction coefficient, wear rate, sound emissions or vibrations but also modify them with electronic control and the adaption of the operation mode [38]. Tribotronics are the application of mechatronic and electronic systems, equipped with an intelligent component making databased predictions using tribological algorithms in order to optimize the system life cycle.

The goals are:

a. increasing life cycle, efficiency and reliability,
b. predicting the remaining service life, and
c. foreseeing the failure risk of the tribological system earlier.

Generally, a tribotronic system consists of four components:

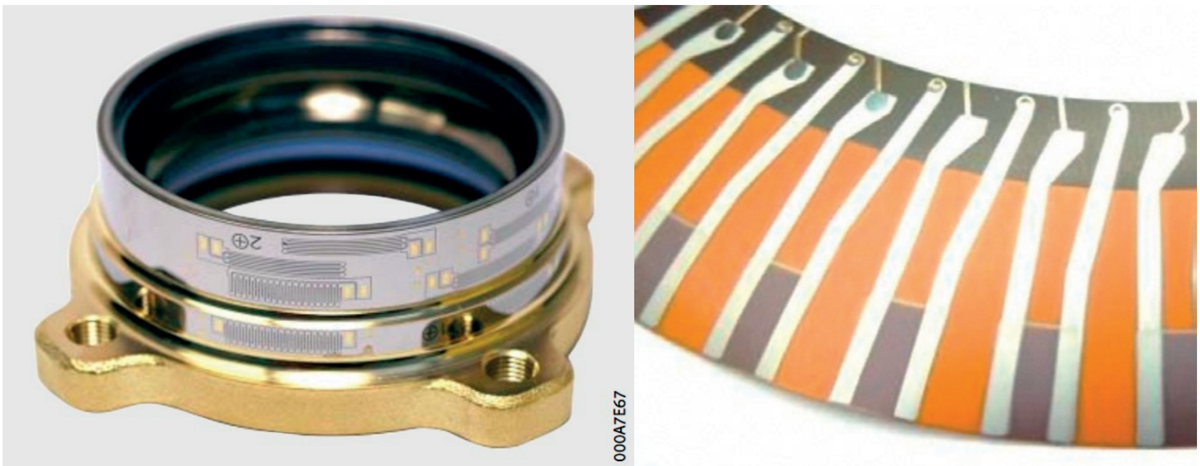
» sensors generating and providing tribological condition data to the tribotronic data center,
» tribological databases enabling predictions and algorithms for the computation of the required action,
» Computer and software as one electronic control unit for real time data processing and the synchronization with tribological algorithms, and



Picture 1: Control loop of a tribotronic system (SCHAEFFLER AG)

» actuators for active intervention into the tribosystem controlled by the electronic control unit.

In tribotronics, the component becomes the sensor or actuator, or in other words - sensor or actuator become the component (see picture 1). For thin-film sensors, this opens a whole new spectrum of new applications. The surface can now deliver data on the functional conditions in real time. That way, critical parameters, such as force, torque, temperature, vibrations, additive concentration and ambient moisture can be measured locally at the component where conventional sensors, such as strain gauges, would not be feasible because they are impaired by material ageing and signal shift from polymer adhesives or transfer films. Metal or carbon-based thin-film sensors, which offer future-oriented development of intelligent sensors with the benefits of low costs, easy handling and excellent sensitivity, are no longer restricted to the capital goods industry but will also be available to end consumers. Furthermore, measurements can be conducted in areas previously not accessible (embedded sensors, see Picture 2) or directly at the tribological contact because thin-film sensors



Picture 2: Thin-film sensor in a wheel bearing (Schaeffler SensoTect, left) and on a polymer substrate for the measurement of temperature and elongation (Oerlikon Balzers Diarc Senso, right)

not only require less installation space, but also feature lower energy consumption.

Tribotronics enable adaptive and/or active operation modes of tribological systems. In addition, tribotronics offer a completely new range of applications for thin-film sensor technologies. Through the combination of power converters, data transfer and transfer structures for supply and energy generation, autonomous measurement systems will also be available for rotating parts in the future.

Tribotronic systems identify overloads, deliver load spectrum data for algorithms extrapolating the remaining life cycle and close the loop to condition monitoring and predictive maintenance. That is why tribotronics make an essential contribution for more sustainability by extending life cycles and increasing efficiency.

The piston assembly is not only the core components in a combustion engine, and with about 50%, it also the largest share of the friction loss. Here, friction and wear could be reduced by installing an electronic control unit in the contact area between piston ring and cylinder liner to measure piston wear with tribo-actuators, which control the oil injection nozzles distributing the lubricant. A tribological algorithm calculates the optimum lubricant volume to be applied thus ensuring efficient lubricant use and minimum wear [39].

A change in the osculation of the rolling bearing raceway enables operating the application in the optimum range, at minimum friction and with a load-bearing capacity adapted to the respective load. Other possible applications in the automotive sector are temperature measurements for condition monitoring of electric motors, torque and noise/vibration/harshness (NVH) monitoring in transmissions and monitoring operating conditions of critical engine components, such as valve trains and pumps.

Bundling the know-how from tribology, electronics, control technology and mechatronics enables developing new embedded tribotronic systems. Tribotronic systems not only improve the performance of industrial machines but also enable innovative solutions for established technologies to increase service life and availability, to reduce friction losses and directly exploit tribological parameters, adjusting the operation modes of mechanical systems.

Condition monitoring can also be used for tires. It is common driving practice to replace tires way before they are worn, i.e. every second tire is replaced with 3 mm remaining tread depth or earlier (see chapter 8.1). Tread wear sensors [40] integrated in the tire could save about 6.6 Megatons of CO_2 in Europe because then tires would be used to their legal tread wear limit of 1.6 mm, ultimately saving 25 Million tires in Europe [41].

7.2. Smart Fluids

Smart fluids are another approach of actively impacting tribological systems. They can change the viscosity of a liquid by application of an electric or magnetic field.

Today's state-of-the-art smart fluids are liquids whose viscosity increase when a magnetic field is applied (MRF). Another important type are electro-rheological fluids whose flow resistance can rapidly and drastically be changed by applying an electric field [42].

Other smart fluids change their surface tension in the presence of an electric field. This effect is used to produce very small controllable lenses: one drop of this fluid confined by oil serves as a lens whose shape can be changed by applying an electric field.

Magneto-rheological fluids (MRF) are functional work media whose flow characteristics can be changed by applying a permanent or variable electromagnetic field over a large range. A magneto-rheological fluid basically consists of a carrier fluid, ferromagnetic particles and optional additives improving certain application-specific properties of the respective products. Special additives are required to minimize the sedimentation tendency of the specifically heavier magnetic particles. The applied magnetic field aligns the magnetic dipoles and forms chains which increase the viscosity.

MRF-products are versatile – they can be used in hydrodynamic, hydrostatic and also for lubrication purposes. Adaptive damping, clutches and programmable brake systems are potential applications, but MRFs are also suitable for the fixation of wear protection agents and serve as sealants for moving shafts.

