Accepted for publication in Tribology International, 5.5.2017

Global energy consumption due to friction and wear in the mining industry

Kenneth Holmberg[a,*], Päivi Kivikytö-Reponen[a], Pirita Härkisaari[b], Kati Valtonen[b], Ali Erdemir[c],

[a] VTT Technical Research Centre of Finland, P.O.Box 1000, FI-02044 VTT, Finalnd

[b] Tampere University of Technology, P.O.Box 589, FI-33101 Tampere, Finland

[c] Argonne National Laboratory, Argonne, IL 60439, USA

[*] Corresponding author. Tel.: +358 40 544 2285; e-mail address: kenneth.holmberg@vtt.fi

Abstract

Calculations on the global energy consumption due to friction and wear in the mineral mining industry are presented. For the first time, the impact of wear is also included in more detailed calculations in order to show its enormous tribological and economic impacts on this industry. A large variety of mining equipment used for the extraction, haulage and beneficiation of underground mining, surface mining and mineral processing were analysed. Coefficients of friction and wear rates of moving mechanical assemblies were estimated based on available information in literature in four general cases: (1) a global average mine in use today, (2) a mine with today's best commercial technology, (3) a mine with today's most advanced technology based upon the adaptation of the latest R&D achievements, and (4) a mine with best futuristic technology forecasted in the next 10 years. The following conclusions were reached:

- Total energy consumption of global mining activities, including both mineral and rock mining, is estimated to be 6.2 % of the total global energy consumption. About 40 % of the consumed energy in mineral mining (equalling to 4.6 EJ annually on global scale) is used for overcoming friction. In addition, 2 EJ is used to remanufacture and replace worn out parts and reserve and stock up spare parts and equipment needed due to wear failures. The largest energy consuming mining actions are grinding (32 %), haulage (24 %), ventilation (9 %) and digging (8 %).
- Friction and wear is annually resulting in 970 million tonnes of CO_2 emissions worldwide in mineral mining (accounting for 2.7 % of world CO_2 emissions).
- The total estimated economic losses resulting from friction and wear in mineral mining are in total 210,000 million Euros annually distributed as 40 % for overcoming friction, 27 % for production of replacement parts and spare equipment, 26 % for maintenance work, and 7 % for lost production.
- By taking advantage of new technology for friction reduction and wear protection in mineral mining equipment, friction and wear losses could potentially be reduced by 15 % in the short term (10 years) and by 30 % in the long term (20 years). In the short term this would annually equal worldwide savings of 31,100 million euros, 280 TWh energy consumption and a CO_2 emission reduction of 145 million tonnes. In the long term, the annual benefit would be 62,200

million euros, 550 TWh less energy consumption, and a CO_2 emission reduction of 290 million tonnes.

Potential new remedies to reduce friction and wear in mining include the development and uses of new materials, especially materials with improved strength and hardness properties, more effective surface treatments, high-performance surface coatings, new lubricants and lubricant additives, and new designs of moving parts and surfaces of e.g. liners, blades, plates, shields, shovels, jaws, chambers, tires, seals, bearings, gearboxes, engines, conveyor belts, pumps, fans, hoppers and feeders.

Keywords: energy, friction, wear, mining

1. Introduction

The global energy demand has been increasing steadily since the beginning of last century due to the growing societal needs and many diverse industrial activities. In the last 40 years, the world's energy demand has doubled and in the year 2013, the global final energy consumption increased by 2.3 % from the previous year to around 9,300 Mtoe (equalling to 390 EJ). Even though the development of renewable energy sources has been increasing, more that 80 % of the total energy still comes from non-renewable fossil fuels like oil, coal and natural gas, which are the major contributors to greenhouse gas (GHG) emissions. In 2012, the energy use of the CO_2 emitting energy sources increased by additional 1.4 % from the year before (IEA 2013, 2016; BP2016).

Mining is the search for, extraction, beneficiation, and processing of solid minerals from the earth's crust through open-pit mining, strip mining, quarrying and underground excavation. Mining has been an essential part of human activity for thousands of years to provide raw materials for improving security and quality of life as well as building the present-day industrial society. Some of the most important mining activities in our history have been the excavation for iron, gold, silver, copper, tin, lead, diamonds and coal for many Centuries. Minerals are defined as naturally occurring, stable at room temperature, represented by a chemical formula, biogenic and have an ordered atomic or crystalline structure. Even if coal does not by all means fit into the definition of minerals, the excavation of coal constitutes a major mining activity and hence is included in this study (US DOE 2002; Darling 2011a,b). Rock excavation from quarry for civil engineering purposes is in some sources considered as mining because the activities involved are largely very similar but excluded in our study

In general, a typical mining activity includes breaking, excavation, loading, hauling, transportation as well as mineral processing to reduce the size of large chunks of mineral containing rocks and to upgrade the concentration of these minerals by physical or chemical benefication methods. Mines are found in all parts of the world. The biggest producers of mineral raw materials (excluding petroleum and natural gas) are China accounting for 33.5 % of the world mineral production, USA 12.0 %, Australia 7.9 %, Russia 7.1%, India 6.4 %, South Africa 4.7 %, Indonesia 4.0 %, Brazil 2.1 % and Canada 2.0 (Reichl et al. 2016). These numbers include production of ferrous metals, non-ferrous metals, precious metals, industrial minerals and solid mineral fuels like coal and uranium, but exclude oil and gas. Coal, in the forms of steam coal, coking coal and lignite, is the largest mining product measured by weight and representing about 60 % of the total mining production. The second largest mining product is iron representing 11.4 %, and next follows aluminium and bauxite 3.9 %, salt 2.1 %, sulphur 1.5 %, gypsum 1.2 %, phosphates 1.0 %, manganese 0.14 % and copper 0.13 % (Reichl et al. 2016).

There are many types and sizes of mines in the world, ranging from small surface quarries to large industrial underground mines, recovering ores at a depth of some kilometres beneath the surface. The deepest is a gold mine in South Africa operating at a depth of 4 kilometres (The top ten deepest 2016). Most of the mining operations are surface mines, which include a variety of mines from large scale coal open-pit mines to small mineral or rock quarries. Still they all include the basic mining processes of drilling, detonating, comminution into manageable size, loading, transportation and further processing for end-use applications.

The mining activity is globally expanding due to the rapid urbanisation that creates a need for more metals and minerals in constructions and all kinds of consumer products, despite society's growing efforts in recycling and dematerialisation. Another reason for this expansion is that the richest ores have long been used up so, at present increasing volumes of rock ore excavation is needed to extract the same amount of pure mineral. The demand for base metals, particularly iron, copper and aluminium, has been projected to double from 2010 to 2025, largely due to increasing global urbanisation and industrialization (Albanese and McGagh 2011, Randolph 2011, Norgate and Haque 2010).

The total amount of energy used in the mining and minerals industry has been estimated to be 4-7% of the global energy output. The main energy sources are typically about one third electricity, one-third diesel oil fuel and one-third coal, natural gas and gasoline (Rabago et al. 2001). Largest amounts of energy are used in rock braking, crushing, grinding, loading, hauling and transportation. Pumping is also a large energy consumer and in underground mines, ventilation consumes significant amount of energy as well. Both friction and wear losses associated with the mining activities have a great influence on energy consumption in mining.

The impact of friction on the global energy consumption has recently been calculated for road transport by Holmberg et al. (2012a, 2014a,b). They determined that nearly one-third of the fuel's energy is spent to overcome friction in passenger cars. The same study advocated that, with the adaptation of more advanced friction control technologies, parasitic energy losses due to friction in cars could be reduced by 18% within the next 5 to 10 years, which would result in global fuel savings of 117,000 million litres annually, and by 61% within the next 15 to 25 years, which would result in fuel savings of 385,000 million litres annually. These figures equal world-wide economic savings of 174,000 million euros in the next 5 to 10 years and 576,000 million euros in the next 15 to 25 years. These calculations were based on oil price level 2011. Such a fuel efficiency improvement in passenger cars would, furthermore, reduce CO_2 emission by 290 million and 960 million tons per year, respectively. This should have a significant positive impact on the global efforts to reduce the greenhouse gas effect and control global warming as overwhelmingly agreed by the world's nations at the 2015 Paris Climate Conference (UN 2015).

In another study, Holmberg et al. (2013) carried out similar calculations for one advanced manufacturing sector represented by paper production. In paper machines 32% of the electrical energy is used to overcome friction, 36% is used for the paper production and mass transportation and 32% is other losses. However, in a paper plant, the electrical energy is only 30% of the total energy consumption because the remaining 70% is process heating by steam. No other industrial sectors has been analysed in such details with regard to friction effect on energy consumption.

The paper production is by its nature much different from mining and mineral production, where the handling of heavy rocks and large quantities of solid materials in harsh, dirty and humid conditions form exceptional challenges. Unlike transportation and manufacturing, in mining, the wear-related energy losses are considerable and wear carries a greater importance as a source for energy consumption. To the best of our knowledge the impact of wear on energy consumption on industrial scale has not yet been adequately addressed in the past in any detailed study in the open literature.

Our earlier papers reviewed the global energy consumption due to friction in passenger cars, heavy duty vehicles and paper machines (Holmberg et al. 2012a, 2013, 2014a). In this study we present calculations of the global energy consumption due to friction and wear and potential savings through the adaption of advanced friction and wear optimisation and control technologies in the mining industry. The focus is on the most energy consuming parts of mining, which is extraction, transportation and the mineral processing. Oil and gas extraction as well as rock excavation for civil engineering uses are excluded. Expected changes and trends, such as automation, remote operation, advanced processing, globalisation and market prices like supercycles (Randolph 2011, Albanese and McGagh 2001, Norgate and Haque 2010), are not included in the present analyses.

2. Methodology

This work was carried out by a methodology previously developed by Holmberg et al. (2012a, 2014a) for calculation of global impact of friction on transportation. Now it was extended to also include wear calculations. The methodology is based on the combination of analyses on several physical phenomena resulting in the energy consumption in mechanical equipment. It includes the following analyses and calculations:

1. An estimation of the global energy consumption by mining industry.
2. Calculation of the friction, wear and energy losses in three major categories of mining units (underground mine, surface mine, and mineral processing).
3. Estimation of operational effects in the three mining categories.
4. Estimation of tribocontact-related friction and wear losses today and in the future.
5. Calculation of the global energy consumption today due to friction and wear losses and potential savings.

The calculations were carried out on the basis of scientific publications, publically available statistical data and unpublished data received directly from some mine operators (Pyhäsalmi mine in Finland and Kiruna mine in Sweden) and the authors' own experience. There are detailed energy statistics for mining for the U.S.A., Canada and Brazil, and these data were taken as a starting point for the estimations on a global level (MAC 2005a,b; US DOE 2002, 2007; Brazilian 2014). On many energy issues in mining, there is no detailed recent data available. Still, it has been relevant to use also fairly old data because we calculate the energy consumption in global average mines which we are estimated to have an age of 25 years.

3. Energy consumption analyses

3.1 Energy consumption in mining industry globally

The Total Final Consumption (TFC) of energy worldwide was 390 EJ (9,300 Mtoe) in the year 2013 and it was distributed as:

- 29% for industry,
- 27% for transport,
- 35% for domestic, including residential, services, agriculture, forestry etc.,
- 9% for non-energy use, typically as raw materials.

The Total Primary Energy Supply (TPES) was 570 EJ (13,540 Mtoe) and of that was 170 EJ used by the energy industry for the energy production, 20 EJ was energy transfer and losses, and the rest forms the Total Final Consumption (IEA 2016).

In the IEA energy statistics, the energy expenditure of mineral mining (as we have defined it above) is included both in the numbers for mining and quarrying (1.81 EJ) and in the iron and steel (21.44 EJ) categories (IEA Tracking Ind Energy 2007; IEA Energy balances 2013; McLellan 2017). There are estimations that the mining and minerals industries worldwide use as much as 4 – 7 % of the total global energy output (Rabago et al. 2001). This would indicate that the mining industry uses between 16 – 27 EJ annually, but this number may, however, also include rock excavation. The energy use for mineral mining in USA, excluding oil, gas and rock excavation, was 1.31 EJ in 2007 (US DOE 2007, Tromans 2008). Correlating this to the USA share of world mineral production results in our estimation **that the mineral mining industry uses worldwide about 12 EJ energy annually.** This is our best estimation of global energy use by mining industry, excluding oil, gas and rock excavation.

In the year 2012, the world minerals production was 10,420 million tonnes in total (excluding oil and gas) and more than 5,400 million USD by value (Reichl et al. 2016). It includes five main groups:

1) ferrous metals, 1,600 million tonnes,
2) non-ferrous metals, 355 million tonnes,
3) precious metals, 30,400 tonnes,
4) industrial minerals, 785 million tonnes and
5) coal and other solid fuels, 7,950 million tonnes.

Rock or stone excavation for aggregates and beneficiation from quarries are not included in this study. Still, it is globally a very large industrial activity with most activities very similar to mineral mining. This causes sometimes confusion since it is not uncommon that no clear indication is given if rock excavation is included or not in published studies and calculations on mining. Rock excavation is the extraction, transportation and processing of rocks for the purpose of civil engineering. This includes quarrying, tunnelling and general contracting for the construction of roads and highways, pipelines, rock fill of dams, foundation preparation, ground levelling and demolition. It also includes dimensional stone quarrying, water well drilling and exploration drilling (Heiniö 1999).

The total amount of mineral ore extracted annually in Finland is about 80 million tonnes while the total amount of excavated rock used for civil engineering purposes is 90-100 million tonnes (Paalumäki et al. 2015). In USA, there are about 1000 mines producing industrial minerals and 3,320 quarries producing crushed rocks (Mining Journal online 2014). According to another source, there was in year 2000 in total 3,453 crushed stone mines out of 13,904 mines totally (US DOE 2002). This would indicate that the industrial rock excavation sector is of the same order of magnitude as the mineral mining sector. In this study, we have chosen to focus only on mineral mining and excluded rock excavation since in literature there is more structured information available on the former but only very few and fragmented reliable data on the latter.

The mineral mining production takes place in both underground and surface mines, and the upgrading of the mineral is done in mineral processing plants that often are integrated with or in close connection to the mines (Darling 2011a) . There is no globally collected reliable data of the number of mines worldwide. Some sources report about 500-750 active mines worldwide (Giancola 2007; Industrial Minerals Directory 2003; Moreno 2002) while other sources estimate up to 125,000 mines and quarries worldwide (Mining Journal 2014) and 13,904 only in USA (US DOE 2002). It is obvious that the big scatter is due to variation in the definitions of mines used. Rock excavation is most probably included in some numbers and not in the others.

From the ten largest mineral producing countries, we found detailed information about the number of mines only from two. In the USA there are 13,904 mines (US DOE 2002, NMA 2013). In Brazil there are 7,054 mines of which 64 are underground mines, 6,978 are surface mines and 12 are mixed mines (IBRAM 2015). USA represents 12.0 % of the world mineral production and Brazil 2.1 %. An estimation of the total number of mines worldwide based on the USA and Brazilian numbers and correlating it to their share of world production would result in between 135,000 and 245,000 mines in total worldwide.

In Brazil, the 200 largest mines are listed separately and our assumption is that they represent the larger industrial mines. This is in the same order as the number of mines reported for Australia (418), Indonesia (217) and South Africa (113) where the volume of the mining production is of the same level (IBRAM 2015). By correlating these numbers with the production of minerals we estimate that there is in total about 150,000 mines and quarries worldwide, including rock mining, and of those **about 5,000 are large industrial mines.**

3.2 Energy consuming functional categories in mining

The main operational categories in mining are the following, see Figure 3.2.1 (US DOE 2007, MAC 2005a&b; Norgate and Haque 2010, Will's 2006, Darling 2011a):

1. Extraction: drilling, blasting, digging, ventilation, and dewatering (pumping).
2. Materials transport and handling: haulage, conveyors, hoisting, and rail transport.
3. Processing: crushing, grinding, and separation.

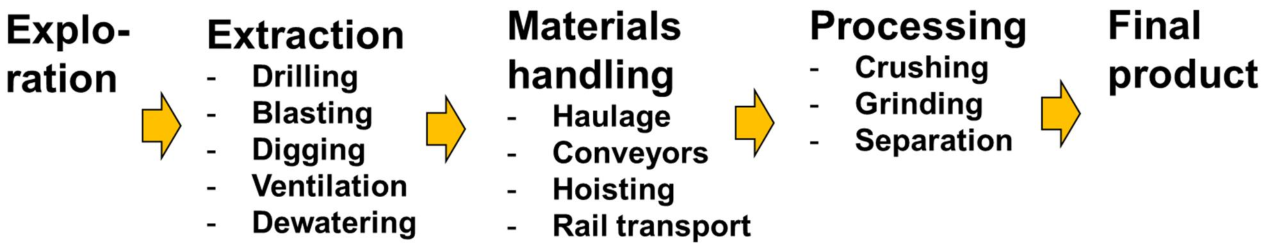

Figure 3.2.1 Main operational categories in mining.

Comminution is the collective term used to describe the progressive reduction in size of "as-mined" ore, including two main processes, crushing and grinding. The "as-mined" ore consists of both valuable minerals and non-desirable barren rocks. Explanation and glossary on mining terminology is found in mining textbooks (Willis 2006, US DOE 2007, Darling 2011).

The strength of the rock has an influence on mining efficiency, equipment wear, and the energy consumption. On a very general level the strength levels are called hard rock and soft rock but there are as well more detailed classifications as the Terzhagi rock mass classification (Carter 2011). In this study, we will use for our calculations these major reference mines: specifically coal, iron, and copper mines as they represent the largest mineral product groups in mining industry, see Section 1.

The power sources for the mining, transportation and processing equipment are dominated by electrical motors and diesel engines. The electrical power is more commonly used underground while diesel engines are most common in surface mining (Chadwick 1992; US DOE 2007).

3.3 Global average mining units and their operating conditions

Based on the analysis in Section 3.1, we choose to further define the following three mining units as representatives of typical mining activities that occur in most mines:

1) A **global average surface mine** represented by a **coal open-pit mine.**
2) A **global average underground mine** represented by a **copper mine.**
3) A **global average mineral processing unit** represented by an **iron rock processing mill.**

Coal is chosen as the surface mining product because it is by far the largest mining product, iron is chosen as mineral processing product because it is the second largest mining product and copper is chosen as underground mining product as a typical representative for the category of non-ferrous and precious metals.

The technical and operational specifications for the three global average mining units are presented in Table 3.3.1. Based on available data from some selected large industrial mines Härkisaari (2015) calculated that the average annual production globally for a coal mine is 10 Mt, for an iron mine 18 Mt, for non-ferrous mines 2 Mt, for precious metals mines 8 t and for industrial metals 3 Mt. The age of mines varies from seven year to more than 150 years and the average age for mines globally is 45 years while the median is 39 years. The annual production of the three global average mining units was adjusted to be in harmony with the energy calculations in Section 4.1. The number of equipment is estimated based on information from literature for surface mines and mineral processing units (US DOE 2002, Nelson 2011) and based on literature as well as data received from the Pyhäsalmi mine in Finland for the underground mine.

Table 3.3.1. Technical specifications of three defined global average mining units (Komonen 2003; Leiviskä 2009; Kunttu et al 2010; US DOE 2002; Härkisaari 2015; Tolonen 2015).

Global Average (GA) mining units		**Mining unit: GA Underground mine**	**Mining unit: GA Surface mine**	**Mining unit: GA Mineral processing plant**
Process		Underground mining	Surface mining	Mineral processing
Commodity		Copper	Coal	Iron
Age (years)		**25**	**25**	**25**
Annual production (Mt)		**4**	**5**	**4**
Depth (m)		**1000**	**-**	**-**
Ore recovery ratio (%)		**50**	**80**	**-**
Availability, stationary equipment (%)		**70**	**70**	**70**
Availability, mobile equipment (%)		**30**	**30**	**30**
OEE Overall Equipment Effectiveness (%)		**55**	**55**	**55**
Annual energy use (TJ)		**3840**	**680**	**2260**
Number of equipment:				
Drills, bolters, jumbos		**20**	**4**	**-**
Continuous miners, backhoes		**-**	**1**	**-**
Loaders, shovels, scrapers etc. (*1)		**16**	**12**	**-**
Haul trucks, water trucks		**16**	**35**	**-**
Drag lines		**-**	**1**	**-**
Hoists, skips		**4**	**-**	**-**
Conveyors		**40**	**-**	**40**
On site crushers		**6**	**-**	**-**
Rail transport		**1**	**-**	**-**
Water pumps		**80**	**6**	**40**
Ventilation fans		**150**	**-**	**10**
Crushers		**-**	**-**	**8**
Grinding mills		**-**	**-**	**4**
Screens, separators, floatation etc. (*2)		**-**	**-**	**40**

(*1) Includes: Loaders, bucket-wheel excavators, mining shovels, track dozers, scrapers, graders, LHD,

(*2) Includes: Screens, cyclones, separators, pelletizers, filters, thickeners, centrifuges, floatation equipment,

The Overall Equipment Efficiency (OEE, %) is defined as

$$\text{OEE} = \text{availability x performance x quality} \quad (3.1)$$

where availability (%) is the ability of the system to carry out a required task during a given time, performance (%) is the ratio of the output and nominal production during the operating time and the quality (%) is the ratio of products that are in the final selling form without defects and ready to be sold to the customer (Komonen 2009).

