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Analysis of the ecological footprint of mining machines in the phase of material extraction and processing in LCA

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Abstract

Sustainability in the mining industry continues to be a challenge. Although there is research in this area, there are still no solutions supporting the assessment of environmental impact in this sector. Therefore, it is important to look for and conduct various types of analyses that will be useful in this area. Therefore, the objective of the research was to analyse the ecological footprint of mining machines in the first phase of the LCA life cycle (obtaining and extracting materials). The analysis was based on the example of a hydraulic actuator, which is considered crucial to control machines in the mining industry. The ecological footprint burdens analysed included direct and indirect land take, sequestration of carbon dioxide (CO_2) emissions, and the use of nuclear energy. Life cycle assessment was carried out using the OpenLCA software with the ecoinvent v3.10 database. It has been shown that the largest amount of emissions occurs during off-site treatment of nonsulphide waste, cogeneration of heat and energy (hard coal), production of ferrochrome, high carbon, 68% Cr, and heat production in an industrial furnace using hard coal. It is proposed to carry out improvement activities that will first contribute to reducing the main environmental burdens. Then, it will be possible to significantly reduce the negative environmental impact of the hydraulic actuator's extraction and processing of materials. The results from the analysis may be useful not only for products from the mining industry but also in other areas of activity using this type of machine.

Keywords

sustainability, LCA, ecological footprint, mining machinery, production engineering, mechanical engineering

Introduction

The mining industry has seen continuous technological growth in recent years. This is mainly due to the mines' difficult working conditions and the general dynamics of market development (Pacana et al., 2014b; Siwiec et al., 2019; Komasi et al. 2023). The development of this sector of activity is necessary because the mining industry provides the vast majority of materials that are used for infrastructure and everyday instruments (Gavurova et al., 2017; Kmecová & Androniceanu, 2024). However, it is associated with increasing concern for the natural environment, including societal consequences (Carvalho, 2017; Pacana & Siwiec, 2021; Zeidyahyaee et al., 2024). Therefore, in mining, attempts are increasingly being made to achieve sustainable development (Ostasz et al., 2022b; Pacana & Siwiec, 2022; Gavurova et al., 2021), for instance, through investments, long-term livelihoods of communities, or protection of the natural environment (Jenkins & Yakovleva, 2006; Siwiec & Pacana, 2022; Soltes and Gavurova, 2014). In this regard, there has been a growing interests of businesses to apply sustainability practices (Fahlevi, 2023; Keelson & Padi, 2024; Rózsa et al., 2023) from specific industries (Devkota et al., 2023) and firms applying these practices have become more competitive (Folgado-Fernández et al., 2023). Moreover, sustainability practices cause firms adopting innovative technologies (Civelek et al., 2023a), improving innovation capabilities (Civelek et al., 2023b), identifying various risk factors in their operations (Kuděj et al., 2023), and improve their social capital through building an atmosphere of trust and cooperation with stakeholders (Rozsa et al., 2022).

