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Application of life cycle assessment (LCA) to analyze the environmental loads of heavy machinery components

Dominika SIWIEC*[1*]*, *Andrzej PACANA*[2]* and ***Martin MIKESKA

Authors' affiliations and addresses:
[1] Rzeszow University of Technology; Faculty of Mechanical Engineering and Aeronautics, al. Powstańców Warszawy 12
35-959 Rzeszów, Poland
e-mail: d.siwiec@prz.edu.pl

[2] Rzeszow University of Technology; Faculty of Mechanical Engineering and Aeronautics, al. Powstańców Warszawy 12
35-959 Rzeszów, Poland
e-mail: app@prz.edu.pl

***Correspondence:**
Andrzej Pacana, Rzeszow University of Technology; Faculty of Mechanical Engineering and Aeronautics, al. Powstańców Warszawy 12
35-959 Rzeszów, Poland
tel.: 178651390
e-mail: app@prz.edu.pl

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Abstract
The heavy machinery used in mining and mineral processing generates significant environmental burdens that cause global warming and also negatively affect human health. This is caused by the use of large amounts of energy by these machines, including the amount of process heat, which generates negative environmental changes. As part of sustainable development, it is necessary to look for more friendly solutions, e.g., life cycle assessment (LCA). Therefore, the objective was to analyse the main environmental loads that arise during the extraction and processing of the component materials used in mining machines. In this case, the subject of the research was a reduction gear with a high utilisation rate in excavators and forklifts used in mining. The environmental impact criteria taken into account in the analysis were ozone depletion, human toxicity, and eutrophication. The analysis was carried out using the OpenLCA programme with the ecoinvent database. The results of the analysis showed that in the extraction and processing phase of the reduction gear materials, the main environmental loads arise for selected criteria arise, among others: during coke production, oil and gas extraction, natural gas transport, and hard coal exploitation. The results of the analysis may contribute to the sustainable development of machines in the mining industry and may be useful in the production of new mining machines in order to eliminate their negative impact throughout their life cycle.

Keywords
LCA, life cycle assessment, sustainable development, extraction and processing of materials, reduction gear, mining industry, mechanical engineering

Introduction

Mining and mineral processing are one of the main areas of research due to dynamic climate changes (Bogusz & Sulich, 2020; Carvalho, 2017). The use of heavy machines that consume significant amounts of electrical and mechanical energy or process heat has a negative impact on the natural environment (Farjana et al., 2019; Siwiec et al., 2019). Therefore, the mining industry and the heavy machinery used in it contribute particularly to global warming, deterioration of human health, and degradation of ecosystems and resources (Simionescu et al. 2021, 2022). As part of the pursuit of sustainable development, it is crucial to perform life cycle assessment (LCA) of these machines to eliminate their negative environmental impact (Chevalier & Le Téno, 1996; Gawlik, 2008; Siwiec et al., 2023). Although there are studies that use the LCA method in the mining sector, these studies are still few.

For example, a life cycle assessment of a gear envelope was carried out. The analyses included a comparison of gears with flood and minimal lubrication (Soares et al., 2022). Other studies, for example Ma & Kim (2015) included modelling of life cycle assessment during the use phase of mining machines. Additionally, automatic sorting algorithms have been developed that adapt to current and new machines. The life cycle of heavy vehicles used in mining was also assessed using the example of a truck (Kljucnikov et al., 2023). An environmental impact assessment was carried out for coal generated in the production of raw materials and energy in mining (Behun et al. 2018, Burchart-Korol et al., 2016). The impact of operating facilities for the recovery of raw materials from mining waste was examined. LCA was used for this within the material extraction and processing phase, as presented in Dino et al. (2020). The possibilities of applying cleaner production to aggregates used in mining were analysed. A life cycle assessment was carried out accordingly and the results were illustrated for industrial aggregate (Schneider et al., 2018). A simplified model has also been developed to support decision making, taking into account the criteria of sustainability and life cycle assessment (LCA), as presented by Pacana et al. (2014). It took into account qualitative, environmental, and economic factors, and the model was tested for mini excavators. Other research (Reid et al., 2009), included a waste management life cycle assessment, which interpreted various tailings management and closure scenarios that apply to an underground copper and zinc mine. Challenges in the mining industry related to the skilful use of the life cycle assessment (LCA) method were also analysed, as presented, for example, by Lee et al. (2022). However, the article Cano Londoño et al. (2019) analysed emergency situations and at the same time evaluated the life cycle in an open-pit mine. The aim was to analyse emissions and the possibility of using renewable and non-renewable energy directly related to mining. The researchers of the work carried out research in the area of the potential for global warming in the life cycle of quarry machines (Bascompta et al., 2022). The analysis results concerned in particular the first phase of LCA, i.e. extraction and processing of materials. Reviews in the literature covering the use of LCA in mining have also been conducted, such as Farjana et al. (2019), Segura-Salazar et al. (2019), Tolomeo et al. (2020).