MRF are also used in suspension systems of particularly heavy vehicles, adjusting the viscosity of the damping fluid to the road conditions, thus reducing wear on both tires and road surface.

The drawbacks of MRF are costs and weight. MRF-solutions cost more than conventional systems but offer faster control operations. Relatively large and heavy ferromagnetic structures must be designed to provide the required magnetic field strength. These drawbacks still impede a broader use of MRF-systems.

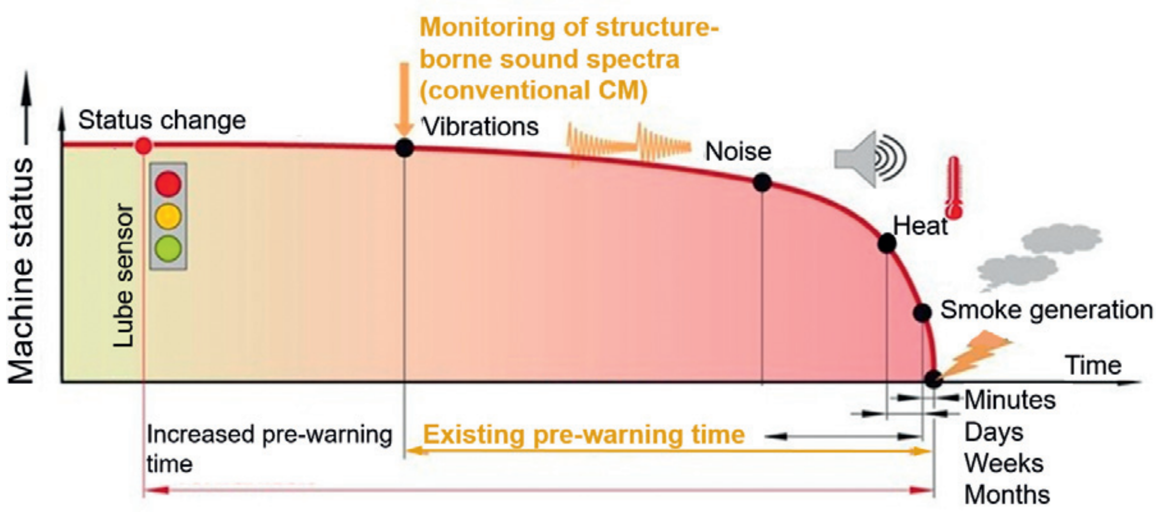
Electro-rheological fluids (ERF) are non-abrasive mixtures of silicone oil and micron-sized polyurethan particles. Under the influence of external electrical fields, the particles form fibrous microstructures changing the flow properties of the fluid (controlled rheology), blazing the trail for new control systems used in industrial and automotive applications. ERFs are suitable to control power and torque output by external electric control. They can also be used for motion and vibration control systems.

The main drawback of ERFs are the high operational voltages restricting their use in the automotive sector.

7.3. Predictive condition monitoring

Among the various maintenance strategies of ISO 17359, predictive condition monitoring and tribotronics are the most future-oriented. Predictive maintenance reduces unscheduled downtimes. Investments in predictive monitoring system offer tremendous increases in availability and profitability. Such systems offer continuous control of component condition and display of abnormal operating conditions with parallel assessment of the remaining system service life. Based on this data, maintenance intervals can be optimized to the actual need and required repairs can be carried out at convenient times. Based on the collected data, the operation can be optimized thus preventing overload situations.

Picture 3 illustrates the advance warning periods of various damage conditions and failure events. Condition monitoring using structure-borne sound spectrums detects damage at an early stage with the drawback that the damage must have occurred on the friction surfaces in order to detect a signal. The lubrication grease sensor (see Picture 2) in comparison, detects relevant changes in the grease condition prior to damage in the rolling bearing. The grease repacking will therefore be conducted according to the actual condition of the grease. That way, downtimes due to bearing replacement can be prevented.



Picture 3: Advance warning periods of methods and events for various machine conditions [43, FAG GreaseCheck]

Concrete figures of a 2.3 Megawatt wind power plant exemplify this: The availability of a wind power plant of 95% in the first year drops to about 82% in the 20th year of its life cycle (average 88.5%) [44]. At the same time, revenues of a wind power plant decrease 7% per year due to falling kWh-prices about. The operation costs make about 75% of the total first investment over the life cycle of 20 years. Unscheduled interventions make up about 50% of the operation and maintenance costs. For the 2.3 MW wind power generator, this translates into operating costs of 1.6 Million Euro in 20 years - 1.1 Million Euro of which are for unscheduled repair and maintenance. If damage is prevented by early detection, predictive maintenance can cut operating cost by 60%.

7.4. Inline condition monitoring of lubricants

One aspect of oil condition monitoring is the economical and ecological exploitation of the performance limits of the various lubricants in their respective application. This is of particular importance for bio-degradable oils, because of significant differences in the ageing stability between lubricants based on unsaturated triglycerides and those based on fully saturated synthetic esters. These differences are often not fully communicated to the user.

Another aspect is the increased oil load induced by higher density, extended service life and lower oil volume. Lubricants have been continuously improved to meet the technological requirements. Many users increasingly request condition monitoring to optimally tap the potentials of improved performance and longer lubricant life.

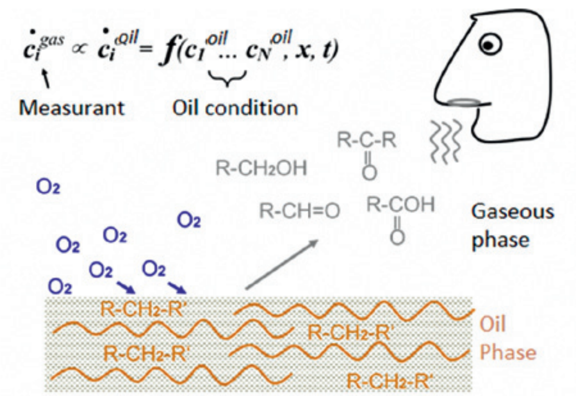
In general, the condition of lubricants can be determined by taking samples in the laboratory offline or directly using sensors online. Originally used in applications with high circulating volumes, e.g. in metalworking, preventive maintenance measures can now be applied for much smaller aggregates. At first, lubricant quality was monitored offline, e.g. by taking samples regularly and examining their most important parameters in the lab. This delivered the oil characteristics, such as viscosity, acid value, additive content, contaminations etc. which were later interpreted by experts. On the one hand, this process is cost-intensive; on the other hand, there is no other option available to detect sudden changes in the lubricant condition during the short interval between two examinations. In a first step towards online monitoring, automated lab processes for very large systems were used directly at the monitored system simulating standardized lab methods. Due to their high costs, such processes never prevailed.

The monitoring method must always correlate with the value of aggregates and lubricants to be monitored. If massive consequential damage is to be expected (e.g. because of wind power systems downtime), plannable, preventive maintenance is considered much more important than the extension of oil change intervals.