In the case of environmental impacts, life cycle assessment (LCA) is crucial (Finkbeiner et al., 2006), but its application in the mining industry is still limited (Awuah-Offei & Adekpedjou, 2011; Krmela & Šimberová, 2023), as concluded from the review of literature on the subject. Among other things, systematic and review studies were carried out, such as those of the study (Santero & Hendry, 2016), which verified current issues for LCA in the metal and mining industries. They presented methodological harmonisations that may improve the consistency and validity of taking into account individual data in this application area. Similarly, the authors of the article (Farjana et al., 2019) reviewed the impact of the mining and processing of materials on their life cycle. However, the authors of the article (Yao et al., 2021) implemented LCA as part of the analysis of impacts on and outside the plant. The mining life cycle and the recultivation of the area after mining were assessed. The authors of the mining industry article conducted analyses of water consumption in the life cycle (Shang et al., 2022). As a result, characterisation coefficients were developed that incorporated raw materials from minerals and metals in the spatial distribution of global mining production. In turn, the study (Erkayaoğlu & Demirel, 2016) made a comparative assessment of the life cycle of off-road vehicles and belt conveyors in opencast mining. Another example is the study (Dino et al., 2020), in which an analysis of the use of mining waste for the recovery of raw materials was carried out for the phase of extraction and processing of materials in LCA. Not only environmental factors but also technological and economic factors were taken into account. Similar research, that is, focussing on LCA for waste from the mining industry, was conducted by the authors of the work (Adrianto et al., 2023). Furthermore, in the context of generating a significant amount of waste from silica sand, the authors of the study performed a life cycle analysis for this material (Mitterpach et al., 2015), as well as an LCA analysis for silica sand presented by the authors of the work (Grbeš, 2015). However, the article (Moreau et al., 2021) made a life-cycle assessment comparing manual and automated equipment in underground copper mining. In this case, automating processes was shown to help reduce global warming. Analyses of the environmental impact of mining and the enrichment of mines with copper sulphate were also carried out. LCA was used for this purpose, and appropriate management actions in this regard were subsequently proposed, as presented in (Tao et al., 2022). Other examples of the application of LCA in the mining and quarrying industries are presented, for example, by (Davidson et al., 2016; Fritz et al., 2020; Masindi et al., 2022). In the context of the Bangladesh community, (Roy et al., 2023) explored ecological sustainability and coal extraction with the LCA approach. The findings established that climate damage accounted for 835kg of carbon emission equivalent. Likewise, (Fang et al., 2024) examined automotive strip steel LCA on carbon footprint. The inspection was conducted in the mining and transportation. The article eradicated outcome shows that the carbon footprint effect is estimated to be 2.721 kg. They recommended that the transition to eco-friendly energy will appreciate the LCA and environmental quality. (Ding et al., 2023) assess the LCA of hydraulic cylinders employing robustness empirical estimators like macroscopic fracturing and finite element evaluation on the end cap structure. The adoption of finite element examination illustrated that the hydraulic cylinder pollution effect was depreciated, improving production efficiency and sustainability. Nguyen et al. (2024) employed the LCA approach to test injection moulding processes for energy utilisation. The article's inspection of various LCAs indicated that it is crucial to look at the environmental effects of energy utilisation injection moulding as it identified the successful principle of LCA software integration in depreciating the ecological footprint.

The use of life cycle assessment (LCA) has been shown to be growing in terms of engineering assessment of products and systems. However, the use of the LCA method is still limited in the mining industry. Therefore, the objective of the investigation was to analyse the ecological footprint of mining machines in the first phase of LCA (the acquisition and extraction of materials in LCA). The analysis was based on the example of a hydraulic actuator, which is considered crucial to control machines in the mining industry. The life cycle assessment for acquiring and extracting materials for the hydraulic actuator was carried out using the OpenLCA programme with the ecoinvent v3.10 database.

Material and Methods

The main components of an excavator and a forklift with a high use rate in the mining industry were analysed. These were hydraulic cylinders. A hydraulic actuator is used to control these machines. There are single-acting and double-acting actuators. The single-sided cylinder has one oil connection. It is controlled by a three-way valve. It has a built-in bearing that slides out of the body through hydraulic oil. It is delivered under pressure. The bearing returns according to the return or gravity spring. On the other hand, double-acting hydraulic cylinders require a different type of pump and two pressure lines. The piston moves in two opposite directions. It is controlled by a four-way valve. The general production process of these elements is shown in Fig. 1.

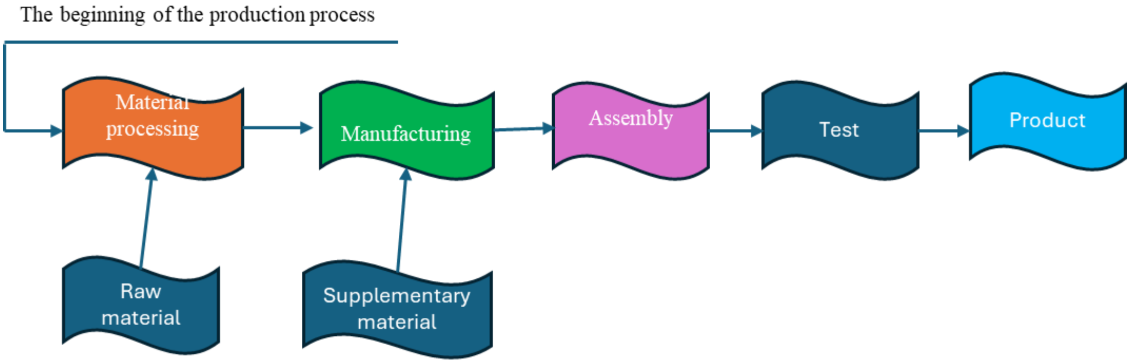

Fig. 1. Simplified diagram of the production process of the main components of an excavator and forklift

According to the authors of the article (Jun et al., 2019), the main elements of an excavator and a forklift include, among others: made of carbon steel and chrome molybdenum steel. A list of these materials (omitting irrelevant materials) is presented in Table 1.