3.4 Energy consumption due to friction and wear

3.4.1 Maintenance in mining

Friction between moving parts of industrial machinery consumes energy but may (similarly to wear) also result in functional problems, failures and machine break down. Such situations cause machinery downtime and possibly production interruptions, maintenance work and costs for replacement parts (Vergne 2008). The maintenance cost varies in the different industrial fields due to the nature of the industrial process, the level of technology used, level of automation, and maintenance methods used and are typically in the range of 1 to 20% of the annual turnover. The Finnish Maintenance Society has collected data about maintenance actions and costs in industry over a long period of years and we have used this information as a starting point for our global estimations of maintenance in mining industry (Komonen 1998a,b, 2003; Leviskä 2009; Kunttu et al 2010; Paalumäki et al 2015; Tolonen 2015).

In Finnish manufacturing industry in general the maintenance costs were over the years 2005-2009 about 6 % of the turnover, the operational time was 70 %, the overall equipment effectiveness (OEE) was 70 % and the availability 90 %. The equipment average age was 19 years (Kunttu et al. 2010). In the USA the average utilisation rate in mining 1972-2013 was 87.3 % while it was in average only 80 % for all industries (Board of Governors 2015). The availability of a haul truck may be in the rage of 65-85 % depending on the level of maintenance actions and for a shovel, it is typically 80 % (Bohnet 2001).

In mining, the maintenance costs are higher than in most other industrial sectors. In Finland they were reported to be 15.2 % of the annual turnover in year 1997 while they were 9.5 % in energy production, 5.9 % in basic metal industry, 5.3 % in paper- and pulp industry, 3.6 % in chemical and polymer industry, 2.6 % in food industry, 2.3 % in textile industry, 1.6 % in metal product industry (Komonen 2003). In reality, the maintenance costs are even higher because several companies report replacement material costs as operational costs. In deep ore mines, the maintenance costs can be as high as 32 % of the total operational costs (Brannon et al. 2011).

A study from a Finnish copper underground mine shows that the maintenance cost were 29 % of the operational costs. More than half (51 %) of the maintenance cost originated from the mineral processing plant, 41 % from the mining unit, and 8 % from other operations. The maintenance costs in the mining unit were distributed as 52 % for replacement parts and 48% labour while in the processing plant, they were 46 % for replacement parts and 54 % was for labour costs (Tolonen 2015).

Our estimation used in this study is that in mining globally:
- the average age of the equipment is 20 years, with frequent wear part replacement,
- the availability in mines is 70 %,
- the typical profit level is 10 – 30 % of the turnover,
- the real maintenance costs including all material and labour costs are 25 % of the turnover,
- half of the total maintenance costs is due to wear, and
- the maintenance costs are distributed as half from replacement part expenses and half are due to labour costs.

The downtime cost is divided into two parts, the downtime spare equipment cost and the downtime production loss cost. The downtime when the equipment is not in function due to maintenance reasons will result in additional costs due to loss of production capacity. The availability in mining is about 70 % and of this we estimate that half is due to wear of parts and components and the other half is due to operational disturbances, such as human errors, accidents, strikes etc. This means that in average the equipment lifetime is reduced by 15 % due to equipment downtime because of wear related maintenance actions. The logic is that if e.g. equipment has a lifetime of 20 years, it then can be in operation only 17 years of that time due to 3 years of stand still because of wear related maintenance actions. This means that the mine needs to invest 15 % more in additional capacity to have other equipment available also during the downtime period.

Some large equipment in mining like e.g., the grinding mills and jumbo drills are critical for the whole production line. There is typically no spare equipment so in case of breakdown there is an interruption in the production and wear failures may result in production loss for the downtime period. Smaller equipment in mining like the haul trucks, pumps, fans, drills etc. are less critical as there are several of them around and in case one breaks down another can be taken to replace it from the fleet in service. A third group of equipment is the one in between the two mentioned and that is consisting of equipment that will cause some reduction in the production in case of breakdown. We consider in our calculations that the equipment distribution in mining is about equally divided in these three groups. We estimate that the production loss cost is about 20% of the maintenance costs (Komonen 1998a,b; Tolonen 2015).

3.4.2 Friction and wear energy indicators

In our previous studies on road vehicles and paper industry, we focused on the effect of friction on energy consumption (Holmberg et al. 2012a, 2013, 2014a). The calculations were in that sense straightforward as there is a universal parameter representing friction, the coefficient of friction, which is the tangential friction force divided by the normal load.

In mining, the wear has a considerable role in energy consumption and thus a tribological study dealing with energy losses in mining without considering the wear aspect would not be very representative. The wear issue is, however, more complicated as there is no general parameter representing wear as in friction. There are parameters like wear rate and wear coefficient which are frequently used but they cannot be used for all wear situations as e.g. in abrasive, corrosive, and erosive wear where the sliding counterpart is not well specified. Thus, in the open literature wear is reported in many forms such as wear coefficient, wear rate, wear volume, wear depth, wear groove dimensions etc. (Meng and Ludema 1995, Holmberg and Matthews 2009).

In Figure 3.4.2.1, we show how the energy is brought to the machinery or to the production system. One part of this goes to overcome friction due to shear in lubricated contacts, shear in the top surface in adhesive sliding contacts and ploughing friction that results from elastic and plastic deformation of the surfaces. These are all friction mechanisms that can be quantitatively represented by the coefficient of friction.

Another part of the energy goes to wear related mechanisms and actions. Wear is the removal of material from the top surface of parts and components by means of deformation, oxidation, abrasion, fracture, fatigue, crack growth and wear particle generation. This results in energy needed for the following actions:

1) energy is needed for producing new parts to replace the worn out parts,
2) energy is needed for producing additional equipment capacity to compensate the capacity loss during equipment downtime and repair and/or maintenance actions due to wear failures.

Relevant data in a unified form as needed for the calculation of the energy parameters related to wear is not available today so this approach is beyond the scope of our study and current state-of-practice. For that reason, we have chosen another approach: that is to calculate the costs related to these energy parameters. This is easier because now we have relevant data available from the industry. It is a common practice largely in industry to follow the maintenance share of the turnover by monitoring the costs for spare parts, maintenance work, and downtime. This is often done both for single machines and for whole systems. In addition, we also calculate the production loss costs at downtime due to wear failure. Thus all kind of wear failures as they are categorised in industrial environment are included in the calculations.

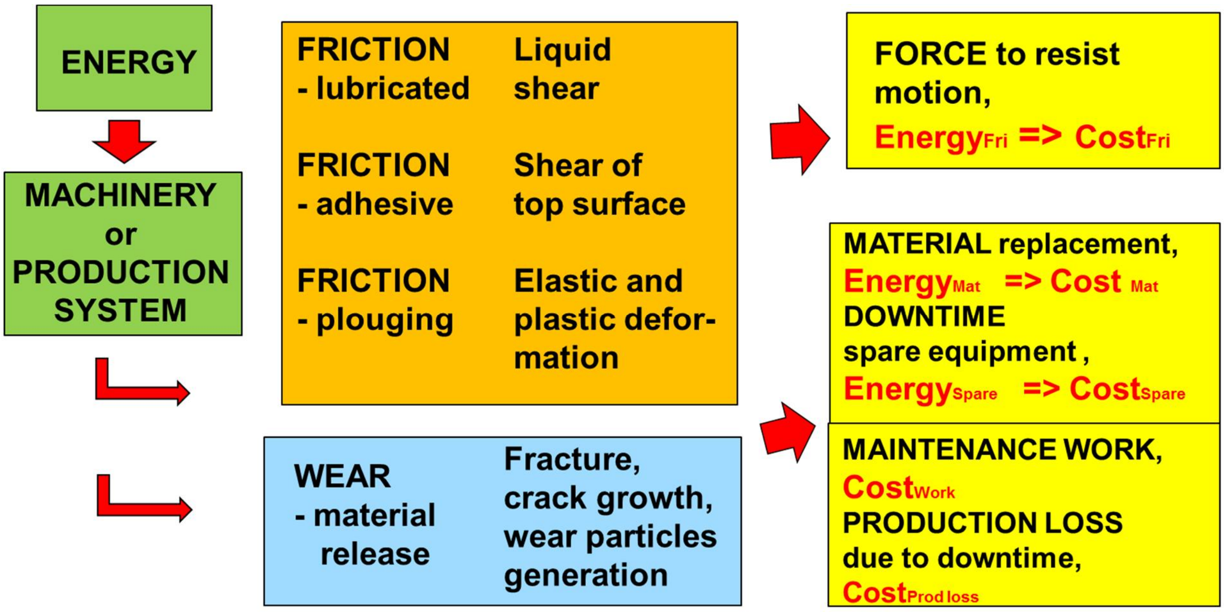

Figure 3.4.2.1 Energy break down in tribological contacts

In the calculations, we consider both energy consumed and related costs. One of these is estimated based on detailed analysis and the others converted from the former. The following parameters are used and converted:

- Energy consumption	Joule	=> Euro	
- Material replacement	Kg	=> Euro	=> Joule
- Maintenance labour	Euro		
- Downtime, spare equipment	Euro	=> Joule	
- Downtime, production loss	Euro		

3.5 Energy loss sources in mining

Energy in mining is needed to carry out the excavation of the minerals, its transportation and its processing to an intermediate product for the market. The main mining operational categories were presented in Section 3.2.

Typical equipment used for the various actions in both surface and underground mining and mineral processing is shown in Figure 3.5.1. In this study we analyse the main energy consuming mining equipment using equipment categories introduced in previous studies (Heiniö 1999; US DOE 2002; MAC 2005a,b; US DOE 2007; Norgate & Haque 2010; Härkisaari 2015).

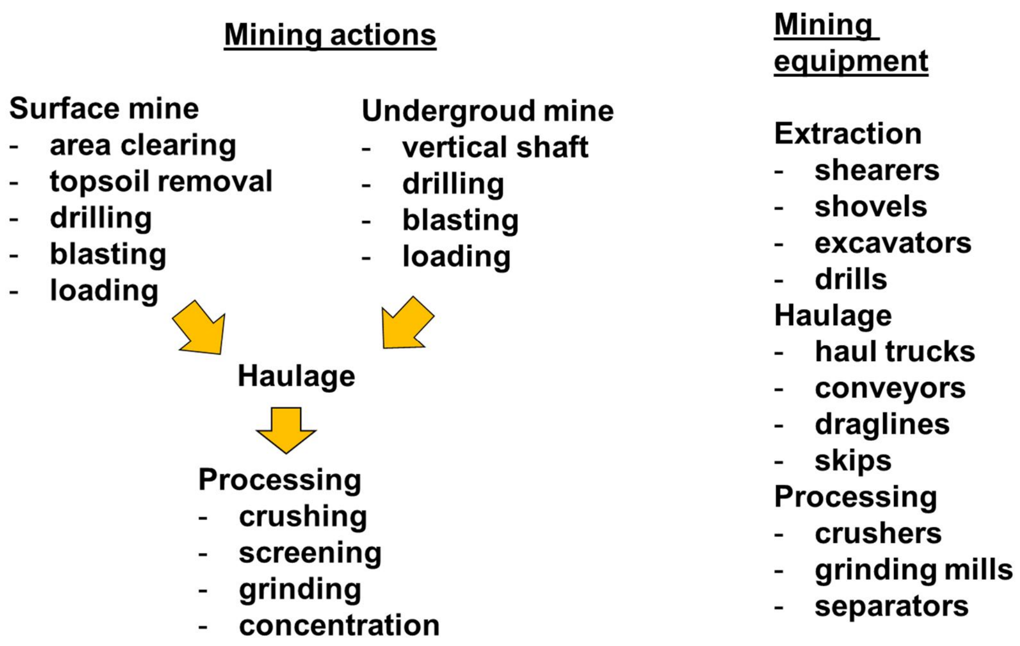

Figure 3.5.1. Underground and surface mining actions and examples of typical equipment used (Härkisaari 2015, US DOD 2007; US DOE 2002).

The energy used in mining is dominated by two sources, electrical power and diesel fuel. In addition coal and natural gas, and to a minor extent also gasoline and wind power are used. Diesel fuel is traditionally and still today much used energy source in surface mining because of the mobility, high efficiency and flexibility of diesel engines. Electrical power is extensively used in underground mining because it does not produce emissions or exhaust gas. Electrical power is the main source for power in mineral processing plants for crushing and grinding operations, as well as for ventilation systems and water pumping, where the machinery is stationary (Chadwick 1992, Smith 1994, US DOE 2002, US DOE 2007, Albanese and McGagh 2011, Errah 2011, LKAB Annual report 2013, Paalumäki 2015).

The energy consumed in U.S. for mining industry comes from 34 % diesel, 32 % electricity, 22 % natural gas, 10 % coal and 2 % gasoline. Materials handling was in average the largest energy consumer (42 %) followed by processing (39 %) and extraction (19%). Diesel fuel is mostly used in material handling to 87 % (US DOE 2002, US DOE 2007). Typical breakdown of energy consumption in single mining equipment and machines is reported in (US DOE 2002).

3.5.1 **Rock drilling machines**

In rock drilling, a drilling equipment is used to open a cylindrical hole for exploration, blasting, or tunnelling. Drilling equipment includes diamond drills, rotary drills, percussion drills, drill boom jumbos and explosive loader trucks. The drills are run mainly by electricity or diesel power or to a minor extent by compressed air. The number of drilling machines per mine is typically 2-6 depending on the mine production capacity (Heiniö 1999, US DOE 2007, Norgate & Haque 2010, Rostami 2011, Rostami & Hambley 2011, Vergne 2008, McCarthy 2011, Paalumäki 2015).

3.5.2 **Excavation machines**

Excavation or digging is done to make a pass into or through, or to remove material from the earth's surface. The goal of digging is to extract as much valuable material as possible and reduce the amount of unwanted materials. Digging equipment includes hydraulic shovels, cable shovels, continuous mining machines, long wall mining machines and drag lines (US DOE 2007, Busfield 2011, Humphrey & Wagner 2011, Paalumäki 2015).

3.5.3 **Draglines, skips and hoists**

Draglines are used in sites of flat geology for transporting load (usually overburden) to a dump point. They are very productive, comparatively low in operating cost and labour requirement and extremely robust with long lifetimes. A drag line can operate from 50 m above and 65 m below its working level, with a bucket of 125 m^2 it has a capacity of moving 30-35 million cubic meters per year (Humphrey & Wagner 2011, Paalumäki 2015). Similar hoisting systems can be used also in underground applications by using skips to carry the primary crushed rock to the surface. The skip is powered by an electric motor and one hoist can carry about 20-40 tonnes (Vergne 2008, Tiley 2011, Härkisaari 2015).

3.5.4 **Haul trucks and loaders**

The main part of all material moving operations in mines is carried out by loaders and haul trucks because of their great flexibility and efficiency. In surface mines, the rocks are typically excavated by shovels, excavators or front-end loaders and loaded on a dump truck for haulage to the processing plants. The wheel loaders have typically a capacity of 50 to 90 tonnes, the shovel units and excavators 200 to 250 tonnes and off-road dump trucks 150 to 300 tonnes. Similar haul trucks are used in both underground and surface mining. In underground mining, however, the circumstances create some limitations and adapted applications are used especially in relation to size, exhaust, road quality and cycle effectivity (Smith 1994, Blackwell 1999, US DOE 2007, Norgate & Haque 2010, Albanese & McGagh 2011, Humphrey & Wagner 2011, Berkhimer 2011, McCarthy 2011, Härkisaari 2015, Paalumäki 2015).

Main part of the equipment used in haulage and transfer of material in mining is powered by diesel engines. In general, diesel fuel powers rubber tire or track vehicles that deliver material in batches, while electricity powers continuous delivery systems such as conveyors and slurry lines (Chadwick

1992, US DOE 2007). Main energy consumers are the engine, the tires or chains and the transmissions.

3.5.5 **Conveyor belt systems**

Conveyor belt systems are an alternative to haul trucks for transporting ore from one process to another on flat areas and high-angle conveyor systems for uphill hauls. Their popularity have increased in the last decades because they are more cost efficient and require less labour costs. The length of a conveyor system can vary from some meters to 20 kilometres (Nordell 1999). Belt conveyors conserve energy because they are driven by electric motors with an efficiency of near 95% and their payload-to-dead load ratio is approximately 4:1. By comparison, the efficiency of the diesel engine in a haulage truck does not exceed 40% and a truck's payload-to-dead load ratio is no better than 1½:1 (Vergne 2008,). A conveyor system is on the other hand more fixed and can transport well fragmented material but cannot take as-mined blasted material, unlike haul trucks. (Nordell 1999, Jansen 2008, Albanese & McGagh 2011, Brown 2011, Humphrey & Wagner 2011, Paalumäki 2015). Much friction is generated and hence energy is consumed by the huge number of bearings and wear is also considerable to reduce lifetime of the bearings, the idling rolls and the belts.

3.5.6 **Rail transportation**

The traditional transport option for long distance and fairly horizontal transportation, including mine to port transport, is by rail. Even if haul trucks have taken a dominating role there is a new interest in rail transport. This is due to new possibilities offered by alternative fuels, hybrid diesel-electric locomotives, energy storing at braking, autonomous train operation, low emissions and low level of energy use (Randolph 2011, Paalumäki 2015).

3.5.7 **Crushers**

Crushing is the process to reduce the size of as-mined material into coarse particles, typically coarser than 5 mm, to a level that grinding can be carried out. Crushing is accomplished by compression of the ore against rigid surfaces, or by impact against surfaces in a rigidly constrained motion path. It is usually a dry process and is performed in several stages. Crushing plants include primary, secondary and tertiary crushers. Primary crushers include jaw crushers and gyratory crushers. Secondary and tertiary crushers include cone crushers, Rhodax crushers, impact crushers, and rotary coal breakers.

Crushing machines are normally powered by electric motors and their efficiency is often very low, normally less than 10 %. The problem lies in the fact that most of the energy input in a crushing or grinding machine is absorbed by the machine itself, and only a small fraction of the total energy is available for breaking the material (Wills & Napier-Munn 2006, US DOE 2007, Vergne 2008, Norgate & Haque 2010, Albanese & McGagh 2011, Brown 2011, Utley 2011, Mosher 2011, Legendre & Zevenhoven 2014, Paalumäki 2015).

3.5.8 **Grinding machines**

Grinding is the process of reducing the size of material into fine particles, typically below 0.1 mm (Will's and Napier 2006; Mosher 2011). Grinding is performed in rotating cylindrical steel vessels. It is accomplished by abrasion and impact of the ore by free motion of unconnected media such as rods, balls or pebbles. It is usually performed wet to provide a slurry feed to the concentration process, although dry grinding has some limited applications.

Grinding mills are classified into two types, tumbling mills and stirred mills. In tumbling mills, the mill shell is rotated and motion is imparted to the charge via the mill shell. The grinding media may be steel rods, balls or the rock itself. In stirred mills, the mill shell has a vertical or horizontal orientation and is stationary and motion is imparted to the charge by the movement of an internal stirrer. There is a large variety of mill types in grinding plants such as semi-autogenous grinding mills (SAG), rod, ball and tube mills, discharge mills, vibratory mills, centrifugal mills, tower mills, stirred mills, roller mills, high pressure grinding roll mills etc. They are normally powered by electric motors and their efficiency can be very low, even as low as 1% has been reported for a ball mill (Fuerstenau et al 2002, Wills & Napier-Munn 2006, US DOE 2007, Tromans 2008, Vergne 2008, Norgate & Haque 2010, Albanese & McGagh 2011, Mosher 2011, Paalumäki 2015).

3.5.9 **Separators, machines for concentration and final processing**

Separation of mineral material is to a large part carried out by physical separations, where the valuable materials are separated from undesired substances based on the physical properties of the materials. A wide variety of equipment is used for separation processes, the largest energy-consuming methods amongst these being centrifugal separation for coal mining, and floatation for metals and minerals mining. Other equipment types are e.g. screens, cyclones, jigging devices, and magnetic and electrostatic separators.

Centrifuges are spinning baskets designed to receive solid-liquid slurries and remove the liquid. Floatation machines isolate valuable ore from non-valuable substances by chemical reagents to bond to the valuable product and make them air-avid and water-repellent. In iron ore mining, screening is the most common separation method. It is used to separate the ore into lump and fines streams, while magnetic separation is used to separate magnetite from barren rock. Final processing includes actions that further prepare the ore to yield the desired product in its purest and most valuable form. These actions include e.g. roasting, smelting, refining. These processes require relatively much less energy (Cohen 1983, Wills & Napier-Munn 2006, US DOE 2007, Vergne 2008, Norgate & Haque 2010, Flintoff & Kuehl 2011, Kawatra 2011).

3.5.10 **Compressed air systems**

Compressed air is used extensively in mining to drive pneumatic systems such as air motors, actuators, instrumentation, and pneumatic tools. It can also be used to cool and clean components or parts and to blow off waste material (Vergne 2008, Hooper 2011, Paalumäki 2015).

3.5.11 **Dewatering, pumping**

Dewatering is the process of pumping water from the mine workings. The sources of water in mining are e.g. inflow of rain water, inflow of ground water, leakage from sea, lakes, rivers or dams, mine service water, drainage from hydraulic backfill or hydraulic mining. In mineral processing most separation processes involve the use of substantial quantities of water. The pumping systems in mining are always large energy consumers (Cochen 1983, Will's 2006, US DOE 2007, Vergne 2008, Peppers 2011, McCarthy and Dorricott 2011, Richards 2011, Paalumäki 2015).