Both distributor and user have a strong interest in using the lubricant to its maximum life but also want to make sure to exchange it in time. Particularly, lubricant manufacturers aim to distinguish their “higher quality“ products from the “poorer quality“ products of the competition.

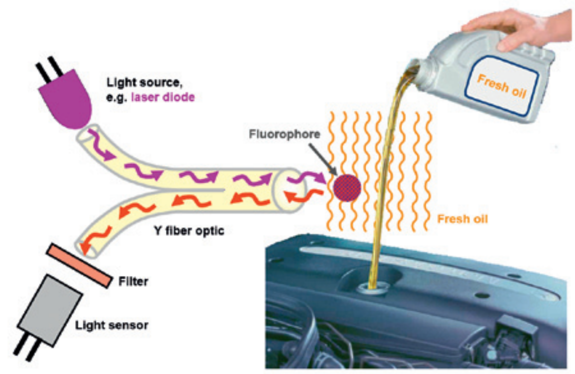
Micro-electronic sensors have offered new opportunities for a broader dissemination, often at the expense of direct comparability with conventional lab processes. Here, data of suitable sensors considering multiple parameters must be correlated with the oil parameters of conventional offline analysis. New evaluation criteria, such as monitoring the dielectric properties of lubricants must be introduced - the capacitive sensors are low-cost, reliable and available on the market. Previously, the dielectric constant was of no special significance in the lab. Viscosity sensor (surface shear and surface acoustic wave transducers) and moisture sensors are available and sometimes grouped in multi-sensor assemblies. Spectroscopic processes have also made inroads in the online monitoring of lubricants; IR- or NIR-sensors (limited to few wave numbers), for example, are available at low costs. A good overview can be found in [45].

It turned out that these measured variables, however, are either difficult to interpret and/or are not sufficient to reliably evaluate the condition of a used oil. This is why additional approaches to oil monitoring are required. One special new system, the so-called “electronic nose“ (see picture Picture 4) delivers semi-quantitative evidence of volatile ageing products of lubricants by means of gas sensors. Every tribologist knows from experience that used lubricants smell different from the corresponding fresh oils [46].



Picture 4: Electronic nose: detection of vaporized ageing products

Further progress is to be expected from intelligent linking of various sensor principles. Multisensor oil condition analyses require mathematical evaluation processes, e.g. multivariant data analysis enabling knowledge-based sample detection. With modern simulation processes creating so-called digital twins, attempts are made to significantly improve the evaluation of the machine condition in dialog with online sensor signals.



Picture 5: Identification of lubricating oils during the filling process by means of fluorescence analysis

An insufficiently tapped potential is the option to use the liquid and continuously circulating oil phase as information transmitter for processes in the machinery, even those not directly connected to the lubricant application, e.g. coolant penetration, fuel dilution, intrusion of condensation, dust, wear particles and other substances.

Another basic problem of all sensors measuring in the lubricant must also be addressed: the contamination during their operation must be considered, the sensor life cycle must not be shorter than the life cycle of the monitored lubricant. Electronic drift and lack of calibration should also be taken into account but can be remedied by lubricant identification and sensor calibration with backed-up lubrication data.

7.5. Oil identification system

In the future, it will be challenging to identify high-performance oils as well as eco-friendly and sustainable lubricants prior to their filling because the high prices of such lubricant grades promote abuse. In the event of an oil change, it must be safeguarded that only approved and eco-friendly lubricants are filled. The lubricant must be identifiable to ensure optimum operational safety, also from the aspect that it allows to calibrate signals from the oil condition sensor. Only if the oil condition sensor "knows" the lubricant, it can perform target-actual value comparisons based on the stored lubrication data (see Picture 5).

Various system can be used for the identification of the lubricant: a sensor-based system identifying the lubricant online (during the filling process). A system using florescence spectroscopy: a previously marked oil can be detected in real time. This only works with fresh oil when the complex matrix of the used oil does not interfere [47].

8. Examples for increased sustainability

8.1. Fine-dust particles from abrasion

Road traffic emissions[16] without those from combustion engines (non-tailpipe), particularly considerable quantities of tire and brake abrasion, are not just a decorative nuisance, but also contribute to 90% of wear particle emissions produced by road traffic vehicles [48]. Even vehicles driven by batteries or fuel-cells will continue to have tires and brakes producing in the future fine-dust particles through abrasion. The tonnage of tires in 2018 in the EU amounted to 5.1 Million tons [49] and 24.8 Million newly produced truck and bus tires about 4.3 Million (17.3%) were retread contributing to waste prevention.

In a metropolitan area, such as Paris (Île-de-France), the fine dust relevant as PM_{10} abrasion from tires and roads amounts to 1.8 kg per inhabitant per year [50,51]. In total, the European Union produces about 1,327,000 tons of tire abrasion annually – Germany about 133,000 tons annually [52] or >160 g tire abrasion per meter of road of which only 4,400 tons were released as PM2.5 and about 6,300 tons as PM10 in the air [53]. In France, the current portion of 33,400 tons of PM_{10}-particles emitted in transport is the lowest since 1990 [54]. These figures demonstrate the effect of wear and wear protection for brakes and tires on SDG #3. Depending on vehicle type, driving style and profile, tire abrasion is between 0.04 and 0.5 g/km [55].

It is therefore not surprising that mileage and abrasion were incorporated in the designation of tires in relation to fuel efficiency and other parameters in the Amendment of Regulation EU/1222/2009 and EU/740/2020, if suitable test methods are available, since due to abrasion, tires unintentionally release significant amounts of microplastic to the environment.

In 2017, vehicle brakes [53] emitted in Germany about 3,000 tons as PM2.5 and about 7,500 tons as PM_{10}, whereby the total amount of brake abrasion amounted to about 111,000 tons [56]. Copper, chrome, zinc and lead contained therein pose additional environmental burden for water and soil.

Picture 6: Porsche Surface Coated Brake (PSCB) with a friction surface made of tungsten carbide (PORSCHE SE)

With more wear-resistant materials while maintaining all other functional properties, tribology can make a significant contribution to the reduction of particle emissions. In fall 2002, the fully

[16] In 2017, PM_{10} fine dust emissions in Europe amounted to about 2,850,000 tons of which 227,000 tons (~8%) were produced by road traffic [European Environmental Agency, air pollutant emissions data viewer].

[17] The total length of interurban traffic roads amounts to 223,000 km (www.bmvi.de), whereby the total road network amounts to about 830,000 km.

functional demonstrator „ELLYPSE“ by RENAULT SaS proved [57] that change intervals for tires and brake systems could be extended to 70,000 km and 100,000 km lowering fine dust emissions produced by vehicles by 42-66%. These results should be reconsidered as valuable approaches for future research activities.

