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Analysis of the main environmental burdens by life cycle assessment of heavy construction equipment in the material extraction phase

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Abstract
Construction activity is considered to be one of the main negative environmental burdens. This is largely due to the equipment used in this activity, particularly complex heavy machinery. Hence, the aim was to analyse the main environmental burdens occurring in the phase of extraction and processing of materials for complex heavy equipment used in construction. The main burdens determining the emission of carbon footprint (CO_2), land occupation, and consumption of material resources were identified. Analyses were carried out using the OpenLCA program with the Ecoinvent 3.10 database. The results showed that the main burdens concern, for instance, the production of pig iron or sintered iron. Directing pro-environmental activities to reduce the identified burdens can contribute to a significant reduction of the negative impact of heavy construction equipment in their life cycle. This procedure is beneficial within the framework of activities for the sustainable development of construction.

Keywords
construction, carbon dioxide emissions, LCA, material extraction, mechanical engineering.

Introduction

In recent years, environmental and energy problems have become increasingly become a priority. Therefore, actions for sustainable development are being increasingly recognised by architects and civil engineers (Bon and Hutchinson, 2000; Ostasz et al., 2022). The scale of the challenges related to environmental degradation and growing energy needs force us to take decisive actions to solve them. In this context, more and more attention is being paid to sustainable development, especially in the field of construction. Sustainable development in this field is gaining importance, as noticed by both architects and civil engineers, who are increasingly trying to consider ecological principles in their projects and activities. The construction industry increasingly promotes sustainable economic development but is still considered a major sector in generating unsustainable environmental practices (Ibadov, 2020; Siwiec et al., 2023). Sustainable construction corresponds to a sustainable building, i.e. one that is friendly to the natural environment (Robichaud and Anantatmula, 2011). Sustainability should be integrated into construction projects from the initial design and feasibility phases, consistently monitored throughout the project's duration, and effective project management is crucial for achieving sustainable results (Kiani et al., 2021). Its creation concerns the creation of innovations to protect the health of society and to minimise the environmental impact based on ecological design principles.

According to the Environmental Protection Agency (Kibert and Coble, 1995), sustainable architecture is one that is based on the entire life cycle of a building, supports the use of environmentally responsible practices, or reduces emissions and protects resources (Ulewicz et al., 2023). This also applies to the thoughtful selection of location, design, and construction method, as well as operation, maintenance, and even possible demolition (Wu and Wang, 2013; Pacana and Siwiec, 2022). The goal of sustainable construction is to reduce the impact of the construction industry on the environment as a whole. This is possible through the selection of materials, the development of efficient energy use patterns, and the concept of using green technologies (Wang, 2023; Siwiec and Pacana, 2022). In this area, frugal innovation is of particular importance, and it is an elementary part of activities for sustainable development. It focuses on the minimum use of resources, the adoption of price savings, and inclusiveness (Pacana and Siwiec, 2021). However, frugal innovation is still not widely practised in the construction industry (Du Plessis, 2007; Korzyński et al., 2009; Ebolor et al., 2022). Therefore, it is important to find effective solutions for sustainable development in this area of activity.