After reviewing the literature, it was observed that previous research was mainly focused on assessing the life cycle of the main components of mining machines. Therefore, the aim was to analyse the main environmental loads that arise during the extraction and processing of the reduction gear materials used in excavators and forklifts used in mining. The environmental impact criteria were ozone depletion, human toxicity, and eutrophication. The analysis was carried out using the OpenLCA 2.0.0 programme with the Ecoinvent 3.10 database.

Materials and Methods

The subject of the research was a reduction gear used in an excavator and a forklift with a high rate of use as mining machines (Jun et al., 2019). The reduction gear is considered to be the main part of machines used in industry, construction, and agriculture. It is used to reduce engine speed while increasing torque power. It is used when the engine is characterised by too high revolutions and has too little power, resulting in a decrease in efficiency under significant loads. A characteristic feature of the transmission is its design, which supports achieving the required torque power through an appropriate engine and oil flow (Matisková et al., 2020; Siwiec & Pacana, 2022). Typically, reduction gears are made of aluminium and cast iron construction, which has high mechanical strength. However, despite the widespread use of reduction gear, the number of studies in the area of life-cycle environmental impact analysis (LCA) is negligible.

Life cycle assessment (LCA) is a method of analyzing the environmental burdens incurred throughout the life cycle of a product or process (Siwiec & Pacana, 2024). It is carried out according to the ISO 14040 standard (Finkbeiner et al., 2006), providing all procedures, input and output data, including environmental assessment methods (Grenz et al., 2023). The basic form of life cycle assessment is "from the cradle to the grave" (Ulewicz et al., 2023), , i.e. taking into account the phases of extraction and processing of materials, transport, production, distribution, use, and end of life, including e.g. recycling (Lagerstedt et al., 2003; Ostasz et al., 2022b; Pacana & Siwiec, 2022). In this study, due to the diversity of applications of the reduction gear, as well as the small number of studies in this field, the focus was on the first and fundamental phase of its life cycle: extraction and processing of materials, as shown in Figure 1.

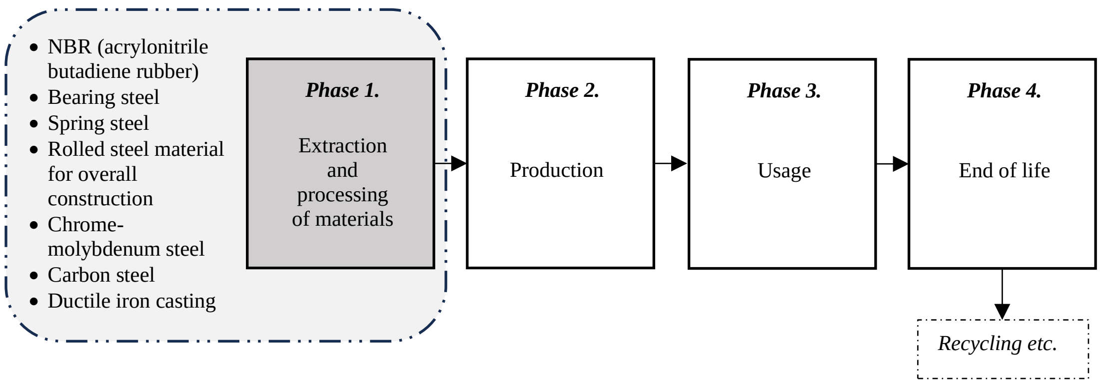

Fig. 1. System boundary for reduction gear LCA.