At the end of 2017, PORSCHE introduced the Porsche Surface Coated Brake (PSCB) [58], a carbide-coated, grey-cast brake disk (PSCB) for the reduction of wear particles from brake abrasion (see picture 6). This brake generates 90% less “brake dust“. Such solution approaches should be taken up again because they offer reduction potentials of 50-75% for fine dust particles generated by vehicles.

The PM_{10}- and $PM_{2,5}$-concentrations in subway stations are usually above those generated by road traffic [59,60]. Trams and trains also contribute to wear particle emissions [61] through

a. pantographs (current collectors),
b. wheels (even if made of steel!), and
c. brakes.

Wear protection and extended service lives of tires, brakes and current collectors correspond with the targets of SDG #3.

8.2. Wind energy plants

The total output of wind energy plants by end 2019 amounted to 651 gigawatts, whereby the average output of one wind energy plant was about 2.5 megawatts (MW). The largest wind energy plants installed in Europe in 2020 had an output of 12-13 MW and wind parks with 20 GW are in the pipeline. In 2018, wind energy in Germany generated about 17.5% of the electricity. Wind energy plants are available with and without transmission[18]. In order to lower the costs for power generation, both types are being further developed in terms of output, reliability and life cycle.

Wind energy plants are designed for a life cycle of about 20 years. Premature failure would impair their profitability. The insurance company, Enser Versicherungskontor (EVK), conducted a study about damage on about 4,500 wind energy plants [62]. Internal operating failures contribute to 67% of all reported damage, followed by lightening with roughly 18%. Of all internal operating failures, the two main components - powertrain generator (1/3) and transmission (2/3) - amount to altogether 30% of the damage. Only 5% of the damage is attributed to rotor blades. Repair or replacement of large components in “airy“ heights is costly. For the period 2009-2016 [63,64], the database of the National Renewable Energy Laboratory (NREL) reports about 76% of transmission failures were caused by rolling bearings and 17% by tooth flanks. Added up, the share of damage generated by the transmission amounts to about 13%.

New alloys

Primary objective is the development of new materials and new heat treatment processes. Rolling bearings are among the most highly stressed components in the powertrain of a wind energy plant and regarding the Hertzian contact stresses within tribology. The powertrain typically contains 20-25 large roller bearings. The most commonly occurring damage phenomena in rolling bearings of wind energy plants are the so-called “white etching areas“ (WEA), “white structure flaking“ (WSF) and “white etching cracks“ (WEC).

Coatings

Wear-resistant thermochemical surface coating treatments (e.g. carbonitriding) or amorphous, hydrogen-containing carbon coatings (a-C:H:W) doped with tungsten, ensure additional protection against micro-pitting (grey staining) and lubrication problems.

Through a combination of factors, the entry of hydrogen promotes white etching cracks. Minimizing chemical impact (passivation) and the reduction of hydrogen diffusion into the bearing steel reduces the risk of WEC-induced failures. “Bluing[19]“ has been established as the most suitable passivation. It also improves wear protec-

[18] The omission of transmissions requires permanent magnets (e.g. made of sintered $Nd_2Fe_{14}B$-alloys) for permanently excited synchronous generators, which contain the rare earth “neodymium“. Such direct-drive gears consume ca. 200 kg Neodym/Dysprosium per MW_{el}.

[19] Bluing (“black oxide“) according to DIN 50 938 applies a thin iron-oxide coating (Fe_3O_4, magnetite; color: black) on iron-based materials

tion in the event of deficiency lubrication. A significant benefit of burnishing is the applicability for large bearings used in wind energy plants.

Condition monitoring

The transmission in a wind energy plant requires about 70% of the lubrication volume (or about 54,000 tons p.a. worldwide). By means of condition monitoring, new alloys for rolling bearing contact surfaces, heat treatment processes and coatings, tribology makes the crucial contribution for wind energy evolving to a completely commercialized and unsubsidized technology.

8.3. Tribology enables resource conservation in machining and forming technology

Longer life cycles as well as refurbishing tools and molds contribute to resource conservation and material efficiency initially motivated to increase profitability. In addition, the innovative power of industrial manufacture promotes the market launch of new high-performance materials.

Tool coatings

The most important motivation for tool coating is to increase productivity by means of faster cutting speeds and feed rates. Simultaneously, manufacturing costs can be reduced by significantly extended tool life cycles at consistently high machining quality. The increase in tool life cycles makes a distinctive contribution for sustainability in mechanical manufacture and forming processes [65].

Machining tools

Since the 1970s, hard material coatings have been used to improve the tribological properties of tools, for example to reduce the cutting edge structure [66]. Today, they are the standard solution for drilling and milling tools, indexable inserts, gear cutting tools, threading, reaming and broaching tools. Historically, the gold-colored TiN was the first coating for HSS- and carbide tools. Today, single layer, multi-layer or nano-structured PVD-coatings made of TiCN, TiAlN or AlCrN with Al_2O_3 are common practice (picture 7). Processing highly abrasive design materials, such CFRP and FRP, as used by the aviation and automotive in-

Picture 7: Tools coated with BALINIT® A (TiN, top) and BALINIT® ALCRONA PRO (AlCrN, bottom)

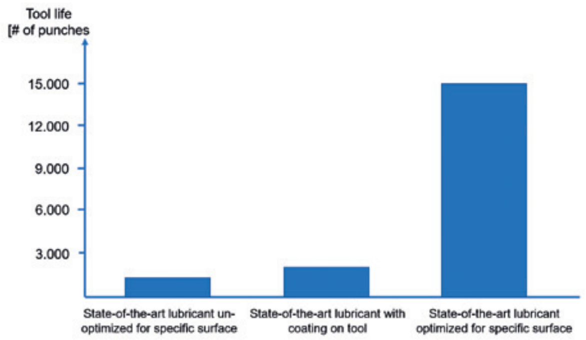
dustry, is often only feasible with WC-carbide tools coated with CVD-diamond.

Forming and master tools

Metal forming, just as machining, is a core sector of industrial manufacturing and its contribution to resource conservation is underestimated. It affects both tribologically demanding forming processes and processes for manufacturing low-wear and long-life products. Compared to purely machined parts, formed parts feature significantly improved wear properties due to work hardening effects during the forming process. Therefore, formed parts usually have a longer life cycle.

In the value-added chain, forming is an intermediate step from metal production to final manufacturing. This offers material savings already during the forming process by using near-net-shape forming processes [67] and limiting down-stream machining processes to a mini¬mum. New, higher-strength materials offer material savings, reduced component thicknesses and thereby lower weight at higher strength, longer life and improved wear protection of the manufactured parts. The automotive industry is the point of departure for multi- and nano-composite coatings, when using higher-strength materials, such as press-hardened or hot-stamped steels. Ductile, chrome-based coatings (e.g. multi-layer CrN) can successfully increase the life cycle of forging tools and are a good example for a hot-forming application. Despite the energy required to preheat the parts, semi-hot and hot forming significantly conserves energy in both forming process and final product.