A literature review on the subject includes actions for the sustainable development of construction. The research was carried out in the area of innovations based on the sustainable development of communities in the context of housing construction projects. The techniques of using straw bale and bamboo trees were analysed as a perspective of reducing the ecological footprint and building new collective actions in the form of exerting a greater impact on society (Seyfang, 2010; Zea Escamilla et al., 2018). Energy savings through building energy efficiency were analysed (Chel and Kaushik, 2018; Pacana et al., 2015). The design of the building, the materials used, the machines (mainly those with low energy demand), and the use of renewable energy sources (RES) technologies were verified. Among the key ones were solar energy, low-energy-intensive building materials, and energy-saving machines and devices. Research was also carried out on the possibilities of using new technologies for processing solid waste, including municipal waste (Peng et al., 2023). It has been observed that the use of properly processed municipal waste can provide over 60% of the use of natural gas and even 39% of the use of coal. Other studies, for instance, Jensen et al. (2018), focused on the analysis of tools supporting design decisions, including certification of sustainable development of buildings. It has been observed that legal regulations are of significant importance in this regard, and traditional energy renovation systems focus primarily on heating and lighting systems with a tendency to emphasise the possibility of social goals. In the work of Ramírez-Villegas et al. (2019), a life cycle assessment was carried out for a residential building where renewable energy is dominant. Different scenarios with reduced room temperatures were analysed, including improving the thermal properties of selected building materials and considering heat recovery for the ventilation system. The energy use processes, including the construction and installation processes, were examined. Analyses were also conducted aimed at changing the building as part of the implementation of government goals for houses on brownfields (for instance, Adams, 2004). In particular, new homes are expected to be built on previously developed land or improved as a result of the reconstruction of existing buildings. The results of these analyses indicate that the construction of brownfields will result in beneficial and future-orientated practices and technologies. The aspects of sustainable development of buildings were also analysed in terms of life cycle assessment, where the analyses focused on environmental and economic aspects. Integrations of building information modelling, including computer simulation, optimisation, and dynamics, have been carried out (for instance, Marzouk et al., 2016).

The issues of sustainable development in construction have been observed to appear in various areas of their application. Despite this, construction is still considered one of those activities that is not conducive to the protection of the natural environment. Therefore, it is important to constantly improve its various areas due to efforts to limit negative climate change and improve the quality of life of society. This is in line with the nature of sustainable development, in which it is justified to perform environmental assessments at each phase of the life cycle of processes and products created from them (Pacana et al., 2023).

Life Cycle Assessment (LCA) is a method for estimating the environmental impact of a product or system in its life cycle. According to ISO 14040, it transforms the input and output elements, where these data should be in an adopted functional unit. It is also necessary to determine the system boundaries, which can be based on four main phases, i.e. material acquisition and extraction, production, use and end of life. The analysis is carried out in terms of the selected criterion or criteria that allow for estimating the environmental impact in relation to them.

In construction, heavy equipment is used mainly, which causes significant environmental burdens already in the early stages of their creation. It is necessary to process a large amount of materials, which includes their acquisition and extraction, i.e. the first phase of life cycle assessment (LCA). In connection with this, the aim of the study was to conduct an analysis of the main environmental burdens that occur in the phase of extraction and processing of materials from the life cycle assessment of complex heavy equipment.

This is consistent with findings by Gavurova et al. (2024), who emphasise the importance of effective management and assessment in various industries, including construction. Similarly, Smolanka et al. (2024) discussed the integration of information technologies, which could assist in efficiently managing construction processes with sustainable practices. Furthermore, Gavurova et al. (2023) highlighted the importance of fuzzy decision support models, which could be applied in evaluating the sustainability of construction projects.

Materials

The subject of the analysis was the complex heavy equipment used in construction to transport and move heavy materials. It is considered a reference object, i.e., a generalisation of products of a similar type. Due to the nature of the analysis focused on the phase of obtaining and extracting materials, it is assumed that this equipment can be presented in a comprehensive form as off-road construction machines with a diesel engine. In this case, these were machines with a bucket attached to the cabin. These machines are characterised by a large size body, a complex structure, and a significant number of components, including high fuel consumption. Additionally, they are highly very durable; depending on their intended purpose, they can have varying yet relatively similar average workloads, where depending on the purpose, they can have a different, but relatively similar, average workload, fuel consumption rate, and level of wear (operation). The generalisation of construction machines in the presented analysis follows the authors of Kwak et al. (2012), where it was assumed that the reference machine weighs 83,000 kg. The set of materials for the analysis is presented in Table 1.