3.5.12 **Ventilation**

Good ventilation is needed in underground mining to bring fresh air to the underground workers while removing stale and contaminated air from the mine and also for cooling work areas in deep underground mines. The electric power required for the ventilation system for a mine is one of the major components of the total electric power consumption and may be even as much as 40% (Chadwick 1982, Mukka 2002, Vergne 2008, Halim & Kerai 2013, Paalumäki 2015).

4. Calculation of energy consumption in mining

4.1 Energy consumption breakdown in the global average mining units

Based on our analysis in Section 3 we make the following estimation as input data for our calculations:

- 12 EJ/a is the global energy consumption of mineral mining industry,
- 150,000 is the total number of mines and quarries (this number includes rock excavation),
- 5,000 of all mines are large industrial mines while the rest are smaller mines and quarries,
- 5,000 large industrial mines worldwide use 80% of all energy in mining industry = 9.6 EJ/a,
- 15% of the large industrial mines are underground mines,
- 85% of the large industrial mines are surface mines,
- 1,700 large mineral processing units worldwide estimated from the assumption that there are 2-4 times more mines than mineral processing units,

Our estimation that the 5,000 large industrial mines use 80% of all energy used in mining may seem high compared to their small number of all mines. Here we have considered that the number of all mines worldwide also includes some mines taken out of use, many mines that are used only occasionally depending on market prices or used only very limited in time. Our estimation correlates fairly well when we compare it to average annual energy use considering energy consumption per tonne ore produced and recovering ratio from the Canadian mining report (MAC 2005a,b).

Typically 30-50% of the energy in mining goes to mineral processing. The energy intensity for surface mining is 5-10 kW/t and for underground mining 20-50 kW/t, which means that it is about four to five times more for underground mining (Cochen 1983, NMA 2013, Rabago et al. 2001, US DOE 2002, MAC 2005a,b; US DOE 2007, Norgate & Haque 2010, Albanese et al. 2011, Nelson 2011). According to another source, the energy intensity in surface mining is 25 kWh/t and in underground mining 180kWh/t (Batterham & Goodes 2007). The ore and coal production in US is 10 times higher in surface mining than underground (Nelson 2011). We conclude that the annual mining production is about seven times bigger in surface mines but their energy intensity is about seven times smaller compared to underground mines, which means that both surface mining and underground mining use about the same amount of energy annually worldwide.

We summarise that the energy consumption for mining globally is distributed as:

- 30% or 3.6 EJ for surface mining,
- 30% or 3.6 EJ for underground mining, and
- 40% or 4.8 EJ for mineral processing.

And further we calculate that the global annual energy consumption in the 5000 large industrial mines is:

- 2.88 EJ in 750 underground mines,
- 2.88 EJ in 4250 surface mines and
- 3.84 EJ in 1700 processing plants.

Now we can calculate the annual energy consumption of our previously defined global average mining units that represent an average of the large industrial mines and it is:

- **3,840 TJ/a** (1.07 TWh/a) for the **global average underground copper mine,** with a production rate of 4 Mt/a,
- **680 TJ/a** (0.19 TWh/a) for the **global average surface coal mine,** with a production rate of 5 Mt/a, and
- **2,260 TJ/a** (0.63 TWh/a) for the **global average iron processing plant,** with a production capacity of 4 Mt/a.

The total energy used in mining industry is consumed by the different mining operational categories as shown in Figures 4.1.1 and 4.1.2. The energy consumption distribution for mining actions is based on data from (Cochen 1983, MAC 2005a, US DOE 2002, MAC 2005b, Willi's 2006, US DOE 2007, Tromans 2008, Norgate & Haque 2010, Härkäsaari 2015).

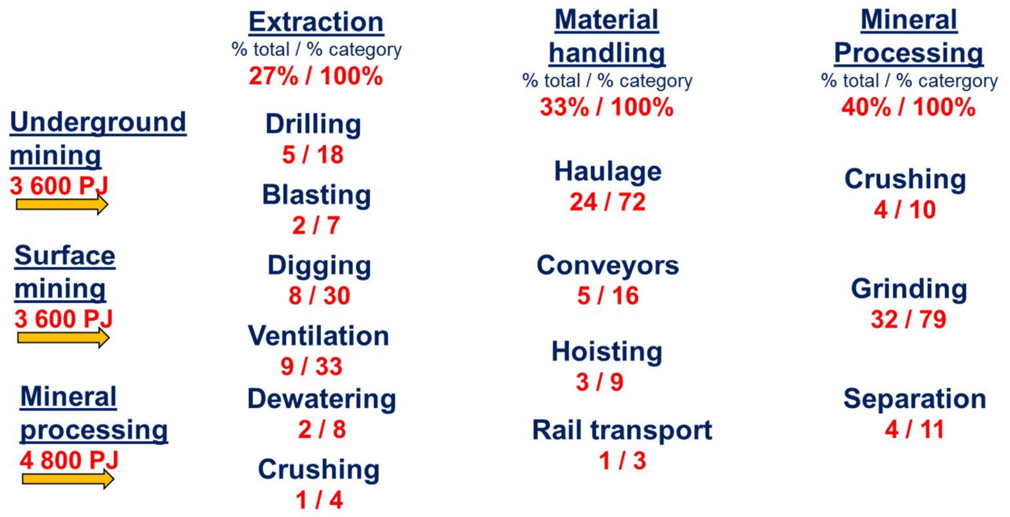

Figure 4.1.1 Share in percentage of the global energy consumption in mining (=12 EJ) in total and according to mining operational categories.

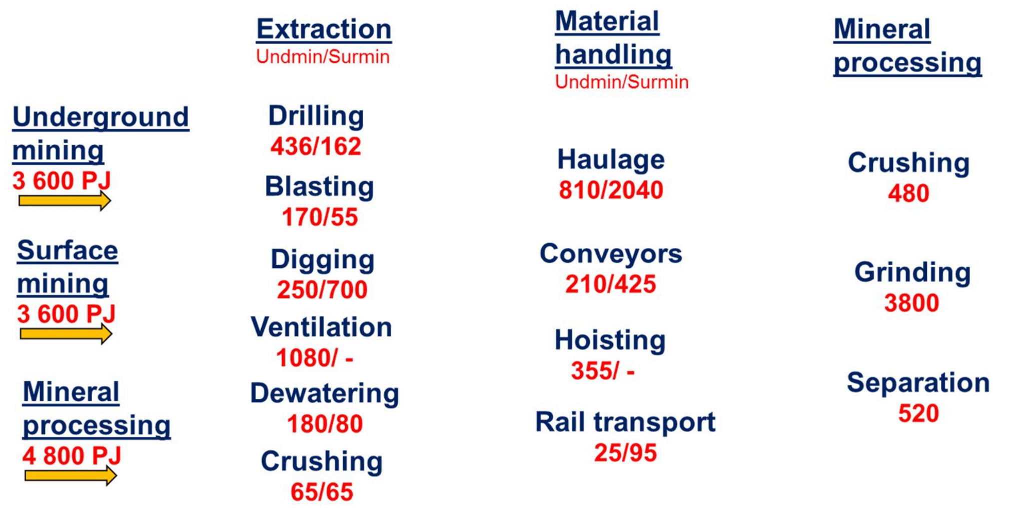

Figure 4.1.2 Global energy consumption in mining (=12 EJ) according to mining operational categories.

4.2 Friction and wear vs energy and economic losses

The friction losses are related both to lubricated and dry contacts in mobile and stationary equipment like engines, gears, transmissions and tires in mining vehicles; electrical motors, transmissions, hydraulics and rollers in stationary mineral processing machines; and hydraulic and ventilation systems. We carried out three case studies where the friction and wear losses were analysed and calculated in detail (Härkisaari 2015). The three cases are a mobile jaw crusher, a grinding mill, and a haul truck, see Figure 4.2.1. They represent three typical equipment categories in mining. The jaw crusher represents a rock demolition equipment used on site, the grinding mill is a large and the most energy consuming equipment in mineral processing, and the haul truck represents a very common mobile vehicle used in material transportation.

Figure 4.2.1 Three case studies were carried out for detailed energy and cost analysis: a mobile jaw crusher, an off-highway haul truck and a grinding mill.

The breakdown of the energy use in the three cases studied are shown in Figures 4.2.2, 4.2.3 and 4.2.4.

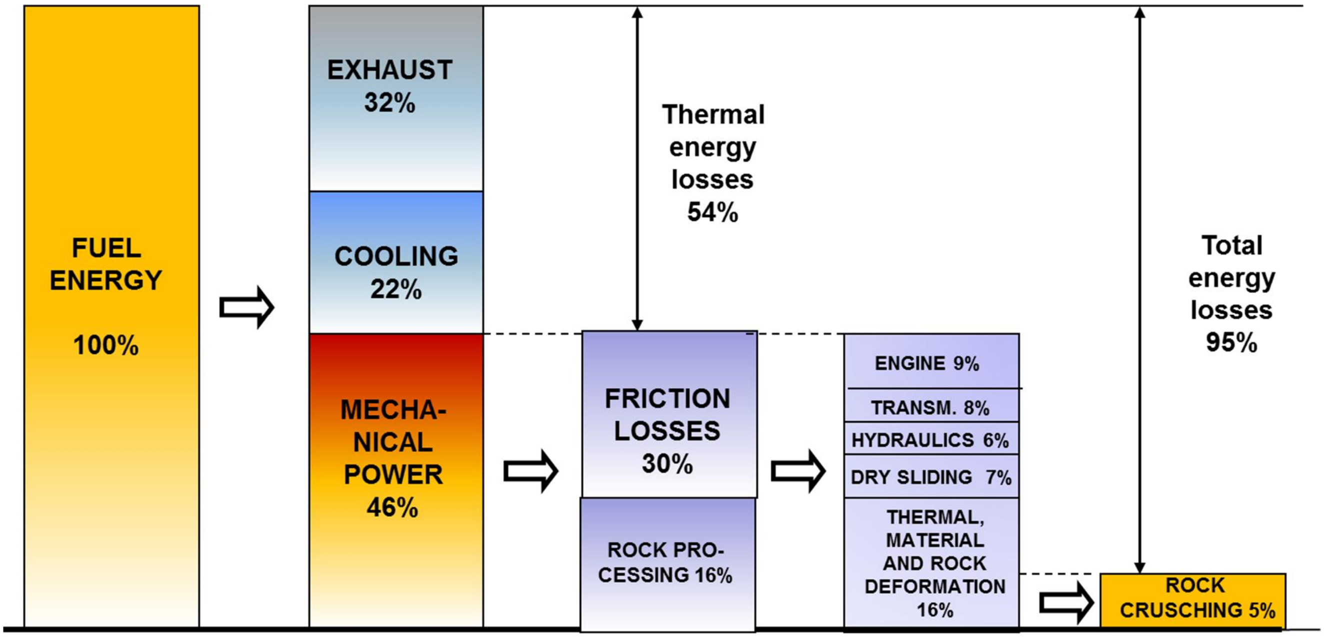

Figure 4.2.2 The energy distribution in a diesel powered mobile jaw crusher typically used in iron ore crushing (weight 50 tons).

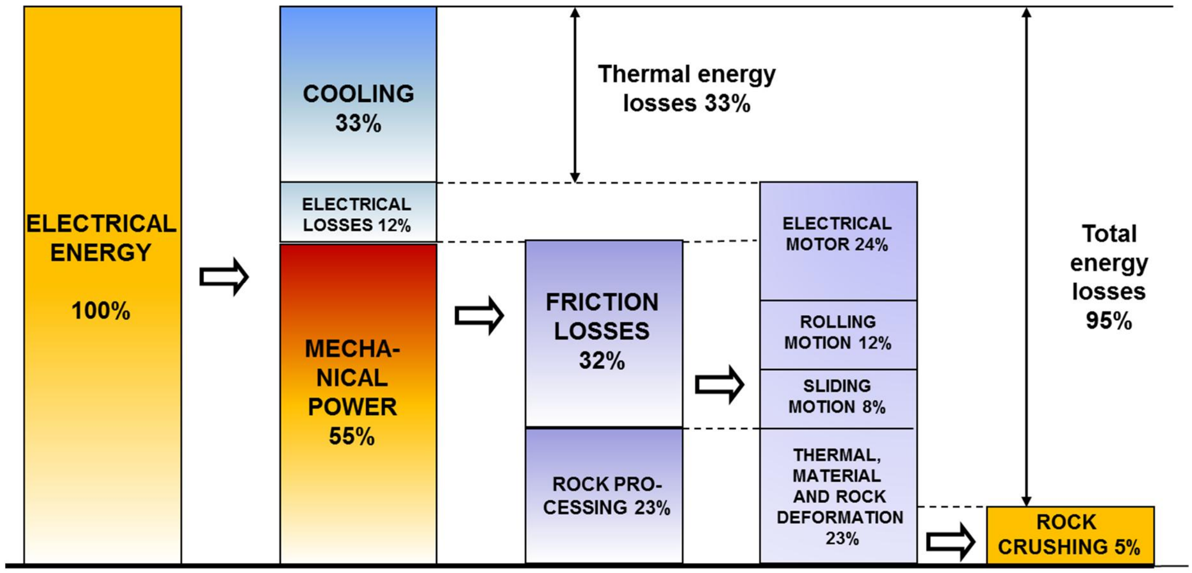

Figure 4.2.3 The energy distribution in an electrically powered autogenous grinding mill typically used in primary milling of iron ore (mill diameter x length = 6 x 6 m).

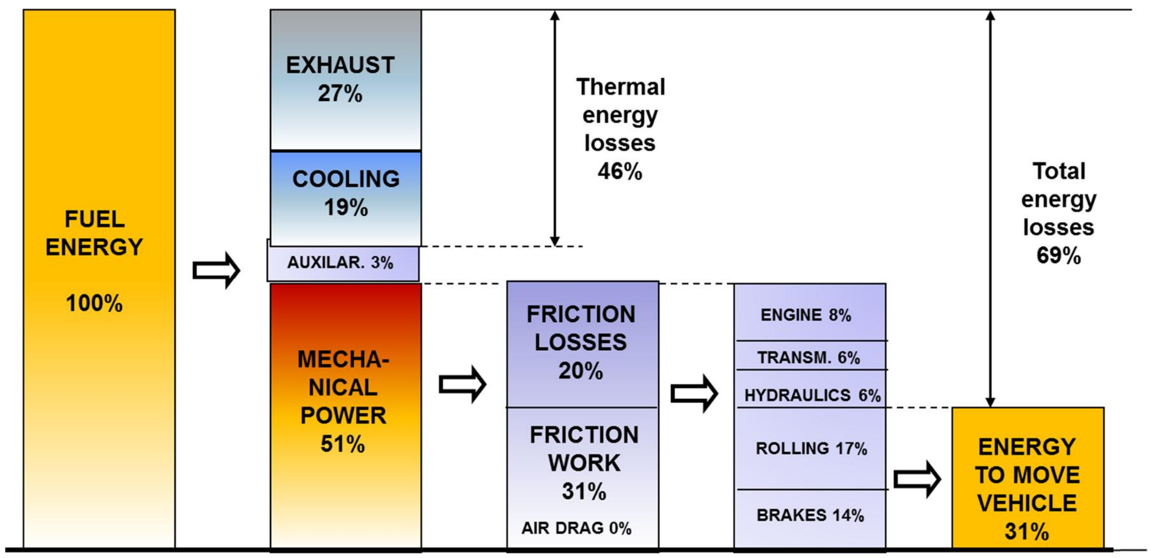

Figure 4.2.4 The energy distribution in a diesel driven off-highway rigid frame 90 tons haul truck used in mining**.**

The energy used for brakes in the haul truck is considered equal to the energy used to accelerate the vehicle and thus it represents the energy of inertia to overcome when moving the vehicle.

The distribution of friction losses according to the various lubrication mechanisms in both mobile and stationary equipment was estimated for both diesel and electric powered machines by using previous friction analysis and applying them to mining conditions; see Table 4.2.1 (Holmberg 2012a, 2014a).

Table 4.2.1 Friction and energy losses in main components as part of the total friction losses.

		Mobile mining vehicle	Stationary mining machinery	
	Lubrication mechanisms	**Diesel engine, e.g. haul truck**	**Diesel engine, e.g. jaw crusher**	**Electrical motor, e.g. grinding mill**
		%	%	%
Friction of total energy input		**51**	**30**	**32**
Engine / motor		**16**	**30**	**38**
- valve train	ML	15	15	
- bearings, seals	HD	30	30	
- piston assembly		45	45	
	HD squeeze	40	40	
	EHDS	40	40	
	ML	10	10	
	BL	10	10	
- pumping, hydraulic	VL	10	10	
Transmission		**12**	**27**	
- gears	EHDSR	55	55	
- bearings	EHDR	20	20	
- viscous losses	VL	20	20	
- seals, forks	ML	5	5	
Hydraulics	VL	**12**	**20**	**-**
Tyres	RF	**33**	**-**	**-**
Braking (~acceleration)		**27**	**-**	**-**
Dry sliding & rolling		**-**	**23**	**62**
Friction total		**100**	**100**	**100**

HD = hydrodynamic lubrication	EHD = elasto-hydrodynamic lubrication
ML = mixed lubrication	EHDS = elasto-hydrodynamic sliding
BL = boundary lubrication	EHDR = elasto-hydrodynamic rolling
RF = rolling friction	EHDSR = elasto-hydrodynamic sliding/rolling
VL = viscous losses	

The results of the analysis of friction losses is summarised in Table 4.2.2. In the conversions we have used global average prices 2014 which were 0.7 €/l for diesel fuel, 0.06 €/kWh (=> 1 MJ costs 0.0166 Euro) for electric power and 6 €/hour for maintenance work.

Table 4.2.2 Summary of annual friction losses in three case studies (Härkisaari 2015).

Operation	Tribo-category	Annual operational use	Annual energy use	Friction loss from total energy	Energy loss due to friction	Energy loss due to friction
Unit	-	h	l & TJ	%	l & TJ	€/a
Jaw crusher	CAW	5,700	8.2 (TJ)	30	2.46 (TJ)	40,800
Grinding mill	AEW	7,000	126 (TJ)	32	40 (TJ)	664,000
Haul truck	LW	4,800	1,220,000 (l)	51	622,200 (l)	435,600

The results of the wear loss calculations is in Table 4.2.3 and both friction and wear losses are summarised in Table 4.2.4.

Table 4.2.3 Summary of annual wear losses in three case studies (Härkisaari 2015)

Operation	Tribo-category	Wear part replacement	Maintenance labour	Maintenance labour	Total
Unit	-	€	h	€	€
Jaw crusher	CAW	90,500	500	3,000	93,500
Grinding mill	AEW	800,000	750	4,500	804,500
Haul truck	LW	64,500	1,150	6,900	71,400

Table 4.2.4 Annual costs of friction and wear vs the estimated purchase price in three case studies (Härkisaari 2015)

Operation	Tribo-category	Purchase price	Annual cost of friction and wear	Friction loss of purchase price	Wear loss of purchase price	Wear and friction / new device
Unit	-	€	€	%	%	%
Jaw crusher	CAW	1,000,000	134,300	4	9	13
Grinding mill	AEW	5,000,000	1,468,500	13	16	29
Haul truck	LW	1,500,000	506,800	29	5	34

From Table 4.2.4 we can observe one interesting feature when comparing costs for friction and wear as percentage of purchase price. The costs for friction and wear losses are of the same level in the grinding mill (13% and 16%), the costs for friction losses are six times higher than for wear losses in the haul truck (29 % and 5 %), and the friction loss costs are about half of the wear loss costs for the jaw crusher (4 % and 9 %). Based on this, we divide all the mining equipment in three tribocategories as illustrated in Figure 4.2.5:

- **crushing abrasive wear, CAW**, where severe abrasive wear, due to the forced stone crushing and severe impact actions, is dominating; represented by the **jaw crusher** and also including other crushers, drills, bolters and jumbos,

- **abrasive erosive wear, AEW**, where moderate abrasive wear, resulting from free falling or moving collisions of rock material, is typical; represented by the **grinding mill** and also including the various digging equipment like loaders, excavators, shovels, dozers, scrapers, graders, LHD, backhoes and continuous miners, pumps, conveyors, skips, and 50% of separation equipment, and
- **lubricated wear, LW,** where lubricated contacts are dominating; represented by the **haul truck** and including all trucks and also hoists, drag lines, fans, railway and 50% of separation equipment like screens, cyclones, separators, pelletizers, filters, thickeners, centrifuges and floatation equipment.

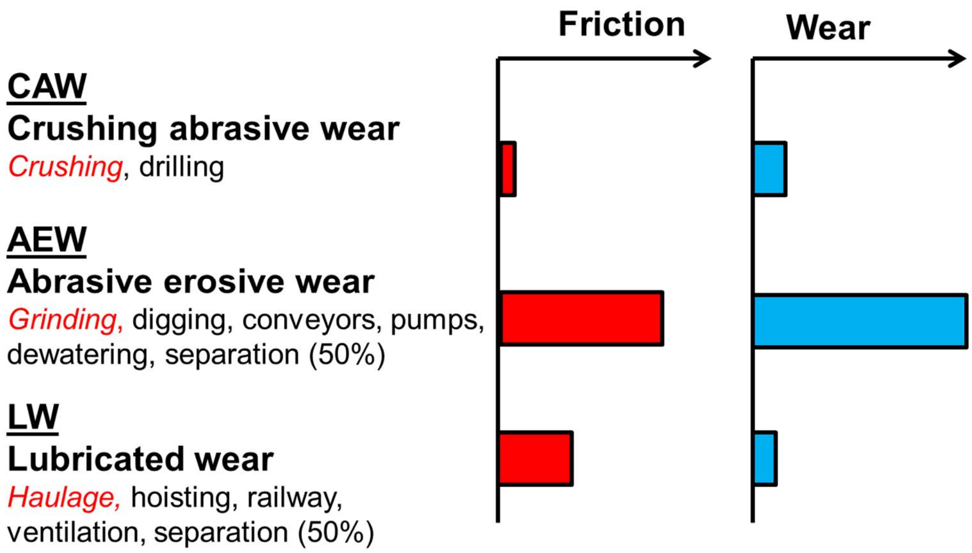

Figure 4.2.5 Annual costs for friction and wear in mining equipment is divided in three tribocategories: crushing abrasive wear dominated (CAW), abrasive erosive wear dominated (AEW), and lubricated wear dominated (LW).