Surface treatment of forming and master tools using PVD- and PACVD-processes multiplies the economic efficiency and precision of high-alloy tools and improves the quality of the manufactured parts. It also reduces the number of faulty parts and the consumption of lubricants and releasing agents, thus conserving resources. Recent research demonstrates that in the tribological collective of tool, workpiece, and lubricant, the lubricant crucially contributes to increasing tool life and ultimately wear protection (see picture 8). In order to achieve this, additive must be mixed with lubricant in a ratio ensuring optimum interaction with tool and workpiece surfaces fully utilizing synergy effects.



Picture 8: Fine-blanking of stainless steel [FUCHS WISURA]

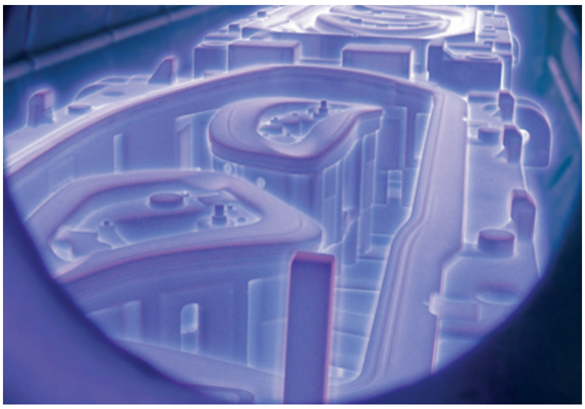
Picture 8 represents field tests for fine-cutting stainless steel illustrating the tribological interaction between thin-film, workpiece and lubricant. With the previous combination (stainless steel – state-of-the-art lubricant – TiCN coating) 500-1000 strokes could be accomplished before tool maintenance was required. Using a more sophisticated AlCrN-coating only yielded a moderate increase in life cycle whereas the adaption of the lubricant to the surface metallurgy of both stainless steel and AlCrN-coating enabled to multiply the tool life.

Tools for metal forming

Apart from wear protection, the main motivation for coating metal forming tools is preventing adhesion of the material to be processed. An optimized lubricant interacting with the coating of the formed material and thus building a stabile separating layer massively supports this effect. Due to the coating, the manufactured parts feature fewer flaws in their surface texture and the tools excel with distinctly longer life cycles. In some applications with longer life cycles, reduced fatigue wear gains additional importance.

Apart from the traditional TiN-coating, long proven in cold steel forming, todays chrome- and aluminum-based coatings lead the way. Chromium-based AlCrN-coatings minimize material adhesion, aluminum-based TiAlN-coating highly protect from abrasive wear and are resistant to oxidation. Such coated tools can be thereby successfully used at higher manufacturing temperatures. For tools used in aluminum forming (NE-metal forming), DLC-thin-films surpass chrome- and aluminum-based coatings.

For a long time, hard-chrome plating was the common surface treatment of large forming tools for wear protection. The PPD®-technology (Pulsed-Plasma Diffusion, see picture 9) avoids hazardous process gases, but also chemicals and substitutes up to 10 galvanic post hard chrome-platings over the utilization period of the tool.



Picture 9: Surface treatment of forming tools by means of BALITHERM® PPD

Possible adhesions between mold and workpiece during grey casting are a “nuisance” because they complicate the demolding process. In order to minimize adhesions, coating the mold surfaces (e.g. with DLC, AlCrN and vanadium-based coatings) has become common practice in addition to traditional release agents. Suitable coatings also protect the tool from corrosive attack from the alloy melt. Plasma-nitriding of the molds prior to coating minimizes crack formation through thermal cycling stresses.

Tools for plastic processing

When forming plastic, mold contact surfaces and plasticizing units are subject to various stresses. This applies for injection molding, extrusion, calendering, foaming as well as rotation and blow forming. The three most important requirements in the area of direct plastic contacts are:

- Abrasion (plastics filled with particles and short fibers),
- Build-up on the mold (particle build-up, island formations all the way to a uniform build-up layer from particles on the surface),
- Corrosion (Surface and pitting corrosion).

Due to their excellent corrosion protection and non-stick properties, a-CH:Si:O-coatings have become the most commonly used coatings.

Refurbishment of tools

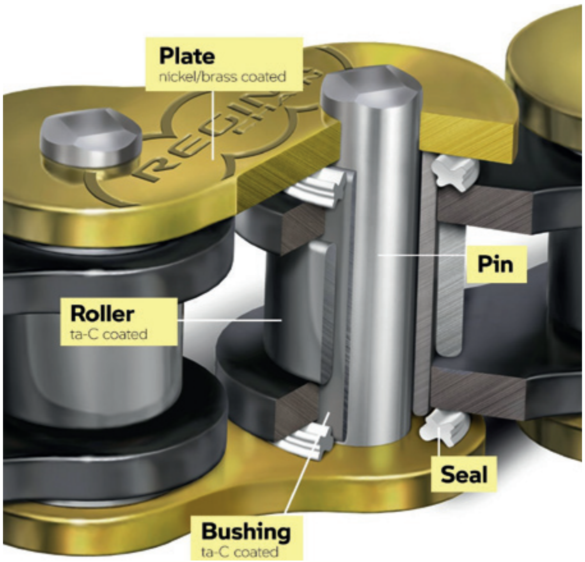
Certain tools can be refurbished after their coating is worn, thus saving up to 50% of the total costs for high-performance tools. The refurbishment includes inspection of the worn tool, regrinding (optionally also de-coating), cleaning and re-coating, ultimately achieving the performance level of a new tool. Not having to purchase a new tool lowers the cost but also reduces tool stocks to a minimum.

By using all the effects, new materials, optimized tool alloys and designs, surface coatings and tailored lubricants, forming can make a large contribution to resource conservation and material efficiency for critical alloy elements by means of wear reduction in the actual forming process but also in the manufactured parts.

8.4. Chain drives

Chain drives are commonly used, high-performance drive, control and handling elements. They are generally used in mechanical engineering, building industry, mining and metallurgy, but also in automotive engineering and transport and conveyor technology. The crucial wear dimension for the service life is the chain elongation. Lubrication determines the life cycle. Chain drives are open and lubricant is inevitably lost to the environment.

Dust and weathering determine the intensity of wear on motorcycle drive chains. The M Endurance chain by BMW Motorrad is the first free-of-maintenance motorcycle chain (see picture 10).



Picture 10: Maintenance-free endurance chain by BMW Motorrad [68]

Permanent lubricant filling between sleeves and pins, as well as lubrication addition for the sprockets are no longer required. The friction areas are coated with hard, tetrahedal amorphous carbon (ta-C) reducing dry friction and forming quasi wear-free tribosystems. Thanks to the ta-C-coating, re-tensioning due to chain elongation caused by regular wear is no longer required. This maintenance-free drive chain eliminates contamination of the environment with lubricants according to SDG #3 and extends the life cycle contributing to resource conservation according to SDG #9.