Tab. 1. Hydraulic cylinder materials. Own study based on (Jun et al., 2019)

Materials	Weight (kg)
NBR (acrylonitrile butadiene rubber)	0.006
PTFE (poly(tetrafluoroethylene))	0.004
Urethane	0.054
Rolled steel material for overall construction	0.898
Bronze	0.330
Chrome-molybdenum steel	21.190
Carbon steel	24.283

A life cycle assessment (LCA) was carried out as part of the environmental impact analysis. The LCA method is an environmental management method. It concerns the assessment of environmental risks posed by a product or process throughout its entire period of use. The main phases of the life cycle are extraction and processing of materials, production of parts/components, use, and recycling. This approach is called "cradle to grave." The LCA method is considered a method of identifying and determining potential environmental loads, the procedure of which is determined by the ISO 14040 standard (Finkbeiner et al., 2006).

In the proposed approach, a life cycle assessment was performed for the first phase, i.e. material acquisition and extraction. This was due to the lack of this type of analysis that would thoroughly analyse the environmental burdens associated with the main products of the mining industry (hydraulic cylinders). The life cycle assessment for the first phase of these products was carried out in terms of ecological footprint, which is one of the key criteria of environmental burden in life cycle analyses (Čuček et al., 2015; Lehmann et al., 2016). The ecological footprint is defined in terms of the biologically productive land and water needed to produce the resources consumed. They are also necessary to remove waste generated during fuel consumption. According to the ecological footprint, the direct and indirect part of land take, sequestration of carbon dioxide (CO_2) emissions and nuclear energy use can be calculated (Mancini et al., 2016; Özbaş et al., 2019).

Life cycle assessment of the extraction and processing of materials for the hydraulic actuator was carried out with the OpenLCA software with the ecoinvent v3.10 database. As mentioned, the criterion for environmental burden was the ecological footprint.

Results

Emissions generated during the extraction and processing of materials necessary for the production of the hydraulic cylinder were limited to five main emissions, i.e., those having the largest amount of emissions compared to the others. The conversion unit was a square metre of impact per year of impact (m^2a). Initially, the sequestration of carbon dioxide (CO_2) emissions was analysed. The result is shown in Figure 2.

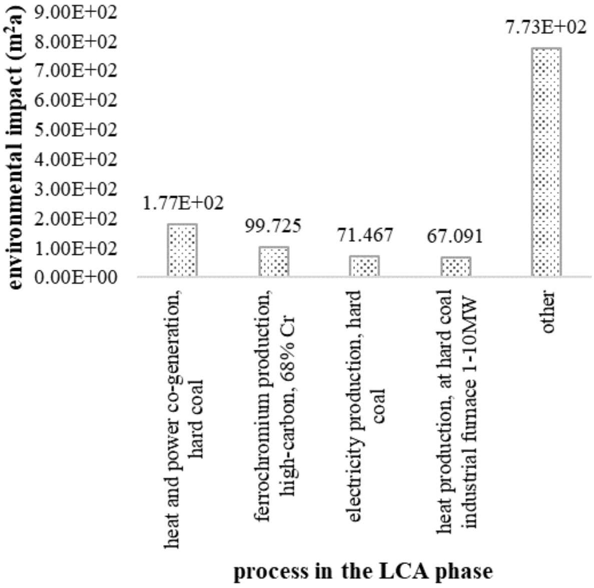

Fig. 2. Sequestration of carbon emissions during the extraction and processing of hydraulic actuator materials.

The highest amount of CO_2 emissions concerns heat and energy cogeneration, which includes hard coal and electricity (1.77E+2 m^2a). A much smaller amount of emissions (99.725 m^2a), but equally important compared to the others, concerns the production of ferrochrome, which has a high carbon content of 68% Cr. Subsequently, significant CO_2emissions (71.467 m^2a) were observed to be related to the production of electricity from hard coal and slightly fewer emissions (67.091 m^2a) arise during the production of heat in an industrial furnace using hard coal (furnace with a power of 1-10 MW). It is possible to observe that, in addition to emissions related to the main processes, 7.73E+02 m^2a of other CO_2 emissions are also produced in the extraction and processing of materials.

Emissions resulting from land occupation during the extraction and processing of materials necessary for the production of the hydraulic actuator were also analysed. The results are shown in Figure 3.