Tab. 1 Materials used in complex heavy machinery

Type of material	kg
Low-Alloyed Steel	51078.2
High-Alloyed Steel	7312.3
Unalloyed Steel	937.9
Cast Iron	14599.7
Aluminum Alloy (AlMg3)	99.6
Primary Aluminum	830
Lead	149.4
Synthetic Rubber	5585.9
Oil	738.7
PP (Polypropylene)	124.5
HDPE (High Density Polyethylene)	356.9
Flat Glass (Coated)	672.3
Others (electronics, switches, control units, etc.)	265.6

Source: own elaboration based on (Kwak et al. 2012).

Materials with a relatively small share of the total materials have been omitted.

Methods

Construction machines were analysed as part of the assessment of the environmental burdens occurring in the first phase of their life cycle, i.e. the acquisition and extraction of materials used for their production. The Life Cycle Assessment (LCA) method, according to ISO 14040 (Finkbeiner et al., 2006), was used for this purpose. Life cycle assessment (LCA) is a method used to assess the total environmental impact quantitatively. In the context of the entire life cycle, it is used "from cradle to grave", where the processes or products made from them are analysed in their entirety, taking into account all life stages (Pacana et al., 2023).

The results of the LCA analysis can be used to make good pro-ecological decisions. Depending on the needs, performing a comprehensive life cycle assessment or focusing the analysis on selected LCA phases is possible. In this case, the system boundaries were narrowed to estimate the negative environmental impact during acquiring and extracting materials from heavy machinery. The boundaries of the adopted system are shown in Figure 1.

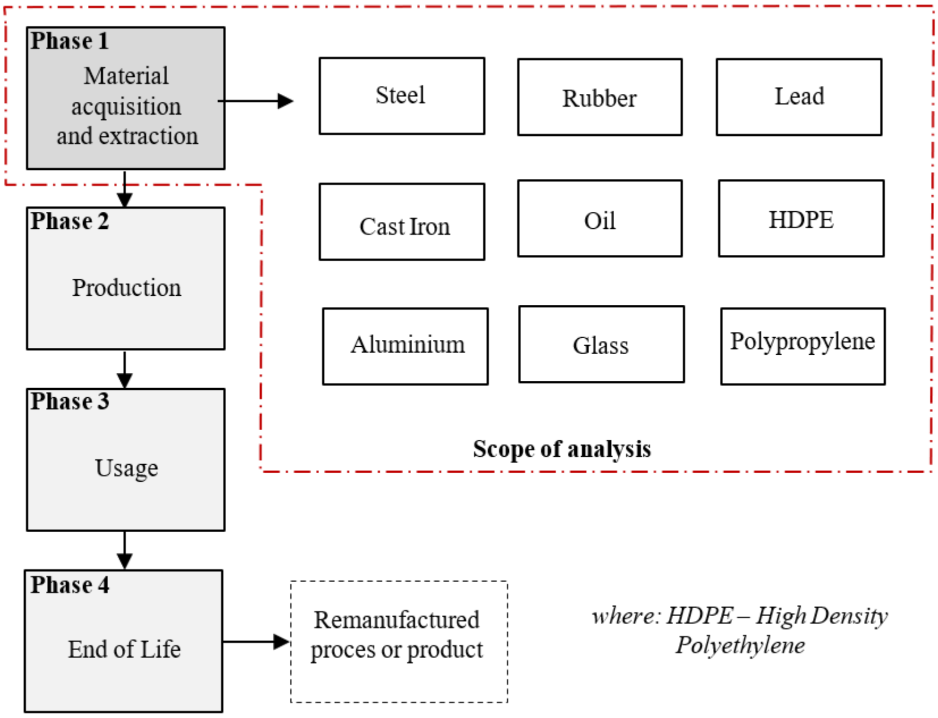

Fig. 1. System boundaries. Own elaboration based on (Kwak et al., 2012).