8.5. Biolubricants

Liquid lubrication is the core technology of tribology for friction reduction and wear protection. The global lubricant market encompasses about 38-41 Million tons annually over all product ranges. Table 7 subdivides the German lubrication market (2019) according to product groups with a total consumption of roughly one Million tons. In addition to the explicitly named automotive operating fluids, significant amounts of transmission oils and hydraulic fluids (shock absorber oils, brake fluids with about 30,000 tons) and compressor fluids (refrigerant oils) are used as operating fluids in motor vehicles. Furthermore, large amounts of radiator anti-freeze are required for cooling engines and batteries. More than 50% of the lubricants used in Germany are attributed to the automotive sector.

60% of the lubricants sold in Germany are recycled by means of used oil collection [69,70,71]. This figure has not significantly changed over the past 20 years. Another portion thereof is thus released to the environment as the result of in motorial combustion, loss lubrication, leakages or other system-related reasons. In Germany, a residual quantity of presumably 20% enter the environment via unknown pathways. The lubricant types in Table 7 contain 245,800 tons from used oil re-refining [69].

The impact of these lubricant pathways on the environment and particularly on the water quality has been obvious and uncontested for a long time. The first specifications for rapidly biodegradable lubricants were published in the VDMA working sheets 24568 and 24569 for hydraulic oils. In 2002, they eventually evolved to DIN ISO 15380 “Environmentally acceptable hydraulic oils“. Parallel, various German ecolabels “Blue Angel“ were developed and as of 2012 they merged to RAL-UZ 178 “Biodegradable lubricants and hydraulic fluids“. In 2005, a European eco-

Table 7: Lubrication market in Germany according to product groups [72]

Lubricant group/application	Tonnage in 2019
Engine oils	245,800
Transmission oils automotive	102,600
Transmission oils industry	25,500
Lubrication greases	32,800
Hydraulic fluids	62,800
Metal working fluids*	81,400
Compressor oils	8,800
Turbine oils	1,400
Electro-insulating oils	12,200
Machine oils	69,900
Other industrial oils not used for lubrication, process oils etc.	333,900
Total	**977,100**

* (Quenchants, water-miscible and not water-miscible metal working fluids, anti-corrosion oils)

label (Euro-Margerite) was introduced for lubricants, as of 2005 as Directive 2005/360/EC, as of 2001 under 2011/381/EU and as of 2020 under 2018/1702/EU. DIN EN 16807:2016 defines the term “biolubricant“. In 2015, biolubricants were assigned their own customs tariff number with the CN-code 3403 19 20 [73]. Currently the contractual duty (standard duty) equals petrochemical lubricants. A future, legal preference for environmentally acceptable cannot be identified for Europe.

All these approaches have internationally consolidated the different eco-toxicological basic requirements to rapidly biodegradable lubricants (biolubricants). They generally feature:

a. Ready/ultimate biodegradability (full mineralization; no primary degradation),

b. 2-3 aquatic toxicities according to OECD 201, 202 and 203, as well as

c. a minimum share of renewable raw materials of 25% or 50%.

Biolubricants are not legally mandatory for general use in Europe. That is why the market share of environmentally acceptable lubricants has not exceeded 3-3.5% (about 120.000 tons annually) in the past 10 years [74].

The U.S.A., a "trailing country" with environmentally acceptable lubricants (EAL), went a different way. The "Vessel General Permit" (VGP) under the Clean Water Act for discharges incidental to the normal operation of vessels, enacted as of 19th December 2013 and prescribing the mandatory use of environmentally-acceptable lubricants for vessels within the territorial waters of the U.S.A. ("Water to sea interfaces"), could act by way of example for Europe.

Generally, rapidly biodegradable lubricants are not formulated from mineral oils or synthetic hydrocarbons. Suitable base oils mostly consist of natural and synthetic, biogenic esters but also of polyalkylene glycols. They both can be synthesized from biomass or renewable raw materials. However, biogenic polyalkylene glycols have been hardly available in the marketplace. Instead, so-called bio-olefines[20] or estolides[21] , obtained from renewable raw materials and considered relatively well biodegradable, may enter the market in the future. Since the tonnage of lubricants corresponds to only 1% of the fuel volume, it can be synthesized from biomasses or renewable building blocks regardless of the desired base oil chemistry. Technically established biolubricants thus contribute to meet the UN sustainability goals #3, #12.2 and #12.4. Today's most important ecolabels for environmentally compatible lubricants (biolubricants):

a. European Ecolabel for lubricants according to EC/2018/1702,
b. second issuance of U.S. Vessel General Permit (VGP 2013, next as VIDA), and
c. biolubricants according to EN16807

stipulate a varying content of renewable raw materials.

8.6. Re-raffinates from used oil

Ecological concerns arise not only during the use of lubricants (see biolubricants as alternative), but also at the end of their use when fresh oils have become used oils. Used oils are classified as hazardous waste and fall under waste stream categories Y8[22] and Y9[23], as well as resource R9 according to the Basel Convention [75]. Used oils fall under Article 21 of the EU Waste Directive 2008/98/EC, amended by 2018/851/EC, with the objective to recycle used oils ultimately meaning re-refining. Secondary refining meets UN target #12.5 having the objective of significantly reducing the generation of waste by 2030 by prevention, reduction, recycling and reuse.

For decades, recycling of used oils has been contributing to de-fossilization by using recycled base oils with a significantly reduced CO_2 footprint in fresh oils. Political decision makers consider the introduction of emission credits for the regenerative sector, since re-raffinates use about 30% less primary energy than fresh oils. ReMade in Italy® quantified the ecological gain of re-raffinates with a saving of 609 kg of CO_2 per ton of re-raffinate[25].

It is a proven fact that used oil re-raffinates are not hazardous to the water quality. Used oil of consumed lubricants is not only hazardous for the water quality it is also a resource. Generally, an available used oil volume of 50% of the sold fresh oil can be assumed. The difference[26] enters into the environment. Re-raffinates exploited from used oils are about 70% with a share of re-refined base oils of about 13% of the total volume of all base oils used in the EU for lubricants (GEIR). Efforts have been made to raise this share to about 34% EU-wide. Here, it must be taken into account that their suitability for low-viscosity and high-performance engine oils is controver-

[20] Bio-olefines can be extracted from biomasses by means of thermochemical biomass-to-liquid processes or by ß-farnesene directly from sugar, lignocellulose or starch using genetically modified yeast or by botryo-coccene from algae.

[21] Estolides are secondary esters and extracted from hydroxy fatty acids, e.g. from castor oil (also from Lesquerella oil). Therefore, they are not in competition with the food chain. Their property profile corresponds with API Group III oils.

[22] Waste stream Y8= Waste mineral oils unfit for their originally intended use

[23] Waste stream Y9= Waste oils/water, hydrocarbons/water mixtures, emulsions

[24] R9= Used oil re-refining or other reuses of previously used oil

[25] ReMade in Italy® is a certification system for products of circular economy regenerated from waste streams. https://www.urbanwins.eu/remade-in-italy/.