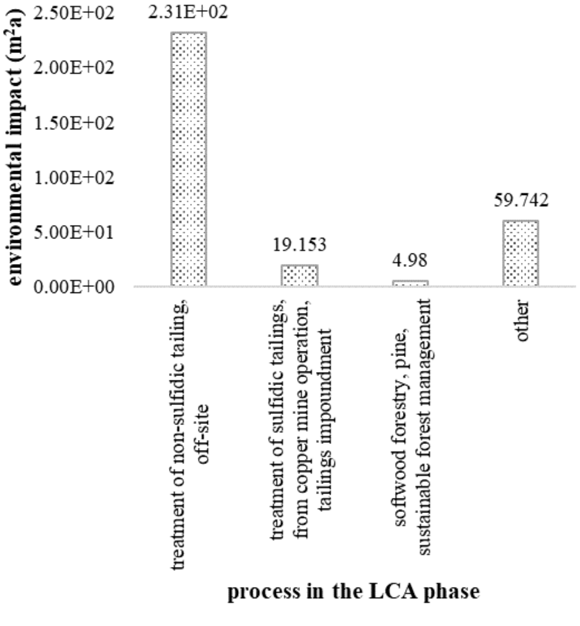

Fig. 3. Emissions from land taken during the extraction and processing of hydraulic actuator materials.

The largest amount of land take emissions resulting from the extraction and processing of hydraulic actuator materials occurs during off-site treatment of non-sulphide waste (2.31E+02 m^{2}a). Significantly fewer emissions are generated during the treatment of copper mines, the storage of post-flotation waste (19.153 m^{2}a), and the occupation of land related to coniferous forests in terms of sustainable forest management (4.98 m^{2}a). Other emissions were also identified in other processes (59.742 m^{2}a).

Then, emissions related to the use of nuclear energy during the extraction and processing of materials were analysed. The result is shown in Figure 4.

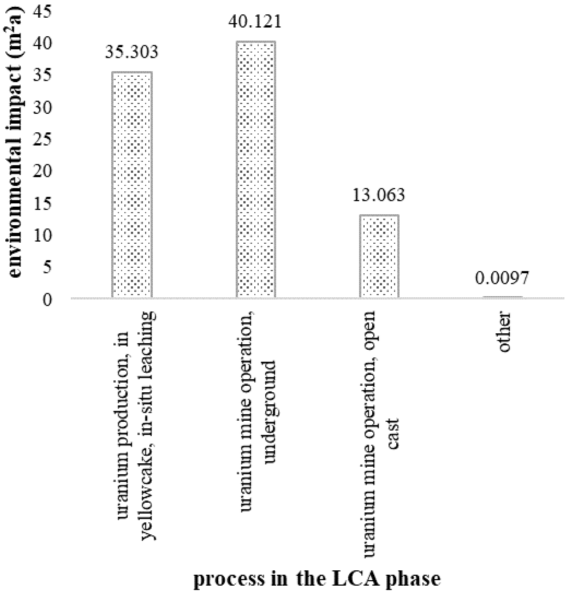

Fig. 4. Emissions related to the use of nuclear energy in the extraction and processing of hydraulic actuator materials.

It can be seen that the largest amount of emissions is related to the operation of underground uranium mines (40.121 m^{2}a). Next, the emissions concern the production of uranium (in this case, in cake, on-site leaching), which amounts to 35.303 m^{2}a. The smallest amount of emissions concerns the operation of a uranium mine (opencast casting), which is 13.063 m^{2}a. The indicated emissions are the most important because the remaining emissions are only 0.0097 m^{2}a.

Then, the total emissions generated during the extraction and processing of materials for the hydraulic actuator were analysed, considering the environmental impact of the ecological footprint. A summary of the most important emissions for this environmental load is presented in Figure 5.

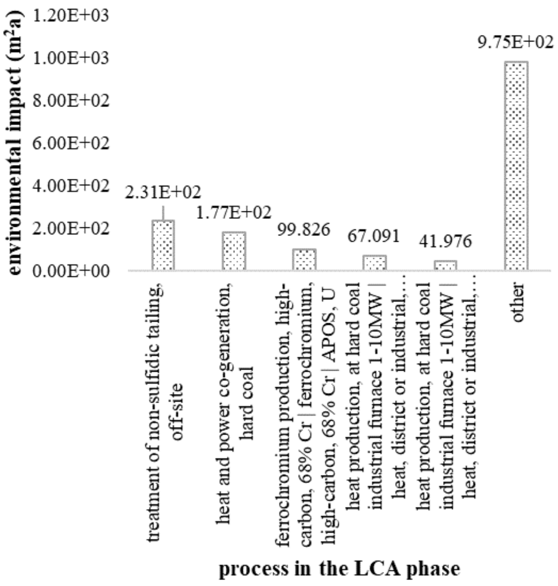

Fig. 5. Environmental footprint burdens created during the extraction and processing of hydraulic actuator materials.