Then, a functional unit was defined according to the life cycle assessment method. It allows the standardisation of the accepted data and supports the uniform comparison of the research subject. The functional unit is usually presented quantitatively in relation to the product function. Its task is to standardise calculations within the estimated environmental loads. Therefore, it can be used as voluntarily as possible in relation to the analysed research product. In the presented example, following the authors of the work (Kwak et al., 2012), it is assumed that the functional unit concerns the service life of heavy machinery used in construction. Hence, it was assumed that the functional unit is an average of 20,000 hours of operation of this type of machinery.

Next, selecting a category for the analysis of environmental burdens was necessary. Based on a review of previous work (Ströbele, 2013; Melià et al., 2014), it was observed that it is important to consider, for example, carbon dioxide (CO_2) emissions, land occupation (including land development and modernisation), or the use of material resources (metals/minerals), i.e. the amount of materials that contribute to the depletion of metal and mineral resources. Due to the occurrence of a large number of different environmental burdens, we limited ourselves to the main ones in each of these categories. The main burdens are considered to be those that have the largest quantitative share in relation to the others, where the larger the share, the more significant the environmental aspect is (it has a greater negative impact on the environment) (Ashby M. F., 2009).

These concepts are also supported by recent research on decision-making models and sustainability in various fields. For example, (Moravec et al., 2025) emphasised the importance of algorithmic personalisation and digital literacy in addressing knowledge gaps in sustainable practices. Similarly, (Skare et al., 2023) discussed large-scale decision-making models that can be applied to funding decisions in infrastructure development, which could benefit from incorporating life cycle assessments in evaluating environmental burdens.

Results

The analysis was performed with OpenLCA 2.0.0 and the Ecoinvent 3.10 database. Initially, the main CO_2 emission burdens were identified as follows:

- pig iron production (1.22E+05 m^2a),
- heat production at hard coal industrial furnace (4.06E+04 m^2a),
- iron sinter production (3.69E+04 m^2a),
- coke production (1.93E+04 m^2a),
- quicklime production, in pieces, loose (1.39E+04 m^2a).

The visualisation of the main environmental burdens for carbon dioxide emission categories is presented in Fig. 2.

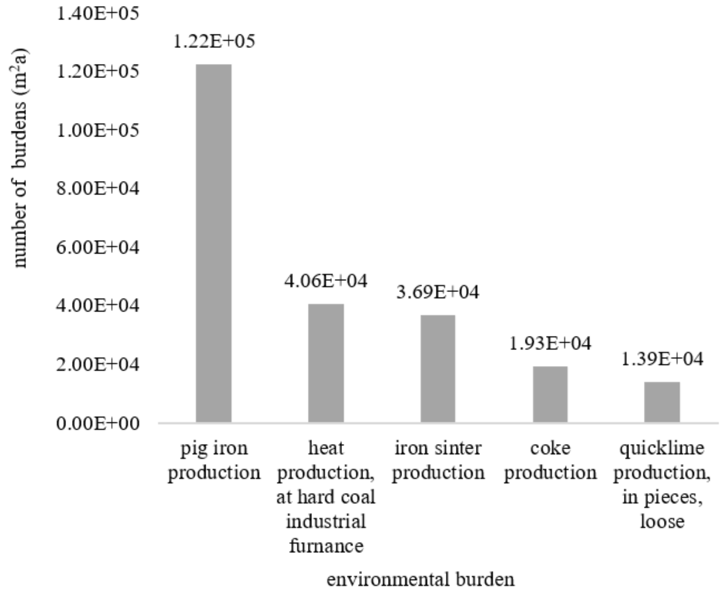

Fig. 2. Main environmental burdens for CO_2 emissions.

In turn, within the framework of land development and modernisation, the main environmental burdens occur for the following reasons:

- hardwood forestry, beech, sustainable forest management (1.81E+03 m^2a),
- hard coal mine operation and hard coal preparation (8.81E+02 m^2a),
- softwood forestry, pine, sustainable forest management (8.41E+02 m^2a),
- hardwood forestry, birch, sustainable forest management (8.29E+02 m^2a),
- road construction (8.15E+02 m^2a).