[26] The most important entry routes into the environment are illegal disposal, co-combustion (e.g. in internal combustion engines), leaks, spills, etc.

sial. On the other hand, re-raffinates are a shining example of how “waste“ (here used oil) can be transformed into new equivalent products.

Engine oils sales in the geographic region of Europe amount to 2,800,000 tons. The current capacity of all re-refining plants in the EU (including UK) for the processing of used oils amounts to 2,000,000 tons, of which only 1,220,000 capacity tons are available for lubricant base oils (predominantly Group[27] I&II, but also II+). When taking a 70% exploitation into account, the potential for base oils made of re-raffinates respectively from the European fresh oil market amounts to 840,000 tons.

The regeneration of used oil for regaining base oils contributes largely to resource conservation and environmental relief, particularly in aquatic environments [76, 77].

8.7. Long-life engine oils

UAt the turn of the century, high-performance engine oils based on synthetic hydrocarbons achieved oil change intervals of 30,000 km and more, later reduced by engine downsizing and complex exhaust gas aftertreatment systems.

Parallel, the lubrication industry introduced rapidly biodegradable engine oils with performance specifications according to ACEA, API and specifications of automobile manufacturers, based on esters and mixtures of esters and hydrocarbons. Products, such as Castrol Greentec LS, ELF Victory HTX 822 or BP Vistra 7000 and FUCHS Titan GT1 (see p) never penetrated the market, probably due to the high raw material-related price and the lack of legal incentives.

Both together lead to the conclusion that even though technical know-how for long and very long oil change intervals also with rapidly biodegradable engine oils is available, but there is no market acceptance and demand from the end customer.

Engine oils of the Castrol Edge BIO-SYNTHETIC series contain 25% base oils from renewable raw materials extracted from sugar cane by biogenic synthesis. If demanded accordingly, tribology and lubrication technology can contribute to sus-

Picture 11: Pictures of rapidly biodegradable high-performance long-life engine oils

[27] According to API 1509 (API= American Petroleum Institute) Group I&II oils are mineral oils. Group II+-oils feature a higher viscosity index than Group II-oils.

tainability through long and very long oil change intervals even with biodegradable engine oils of low aquatic toxicities (so-called bio-no-tox engine oils) and based on renewable raw materials. The engine oil FUCHS Titan GT1 0W-20 in picture 11 consists of more than 50% of renewable raw materials

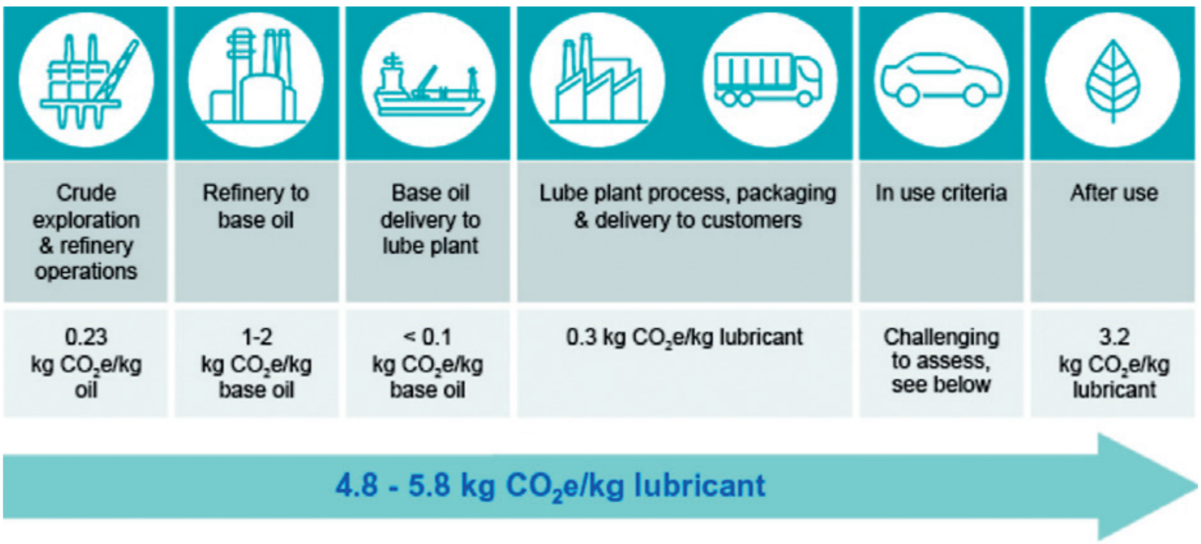
Recently, market leader U.S.A. has promoted an automobile engine oil [78] which guarantees oil change intervals of 20,000 miles. This would be a remarkable increase in life cycle, ultimately generating less waste on a market with oil change intervals of typically 5,000 miles. Quadrupling the life cycle would significantly contribute to resource conservation.

A simple example illustrates the contribution of lubricants to sustainability (see p). Taken the average consumption of new vehicles in EU28 from 2018 with 120.6 g of CO_2/km or 5.2 l/100 km. On a driving distance of 30,000 km, one oil change is required, consuming a total of 1,560 l of combusted fuel and 10 l of engine oil. With higher-quality engine oil, it would be feasible changing the oil in an interval of 30,000 km, thus saving 1% of fuel. Over 30,000 km the consumption of fuel could be reduced by 15.6 l and the consumption of oil by 5 l. According to a study conducted by NESTE Oyj [79], the CO_2 footprint of engine oil from fossil resources (Group I-III, PAO, GTL) amounts to 4.5 to 5.5 of CO_2 kg (equivalents). The total reduction of CO_2 emissions over 30,000 km multiplied with 268 Million automobiles in EU28 in 2018 would amount to 60±2.5 kg CO_2

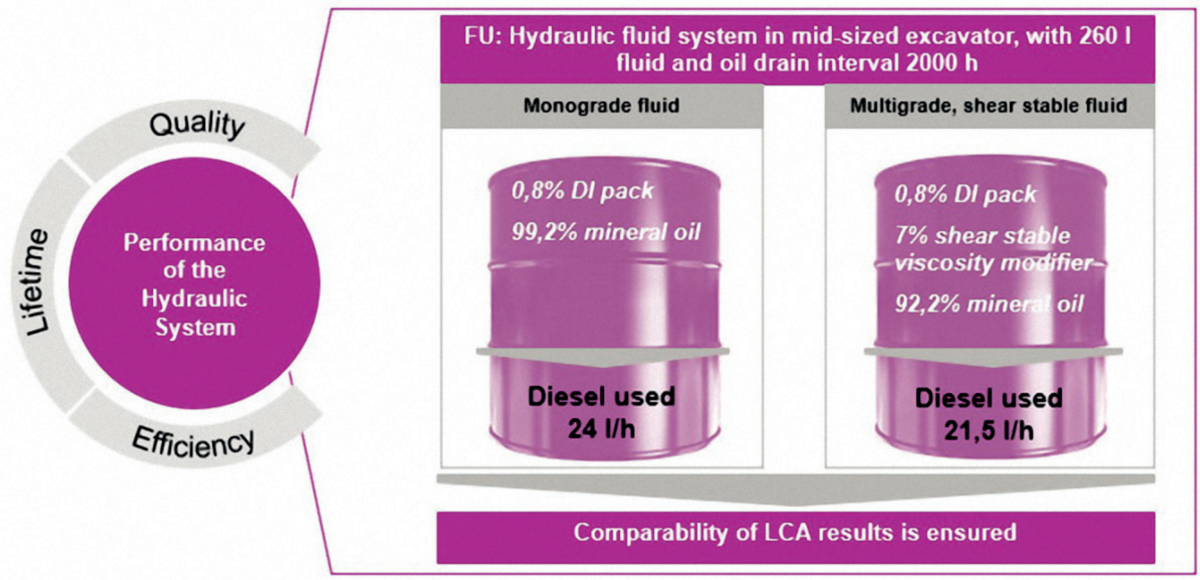
8.8. Life cycle analysis of an efficiency-boosting hydraulic fluid