Based on (Jun et al., 2019), the main materials of the reduction gear used in excavators and forklifts of the mining industry were determined, as shown in Table 1.

Tab. 1. Materials used for reduction gear.

Reduction gear materials	Weight (kg)
NBR (acrylonitrile butadiene rubber)	0.340
Bearing steel	12.500
Spring steel	0.210
Rolled steel material for overall construction	0.910
Chrome-molybdenum steel	140.820
carbon steel	5.910
Cast from ductile iron	241.440

The largest share of materials in the analysed reduction gear is cast from ductile iron, followed by chrome-molybdenum steel. Bearing steel and carbon steel have a smaller material share. Minor amounts of materials include NBR, spring steel, rolled steel material for general construction, and carbon steel.

The research was focused on the analysis of selected environmental loads from environmental categories for the CML method, which concerns environmental impacts expressed in the form of pollutants emissions into the environment (Belok & Wilk-Słomka, 2013). The environmental impact categories selected for this analysis included: ozone depletion, human toxicity, and eutrophication. The ozone layer is understood as a gas occurring naturally in the stratosphere. Ozone particles accumulate there. It decomposes, and there is a certain balance between the formation of the ozone layer and its degradation. However, when the ozone layer is depleted, an effect of depletion occurs, which is called the ozone hole. It occurs when the depletion level is lower than 200 Dobson units (DU) (Anwar et al., 2016). In this study, the environmental loads of ozone depletion are expressed in the unit of kg CFC-11-Eq, which includes the equivalent of a kilogramme of trichlorofluoromethane (R-11); therefore, it is a kilogram of CFC-11 equivalent (Tarannum et al., 2021). The toxicity to humans reflects the possible harmfulness of a given chemical substance that is released into the environment. At the same time, it takes into account the inherent toxicity of the compound at its potential dose (Hertwich et al., 2001). The conversion unit for human toxicity is kg 1,4-DCB-Eq, i.e., the equivalent of a kilogramme of dichlorobenzene (1,4), meaning a kilogramme of 1,4-DCB equivalent (Iosifov et al., 2020). In turn, eutrophication is an increase in the supply of nutrients to surface waters, which causes an increase in overenrichment, and thus an increase in primary productivity and other negative effects accompanying it (Akinnawo, 2023). The conversion unit in this case is the equivalent phosphate (kg PO4-Eq) (Konstantzos et al., 2019).

The analysis of impact categories was limited to five main environmental burdens. This is due to the breadth of the issue, including the multitude of different environmental burdens. The main loads are those that have the largest share in relation to the remaining loads arising in a given environmental impact category (Pacana et al., 2014; Pacana & Siwiec, 2021b; Siwiec & Pacana, 2021).

Results

As part of the analysis of environmental loads that arise in the extraction and processing of materials for the reduction gear during its life cycle, the analyzes were carried out using the OpenLCA 2.0.0 programme with the Ecoinvent 3.10 database.

Initially, the environmental loads causing the formation of the oz layer were analysed. The main loads are shown in Figure 2.