Analysing the overall environmental burden on the ecological footprint of the process of extraction and processing of materials for the hydraulic actuator, it was shown that the largest amount of emissions arise during off-site treatment of non-sulphur waste (2.31E+02 m^2a). The heat and energy cogeneration (hard coal) is characterised by half as many emissions but is equally effective (1.77E+02 m^2a). Next, it is the high carbon ferrochrome production process, 68% Cr, for which 99.826 m^2a of emissions were recorded. Relatively slightly fewer emissions are produced during heat production processes using an industrial hard coal furnace (67.091 m^2a and 41.976 m^2a). It has been shown that improvement actions are necessary to limit the negative environmental impact in the indicated processes related to the extraction and processing of materials. It is then possible to significantly reduce the environmental burden on the ecological footprint and thus reduce the overall emissions over the life cycle of the hydraulic actuator.

Discussion and conclusions

The mining industry provides a significant number of materials that are used in other industries. Increased activity in the mining and mining sector is also associated with the emergence of an increasing number of negative environmental impacts (Ostasz et al., 2022a; Pacana et al., 2014a; Siwiec & Pacana, 2021). However, the issue of reducing environmental impacts in mining is still an open topic. This applies not only to materials obtained in the mining process but also to the machines and equipment used for this purpose.

Therefore, the objective of the investigation was to analyse the ecological footprint of mining machines in the first phase of LCA (the acquisition and extraction of materials in LCA). The analysis was based on the example of a hydraulic actuator, which is considered crucial to control machines in the mining industry. The life cycle assessment for the acquisition and extraction of materials for the hydraulic actuator was carried out using the OpenLCA software with the ecoinvent v3.10 database. After the analysis, it was concluded that the main environmental burdens for the ecological footprint concerned:

- for CO_2 emissions: heat and energy cogeneration process (1.77E+2 m^2a), ferrochrome production, high carbon 68% Cr (99.725 m^2a); production of electricity from hard coal electricity production (71.467 m^2a); heat production using an industrial furnace fuelled with hard coal (furnace with a power of 1-10 MW) (67.091 m^2a),
- for land take: off-site treatment of non-sulphur waste (2.31E+02 m^2a); the processing of sulphur waste from copper mines, storage of post-flotation waste (19.153 m^2a); occupation of the area concerning coniferous forestry in terms of sustainable forest management (4.98 m^2a),
- for nuclear energy: underground uranium mine exploitation (40.121 m^2a); uranium production (in this case in cake, leaching on site) (35.303 m^2a) and uranium mine exploitation (opencast casting) (13.063 m^2a).

In the case of a comprehensive analysis of environmental loads for the ecological footprint in the process of extraction and processing of materials for a hydraulic actuator, it was shown that the largest amount of emissions arise during the treatment of non-sulphide waste off-site (2.31E+02 m^2a), and then during the heat and energy cogeneration process (hard coal) (1.77E+02 m^2a). Other processes that also have a significant negative impact on the high carbon environment are the ferrochrome production process, 68% Cr (99.826 m^2a), and the heat production process in an industrial hard coal furnace (67.091 m^2a and 41.976 m^2a).

It was concluded that improvement activities that limit the negative impact on the environment in extracting and processing materials for the hydraulic actuator should be related to the identified main environmental impacts. These actions should be taken first for the largest emissions and then for the next ones that have a significant contribution to the creation of the ecological footprint.

A limitation of the research is that the analysis focuses only on the first phase of LCA (material extraction and processing). Additionally, remember that the analysis results may vary depending on the assumptions made or the system's limits. Therefore, as part of future research, it is planned to extend the life cycle assessment to other phases and to conduct this type of analysis for other mining products.

The analysis results may be useful not only in improving hydraulic actuators in the mining industry. They can be an important source of knowledge for taking pro-environmental activities in other areas of activity, for instance, enterprises using this type of machine and striving for sustainable development.

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