The ratio of friction costs / wear costs is according to Table 4.2.4 for CAW 1 : 2.25, for AEW 1.2 : 1 and for LW 5.8 : 1. We use in this study the following ratios for the friction to wear costs:

- Crushing abrasive wear (CAW) = 1 : 2
- Abrasive erosive wear (AIW) = 1 : 1
- Lubricated wear (LW) = 6 : 1

4.3 Calculations of friction and wear energy losses and costs

Based on available global statistics found on web and considering that the largest mining activities are found in China, USA, Australia, India and Russia, we have considered to use the following prices and global average values in our calculations:

- 0.7 €/litre as price for diesel fuel,
- 0.06 €/kWh as price for electricity, and
- 6 €/hour as price for maintenance work.

One litre diesel fuel has an energy content of 35.9 MJ. The price of one GJ diesel fuel is thus 19.5 €. From above, the price of electricity for one GJ is 16.7 €. In our calculations below, we use as the global average energy price, 1 GJ = 18 € or 1 TJ = 18 k€.

The annual friction and wear losses for the three global average (GA) mining units as shown in Table 4.3.1 were calculated as follows:

1. the total energy use for the GA underground mining, surface mining and mineral processing plants is taken from Section 4.1 calculations, and the distribution of the energy consumption for the various mining actions is according to Figure 4.1.2 and reduced to 80 % for the large industrial mines,
2. the mining actions are classified in three tribocategories as described in Section 4.2 and shown in Figure 4.2.1, and the number of units are as calculated in Section 4.1,
3. the friction losses for each mining action is calculated as part of the total energy consumption based on data from Table 4.2.2 for the representative case study:
    a. 30 % friction losses for CAW, represented by the jaw crusher
    b. 32 % friction losses for AEW, represented by the grinding mill, and
    c. 51 % friction losses for LW, represented by the haul truck.
4. the friction energy losses in TJ is converted to energy costs in Euro (1 TJ = 18 k€)
5. based on the ratio for friction and wear costs in the three case studies in Section 4.2, we calculate the wear-related costs from the friction costs by using the ratios:
    a. CAW friction/wear cost ratio = 1 : 2
    b. AEW friction/wear cost ratio = 1 : 1
    c. LW friction/wear cost ratio = 6 : 1
6. the energy used to manufacture the failed machine components and tools are calculated from their value in Euro (step 5) using the following price, energy for prime value and energy after processing value (Cranta Design – CES Selector 2015):
    a. Steel: 0.44 €/kg – 33 MJ/kg – 65 MJ/kg
    b. Steel, wear parts: 1.2 €/kg – 30 MJ/kg – 50 MJ/kg
    c. Rubber: 3.6 €/kg – 115 MJ/kg – 135 MJ/kg
    d. Drill tool: 95 €/kg - 1370 MJ/kg – 1385 MJ/kg

    resulting in 1 k€ = 0.035 TJ for wear parts and 1 € = 0.05 TJ for whole equipment
7. we have in §3.4.1 estimated that the maintenance labour costs are half of total maintenance costs, and the cost for the wear parts is the other half,
8. from Section 3.4.1 we know that the downtime due to wear reduces the equipment availability with 15% and we assume an average lifetime (AL) of 20 years for the mining equipment, we also assume that half of downtime is covered with spare equipment,
9. form Section 4.2 Table 4.2.4 we get that the ratio of annual friction and wear costs (FWC) / purchase price (PP) (=equipment replacement value), is:
    a. 0.13 for CAW represented by jaw crusher,
    b. 0.29 for AEW represented by grinding mill, and
    c. 0.33 for LW represented by haul truck.
10. Based on step 8 and 9 we now calculate the downtime spare equipment cost (DSEC) from the equation:

    DSEC = 0.15 x PP / AL x 2 = 0.15 x FWC / AL x (FWC/PP ratio) x 2 (4.1)

11. the energy used to produce the replacement equipment is calculated from the downtime costs in similar way as for the replacement components previously (step 6) but now estimated for the whole equipment by using the conversion 1 € = 0.05 TJ,
12. the production loss costs are estimated to be 25 % of the total maintenance costs, and the mining equipment is estimated to be distributed equally in the three criticality levels, as described in §3.4.1:
    a. high criticality level are equipment like: grinding mills, hoists,
    b. average criticality level are equipment like: conveyers, pumps, crushers, separators, feeders, drills,
    c. low level are most other equipment like: trucks, fans, loaders, excavators, scrapers, etc.

    we assume that half of the downtime is due to total stop in production resulting in loss of profit and calculate that the average production loss cost due to friction and wear = (total maintenance costs) * 0.25 / 2
13. finally we sum up the total downtime costs, energy consumption and total costs for each GA unit.

The main results of current global energy consumption in mining are presented in Tables 4.3.1 and 4.3.2.

Table 4.3.1 Energy loss and costs due to friction and wear in a global average underground mine, surface mine and mineral processing unit.

Mine 1990	Number of mines	Total energy	Friction		Wear replacment parts		Maintene labour	Downtime spare equipment		prod loss	Wear total	total	Total friction and wear	
Parameter			energy	cost	energy	cost	cost	energy	cost	cost	energy	cost	energy	cost
Unit		TJ	TJ	kEuro	TJ	kEuro	kEuro	TJ	kEuro	kEuro	TJ	kEuro	TJ	kEuro
Calc step	2	1	3	4	6	5	7	11	8,9,10	11,12	13	13	13	13
GA underground	750	3638	1614	29046	469	13408	13408	32	646	3352	502	30815	2115	59861
Crushing wear CAW		534	160	2886		5772			250					
Abr impact wear AIW		683	218	3932		3932			102					
Lubricated wear LW		2421	1235	22228		3705			295					
GA surface mine	4250	671	290	5227	83	2383	2383	5	103	596	89	5464	379	10691
Crushing wear CAW		43	13	231		461			20					
Abr impact wear AIW		227	73	1307		1307			34					
Lubricated wear LW		402	205	3689		615			49					
GA processing plant	1700	2259	742	13348	477	13632	13632	20	405	3408	497	31076	1239	44424
Crushing wear CAW		226	68	1220		2440			106					
Abr impact wear AIW		1911	611	11005		11005			285					
Lubricated wear LW		122	62	1123		187			15					

Table 4.3.2 Energy loss and costs due to friction and wear worldwide in underground mining, surface mining and mineral processing.

Mine 1990	Friction		Wear replacment parts		Maintene labour	Downtime spare equipment		prod loss	Wear total	total	Total friction and wear	
Parameter	energy	cost	energy	cost	cost	energy	cost	cost	energy	cost	energy	cost
Unit	PJ	MEuro	PJ	MEuro	MEuro	PJ	MEuro	MEuro	PJ	kEuro	PJ	MEuro
Underground mining	1513	27230	440	12570	12570	30	606	3143	470	28889	1983	56119
Surface mining	1543	27766	443	12659	12659	27	545	3165	470	29028	2013	56794
Mineral processing	1576	28364	1014	28967	28967	43	861	7242	1057	66037	2633	94402
	4631	83361	1897	54197	54197	101	2012	13549	1997	123954	6629	207315

4.4 Emissions and summary of analysis

A study on energy and greenhouse gas impacts of mining and mineral processing showed that loading and hauling make the largest contribution to the total greenhouse gas emissions for mining and processing of iron ore and bauxite. In the case of copper ore, the crushing and grinding makes the largest contribution of greenhouse gases in the production of copper ore (Northgate et al 2010). A potential of reducing the CO_2 emissions by 40 Mt in the USA and by 6 Mt in the North-East Russia region has been shown (US DOE 2007, Keikkala et al 2007).

We calculate the CO_2 emissions related to friction and wear directly from the energy consumption. We use the estimation of Rabago et al. (2001) that in mining 1/3 of the energy requirement is met by electricity, 1/3 by diesel fuel, and 1/3 by coal, natural gas and gasoline. The calculated emissions for Mine 1990 are shown in Table 5.2.1.

A summary of the calculation process and the sources for the data used is shown in the flowchart in Figure 4.4.1. It summarises that 2015 the impact of friction and wear was resulting in 6.6 EJ energy consumption, 970 million tonnes CO_2 emissions, and 210,000 million economical costs in the mineral mining industry worldwide.

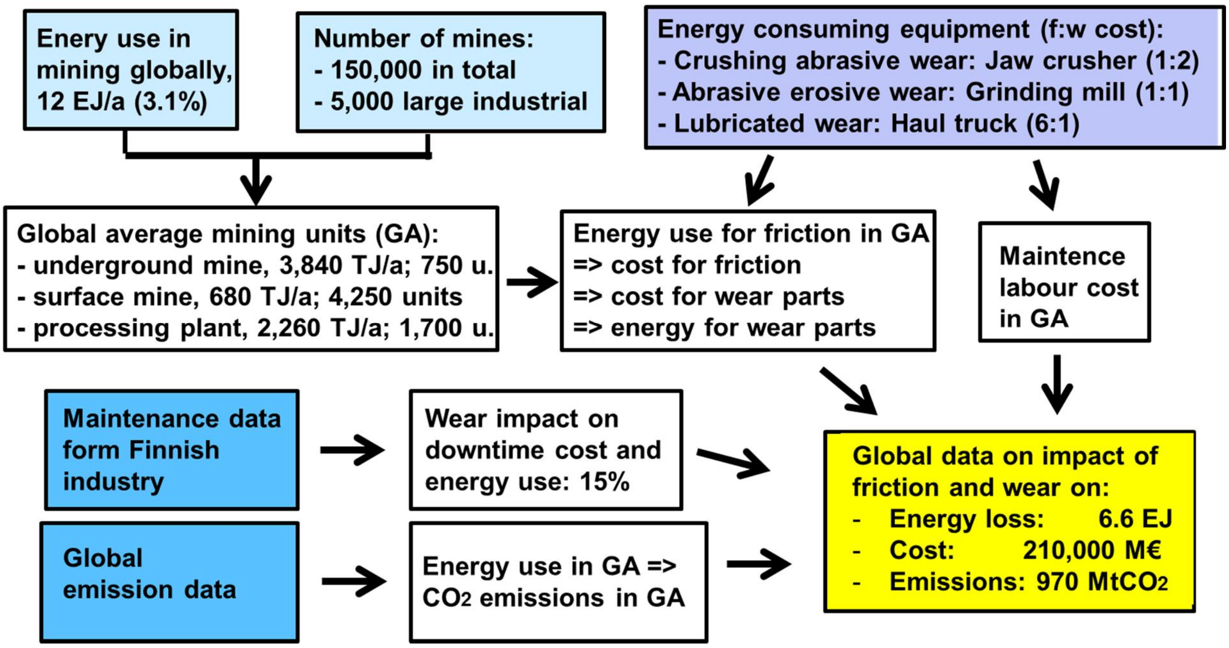

Fig. 4.4.1 Flow chart for calculations of global impact of friction and wear on mineral mining industry

5. Trends in friction and wear reduction and potential savings

5.1 Tribocontact friction and wear losses today and in future

The basic friction and wear mechanisms have been extensively studied and are described in the tribological literature (Bhushan 1999, Sethuramiah 2003, Stachowiack et al 2005, Blau 2009, Totten 2006, 2012). There is a good understanding of how various contacts can be classified and what level of frictional losses and wear rates they typically represent. However, not so much of the literature is especially focusing on machines and vehicles working under mining conditions. The tribological mechanisms have some special features in mining industry and that is especially the very heavy loading conditions and the very dusty and often also humid environment. In this study we have estimated the coefficients of friction and the wear rates in various tribocontacts based on published data in the literature and adjusted them to better suit the mining conditions.

Friction and wear levels for different tribocontacts in four types of global average mines were separately estimated: the typical 25-year-old mine in use today (designated hereafter as “Mine 1990”), a mine that represents a combination of today’s most advanced commercial tribological solutions (“Com 2015”), a mine that represents the best tribological solutions demonstrated in research laboratories today (“Lab 2015”), and a mine that reflects estimations by the best experts in the field of what is possible to achieve in the future after about 10 years extensive R&D work (“Mine 2025”).

The coefficients of friction and the relative wear level based on the above classifications are given in Table 5.1.1 and 5.1.2 and shown in Fig. 5.1.1 and 5.1.2. The references in the tables relate mainly to the friction and wear values for Com 2015 and Lab 2015, while the friction values for Mine 1990 and Mine 2025 are estimates by the authors based on available present information and their own experience. Potential technical solutions for friction and wear reduction are discussed in Section 6.

Table 5.1.1 presents friction coefficients for common tribological contacts. Friction can be reduced and controlled by advanced technological solutions. The friction estimates in Table 5.1.1 are based on commercial oil lubrication for Mine 1990 and Com 2015 and on a new kind of lubrication, sometimes non-petroleum-based (e.g., a water-based lubricant such as polyalkylene glycol) for Lab 2015 and Mine 2025.

Viscous losses in transmission systems are due to shear and churning of oil in the transmission case. Part of the energy losses in engine systems, pumping and hydraulic systems are related to viscous losses. Viscous losses are included in this analysis because, even if they are not directly friction losses, they can be reduced by tribological solutions with lower viscosity lubricants and thus also lower viscous losses.

In table 5.1.1, we have used as starting point the values estimated for heavy duty vehicles reported previously (Holmberg et al 2014a) and modified them for mobile equipment in mining conditions especially considering the much harsher and dusty conditions in the following ways:

- the friction in lubricated contacts is estimated to be 50% higher for Mine 1990 and Com 2015 and three times higher for Lab 2015 and Mine 2025 compared to heavy duty road vehicles because of the more contaminated conditions, higher loads, and lower speeds used,
- the tire rolling friction is estimated to be 0.035 in modern mines (Com 2015) because of the more rigid tire design and the rougher surfaced roads in mines (NRC 2006, Wicaksana 2011), and
- the viscosity used is estimated to be thicker in some mining equipment and the change to lower viscosity oils is more unlikely due to thicker lubricant film requirement from dusty conditions and occasional heavy impact loading.

Table 5.1.1 Tribological contact performance for the chosen four types of mines (Thompson & Vissner 2003, Wetherelt & Wielen 2011, Thompson & Visser 2003, Wicaksana et al. 2011, NRC 2006, Holmberg et al. 2014a, Coal Age 2015).

Contact types acting as friction sources	**Coefficients of friction**			
	Mine 1990	**Com 2015**	**Lab 2015**	**Mine 2025**
Boundary lubrication (BL)	0.2	0.15	0.03	0.015
Mixed lubrication (ML)	0.15	0.08	0.03	0.015
HD lubrication (HD)	0.04	0.015	0.006	0.003
EHD sliding (EHDS)	0.12	0.06	0.03	0.015
EHD sliding-rolling (EHDSR)	0.09	0.05	0.015	0.003
EHD rolling (EHDR)	0.015	0.003	0.003	0.002
Tire rolling (TR)	0.05	0.035	0.025	0.02
Resistance to viscous shear (VL), ν (cSt at 80ºC)	40	30	25	20

In Table 5.1.2 we have used the previously introduced classification of typical wear conditions in mining industry: forced crushing abrasive wear dominated, free movement abrasive erosive wear dominated, and lubricated wear dominated. Due to the complexity of the wear process there is no universal physically based unit, like coefficient of friction, that can be used to reflect prevailing wear conditions. Thus we express the improved lower wear conditions as relative wear reduction in percentage as compared with the level of Mine 1990. The improvements in wear resistance were estimated based on data collected in Section 6.

Table 5.1.2 Estimated relative friction and wear rate reduction trends and possibilities in mining machines and equipment over the period 1990 to 2025 (based on references given in section 6).

	Relative friction and wear reduction		
Contact conditions	**from Mine 1990 to Com 2015**	**from Mine 1990 to Lab 2015**	**from Mine 1990 to Mine 2025**
	%	%	%
Friction reduction			
- crushing abrasive wear dominating, CAW	20	40	50
- abrasive erosive wear dominating, AEW	20	40	50
- lubricated wear dominating, LW	40	80	90
Wear reduction			
- crushing abrasive wear dominating, CAW	40	60	70
- abrasive erosive wear dominating, AEW	50	75	85
- lubricated wear dominating, LW	30	40	50

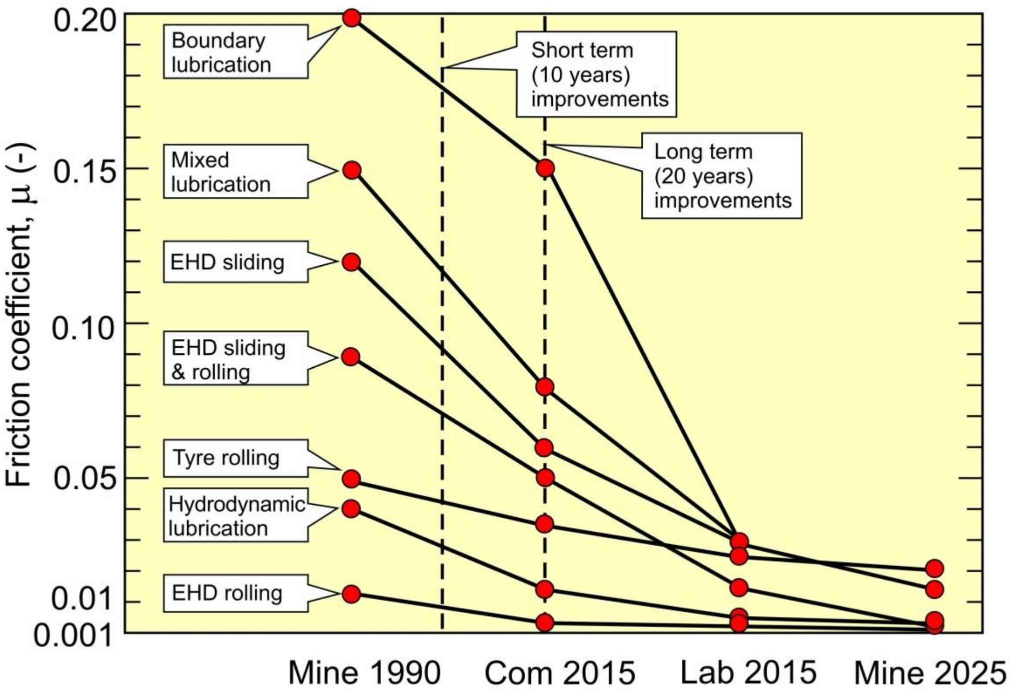

Figure 5.1.1 Trends in friction reduction by new tribological solutions for different lubrication and contact conditions in mining applications.

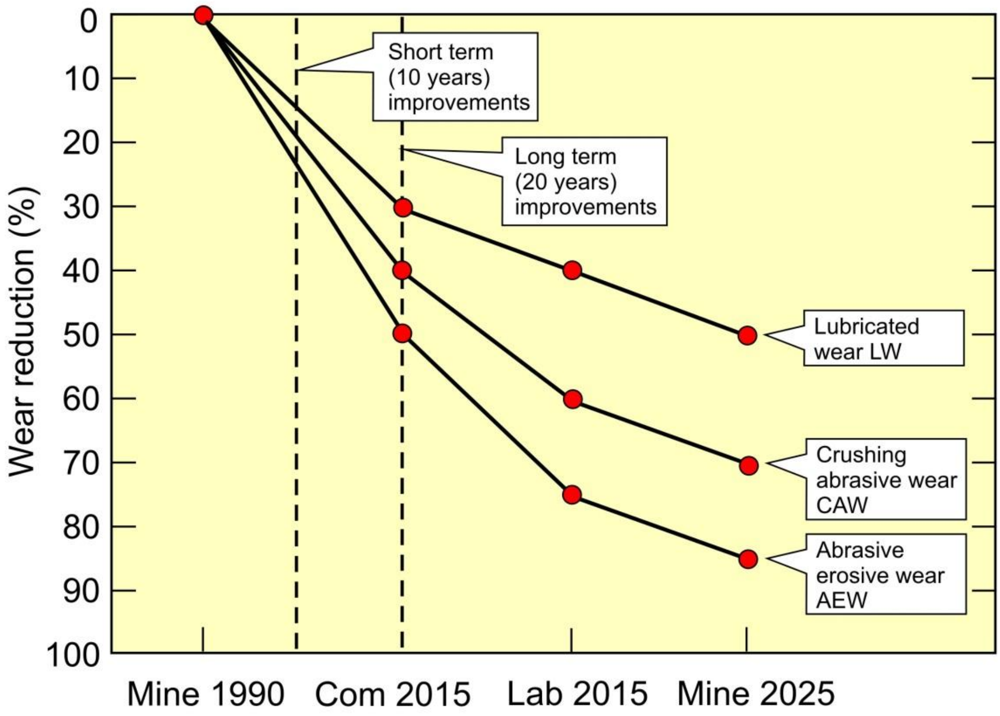

Figure 5.1.2 Trends in wear reduction by new tribological solutions for different contact severity levels in mining applications.