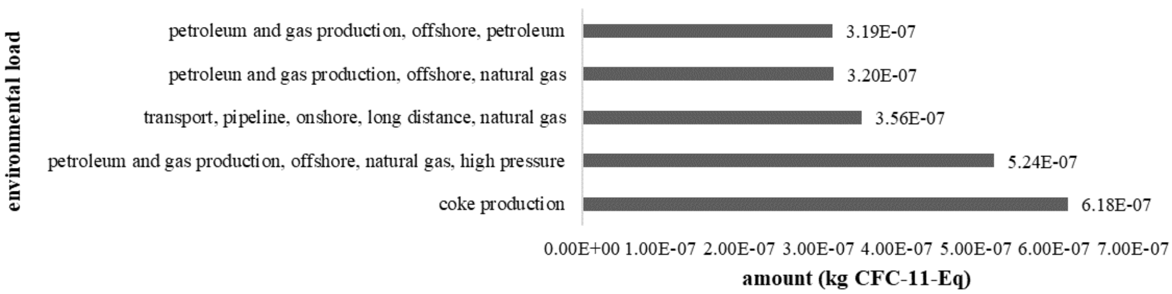

Fig. 2. The main environmental stresses causing the ozone layer in the extraction and processing of reduction gear materials.

The main environmental burden that causes the formation of the ozone layer in the extraction and processing of the reduction gear materials was observed to be the production of coke (6.18E-07 kg CFC-11-Eq). Relatively little less environmental burden occurs during oil and gas extraction under high pressure (5.24E-07 kg CFC-11-Eq). Other significant environmental burdens arise from the transportation of natural gas by pipeline (on land over long distances) and also from the extraction of crude oil and natural gas. These loads are characterised by a relatively similar amount (average 3.32E-07 kg CFC-11-Eq). Then, environmental loads causing toxicity to humans were analysed. The results are shown in Figure 3.

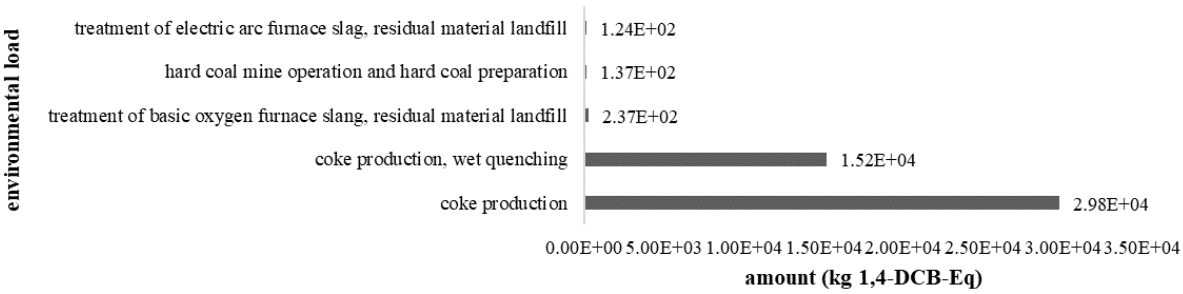

Fig. 3. The main environmental stresses causing toxicity to humans in the extraction and processing of reduction gear materials.

It has been shown that during the extraction and processing of the reduction gear materials, significant environmental loads that cause toxicity to humans arise during the production of the basket (2.98E+04 kg 1,4-DCB-Eq) and its subsequent wet hardening (1.52E+04 kg 1,4-DCB-Eq). Then, it is the primary oxygen furnace treatment process, including waste storage (2.37E+02 kg 1,4-DCB-Eq). A relatively similar number of environmental loads (average 1.31E+02 kg 1.31E+02) that generate toxicity for humans concerns the hard coal mine operation (including hard coal processing) and the treatment of arc furnace slag (including storage of residual materials). Subsequently, the environmental loads causing eutrophication were analysed. The result of the main environmental loads is shown in Figure 4.