Hydraulic oils amount to 8-10% of the tonnage sold on the lubrication market. Highly shear stable multigrade hydraulic fluids with a high viscosity index have been tried and tested in the field as effective measure to boost productivity and lower energy demand. In numerous field tests, the improvement versus monograde oils has been demonstrated particularly with construction machinery. In addition to increased productivity, the significantly extended oil change intervals, due to the longer life cycle and the elimination of oil changes between summer and winter, play an important role. Despite all these benefits, most construction machines still use monograde oils.

With a life cycle analysis, picture 13 compares the saved CO_2 emissions as CO_2 footprint and handprint of a conventional monograde hydraulic fluid (reference) with a high shear-strength multigrade hydraulic fluid with high viscosity index. Instead of the extended oil life cycle, the oil use over 2,000 hours in a mid-sized excavator was considered, based on several statistically assessed field tests yielding fuel savings between 8 and 13% with an average of 10.5% fuel saving (Diesel). For the same work, an excavator with monograde fluid consumes 24 l of Diesel per hour compared to 21.5 l Diesel per hour with multigrade oil.



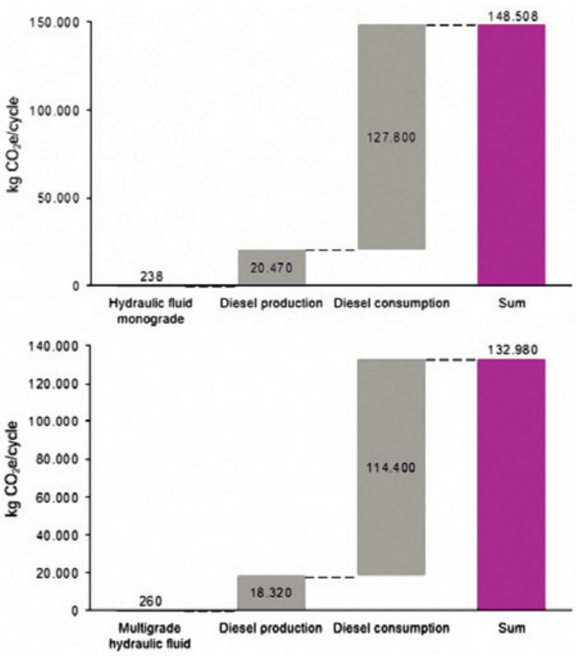
Picture 12: Carbon footprint of fossil-based engine oil production [79]



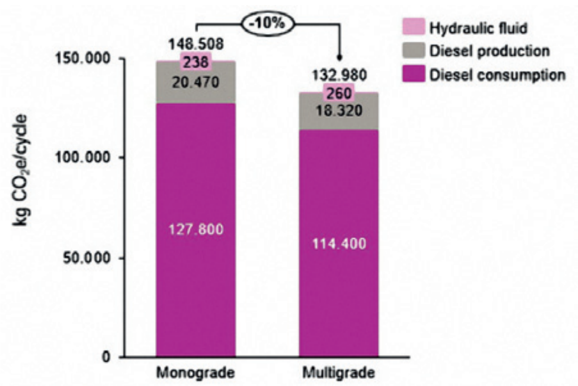
Picture13: Parameter for the life cycle analysis of hydraulic oils in a mid-sized excavator during 2,000 operating hours (EVONIK) [80]

The following graphs in pictures 14 and 15 show the eco-balances for hydraulic systems with monograde oil and efficient multigrade oil. More functional additives used in the multigrade oil yield a lightly higher CO_2 footprint in the production compared to the monograde oil. Considering a three- to four-fold higher oil life would lead to even more favorable figures. Since they are outweighted by the difference in fuel consumption, however, they are of hardly any significance.

Unfortunately, the lack of knowledge and short-term oriented mindset did not raise enough awareness for these long-term, ecological and also monetary benefits. Eventually, it is only the purchase price of the hydraulic fluid that counts. Efficient hydraulic fluids are also backward compatible and unfold even more efficiency in older, less efficient machinery. It is amazing in how many different applications simply exchanging the hydraulic fluid effect improvements.



Picture 14: Total CO_2 emissions [CO_2 e/cycle] for a monograde hydraulic oil (top) and an efficient multigrade oil (bottom) [80]



Picture 15: Comparison of total CO_2 emissions [CO_2 e/cycle] for a monograde hydraulic oil (left) and an efficient multigrade oil (right) over 2,000 operating hours [80]

9. Conclusions

The public discourse over CO_2 emissions and sustainability misconceives the cause and effect between friction and CO_2 emissions, the correlation between wear protection and sustainability, and ultimately the interaction between wear protection and CO_2 emissions. Unfortunately, the political debate has not yet considered the potentials of tribology for the reduction of energy and material losses.

Tribology offers minimum three wedges of significant CO_2 reduction potentials by:

a. CO_2reduction through friction reduction (energy efficiency)

and

b. Reduction of the material footprint (resource conservation, material efficiency).

A presumed savings potential of 30-40% of friction losses lowers the global CO_2 emission by 2.66-4.93 gigatons of CO_2 annually.

Wear protection hypothetically doubling the overall life cycle and condition monitoring saves about 8.8 gigatons of estimated resources annually with an equivalent of > 1 ton of CO_{2eq} per ton of resource/base material.

The addition of both results in medium- and long-term reduction potentials by tribology of > 11 gigatons CO_2 or >29% of the globally emitted 37.9 gigatons of CO_2 emitted directly in 2019 or >1.1 gigatons of CO_2 of the 3.76 gigatons of CO_2 emitted in EU27 (without UK) in 2018. From another standpoint, wear protection can help to double the utility value while consuming the same resources.

Note: The reductions by wear protection extending service life and condition monitoring is currently difficult to estimate since the saved tonnages cannot so far be quantified and directly allocated to applications and end-uses with tribosystems or being affected by tribosystems. This requires further investigations and research. This lack of knowledge will not affect the order of magnitude.

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