In the estimations above, we have considered that in the global average mine (i.e, Mine 1990) the machines and equipment components are not all that old but have partly been replaced by newer and more modern ones during the maintenance actions. The average lifetime for mining machines and devices is about 20 years and the average age is about 12 years. Considering that some parts have been renewed at maintenance then the average age of components in function is about 8-10 years, excluding the “wear parts” that are replaced more frequently.

5.2 Potential savings

The energy, costs and emissions were calculated for Com 2015, Lab 2015 and Mine 2025 in the same way as previously for Mine 1990 in Section 4.3 but now including the reductions in friction and improvements in wear resistance estimated in Section 5.1. The results are shown in Table 5.2.1.

Table 5.2.1 Global annual energy consumption, costs and emissions due to friction and wear in mineral mining and calculated reduced values if new technical solutions would be implemented in full extent in all mines worldwide.

	Energy losses			Costs			Emissions		
	friction	wear	total	friction	wear	total	friction	wear	total
Unit	PJ	PJ	PJ	MEuro	MEuro	MEuro	MtCO2	MtCO2	MtCO2
Mine 1990									
Underground mining	1513	470	1983	27230	28889	56119	221	69	290
Surface mining	1543	470	2013	27766	29028	56794	225	69	294
Mineral processing	1576	1057	2633	28364	66037	94401	230	154	384
Mining total	4632	1997	6629	83360	123954	207314	676	292	968
Com 2015									
Underground mining	555	283	838	12561	17325	29886	81	41	122
Surface mining	724	271	995	13043	16625	29668	106	40	145
Mineral processing	880	556	1436	15839	34498	50337	128	81	210
Mining total	2160	1110	3270	41442	68448	109890	315	162	477
Lab 2015									
Underground mining	317	193	510	5706	11894	17600	46	28	75
Surface mining	349	174	523	6289	10756	17045	51	25	76
Mineral processing	636	306	942	11453	18856	30309	93	45	138
Mining total	1303	673	1976	23448	41506	64954	190	98	288
Mine 2015									
Underground mining	209	145	354	3765	8964	12729	31	21	52
Surface mining	240	126	366	4309	7810	12119	35	18	53
Mineral processing	524	199	723	9432	12123	21555	77	29	106
Mining total	973	470	1443	17505	28897	46402	142	69	211

It is not realistic to think that new energy, cost and emission reducing tribological solutions can be very quickly implemented in the mining industry worldwide. The reason is the great number of mines, the great number and variety of owners that are not well organised worldwide and the conservative attitude to implementing new technology in many parts of the mining industry and in many countries. Here is a great difference with e.g. the heavy duty vehicle sector in transportation where the fleet owners are well organised and the manufacturers are in the forefront of implementing new technology.

We estimate that a large scale implementation of existing technology and development of new advanced solutions could have the effect that energy, cost and emission would be reduced to more than half of the difference between Mine 1990 and Com 2015 (15 %) during the time range of 10 years and to more than the level of Com 2015 (30 %) during the time range of 20 years. Tables 5.2.2 and 5.2.3 show the potential savings based on this estimation.

Table 5.2.2 Potential global annual energy savings, and costs and emission reductions by implementing new technology on short term (10 years) and long term (20 years).

	Energy losses			Costs			Emissions		
	friction	wear	total	friction	wear	total	friction	wear	total
Unit	PJ	PJ	PJ	Meuro	Meuor	Meuor	MtCO2	MtCO2	MtCO2
Short term (10 years, 15 %)									
Underground mining	227	71	297	4085	4333	8418	33	10	43
Surface mining	231	71	302	4165	4354	8519	34	10	44
Mineral processing	236	159	395	4255	9906	14160	35	23	58
Mining total	695	300	994	12504	18593	31097	101	44	145
Long term (20 years, 30 %)									
Underground mining	454	141	595	8169	8667	16836	66	21	87
Surface mining	463	141	604	8330	8708	17038	68	21	88
Mineral processing	473	317	790	8509	19811	28320	69	46	115
Mining total	1390	599	1989	25008	37186	62194	203	87	290

Table 5.2.3 Potential energy and cost savings, and emission reduction by new tribological technology on short term (10 years) and by country estimated based on their share of the global mineral raw material production (Reihel 2016).

Production of mineral raw materials (excluding petrol and gas)	Energy savings (TJ/a)	Cost savings (million euro/a)	CO_2 emission reduction (million tonnes/a)
World (100%)	995,000	31,100	145
China (33.5 %)	335,000	10,400	48.6
USA (12.0 %)	120,000	3,730	17.4
Australia (7.9 %)	78,600	2,420	11.5
Russia (7.1 %)	70,600	2,210	10.3
India (6.4 %)	63,700	1,990	9.3
South Africa (4.7 %)	46,800	1,240	6.8
Indonesia (4.0 %)	40,000	1,300	5.8
Brazil (2.1 %)	20,900	650	3.0
Canada (2.0 %)	20,000	620	2.9
Finland (0.02 %)	200	6.2	0.03

6. Means of reducing wear, friction and energy use in mining

In this section, we present some new technical solutions that can be implemented to achieve friction and wear reductions in mining equipment. The examples mainly describes what we have named "today's best solution on the laboratory level" (Lab 2015). Some of the new solutions for friction and wear reduction can be directly implemented by the users to existing machines. Such are the changes to new type of engine lubricant, lubricant additives and tires with new materials and new design as well as frequently replaced wear parts. On the other hand, many of the new friction and wear reducing solutions need re-design or replacement of existing components, like the introduction of new materials, surface treatments, coatings and textured components or new design solutions. This kind of improvements need to be introduced by the machine producers and will come out on the market, when the new products are launched.

6.1 Wear reduction in critical parts subject to crushing abrasive wear

Material wear resistance is a system property, which is a combination of mechanical properties, microstructure of the material and the wear environment including abrasive material, contact mechanism, load or impact energy, moisture and temperature. Severe abrasive and impact wear conditions with forced crushing wear (which was defined earlier in section 4.2) as crushing abrasive wear (CAW), occur typically in various types of crushers, bolters, drills and jumbos. This means high-stress abrasive or impact-abrasive wear resulting from direct rock contact. The large range of properties of the mined ores, minerals and rocks makes the material selection for different mines very challenging (Chattopadhyay 2001, Sare 2001, Scott 2006, Rostami 2011, Bruce 2012, Ratia 2014, Tolonen 2015).

6.1.1. Rock crushing

In mining operations, the selected process including crushing and grinding, depend on the mined ore and the mineral. Jaw crushers are mostly used as primary or secondary crushers for hard minerals. Gyratory crushers are selected for higher capacity and horizontal impactors for feed with lower hardness. For the final crushing stage, cone crushers, vertical shaft impactors (VSI), and high pressure grinding rolls (HPGR) are typical options [Metso 2016].

In wear parts of jaw, cone, and gyratory crushers, austenitic high-manganese steels have been the conventional materials for decades. The strain hardening ability combined with high toughness and ductility makes them a cost effective choice [Lindroos 2015]. The work hardened layer may be up to 15 mm deep with hardness of up to 600 HV. However, the hardenability also limits its use in crushing of softer materials and other applications with lower loads. Hard metals with high abrasion resistance, but lower ductility are used when high impact resistance is not needed. Rubbers are used in sieves and in conveyer belts, where their high hardness-elasticity ratio outperforms steels.

A change from low hardness martensitic wear resistant steel with hardness of 460 HB, commonly used in old mining components, to high harness martensitic steel with 530 HB hardness reduced the wear with 20 – 30 % in crushing conditions (Ratia et al. 2013).

There are many studies, where the wear performance of manganese steels has been examined [Lindroos 2015, Yue 2014, Erdakov 2014, Lindqvist 2005]. A 20 % increase in the wear life just by optimizing the manufacturing process of the wear parts has been reported [Erdakov2014]. The wear resistance of tool steels with large, hard carbides may be double compared to manganese steels and even five times higher with hard metals [Siitonen 2009]. Powder metallurgical tool steels and metal matrix composites (MMC) have been investigated for cone crusher applications [Kivikytö-Reponen 2009]. The lowest wear rates were gained with tool steel reinforced with recycled and crushed WC/Co hard metal.

White cast irons have high hardness, but they are much less ductile than manganese steels. They are still potential materials for some applications like e.g. for vertical shaft impactors. In a laboratory study with hammer-mill type high-stress impact wear device, white cast iron wear resistance was of the same level with powder metallurgical metal matrix composites [Osara 2001].

Fe–Cr–B are iron-based alloys with wear-resistant eutectic borides M_2B forming a network structure. In a crusher hammer test with dolomite, Fe–8Cr–2B alloy with 850 HV hardness had 150–180 % times higher service life than Mn13Cr2 high manganese steel [Yue 2014]. These kinds of low alloyed steels have also potential for crusher applications.

6.1.2 Rock drilling

The drill bits consist of steel base with hard buttons on the drill face. Quench and tempering steels are used as base material due to good toughness and strength, reasonable high wear resistance and fatigue strength, and dimensional stability when hardened [Plinninger 2002, Ovarock 2008, Rostami & Hambley 2011]. The drill buttons are typically made of cemented carbides e.g. WC-Co that is a hard and tough material for repeated high energy impacts against hard rock in rotary percussive drilling. In rotary crushing drilling, the drill bit is rotated against the rock and thus the method is typically used for relatively softer rock materials [Beste 2004].

Fine grained hard metals result in improved wear resistance compared with wear parts of conventional materials (Nordgren 2015). The alternative sintering processes, like field assisted sintering, spark plasma sintering and pulsed electric current sintering, make it possible to produce very fine structures. Moreover, the abrasive wear resistance of cemented carbides can be significantly increased by diamond coatings or diamond inserts. Diamond coatings can be deposited on rock drilling bits using the hot flame method [Alahelisten 1995], PVD, or CVD coatings [Liu 2005]. Polycrystalline diamond compacts (PDC) are mainly used for cutters in softer rocks [Li 2001]. Diamond inserts are also used in percussive drilling. The polycrystalline diamond inserts are reported to drill even ten times deeper (Element Six 2016).

6.2 Wear reduction in wear parts targeted to free movement abrasive wear

Moderate wear conditions with wear resulting from free falling or moving rock material, earlier defined in section 4.2 as abrasive erosive wear (AEW), occur typically in grinding mills, and in digging equipment like loaders, excavators, shovels, dozers, scrapers, graders, LHD, backhoes, and in continuous miners, pumps, conveyors, hoppers, shakers, skips, and in separation equipment in mineral processing like screens, cyclones, separators, pelletizers, filters, thickeners, centrifuges and floatation equipment. The wear parts include components such as linings, grinding media, side plates, shields, and nozzles (Lynch 2015, Taylor et al. 2015). The dominating wear mechanism is low-stress scratching abrasion and erosion where the abrasive particle remains intact as it moves freely across the wear surface (Hawk 2001).

The wear parts in moderate abrasive wear solutions are mainly steels and cast irons, ceramics, and polymers, such as elastomers or composite structures. A wide range of materials is used to resist wear in the comminution processes (Durman, 1988**).** The comminution media is often manganese steels containing additional alloying elements, such as Cr, Ni and Mo. Low alloy, low carbon steels are recommended for rough grinding only, where metallic contamination is not a problem. The austenitic stainless steels are typically only used in acid media or when requiring non-magnetic balls, owing to their high cost. The Ni–Cr cast irons are also used as grinding media. Chromium carbides are harder than iron carbides and therefore more wear resistant, and also play a major role in wear resistance in corrosive environments (Aldrich 2013). The material selection is depending on the mineral process e.g., the movement type of the mineral particles. Ductile behaving materials commonly show a peak of erosion rate at small impact angles, while the brittle materials often show maximum wear behaviour for normal incidence (Finnie 1995, Chattopadhyay 2001, Sare et al. 2001, Jones 2011, Bruce 2012, Levchenko 2013).

Bionic research has given inspiration to develop surfaces with improved erosive and impact wear resistance by topographical surface design. The solutions used by nature are e.g. microtextures, such a bumps and grooves, and surface curvature on desert scorpions (Han et al 2012,2017) and directional windward surface ring features on desert plants (Han et al 2013a,b).

Steel and iron. Wear resistant steels, chromium-molybdenum steel alloys, tool steels, work hardening steels and white cast iron are widely used in mineral processing. There are several microstructural ways to improve strength, toughness and as consequence the wear resistance of materials by e.g., work hardening, boundary strengthening, solid-solution strengthening, particle hardening, two phase aggregates, ductile binder phase, and extrinsic crack-tip shielding mechanism. Work hardening steels require operation conditions, where surface hardening occurs, therefore they are not the best solutions for moderate wear conditions (Clark & Llewellyn 2001, Ojala et al 2014*).*

Carbide free bainitic steels have shown good abrasive and erosive wear performance with 35 - 80 % lower wear and five times longer lifetime compared to the standard quenched and tempered steel (Vuorinen et al. 2016). An improvement in decreased wear rate of 43 % was measured for hypereutectic white iron compared to the standard high chrome eutectic white iron (Llewellyn & al 2004, Walker & Robbie 2013). Wear resistance improvements of more than one order of magnitude

was measured for overlay welded high chromium white iron in comparison with the quenched and tempered low alloyed carbon steel in laboratory drum testing (Allebert et al. 2015).
An upgrade of concrete mixer material from mild steel of 130 HV to quenched and tempered martensitic steel of 680 HV increased lifetime by a factor of 7 in sliding wear and by a factor of 3 in high-angle mild impact wear. A hardness level of more than 400 HV was needed for significant increase in lifetime followed by a clear relationship between hardness and wear (Jungedal 2012). Similar results have been reported in wear tests simulating various mining conditions (Dommarco et al 2001, Rendon & Olsson 2009, Parent & Li 2013, Walker & Robbie 2013, Allebert et al 2015, Wang et al 2016).

Ceramics are very hard and have a very good resistance to sliding wear. However, often they are too brittle in many mineral processing applications, where the certain level of toughness is required. In order to achieve the higher strength and toughness of metallic materials, refinement of the microstructure or composite structures have been developed (Curry & Clermont 2016).

Composites, hard coatings and microstructure tailoring. In order to achieve the higher strength and toughness of metallic materials, refinement of the microstructure or composite structures have been developed (Berns 2003). Promising solutions for wear reduction are the composites, either metal/ceramic composites or elastomeric/ceramic composites. One solution is the so-called “double dispersion” type of structure in metal matrix composites, where hardmetals improve fracture toughness and bending strength simultaneously. An increase of the hard particle size in the material microstructure simultaneously raises the fracture toughness and hence the abrasive wear resistance. The bending strength will decrease, because the crack length caused by fracturing hard particle increases. When coarse hard particles are dispersed in the metal matrix, the ‘long cracks’ are eliminated (Berns 2003).

The use of new material solutions resulted in a five times wear life improvement in semi-autogenous grinding mills compared to normally used manganese steel (Siitonen 2009). The erosion resistance of a hard internal surface of an AISI 1045 steel pipe was more than five times better than that of AISI 1020 steel, which represents the standard, non-hardened, carbon steel line pipe material in slurry handling (Clark 2001). A three times lifetime improvement was achieved by the use of chrome white cast irons compared to the conventional grades in slurry pump service (Llewellyn 2004). By replacing the whole pumping systems, the lifetime of the pumps was reported to increase over 70 % and the energy savings were up to 30 % (Metso Showroom 2013).

Elastomer wear parts and rubber-like wear parts are used in several applications in mineral processing industry (Metso 2016). However, changes in wear environment, the presence of certain metallic ions, or the increase in temperature can all lead to rapid failure. For natural rubber such problematic environments are oils, greases and solvents (Sare 2001). It is well known that mechanical properties of the polymers are highly affected by the chemical composition and exposure to UV light (Rattanasom 2009, Darestani Farahani 2006, Busca 2010).

The best performing natural rubber showed a 14 times improved relative erosion resistance in SiC slurry compared to AISI 10 18 steel and over 2 times improvement compared to chromium white iron and WC/NiBSi PTA W overlay in conditions relevant for piping and tubular components such as pumps, valves and cyclones (Jones 2011). WC-3.3%Co performed extremely good in the same test, 59 times better relative wear resistance compared to AOSO1018 steel (Jones 2011).

Generally the wear resistance is a trade-off of wear part price, life-time, functionality and recyclability. The new business models e.g. shearing or leasing may introduce new possibilities for new innovations, that earlier were considered to be too expensive for specific wear parts.

6.3 Wear and friction reduction in lubricated contacts in mining machines

Wear conditions when lubricated contacts are dominating (LW) are found in all of the mining trucks and in hoists, drag lines, fans, railway and some separation equipment like screens, cyclones, separators, pelletizers, filters, thickeners, centrifuges and floatation equipment. Common for all machines and equipment working in mining is the dusty environment and rough loading conditions, sometimes combined with space constrains and humidity. Although the machines themselves are associated with mining, their elements are ubiquitous. It is their size, configuration, and operating conditions that are challenging (Scott 2006). Wear and friction mechanisms in lubricated conditions and new tribological solutions have been reviewed by Sethuramiah (2003) and Cha and Erdemir (2015) and means for friction reduction in heavy duty vehicles like trucks and buses were reported by Holmberg et al (2014a).

Considering the severe contact conditions involving dust and dirt accumulation in lubricating oils; the components used in mining operations must have high hardness, strength and toughness in order to combat wear and maintain low friction. Various hardfacing treatments based on plasma spray processes may provide a relatively thick and hard surface layer that can resist wear. Alternatively, ultra-fast boriding and nitriding treatments can also be considered as they produce fairly thick (100-200 micrometer) and hard boride and nitride layers on top of a thick diffusion layer (Kartal et al 2010). Carburising can also help but the hardness of the treated layer may not be high enough to counteract the very abrasive nature of contaminated oils. Carburizing may serve as a hard transition layer for ultra-hard coating that may be produced on the affected surfaces by CVD and PVD processes.

6.3.1 Surface treatment and microstructural material design

Considerable improvements in wear resistance of lubricated components have been achieved over the last decades by improving the surface properties of the components. This has been possible partly by improved material processing methods resulting in higher quality materials free from defects, contaminations and inhomogeneity. The near surface material layers have been developed to better resist the loading cycles by optimising the microstructures, often resulting in harder and more wear resistant surfaces. The development of rolling contact bearings is in the forefront of this development and a good example (Scherge 2003b, Glaeser 2012, Jahanmir 2012, Kotzalas 2012, Chang 2012, Scharf 2012, Bosman 2010,2011, Chen et al 2015). In the following, we will mention only few recent examples.

The group of Mattias Scherge has in a series of studies investigated the ultra-low wear taking place in properly lubricated sliding contacts typical for engines, transmissions, motors etc. They showed that even under low wear conditions, morphology, crystalline arrangements, and chemical bonds of the surface and subsurface are modified significantly and considerable plastic deformation occurs up to a depth of 1 μm (Scherge 2003a,b, Shakhvorostov 2007). The tribological conditions lead to complex and strongly inhomogeneous layered structures. A combination of nano-crystalline top layer and a work-hardened subsurface was found to have high wear resistance and low friction. In lubricated tests they showed how proper heat treatment of an AlSi11Cu3 disk in sliding contact with a 100Cr6 pin resulted in a reduction of wear by one order of magnitude and a drop in friction coefficient from 0.04 to 0.01 (Linsler 2015). Further improvement of the wear resistance was achieved by implementing an optimal running-in corridor (Scherge 2015).

The wire to roller contact in industrial cranes and hoists is boundary lubricated and the wear is dominated by plastic flow of the top surface and microscale fatigue. Real contact simulating twin-disc tests showed that an advanced partially chilled ductile cast iron roller material could considerably improve the tribological performance compared to the present state-of-art material, a non-hardened cast iron (GJS600-10) roller. The coefficient of friction decreased from 0.05 to 0.005 and the wear rate by two orders of magnitude (Oksanen 2015, FIMECC 2014).

6.3.2 Thin surface coatings

There are many lubricated contacts where surface coatings can improve the efficiency, performance, and durability in engines, drive trains and transmissions. The main tribocontacts resulting in friction losses are typically the piston ring and cylinder liners, gears, bearings, valves, and cam and follower contacts.

Research on low-friction and low-wear coatings has been extensive, because the traditional lubrication techniques cannot in many cases alone meet the increasingly more demanding operational conditions of modern mechanical systems. New advanced techniques for physical and chemical vapor deposition (PVD and CVD) plasma, and thermal spraying methods, etc., have made it possible to deposit engine components with coatings with good reliability and cost effectively (Holmberg et al 2009, Erdemir 2005,Donnet et al 2004, Jacobson 2012, Scharf 2012, Doll & Matthews 2012, Davies 2001,2004, Cha & Erdemir 2015). The tribological performance and durability of such coatings have been further improved by using advanced computer codes and finite element modelling (Holmberg et al 2005, 2007, 2012b, 2014c,d).

Low-friction coatings such as diamond-like carbon, MoS_2, etc., can drastically reduce the friction coefficients of dry and lubricated sliding contacts by more than 90% [Holmberg et al 2009]. Such huge reductions are typically for boundary-lubricated regimes, where direct metal-to-metal contacts occur In HD and EHD regimes, there are very few asperity contacts, and shearing takes place within the fluid film itself. The use of hard and low-friction coatings, have been reported to increase as much as ten-fold the fatigue lifetime in rolling contacts, reduce bearing wear by seven-fold and increase gear lifetime by three-fold [Holmberg et al 2009, Doll 2011].