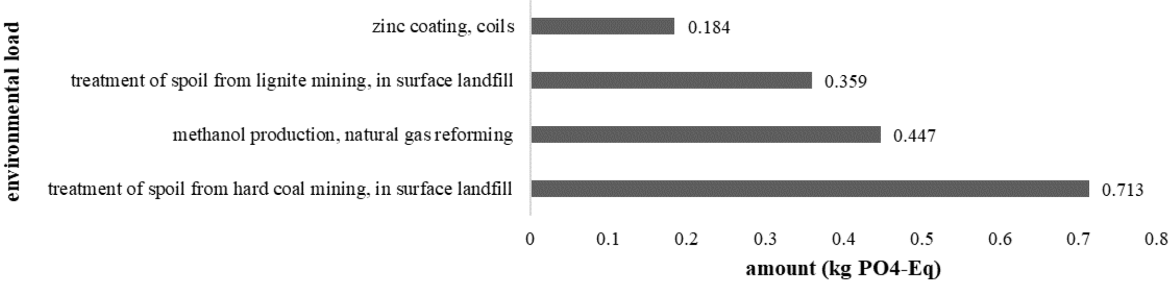

Fig. 4. Main environmental stresses causing eutrophication in the extraction and processing of reduction gear materials.

It has been observed that there are environmental stresses that generate eutrophication during the extraction and processing of reduction gear materials. However, these stresses are relatively negligible. They concern the following processes: processing of output from hard coal mining in a surface storage facility, methanol production (natural gas reforming), processing of output from lignite mining in a surface storage facility, and zinc coating. The amount of environmental loads generated during these processes ranges from 0.184 to 0.713 kg PO4-Eq.

As a summary of the results of the analysis, the environmental loads obtained for the three selected categories of impacts were summarised. This is shown in Table 2.

Tab. 2. Total number of main environmental loads of selected impact categories for the extraction and processing of reduction gear materials.

Environmental load category	Ozone depletion	Human toxicity	Eutrophication
Unit	kg CFC-11-Eq	kg 1,4-DCB-Eq	kg PO4-Eq
Amount	2.14E-06	4.54E+04	1.703

It has been observed that the greatest number of environmental burdens arise within the category of human toxicity. In total it is 4.54E+04 kg 1,4-DCB-Eq. Then a much smaller amount of environmental burden is generated in the case of eutrophication (1.703 kg PO4-Eq), and, subsequently, the creation of the ozone layer (2.14E-06 kg CFC-11-Eq).

Discussion and Conclusion

Sustainable development encourages enterprises to look for effective solutions that reduce the negative impact on the environment (Gajdzik, 2022; Ostasz et al., 2022a; Pacana & Siwiec, 2021a). One of them is to assess the environmental impact throughout the life cycle of products and processes. However, this is a difficult task and is not very common in the mining industry. Therefore, the objective was to analyse the main environmental loads that arise during the extraction and processing of the reduction gear materials used in excavators and forklifts used in mining. The main environmental stresses that cause the formation of the ozone layer, human toxicity and eutrophication during the extraction and processing of reduction gear materials were:

- coke production;
- oil and gas extraction under high pressure;
- transportation of natural gas by pipeline (on land over long distances);
- oil and natural gas extraction;
- wet hardening of the basket;
- operation of a hard coal mine (including hard coal processing);
- treatment of arc furnace slag (including storage of residual materials);
- processing of spoil from hard coal mining in a surface landfill;
- methanol production (natural gas reforming);
- processing of output from lignite mining in a surface dump and zinc coating.

It was concluded that the greatest number of environmental burdens arise within the categories of human toxicity, followed by eutrophication and the formation of the ozone layer. Therefore, it is best to take first improvement actions for the main burdens from the point of view of toxicity to humans. However, it can be concluded that a relatively small amount of environmental loads for the impact categories arises during the extraction and processing of the reduction gear materials.

It was thus demonstrated that the first phase of the life cycle of the reduction gear does not generate excessive environmental problems, considering the formation of the ozone layer, toxicity to humans, and eutrophication. However, it is necessary to mention that the analysis results only cover the first phase of LCA. Therefore, it is necessary to analyse the subsequent LCA phases, where these loads may be much higher.

Therefore, future research will analyse the remaining phases of the reduction gear life cycle and the resulting loads. It is also planned to evaluate the life cycle of other machines used in mining, including analysis of other types of environmental impact categories.

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