The development of diamond-like carbon (DLC) coatings has been of great interest in recent years, since they provide the best overall and robust friction and wear performance under lubricated and dry conditions (Erdemir et al 2006, Kano 2006, Podgornik et al 2005, Gåhlin et al 2001, Ronkainen 2016, Kalin 2013). Some engine components are nowadays coated with DLC and used in actual cars and trucks (Donnet & Erdemir 2008, Cha&Erdemir 2015). Other hard and low-friction materials and coatings developed for improved friction and wear performance in engine components include Cr-N, TiN, Ni-SiC, MoS_2, WC/Co, AlTiN, W-C:H, MoN-Cu composite coatings along with TiN, TiC, or TiB_2 particles embedded in ceramic matrices, and various nanostructured and nano-layered coatings (Tung 2004, Merlo 2003, Holmberg et al 2005, Enomoto 1998, Lampe 2003, Canter 2009, Cook et al 2010, Farley et al 2010, Erdemir et al. 2016).

6.3.3 Thick composite coatings

There is a range of techniques to deposit thick wear resistant coatings, such as welded overlays, thermal spraying, cladding, electroplating and thermoreactive deposition. Thermal spray coatings is a family of thick hard composite coatings with good wear resistance in the thickness rage of about 0.1-50 mm. Generally, the wear resistance of the coatings increases with their density and cohesive strength. Composite structures with carbide particles embedded in an often metallic matrix with higher elasticity and toughness provides good wear protection. A porous surface structure can be beneficial in lubricated sliding contacts as the oil pockets in pores can improve the lubrication and avoid starvation.

Thermal spray coatings has been used successfully to reduce wear in e.g. powertrain components, cylinder bore and piston rings, crank and transmission shafts, valves, clutches, disc brakes, pumps, turbine and compressor shafts, bearing journals, thrust collars, seals, axles, pins, rollers in conveyors and hydraulic cylinders. Popular coatings to provide wear resistance are e.g. WC/Co, WC/Ni, WC/CoCr, CrC/NiCr and Co-Cr-Si-Mo alloys (Davis 2001, 2004).

Advanced thermal spray technology was used to coat the cylinder surface of aluminium and magnesium engines with wear resistant metal matrix composite coatings with residual porosity values of about 2 % and resulted in 30 % reduction in friction and 2 – 4 % decrease in fuel consumption (Gerard 2006). Mo and CrC based thermal spray coatings could considerably improve the tribological performance compared to the present state-of-art material solution, a non-hardened cast iron (GJS600-10) roller, in twin-disc tests simulating the real contact of wire against roller in industrial cranes. The coefficient of friction decreased from 0.05 to 0.002 and the wear rate by two orders of magnitude (FIMECC 2014). Thermally sprayed WC-CoCr coated hydraulic cylinders were compared to the state-of-art hard chrome plated cylinders in lubricated tribotesting and the WC-CoCr cylinders showed 20 % reduced friction, considerably lower wear and reduced hydraulic leakage (Castro et al 2014).

6.3.4 Surface texturing

The roughness and surface topography have a remarkable influence on friction, wear, and fatigue life performance in tribological components. Researchers have been concerned about formation of deep scratches and larger dimples on sliding surfaces that result in higher friction and wear.

However, lately it has become clear that when prepared properly, dimples, grooves, and protrusions can have very beneficial effects even at the nanoscale (Al-Azizi et al 2013), although the underlying mechanisms become very complex (Johansson 2012).

Recent reports have shown that micro- and nano-scale dimples created by laser beams or lithographic techniques can considerably improve the friction and wear performance under lubricated conditions (Andersson et al 2007, Etsion 2012, Ronkainen 2016). Laser surface texturing of piston rings has reduced fuel consumption of engines by as much as 4% (Kovalchenko et al 2004, Klingerman et al 2005, Etsion et al 2009, Wang 2010, Ryk 2006). Fine particle shot-peening of surfaces produces a topography with micro-dimples which was found to reduce friction in lubricated contacts by up to 50% (Ishida et al 2009). A laboratory test showed considerable reduction in hydrodynamic friction by applying hydrodynamically tailored textures on cylinder liner surfaces in heavy duty diesel engines (Johansson 2012).

6.3.5 Lubricants and nanotechnology based additives

The sliding or rolling surface contacts in engines are lubricated by oils. The lubricants contain a range of anti-friction, anti-wear, and extreme pressure additives for the formation of a chemical boundary film that supresses wear damages. Our analysis showed that viscous losses and shear in hydrodynamic contacts result in significant energy losses. If the lubricant viscosity is further reduced while the low friction and wear protection functions are maintained, a very large energy saving in engines could be achieved.

Optimised bearing design based on boundary slippage technology can reduce the bearing friction as much as 60 % (Zhang 2014, 2016). A potential alternative to mineral oils and synthetic-based hydrocarbon oils are the polyalkylene glycol (PAG)-based lubricants today considered for engine lubrication (Cuthbert et al 2016). They have a lower viscosity and better environmental compatibility and have for that reason been the object of several studies [Van Voorst 2000]. Work by Green et al. [Green et al 2011] shows a reduction in fuel consumption of a single-unit truck of 1.3% to 2.1%, depending on which driving cycles are applied, when changing from “mainstream” lubricants in the engine, gearbox, and rear axle to lower viscosity oils.

It has turned out to be very difficult to reach friction coefficients below 0.04 in boundary lubricated sliding conditions by using the traditional oils and additives, such as the well-established mineral or synthetic oils with typical anti-friction, anti-wear, and extreme pressure (EP) additives containing sulphur, chlorine, and phosphorous. New research shows that, with different types of additives in combination with low-friction coatings like DLC, it is possible to achieve much lower friction.

The use of the friction modifier additive glycerol mono-oleate (GMO) in a polyalphaolefin (PAO) oil resulted in a friction coefficient of 0.05 in sliding DLC coated contact. The same material combination resulted in a considerable friction reduction to a coefficient of friction of 0.005 when lubricated by pure glycerol [Martin 2009, Barros Bouchet 2010, Martin 2010]. This friction is about one-tenth of what today can be achieved with the best engine lubricants. In hydrodynamic lubrication has similar levels of friction reductions been achieved by the use of organic friction modifiers [Choo et al 2007] or by liquid crystal mesogenic fluids [Amann 2010]. Using a series of novel additives, Li et al. [2013] report coefficients of friction as low as 0.001 under liquid-lubricated sliding surfaces.

The use of ionic liquids and nanomaterials as anti-friction and anti-wear additives in lubrication is another interesting and potential technology. Ionic liquids are highly polar, because they consist of many types of anions and cations, while conventional oil consist of relatively inert hydrocarbon molecules [Minami 2009, Somers et al 2013]. The viscosity of ionic liquids can controlled largely from 50 to 1500 cP at 23 °C and some ammonium-based ionic liquids have shown a very low friction coefficient down to 0.06. Friction reduction of 20 to 35 % and wear reduction of 45 to 55 % has been reported [Qu et al 2006, 2009a,b].

Laboratory-scale experiments have shown considerable reductions in friction and wear of sliding surfaces by the use of nanomaterials as low friction and anti-wear additives. They are typically carbon-based and include nano-diamonds, onion-like carbons, carbon nano-tubes, graphene, and graphite. Some inorganic fullerenes of transition metal dichalcogenides, (e.g. MoS_2 and WS_2) and metallic, polymeric, boron-based nanoparticles, and Sb doped SnO_2 have been considered as well [Martin et al 2008, Kalin 2012,2013, Ge et al 2015].

6.3.6 Reduced contamination in tribocontacts

The heavy dust and contamination rich environment often in combination with high humidity is most challenging for all mining equipment and results in increased wear and higher friction. A major source of machine failure in mining is due to solid contaminants. When dust particles have the possibility to enter tribological contacts relying on very thin lubricant films like in EHL and boundary lubrication they cause scratches and indents in the sliding surfaces. This results in increased wear and reduced lifetime (Ioannides & Jacobson 1989, Scott 2006, Ioannides 2012). Contamination critical lubricated components are e.g. bearings, gears, seals, wire ropes, hydraulic systems and components in engines and electrical motors.

Filtration is an effective way of removing solid contaminants from the lubrication system. However, even though effective filtration often is available it can be expensive and thus there is a trade-off compared to regular filtering and component replacement. Due to the very large amount of solid contaminants in mining environment it is often necessary with a by-pass valve, which ensures that the filter cannot cut off the lubricant supply completely when clogged. An external by-pass filtering system in the form of a mobile cart is a good solution.

Seals are used both to keep the lubricant escaping from the tribocontacts and to prevent contaminants from entering into the mechanical system. The contacting surfaces in dynamic seals typically operate in the boundary or hydrodynamic lubrication regime and are thus also critical for contamination (Lai 2012, Flitney 2012). When extra sealing in mining is needed, often a design with two or more seals fitted in series is used. Magnetohydrodynamic sealing by ferrofluids offers an advanced solution to avoid leakage and hinder entry of non-metallic contaminants (Eitel 2005).

An important issue is the selection of viscosity level in thin lubricant film sliding contacts. This is an optimisation task between two conflicting requirements. On one hand it is beneficial to have a thicker oil film that allows hard contaminant particles without causing surface scratching. On the other hand it is beneficial to use low viscosity lubricants, as discussed above, resulting in lower shear and reduced friction. Monitoring of real contaminant particle sizes and calculations of film thickness in tribocontacts form a tool for optimal design with regard to both energy consumption and wear life.

It is good to favour grease lubrication in mining compared to oil lubrication, when possible, as the grease also has the ability to capture contaminant particles and hinder them from entering into heavily loaded contacts. An example of a special design for mining environment is the design of a nonseizure bearing for conveyer idler rollers (Scott 2006).

6.3.7 Tires

There has been much development on road vehicle tire material and design during the last five decades but a large part of that is not in the open literature. However, new technologies could be used for considerable improvement of tire materials, tread designs, weight reduction, optimized pressure monitoring, and new maintenance technologies [Zhao et al 2013, NRC 2006, Leduc 2009].

In mining, mobile vehicles like haul trucks, loaders, shovels etc. the tire wear is a major concern. The material is typically fibre reinforced rubber. The wear behaviour of haul truck tires is not well understood. Factors affecting the tire wear are the load on the tires, driving speed, driving style, road conditions as well as tire properties and tire maintenance. The main reason for rubber wear is scrubbing in different forms. Scrubbing occurs at acceleration, braking and when the tire slides. The wear depth of a haul truck tire can be even as much as 10 mm/month. The operational lifetime of haul truck tires in an underground mine would be typically 2000 service hours or 5 months (Woodman & Cutler 2002, Carter 2007, Parreira & Meech 2012, Härkisaari 2015).

6.4 Crusher and grinding mill design

Today, the driving forces for mineral handling equipment design, solutions and optimization are typically reduction of energy losses and increase of production volumes. Furthermore, the design has an effect on dematerialization, low impact of materials, cleaner productions, longer lifetime through improved wear performance, but also through disassembly and remanufacturing.

Wear is the primary target in cases when it may cause catastrophic increase of costs or loss of production volumes. Below we give some examples of how wear can be reduced by new equipment design solutions.

The geometry of liners and also other wear parts has been optimised in relation to the final product performance. When liners are worn and the geometry is changed, the shape of the cavity is changed. There have been extensive studies and predictions of the worn geometry of wear parts in crushing environments (Lindqvist 2005). A new crusher chamber design and the introduction of new wear resistant materials in a primary gyratory crusher resulted in reduced energy consumption of 28 % (Hämäläinen 2013).

It has been observed that mills underperform over a significant part of the liner life, typically10–25 % of the liner life in the beginning and 5–10 % in the end (Yahyaei 2015). New methods have been proposed for improved liner design resulting in a predicted 3.7 % increase in throughput per annum (Toor 2013, Yahyaei 2015). Computational modelling is often used as a tool for improved design. An optimum liner design depends on liner geometries, material, processed mineral, and the process conditions. In modelling optimisation for improved design the focus has been on mill performance in order to control the energy intensive mineral process, especially grinding. A variety of control approaches for process simulation such as ore size reduction and mineral separation processes were reviewed by (Hodouin 2001). Discrete element modeling simulations have been used to calculate impact energy spectrum, collision rates and frequency of balls in a large industrial grinding mill (Herbst 2004, Powell 2011). The combined use of computational fluid dynamics and discrete element modelling has provided valuable insights on changes in the operating variables, and component wear behavior (Lichter 2007).

7. Discussion

7.1 Confidence in used method, data and sources

In this study we used a methodology for calculating global impact of friction and wear on mining industry similar to what we used previously to calculate impact of friction for passenger cars, buses, trucks and paper machines. The accuracy of the calculations depends on the accuracy of the data that we could extract from open sources. In many cases we have found good statistical data to use but there have also been cases of lack of reliable data that were needed. In such cases we have used estimations based on our best expert understanding. We have all the way through the calculation process crosschecked our results with data from available sources and made corrections accordingly. Thus we are convinced that the results from the calculations are in the right order of magnitude and show the relevant trends even if the absolute values should not be considered as precise.

In this mining study we had problems with finding good global data on topics like the number of mines, number of large industrial mines, number of mineral processing units, energy consumption in mines and processing units, wear data from mines, maintenance data, etc. However, we found some detailed studies carried out in USA, Canada, Finland, Brazil (Komonen 1998a, 2003, 2009; DOE 2002, 2007, MAC 2005 a,b, IBRAM 2015, Tolonen 2015) and based on these it was possible to estimate the global data used in our calculations.

7.2 Comparison with state-of-art

To the best of our knowledge no similar studies on global impact of friction and wear in mining has previously been carried out. However, there are a few studies that used a somewhat similar approach in calculations of energy consumption on national scale. In the USA study (US DOE 2007) average energy consumption of mining equipment was calculated and savings were estimated for four cases: current, best practice, practical minimum and theoretical minimum. Here is a similarity in thinking with the four cases we have calculated: Mine 1990, Com 2015, Lab 2015 and Mine 2025. In the Canadian studies (MAC 2005a,b) costs and energy use of the functional categories in underground and open-pit gold, copper, lead, iron and oil sand mines, which are relevant for Canada, and potential savings were estimated. The results from these studies are broadly in line with our calculations.

The big potential of energy saving especially in some of the very energy consuming parts of mining and mineral processing, such as especially grinding, hauling, ventilation and digging, is shown in our study and similarly in some other studies based on different methods for energy consumption estimation (Rabago et al 2001, Sare et al 2001, MAC 2005a,b, Keikkala et al 2007, US DOE 2007, Norgate & Haque 2010).

One unique feature in this study is that for the first time we calculate both the impact of friction and wear in one industrial sector. It shows that in mining the impact of wear is about half of the impact of friction with regards to energy consumption and CO_2 emissions and even larger than the impact of friction with regards to costs. This should not be directly generalised for other industrial sectors since mining is an extremely heavy and rough activity with much wear. The maintenance costs are of the level of one fifth of the turnover in mining while it is often below 5% in other sectors. Anyway, we can conclude that globally the impact of wear on energy consumption, costs and emissions is of the same order of magnitude as the impact of friction. Still the impact of friction seems to be higher and the impact of wear is perhaps only half of that.

7.3 Role of rock mining

Some of the data for mining that is available is confusing because of the various definitions used on what all is included in mining. We have restricted our study to mineral mining, including bauxite which in some data is excluded, and excluding excavation of petrol and gas. With this definition, it has been possible to find fairly good statistical data on the mining activity structure, energy consumption, equipment and costs. We have excluded rock mining because there is not at all similar good statistical data available on that. However, the rock mining activity is to our understanding about of the same volume as mineral mining globally and the equipment and energy consumption structure very much the same. Thus, a first estimate of the impact of friction and wear in the whole mining sector, now including also rock mining, would be to double using the results from mineral mining.

8. Conclusions

We have studied the global energy consumption due to friction and wear in the mining industry and the following can be concluded:

- Total energy consumption of global mining activities, including both mineral and rock mining, is estimated to be 6.2 % of the total global energy consumption. About 38 % of the consumed energy in mineral mining (equalling to 4.6 EJ annually on global scale) is used for overcoming friction. In addition 2 EJ is used to remanufacture and replace worn out parts and reserve spare parts and equipment needed due to wear failures. The largest energy consuming mining actions are grinding (32 %), haulage (24 %), ventilation (9 %) and digging (8 %).
- Friction and wear is annually resulting in 970 million tonnes of CO_2 emissions worldwide in mineral mining (2.7 % of world CO_2 emissions).
- The total estimated economic losses resulting from friction and wear in mineral mining are in total 210,000 million Euro annually distributed as 40 % for overcoming friction, 27 % for production of replacement parts and spare equipment, 26 % for maintenance work, and 7 % for lost production.
- By taking advantage of new technology for friction reduction and wear protection in mineral mining equipment, friction and wear losses could potentially be reduced by 15 % in the short term (10 years) and by 30 % in the long term (20 years). In the short term, this would annually equal worldwide savings of 31,100 million euros, 280 TWh energy consumption and a CO_2 emission reduction of 145 million tonnes. In the long term, the annual benefit would be 62,200 million euros, 550 TWh energy consumption, and a CO_2 emission reduction of 290 million tonnes.

Potential new remedies to reduce friction and wear in mining include the use of new materials, materials with improved strength and hardness properties, more effective surface treatments, high performance surface coatings, new lubricants and lubricant additives, and new designs of moving parts and surfaces of e.g. liners, blades, plates, shields, shovels, jaws, chambers, tires, seals, bearings, gearboxes, engines, conveyor belts, pumps, fans, hoppers and feeders.

Acknowledgements

We want to acknowledge Kari Komonen and Seppo Tolonen, Finland, for their most valuable contributions with expertise on maintenance and mining.

This study has been carried out as part of the Finnish joint industrial consortium strategic research action coordinated by DIMECC Ltd within the program on Breakthrough Materials called BSA in the O'DIGS Project. We gratefully acknowledge the financial support of Tekes, the Finnish Technology Agency, the participating companies, and VTT Technical Research Centre of Finland. Additional support was provided by the U.S. Department of Energy, Basic Energy Sciences, Office of Energy Efficiency and Renewable Energy, under contract DE-AC02-06CH11357.

Appendix A1 Friction and wear loss & costs globally (all mines = 12 EJ)

Mine 1990		Friction		Wear replacment		Maintenene	Downtime			Wear		Total friction and	
				parts		labour	spare equipment		prod loss	total	total	wear	
Parameter		energy	cost	energy	cost	cost	energy	cost	cost	energy	cost	energy	cost
Unit		PJ	MEuro	PJ	MEuro	MEuro	PJ	MEuro	MEuro	PJ	kEuro	PJ	MEuro
Underground mining		1513	27230	440	12570	12570	30	606	3143	470	28889	1983	56119
Surface mining		1543	27766	443	12659	12659	27	545	3165	470	29028	2013	56794
Mineral processing		1576	28364	1014	28967	28967	43	861	7242	1057	66037	2633	94402
		4631	83361	1897	54197	54197	101	2012	13549	1997	123954	6629	207315

Com 2015		Friction		Wear replacment		Maintenene	Downtime			Wear		Total friction and	
				parts		labour	spare equipment		prod loss	total	total	wear	
Parameter		energy	cost	energy	cost	cost	energy	cost	cost	energy	cost	energy	cost
Unit		PJ	MEuro	PJ	MEuro	MEuro	PJ	MEuro	MEuro	PJ	kEuro	PJ	MEuro
Underground mining		979	17617	263	7528	7528	19	388	1882	283	17325	1262	34942
Surface mining		1016	18293	253	7234	7234	17	347	1809	271	16625	1287	34918
Mineral processing		1234	22214	528	15082	15082	28	562	3771	556	34498	1790	56712
		3229	58124	1045	29845	29845	65	1297	7461	1109	68448	4339	126571

Lab 2015		Friction		Wear replacment		Maintenene	Downtime			Wear		Total friction and	
				parts		labour	spare equipment		prod loss	total	total	wear	
Parameter		energy	cost	energy	cost	cost	energy	cost	cost	energy	cost	energy	cost
Unit		PJ	MEuro	PJ	MEuro	MEuro	PJ	MEuro	MEuro	PJ	kEuro	PJ	MEuro
Underground mining		445	8003	182	5188	5188	11	221	1297	193	11894	637	19897
Surface mining		490	8820	164	4695	4695	10	193	1174	174	10756	664	19575
Mineral processing		892	16064	288	8216	8216	19	371	2054	306	18856	1199	34920
		1827	32887	633	18098	18098	39	785	4525	673	41506	2500	74393

Mine 2015		Friction		Wear replacment		Maintenene	Downtime			Wear		Total friction and	
				parts		labour	spare equipment		prod loss	total	total	wear	
Parameter		energy	cost	energy	cost	cost	energy	cost	cost	energy	cost	energy	cost
Unit		PJ	MEuro	PJ	MEuro	MEuro	PJ	MEuro	MEuro	PJ	kEuro	PJ	MEuro
Underground mining		293	5280	137	3913	3913	8	160	978	145	8964	438	14244
Surface mining		336	6043	119	3410	3410	7	138	852	126	7810	462	13854
Mineral processing		735	13227	184	5262	5262	14	284	1315	198	12123	933	25351
		1364	24550	440	12585	12585	29	582	3146	470	28897	1833	53448

Appendix A2
Conversion factors

Energy conversions	
1 kWh	= 3.6 MJ
1 Mtoe	= 41 868 TJ
1 kWh	= 0.06 Euro as global average 2014
1 hour labour	= 6 Euro salary cost as global average 2014
Diesel fuel conversions	
1 litre	= 0.832 kg
1 MJ	= 0.028 l
1 l	= 35.9 MJ
1 kg	= 43.1 MJ
1 kg	=> 3.16 kg CO_2 emission
1 l	=> 2.63 kg CO_2 emission
1 liter	= 0.7 Euro as global average 2014
Energy to emission conversions	
1 PJ diesel oil	=> 0.07364 $MtCO_2$
1 PJ coal	=> 0.2278 $MtCO_2$
1 PJ gas	=> 0.1361 $MtCO_2$
1 PJ mining average	=> 0.146 $MtCO_2$

References

Alahelisten A, Abrasion of hot flame-deposited diamond coatings. Wear 185(1995)1-2, 213-224.

Al-Azizi A, Eryilmaz O, Erdemir A, Kim SH, Effects of nanoscale surface texture and lubricant molecular structure on boundary lubrication in liquid. Langmuir 29(2013)13419–13426.

Albanese T, McGagh J, Future trends in mining. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration, USA, 2011, 21-38.

Aldrich C, Consumption of steel grinding media in mills – A review. Minerals Engineering 49(2013)77–91.

Allebert J, Jungedal M, Waara P, Wear on overlay welded HCWI vs. quenched and tempered low alloyed carbon steel evaluated with granite in a laboratory drum test machine. Wear 330-331(2015)364-370.

Amann T, Kailer A, Ultralow friction of mesogenic fluid mixtures in tribological reciprocating systems. Tribology Letters 37(2010)343–352.

Andersson P, Koskinen J, Varjus S, Gerbig Y, Haefke H, Georgiou S, Zhmud B, Buss W, Microlubrication effect by laser-textured steel surfaces. Wear 262(2007)369–379.

Barros Bouchet M, Martin JM, The future of boundary lubrication by carbon coatings and environmentally friendly additives. In: Luo J., Meng Y., Shao T., Zhao Q, (eds) Advanced Tribology, Bejing, China, Tsinghua University Press, Springer, 2010. p. 598–599, Proceedings of CIST & ITS-IFToMM2008.

Batterham RJ, Goodes C, Energy and climate change – Challenges and opportunities for the mining industry. 28th Int. Mineral Processing Congress, 17-20.9.2007, Szklarska Poreba, Poland.

Berkhimer EN, Selection and sizing of excavation, loading, and hauling equipment. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 931-939.

Berns H, Comparison of wear resistant MMC and white cast iron. Wear 254(2003)1-2,47–54.

Beste U, On the nature of Cemented Carbide Wear in Rock Drilling, PhD Thesis, Comprehensive Summaries of Uppsala Dissertations, Faculty of Science and Technology 964, 2004.

Bhushan B, Principles and applications in tribology. John Wiley & Sons, New York, USA, 1999.

Blackwell GH, Estimation of large open pit haulage truck requirements. CIM Bulletin 92(1999)1028, 143-149.

Blau P, Friction science and technology – from concepts to applications. STLE, CRC Press, Taylor & Francis Group, New York, USA, 2009.

Board of govenors of the Federal Resreve System, Industrial production and capacity utilization – G.17. (On line). Available: http://www.federalreserve.gov/releases/g17/current, 20.11.2015

Bohnet E, Comparison of surface mining methods. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 405-413.

Bosman R, Schipper DJ, On the transition form mild to severe wear of lubricated, concentrated contacts: The IRG (OECD) transition diagram. Wear 269(2010)581-589.

Bosman R, Schipper DJ, Mild wear prediction of boundary-lubricated contacts. Tribology Letters 42(2011)169-178.

BP Statistcal Review of World Energy 2014, [Online] Available: http://www.bp.com/content/dam/bp-country/de_de/PDFs/brochures/BP-statistical-review-of-world-energy-2014-full-report.pdf 22.9.2016

Brannon CA, Carlson GK, Casten TP, Block caving. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 1437-1451.

Brown I, Quarrying. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 1031-1046.

Brazilian Energy Balance 2014. Ministry of Mines and Energy, Rio de Janeiro, Brazil, 2014.

Bruce RW (ed), Hanbook of Lubrication and Tribology, Vol. II Theory and Design. 2nd edition, CRC Taylor & Frances, STLE, London, UK, 2012.

Busca A, Bobancu S, Duta A, Mechanical properties of rubber – an overview, Bulletin of the Transilvania University of Brasov, Series I: Engineering Sciences 3(2010)52.

Busfield J, Soft-rock equipment selection and sizing. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 1157-1178.

Canter N, BAM: Antiwear and friction-reducing coating. Tribology & Lubrication Technology March (2009)14–15.

Carter P, Selection process for hard-rock mining. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 357-376.

Carter RA, Maximizing mining tire life. WOMP The E-Mining Journal & E&MJ Engineering and Mining Journal 5(2007), http://www.womp-int.com/story/2007vol5/story026.htm/4.5.2016

Castro RM, Cavaler LCC, Marques FM, Bristot VM, Rocha AS, Comparative of the tribological performance of hydraulic cylinders coated by the process of thermal spray HVOF and hard chorme plating. Tribology in Industry 36(2014)79-89.

Cha SC, Erdemir A (eds), Coating Technology for vehicle applications. Springer International Publishing, Switzerland, 2015.

Chattopadhyay R, Surface Wear, Analysis, Treatment, and Prevention. ASM International, The Materials Information Society, Ohio, USA, 2001.

Chadwick J, Diesel or electric? Mining Magazine August 1992, 92-98.

Chang L, Friedrich K, Composite materials. In: Totten G (ed.) Handbook of Lubrication and Tribology, 2nd edition, CRC Taylor & Francis, London, UK, Vol 2, Chapter 37, 2012.

Chen H, Ren J, Du F, Zhao F, Pan J, Wang C, Zhu L, Hong H, Friction and wear behaviour of in-situ transformed C_f/Al_3O_3 composite under different lubrication conditions. Wear 332-333(2015)918-925.

Choo JH, Forrest AK, Spikes HA, Influence of organic friction modifier on liquid slip: A new mechanism of organic friction modifier action. Tribology Letters 27(2007)239–244.

Clark HM, Llewellyn RJ, Assessment of the erosion resistance of steels used for slurry handling and transport in mineral processing applications. Wear 250(2001)32–44.

Coal Age, Leveraging Lubrication. http://www.coalage.com/features/3232-leveraging-lubrication.html/10.12.2015

Cohen HE, Energy usage in mineral processing. Trans. Instn Min. Metall., Sect. C: Mineral Process. Extr. Metall. 92(1983)C160-C164.

Cook BA, Harringa JL, Anderegg J, Russell AM, Qu J, Blau P, Higdon C, Elmoursi AA, Analysis of wear mechanisms in low-friction $AlMgB_{14}$-TiB_2 coatings. Surface and Coatings Technology 205(2010)2296–2301.

Cranta Design – CES Selector 2015, https://www.grantadesign.com/products/ces/ 1.9.2015

Curry DC, Clermont B, Improving the efficiency of fine grinding – Developments in ceramic media technology. http://www.isamill.com/EN/Downloads/Downloaded%20Technical%20Papers/Improving_The_Efficiency_Of_Fine_Grinding-_Developments_.pdf/19.8.2016

Cuthbert J, Gangopadhyay A, Elie L, Liu Z, Mcwatt D, Hock ED, Erdemir A, Engine Friction and Wear Performances with Polyalkylene Glycol Engine Oils, SAE Technical Paper 2016-01-2271.

Darestani Farahani T, Bakhshandeh GR, Abtahi M, Mechanical and viscoelastic properties of natural rubber / reclaimed rubber blends. Polymer Bulletin 56(2006)495-505.

Darling P (ed.), SME Mining Engineering Handbook. 3rd edition, Society for Mining, Metallurgy and Exploration, USA, 2011a.

Darling P, Mining: Ancient, modern and beyond. In: Darling P (ed.) SME Mining Engineering Handbook. 3rd edition, Society for Mining, Metallurgy and Exploration, USA, 2011b, 3-9.

Davies JR (Ed.),Surface engineering for corrosion and wear resistance. ASM International, USA, 2001.

Davies JR (Ed.), Handbook of thermal spray technology. TTS ASM Thermal Spray Society, ASM Internationa, USA, 2004.

Doll G, Life-limiting wear of wind turbine bearings: Root cause and solutions. 18th International Conference on Wear of Materials, Philadelphia, USA, 3–7 April 2011.

Doll GL, Matthews A, Wear coatings and treatments. In: Totten G (ed.) Handbook of Lubrication and Tribology, 2nd edition, CRC Taylor & Francis, London, UK, Vol 2, Chapter 40, 2012.

Dommarco R, Galarreta I, Ortiz H, David P, Maglieri G, The use of ductile iron for wheel loader bucket tips. Wear 249(2001)101-108.

Donnet C, Erdemir A, Historical developments and new trends in tribological and solid lubricant coatings. Surface and Coatings Technology 180-181(2004)76–84.

Donnet C, Erdemir A, Tribology of diamondlike carbon films: fundamentals and applications. New York, Springer, 2008.

Durman RW, Progress in abrasion-resistant materials for use in comminution processes. Int. Journal of Mineral Processing 22(1988)1-4, 381-399.

Eitel E (ed.) Magnets seal it off. Machine design. 1.5.2005, http://machinedesign.com/print/archive/magnets-seal-it, 2.12.2015

Element Six, Superior performance drives productivity. Element Six (2016) Online available: http://www.e6.com/wps/wcm/connect/6dde14f2-07b2-4165-bb18-cabbcd102011/E6_Combined+MiningTools_A4 28pp_English_awVIZ.pdf?MOD=AJPERES&CACHEID=6dde14f2-07b2-4165-bb18-cabbcd102011 22.9.2016

Enomoto Y, Yamamoto T, New materials in automotive tribology. Tribology Letters 5(1998)13–24.

Erdakov IN, Tkachev VM, Novokreshchenov VV, Increase of wear resistance of steel plates for crushing stations. Journal of Friction and Wear 35(2014)6, 739-745.

Erdemir A, Engineered tribological interfaces for improved boundary lubrication. Tribology International 38(2005)249–256.

Erdemir A, Donnet C, Tribology of diamondlike carbon films: Current status and future prospects. Topical review. Journal of Physics D: Applied Physics 39(2006)R311–27.

Erdemir A, Holmberg K, Energy consumption due to friction in motored vehicles and low-friction coatings to reduce it. In: Sung CC, Erdemir A (eds), Coating Technology for vehicle applications. Springer International Publishing, Switzerland, Chapter 1,2015, 1-23.

Erdemir A, Ramirez G, Eryilmaz O, Liao Y, Narayanan B, Sankaranarayanan S, Carbon-based Tribofilms from Lubricating Oils, Nature 536(2016)67-71.

Errath RA, Electric power distribution. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 683-703.

Etsion I, Surface texturing. In: Totten G (ed.) Handbook of Lubrication and Tribology, 2nd edition, CRC Taylor & Francis, London, UK, Vol 2, Chapter 53, 2012.

Etsion I, Sher E, Improving fuel efficiency with laser surface textured piston rings. Tribology International 42(2009)542–547.

Farley J, Wrobel LC, Mao K, Performance evaluation of multilayer thin film coatings under mixed rolling-sliding contact conditions. Wear 268(2010)269–76.

Finnie I, Some reflection on the past and future of erosion. Wear 186-187(1995)1-10.

Flitney RK, Lip seals. In: Totten G (ed.) Handbook of Lubrication and Tribology, 2nd edition, CRC Taylor & Francis, London, UK, Vol 1, Chapter 20, 2012.

Flintoff B, Kuehl II R, Classification by screens and cyclones. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 1481-1506.

FIMECC, Demanding applications – DEMAPP, Breakthrough materials for demanding applications – from science to solutions. FIMECC Ltd, Tampere, Finland, FIMECC Report No 3 (2014).

Fuerstenau D, Abouzeid AA, The energy efficiency of ball milling in comminution. International Journal of Mineral Processing, 67(2002)161-185.

Ge X, Xia Y, Shu Z, Zhao X, Conductive grease synthesized using nanometer ATO as an additive. Friction 3(2015)1, 56-64.

Gerard B, Application of thermal spraying in the automotive industry. Surface and Coatings Technology 201(2006)2028-2031.

Giancola D (ed), Canadian & American Mines handbook 2007-2008. Business Information Group, BIG Mining Pub., Toronto, Canada, 2007.

Glaeser WA, Bruce RW, Wear materials. In: Totten G (ed.) Handbook of Lubrication and Tribology, 2nd edition, CRC Taylor & Francis, London, UK, Vol 2, Chapter 33, 2012

Green DA, Selby K, Mainwaring R, Herrera R, The effect of engine, axle and transmission lubricant and operating conditions on heavy duty diesel fuel economy, Part 1: Measurements. JSAE 20119224 2011, SAE Paper 2011-01-2129:2024–31.

Gåhlin R, Larsson M, Hedenqvist P, ME-C:H coatings in motor vehicles. Wear 249(2001)302–309.

Han Z, Zhang J, Ge C, Li W, Ren L, Erosion resistance of bionic functional surfaces inspired from desert scorpions. Langmuir 28(201292914-2921.

Han Z, Yin W, Zhang J, Niu S, Ren L, Active Anti-erosion protection strategy in Tamarisk (Tamarix aphylla). Scientific Reports 2013a, DOI: 10.1038/srep03429, 1-7.

Han Z, Yin W, Zhang J, Jiang J, Niu S, Ren L, Erosion-resistant surfaces inspired by Tamarisk. Journal of Bionic Engineering 10(2013b)479-487.

Han Z, Zhu B, Yang M, Niu S, Song H, Zhang J, The effect of the micro-structure on the scorpion surface for improving the anti-erosion performance. Surface and Coatings Technology, in press, Jan. 2017.

Halin A, Kerai M, Ventilation requirement for "Electric" underground hard rock mines – A conceptual study. The Australian Mine Ventilation Conf., 1-3.7.2013, Adelaide, Australia, 215-220.

Hawk JA, Wilson RD, Tribology of earthmoving mining and minerals processing. In: Bhushan B (ed.) Modern Tribology Handbook, Chapter 35, Vol. 1-2, CRC Press, USA, 2001.

Heiniö, M. (ed.), Rock excavation handbook. Sandvik Tamrock Corp., 1999, http://www.metal.ntua.gr/uploads/3290/254/Excavation_Engineering_Handbook_Tamrock.pdf / 19.10.2015

Herbst JA, A microscale look at tumbling mill scale-up using high fidelity simulation. Int. J. Miner. Process. 74S(2004)S299–S306.

Hodouin D, Jämsä-Jounela SL, Carvalho MT, Bergh L, State of the art and challenges in mineral processing control - Review. Control Engineering Practice 9(2001)9,995–1005.

Holmberg K, Laukkanen A, Ronkainen H, Wallin K, Tribological analysis of fracture conditions in thin surface coatings by 3D FEM modelling and stress simulations. Tribology International 38(2005)1035–1049.

Holmberg K, Ronkainen H, Laukkanen A, Wallin K, Erdemir A, Eryilmaz O, Tribological analysis of TiN and DLC coated contacts by 3D FEM modelling and stress simulation. Wear 264(2007)877–884.

Holmberg K, Matthews A, Coatings Tribology – Properties, Mechanisms, Techniques and Applications in Surface Engineering. Elsevier Tribology and Interface Engineering Elsevier series. Amsterdam, The Netherlands: Elsevier; 2009 No. 56.

Holmberg K, Andersson P, Erdemir A, Global energy consumption due to friction in passenger cars. Tribology International 47(2012a)221-234.

Holmberg K, Laukkanen A, Wear Models. In: Bruce R (ed.) Handbook on Lubrication and Tribology, vol. II: Theory and Design. second edition. New York, USA, CRC Press; 2012b. Chapter 13:1–21.

Holmberg K, Siilasto R, Laitinen T, Andersson P, Jäsberg A, Global energy consumption due to friction in paper machines. Tribology International 62(2013)58-77.

Holmberg K, Andersson P, Nylund PO, Mäkelä K, Erdemir A, Global energy consumption due to friction in trucks and buses. Tribology International 78(2014a)94-114.

Holmberg K, Erdemir A, Global impact of friction on energy use in transportation and industry. 2nd Int. Brazilian Conf. on Tribology – TriboBR 2014b, 3-5.11.2014, Foz do Iguacu, Brazil, ABM Brazilian Association for Metallurgy, Materials and Minerals, Sao Paolo, Brazil, 2014b

Holmberg K, Laukkanen A, Ghabchi A, Rombouts M, Turunen E, Waudby R, Suhonen T, Valtonen K, Sarlin E, Computational modelling based wear resistance analysis of thick composite coatings. Tribology International 72(2014c)13–30.

Holmberg K, Laukkanen A, Turunen E, Laitinen T, Wear resistance optimisation of composite coatings by computational microstructural modelling and simulation. Surface and Coatings Technology 247(2014d)1-13.

Hooper J, Compressed air. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 705-716.

Humphrey JD, Wagner JD, Mechanical extraction, loading, and hauling. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 903-929.

Hämäläinen E, Optimized crushing chamber. Results Minerals & Aggregates (2013)1,16-18.

Härkisaari P, Wear and friction effects on energy consumption in the mining industry. MSc thesis at Tampere University of Technology, Faculty of Engineering Sciences, Tampere, Finland, April 2015, 77 p.

IBRAM Brazilian Mining Assosiation. Privat communication based on information available on web at http://www.revistaminerios.com.br/Edicoes/269/Outubro_2013.aspx, 19.10.2015

IEA Tracking Industrial Energy Efficiency and CO_2 Emissions. In Support of the G8 Plan of Action, Energy Indicators. OECD/IEA, Paris, France, 2007.

IEA International Energy Agency, Redrawing the Energy Climate Map. World Energy Outlook Special Report, 10.6.2013, IEA, Paris, France.

IEA Energy balances of non-OECD countries. International Energy Agency, Paris, France, 2013.

IEA International Energy Agency ”Key World Energy Statistics 2015”, 2016 [Online] Available: https://www.iea.org/publications/freepublications/publication/KeyWorld_Statistics_2015.pdf, 22.1.2016

Industrial Minerals Directory. 5th edition, Metal Bulletin Books Ltd, USA, 2003.

Ishida Y, Usami H, Hoshino Y, Effect of micro dimples on frictional properties in boundary lubrication condition. In: Proceedings of the World Tribology Congress, Kyoto, Japan, 6–11.9.2009.

Ioannides E, Jacobson B, Dirty lubricants – reduced bearing life. Ball Bearing Journal Special (1989)22-27.

Ioannides E, Morales-Espejel GE, Lubrication of rolling element bearings. In: Totten G (ed.) Handbook of Lubrication and Tribology, 2nd edition, CRC Taylor & Francis, London, UK, Vol 2, Chapter 49, 2012

Jacobson S, Coatings and surface treatments: Interactions with lubricants. In: Totten G (ed.) Handbook of Lubrication and Tribology, 2nd edition, CRC Taylor & Francis, London, UK, Vol 2, Chapter 41, 2012

Jahanmir S, Wear and lubrication of ceramics. In: Totten G (ed.) Handbook of Lubrication and Tribology, 2nd edition, CRC Taylor & Francis, London, UK, Vol 2, Chapter 36, 2012

Jansen M, The development of energy-optimized conveyor belts. World of Mining – Surface and Underground 60(2008)2,83-87.

Johansson S, A surface engineering approach to reduction of frictional losses of heavy duty diesel engines (PhD Thesis). Dept. Materials and Manufacturing, Chalmers University of Technology, Gothenburg, Sweden, 2012.

Jones LC, Low angle scouring erosion behaviour of elastomeric materials. Wear 271(2011)1411– 1417.

Jungedal M, Mild impact wear in a concrete mixer. An evaluation of wet abrasive wear. MSc Thesis, KTH Royal Institute of Technology, Material Science and Engineering, Stockholm, Sweden, 9.11.2012

Kalin M, Kogovsek J, Remskar M, Mechanisms and improvements in the friction and wear behaviour using MoS_2 nanotubes as potential oil additives. Wear 280-281(2012)36-45.

Kalin M, Kogovsek J, Remskar M, Nanoparticles as novel lubricating additives in a green, physically based lubrication technology for DLC coatings. Wear 303(2013)480-485.

Kano M, DLC coating technology applied to sliding parts of automotive engine. New Diamond and Frontier Carbon Technology 16(2006)201–210.

Kartal G, Timur S, Eryilmaz OL, Erdemir A, Influence of Process Duration on Structure and Chemistry of Borided Low Carbon Steel, Surface and Coatings Technology 205(2010)1578-1583.

Kawatra SK, Fundamental principles of floatation. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 1517-1531.

Keikkala G, Kask A, Dahl J, Malyshev V, Kotomin V, Estimation of the potential for greenhouse gas emission in North-East Russia: A comparison of energy use in mining, mineral processing and residential heathing in Kiruna and Kirovsk-Apatity. Energy Policy 35(2007)1452-1463.

Kivikytö-Reponen P, Ala-Kleme S, Hellman J, Liimatainen J, Hannula SP, The correlation of material characteristics and wear in a laboratory scale cone crusher. Wear 267(2009)1-4, 568-575.

Klingerman Y, Etsion I, Shinkarenko A, Improving tribological performance of piston rings by partial surface texturing. Transactions of the ASME, Journal of Tribology 127(2005)632–638.

Komonen K, The structure and effectiveness of industrial maintenance. PhD Thesis at Helsinki University of Technology, Acta Polytechnical Scandinavica, Mathematics, Computing and Management in Engineering Series No 93, The Finnish Academy of Technology, Espoo, Finland, 1998a.

Komonen K, Teollisuuden kunnossapidon rakenne ja tehokkuus (in Finnish), The structure and effectiveness of industrial maintenance. Helsinki University of Technology, Department of Industrial Management, Report No 5/1998/Industrial Management, 1998b.

Komonen K, Maintenance key numbers – Results from 2002 year survey / Kunnossapidon tunnuslukuja - Vuotta 2002 koskevan kyselyn tuloksia (in Finnish), Finnish Maintenance Society, Helsinki, Finland, 12(2003) 31 p.

Komonen K, Introduction to operations and maintenance (O&M) management. In Leiviskä K (ed), Process and maintenance management. Papermaking Science and Technology book series, Paper Engineer's Assosiation/Paperi ja Puu Oy, Helsinki, Finland, Nr 14, Chapter 9, 2009, 236-248.

Kotzalas MN, Rolling contact fatigue wear. In: Totten G (ed.) Handbook of Lubrication and Tribology, 2nd edition, CRC Taylor & Francis, London, UK, Vol 2, Chapter 9, 2012

Kovalchenko A, Ajayi OO, Erdemir A, Fenske GR, Etsion I, The effect of laser texturing of steel surface and speed-load parameters on lubrication regime transition from boundary to hydrodynamic. Tribology Transactions 47(2004)299–307.

Kulkarni M, Shim T, Zhang Y, Shift dynamics and control of dual-clutch transmissions. Mechanism and Machine Theory 42(2007)168–182.

Kunttu S, Komonen K, Ahonen T, Niemelä M, Maintenance yearbook 2010 / Kunnossapidon vuosikirja 2010 (in Finnish). Promaint KP-Media, Finnish Maintenance Society, Helsinki, Finland, 2010.

Lai TW, Face seals. In: Totten G (ed.) Handbook of Lubrication and Tribology, 2nd edition, CRC Taylor & Francis, London, UK, Vol 2, Chapter 56, 2012

Lampe T, Eisenberg S, Rodriguez Cabeo E, Plasma surface engineering in automotive industry – Trends and future perspectives. Surface and Coatings Technology 174-175(2003)1–7.

Leduc G, Longer and heavier vehicles – An overview of technical aspects. Luxembourg: Office for Official Publications of the European Communities, Joint Research Centre – Institute for Prospective Technological Studies, JRC 52392 EN, 2009.

Legendre D, Zevenhoven R, Assessing the energy efficiency of jaw crusher. Energy 74(2014)119-130.

Leiviskä K (ed), Process and maintenance management. Papermaking Science and Technology book series, Paper Engineer's Assosiation/Paperi ja Puu Oy, Helsinki, Finland, Nr 14, 2009, 379 p.

Levchenko GV, Svistelnik OY, Plyuta VL, Sychkov AB, Nesterenko AM, Manufacturing technology for cast inserts of new wear resistant alloys for combined mill linings. Metallurgist 56(2013) 9–10 Jan. 2013 (Russian Original 9–10 Sept.–Oct. 2012)

Li J, Zhang C, Ma L, Liu Y, Luo J, Superlubricity achieved with mixtures of acids and glycerol. Langmuir 29(2013)271–275.

Li XB , Summers DA, Rupert G, Santi P, Experimental investigation on the breakage of hard rock by the PDC cutters with combined action modes. Tunnelling and Underground Space Technology 16(2001)2, 107-114.

Lichter J, Potapov AV, Peaker R, The use of computational fluid dynamics and discrete element modeling to understand the effect of cell size and inflow rate on flotation bank retention time distribution and mechanism performance. Proc. 39th AGM of Canadian Minerals Processing, CIM, Canada, (2007)473-496.

Lindroos M, Valtonen K, Laukkanen A, Holmberg K, Kuokkala VT, Kemppainen A, Wear behavior and work hardening of high strength steels in high stress abrasion. Wear 322-323(2015)32-40.

Lindqvist M, Wear in cone crusher chambers. PhD thesis, Dept. Applied Mechanics, Chalmers University of Technology, Göteborg, Sweden, 2005.

Linsler D, Schlarb T, Weingärtner T, Scherge M, Influence of subsurface microstructure on the running-in of an AlSi alloy. Wear 332-333(2015)926-931.

Liu Y, Wang H, Long Z, Yang J, Zhang W, Enhancement on the transverse fracture strength of functional graded structure cemented carbides. Journal of Materials Science 40(2005)20, 5525-5527.

LKAB Annual and sustainability report 2013. LKAB, Vinter & KPMG, Luleå, Sweden, 2013.

Llewellyn RJ, Yick SK, Dolman KF, Scouring erosion resistance of metallic materials used in slurry pump service. Wear 256(2004)592–599.

Lynch A (ed.), Comminution handbook. Australian Institute of Mining and Metallurgy, Spectrum Series 21, Carlton Victoria, Australia, 2015.

MAC Mining Association of Canada, Benchmarking the energy consumption of Canadian underground bulk mines. Report prepared for the Mining Association of Canada and Natural Resources Canada, Ottawa, Canada, 2005a.

MAC Mining Association of Canada, Benchmarking the energy consumption of Canadian open-pit mines. Report prepared for the Mining Association of Canada and Natural Resources Canada, Ottawa, Canada, 2005b.

Martin, JM, Ohmae N, Nanolubricants. John Wiley & Sons Ltd., New York, USA, 2008.

Martin JM, Barros Bouchet MI, Sagawa T, Green tribology: Lubricant compliant superhard DLC coatings. In: Proceedings of the 4th World Tribology Conference, Kyoto Japan; 6–11.9.2009.

Martin JM, Barros Bouchet MI, Matta C, Zhang Q, Goddard III WA, Okuda S, Sagawa T, Gas-phase lubrication of a ta-C by glycerol and hydrogen peroxide: Experimental and computer modelling. Journal of Physical Chemistry C114(2010)5003–5011.

McCarthy PL, Hard-rock equipment selection and sizing. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 1143-1155.

McCarthy PL, Dorricott MG, Dewatering underground operations. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 765-780.

McLellan BC, The minerals-energy nexus: past, present and future. In: Matsumoto et al. (eds), Sustainability through innovation in product lifecycle design, EcoProduction, Springer, Japan, 2013, 619-631.

Meng HC, Ludema KC, Wear models and predictive equations: Their form and content. Wear 181-183(1995)443-457.

Merlo AM, The contribution of surface engineering to the product performance in the automotive industry. Surface and Coatings Technology 174-175(2003)21–26.

Metso Wear lining and sheeting, Hanbook. Version 1.2, http://www.metso.com/miningandconstruction/MaTobox7.nsf/DocsByID/C525FD49541A9098C2257C7E0043C04B/$File/2976_LiSh_Handbook_1403121_FINAL%20LR.pdf / 4.5.2016

Metso Showroom, Optimized wears increase production at KMARuda iron ore mine, http://www.metso.com/showroom/mining/kmaruda/ 30.4.2013

Minami I, Ionic liquids in tribology. Molecules 14(2009)2286–2305.

Mining Journal online, Mining explained, An introduction to mining, or a place to refresh your understanding of the basic industry rules of thumb. From: http://www.mining-journal.com/knowledge/Mining-Explained / 3.4.2014

Moreno AM (ed.), Metal Producers of the World 2002. Worcester Park, UK: Metal Bulletin Books Ltd, 2002.

Mosher J, Crushing, milling, and grinding. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 1461-1480.

Mukka L, Mine ventilation at Kiruna. Mining Engineering 10(2002)10,2-6.

Naunheimer H, Bertsche B, Ryborz J, Novak W, Automotive Transmissions – Fundamentals, Selection, Design and Application. Second edition, Springer, Heidelberg, Germany, 2011.

Nelson MG, Evaluation of mining methods and systems. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 341-348.

NMA National Mining Assosiation, The economic contributions of US mining (2011). A report prepared by the NMA National Mining Assosiation, Washington, USA, September 2013.

Nordell K, A new era in overland conveyor belt design. E&Mj, April(1999)40-42.

Nordgren S, García J, Blomqvist A, Trends in the P/M hard metal industry, International Journal of Refractory Metals and Hard Materials 48(2015)31-45.

Norgate T, Haque N, Energy and greenhouse gas impact of mining and mineral processing operations. Journal of Cleaner Production 18(2010)266-274.

NRC, Tires and passenger vehicle fuel economy – Informing consumers, improving performance. Transportation Research Board, Special Report 286, National Research Council of the National Academies, Washington D.C., USA, 2006.

Ojala N, Valtonen K, Heino V, Kallio M, Aaltonen J, Siitonen P, Kuokkala VT, Effects of composition and microstructure on the abrasive wear performance of quenched wear resistant steels. Wear 317(2014)225-232.

Oksanen V, Valtonen K, Andersson P, Vaajoki A, Laukkanen A, Holmberg K, Kuokkala VT, Comparison of laboratory rolling-sliding wear tests with in-service wear of nodular cast iron rollers against wire ropes. Wear 340-341(2015)73-81.

Osara K, Tiainen T, Three-body impact wear study on conventional and new PM/ + HIPed wear resistant materials. Wear 250-251(2001)785-794.

Ovarock – Steels for Mining and Rock Drilling Applications from Ovako, Ovako, 2008.

Paalumäki T, Lappalainen P, Hakapää A (eds), Mining and excavation technology / Kaivos- ja louhintateniikka (in Finnish). Finnish National Board of Education, Helsinki, Finland, 3rd edition, 2015, 479 p.

Parent LL, Li DY, Wear of hydrotransport lines in Athabasca oil sand. Wear 301(2013)477-482.

Parreira J, Meech J, Simulation of an open pit mine to study autonomous haulage trucks. In: Proc. CIM 2012 Convention, 6-9.5.2012, Edmonton, Canada, Canadian Institute of Mining, Canada.

Peppers PR, Dewatering surface mines. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 743-763.

Plinninger R, Spaun G, Thuro K. Predicting tool wear in drill and blast. Tunnels & Tunnelling International Magazine (2002) 1-5.

Podgornik B, Vizintin J, Tribological reactions between oil additives and DLC coatings for automotive applications. Surface and Coatings Technology 200(2005)1982–1989.

Powell MS, Weerasekara NS, Cole S, LaRoche RD, Favier J, DEM modelling of liner evolution and its influence on grinding rate in ball mills. Minerals Engineering 24(2011)341–351.

Qu J, Truhan JJ, Dai S, Luo H, Blau PJ, Ionic liquids with ammonium cations as lubricants or additives. Tribology Letters 22(2006)207–214.

Qu J, Blau P, Dai S, Luo H, Meyer III HM, Ionic liquids as novel lubricants and additives for diesel engine applications. Tribology Letters 35(2009a)181–189.

Qu J, Blau P, Dai S, Luo H, Meyer III HM, Truhan JJ, Tribological characteristics of aluminium alloys sliding against steel lubricated by ammonium and imidazolium liquids. Wear 267(2009b)1226–1231.

Rabago KR, Lovins AB, Feiler TE, Energy and sustainable development in the mining and minerals industries. MMSD Mining, Minerals and Sustainable Development, UK, Jan. 2001, No 41.

Randolph M, Current trends in mining. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration, USA, 2011, 11-19.

Ratia V, Valtonen K, Kemppainen A, Kuokkala VT, High-Stress abrasion and impact-abrasion testing of wear resistant steels. Tribology Online 8(2013)2,152-161.

Ratia V, Heino V, Valtonen K, Vippola M, Kemppainen A, Siitonen P, Kuokkala VT, Effect of abrasive properties on the high-stress three-body abrasion of steels and hard metals. Finnish Journal of Tribology 32(2014)1, 3-18.

Rattanasom N, Prasertsri S, Ruangritnumchai T, Comparison of the mechanical properties at similar hardness level of natural rubber filled with various reinforcing-fillers. Polymer Testing 28(2009)8-12.

Reichert J, Schäfer P, Reibungsreduzierende Motorabdichtung bei (Reduced friction in engine sealing system for truck engines). MTZ – Motortechnische Zeitschrift 71(2010)258–264. (In German).

Reichl C, Schatz M, Zsak G, World Mining Data - Minerals production. International Organizing Committee for the World Mining Congress, Vienna, Austria, Vol. 31, 2016.

Rendon J, Olsson M, Abrasive wear resistance of some commercial abrasion resistant steels evaluated by laboratory test methods. Wear 267(2009)2055-2061.

Richards M, Hydraulic mining. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 1049-1122.

Ronkainen H, Elomaa O, Varjus S, Kilpi L, Jaatinen T, Koskinen J, The influence of carbon based coatings and surface finish on the tribological performance in high-load contacts. Tribology International 96(2016)402-409.

Rostami J, Mechanical rock breaking. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 417-434.

Rostami J, Hambley DF, Blasthole drilling. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 435-441.

Ryk G, Etsion I, Testing piston rings with partial laser surface texturing for friction reduction. Wear 261(2006)792–796.

Sare IR,Mardel JI, Hill AJ, Wear-resistant metallic and elastomeric materials in the mining and mineral processing industries – an overview. Wear 250(2001)1–10.

Scharf TW, Metals. In: Totten G (ed.) Handbook of Lubrication and Tribology, 2nd edition, CRC Taylor & Francis, London, UK, Vol 2, Chapter 35, 2012

Scherge M, Linsler D, Schlarb T, The running-in corridor of lubricated metal-metal contacts. Wear 342-343(2015)60-64.

Scherge M, Pöhlmann K, Gerve A, Wear measurement using radionuclide-technique (RNT). Wear 254(2003a)801-817.

Scherge M, Shakhvorostov D, Pöhlmann K, Fundamental wear mechanisms of metals. Wear 255(2003b)395-400.

Scott W, Mining indurty. In: Totten G (ed.) Handbook of Lubrication and Tribology, 2nd edition, CRC Taylor & Francis, London, UK, Vol 1, Chapter 20, 2006.

Sethuramiah A, Lubricated Wear – Science and Technology. Elsevier Tribology Series Nr 42, Elsevier Science, The Netherlands, 2003.

Shakhvorostov D, Gleising B, Büscher R, Dudzinski W, Fischer A, Scherge M, Microstructure of tribologically induced nanolayers produced at ultra-low wear rates. Wear 263(2007)1259-1265.

Siitonen P, Kallio M, New materials for wear parts in rock and mineral crushing. “Between a Rock and a Hard Place…” Seminar on heavy abrasive wear, 29.4.2009, Tampere University of Technology, Tampere, Finland.

Smith J, The McCoy truck study, large vs small, mechanical vs electrical. E&MJ February 1994, 24-28.

Somers AE, Howlett PC, MacFarlane DR, Forsyth M, A review of ion liquid lubricants. Lubricants 1(2013)3–21.

Stachowiack GW, Batchelor AW, Engineering Tribology. Elsevier, Amsterdam, The Netherlands, 2005.

Taylor S, Fitzsimons M, Hewett C, Russell J, Mill liners. In: Lynch A (ed.), Comminution handbook. Australian Institute of Mining and Metallurgy, Spectrum Series 21, Carlton Victoria, Australia, 2015, 125-144.

The top ten deepest mines in the world. Mining-technology.com, http://www.mining-technology.com/features/feature-top-ten-deepest-mines-world-south-africa/ 2.9.2016

Tiley P, Hoisting systems. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 1295-1326.

Tolonen S, Maintenance and plant services / Kunnossapito ja tehdaspalvelu (In Finnish), In: Paalumäki T, Lappalainen P, Hakapää A (eds), Mining and excavation technology / Kaivos- ja louhintateniikka (in Finnish). Finnish National Board of Education, Helsinki, Finland, 3rd edition, 2015, 365-387.

Toor P, Franke J, Powell M, Bird M, Waters T, Designing liners for performance not life, Minerals Engineering 43–44(2013)22–28.

Totten G (ed.), Handbook of Lubrication and Tribology, Vol 1 Application and Maintenance, 2nd edition, CRC Taylor & Francis, London, UK, 2006.

Totten G (ed.), Handbook of Lubrication and Tribology, Vol 2 Theory and design. 2nd edition, CRC Taylor & Francis, London, UK, 2012.

Tromans D, Mineral comminution: Energy efficiency considerations. Minerals Engineering 21(2008)613-620.

Tung SC, McMillan ML, Automotive tribology overview of current advances and challenges for the future. Tribology International 37(2004)517–536.

UN United Nations, Framework Convention on Climate Change, The Paris Agreement, FCCC/CP/2015/L.9/Rev.1, Paris, France, 2015.

US DOE, Mining industry of the future – Energy and environmental profile of the U.S. mining industry. Prepared by BCS Onc., U.S. Dept. of Energy, Dec. 2002

US DOE, Mining Industry Enenrgy Bandwidth Study. Prepared by BCS Inc., U.S. Dept. of Energy, Industrial Technologies Programme, June 2007

Utley RW, In-pit crushing. In: Darling P (ed.), SME Mining Engineering Handbook, 3rd edition, Society for Mining, Metallurgy and Exploration Inc., USA, 2011, 941-956.

Van Voorst R, Polyglycols as base fluids for environmentally-friendly lubricants. Journal of Synthetic Lubrication 16(2000)313–322.

Vergne de la J, Hard Rock Miner's Handbook. 5th edition, Stantec Consulting, Edmonton, Canada, 2008.

Vuorinen E, Ojala N, Heino V, Rau C, Gahm C, Erosive and abrasive wear performance of carbide free bainitic steels – comparison of field and laboratory experiments.Tribology International 98(2016)108–115.

Walker CI, Robbie P, Comparison of some laboratory wear tests and field wear in slurry pumps. Wear 302(2013)1026-1034.

Wang X, Yu H, Huang W, Surface texture design for different circumstances. In: Proceedings of the 1st International Brazilian Conference on Tribology, TriboBR 2010, Rio de Janeiro, Brazil, November 24–26 2010, p.97–107.

Wang C, Li X, Chang Y, Han S, Dong H, Comparison of three-body impact wear behaviours for quenching-partitioning-tempering and quenching-tempering 20Si2Ni3 steels. Wear 362-363(2016)121-128.

Wicakasana Y, Widodo NP, Kramadibrata S, Wattimena RK, Sigalingging JW, Rizky M, Nardono, Determining rolling resistance coefficient on Hauling road using dump-truck in open coal mine. International Symposium on Earth Science and Technology, 6-7.11. 2011, Fukuoka, Japan, CINES Cooperative International-Network for Earth Science and Technology, 2011.

Wills BA, Napier-Munn T, Will's Mineral Processing Technology – An introduction to the practical aspects of ore treatment and mineral recovery. 7th Edition, Elsevier, Amsterdam, The Netherlands, 2006

Wolf T, Neue Lagertechnologie ermöglicht hohes CO_2-Einsparpotenzial (New bearing technology enables significant CO_2 savings). ATZ 2009;111(9):668–671. (In German).

Woodman CA, Cutler AT, Tyre selection, use and operational issues to maximise tyre life. Otraco Int. Web Publications, 2002, https://www.otraco.com/custom/files/docs/otraco-web-publications-maximising-tyre-life-september-2002.pdf/54.5.2016

Yahyaei M, Powell MS, Toor P, Tuxford A, Limpus A, Relining efficiency and liner design for improved plant performance. Minerals Engineering 83(2015)64–77.

Yue M, Han-Guang F, Shang-Lin M, Yong-Ping L, A study of microstructure and performance of cast Fe–8Cr–2B alloy. Materialwissenschaft und Werkstofftechnik 45(2014)10, 912-919.

Zhang YB, A new type of energy conserved hydrodynamic journal bearing. Patent: CN201410563019.7 (2014)

Zhang YB, An energy conserved hydrodynamic journal bearing by the boundary slippage technology. Recent Patents on Mechanical Engineering 9(2016)1,63-70.

Zhao H, Burke A, Miller M, Analysis of class 8 truck technologies for their fuel savings and economics. Transportation Research Part D 23(2013)55–63.

Figure captions

Figure 3.2.1 Main operational categories in mining.

Figure 3.4.2.1 Energy break down in tribological contacts

Figure 3.5.1. Underground and surface mining actions and examples of typical equipment used (Härkisaari 2015, US DOD 2007; US DOE 2002).

Figure 4.1.1 Share in percentage of the global energy consumption in mining (=12 EJ) in total and according to mining operational categories.

Figure 4.1.2 Global energy consumption in mining (=12 EJ) according to mining operational categories.

Figure 4.2.1 Three case studies were carried out for detailed energy and cost analysis: a mobile jaw crusher, an off-highway haul truck and a grinding mill.

Figure 4.2.2 The energy distribution in a diesel powered mobile jaw crusher typically used in iron ore crushing (weight 50 tons).

Figure 4.2.3 The energy distribution in an electrically powered autogenous grinding mill typically used in primary milling of iron ore (mill diameter x length = 6 x 6 m).

Figure 4.2.4 The energy distribution in an diesel driven off-highway rigid frame 90 tons haul truck used in mining**.**

Figure 4.2.5 Annual costs for friction and wear in mining equipment is divided in three tribocategories: crushing abrasive wear dominated (CAW), abrasive erosive wear dominated (AEW), and lubricated wear dominated (LW).

Figure 4.4.1 Flow chart for calculations of global impact of friction and wear on mineral mining industry

Figure 5.1.1 Trends in wear reduction by new tribological solutions for different contact severity levels in mining applications.

Figure 5.1.2 Trends in wear reduction by new tribological solutions for different contact severity levels in mining applications.