The visualisation of the main environmental burdens for land occupation emission categories is presented in Fig. 3.

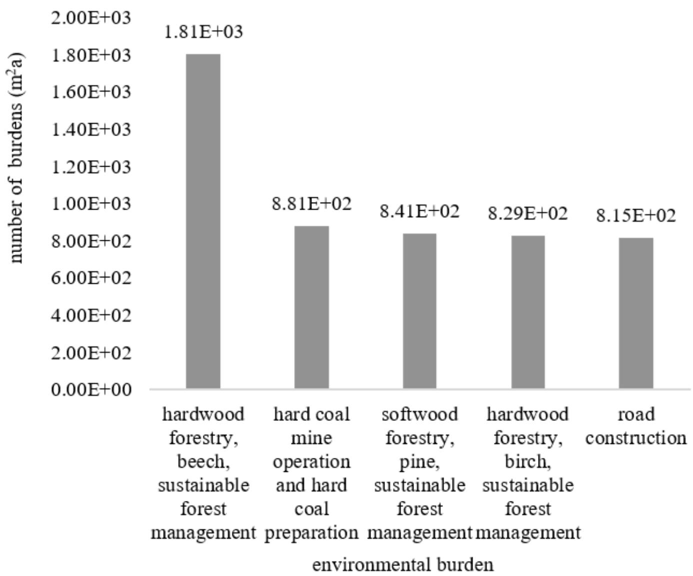

Fig. 3. Main environmental burdens for land occupation emissions.

However, in the case of the consumption of material resources (considering metals and minerals), the main environmental burdens were identified for:

- chromite ore concentrate production (5.79E-01 kg Sb eq.),
- copper mine operation and beneficiation, sulfide ore (3.90E-01 kg Sb eq.),
- zinc mine operation (1.46E-01 kg Sb eq.),

- ferronickel production (1.31E-01 kg Sb eq.).

The visualisation of the main environmental burdens for nuclear emission categories is presented in Fig. 4.

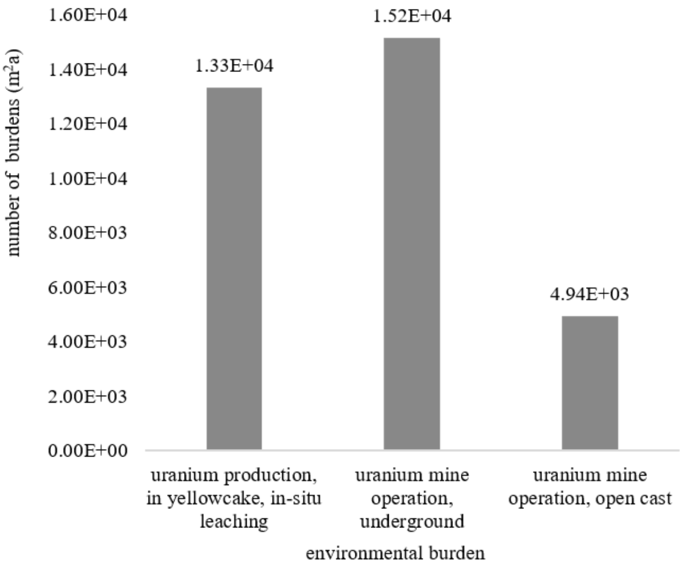

Fig. 4. Main environmental burdens for nuclear emissions.

In the case of the environmental categories, the conversion unit was a square metre of impact per year of a given impact (m^2a) or a kilogramme of antimony equivalents (kg Sb eq). It was concluded that it is effective to take action to reduce negative environmental impacts during the production of pig iron, successively within the production processes (heat generation and iron sintering). A slightly smaller, similar amount of environmental burdens is generated during the production of coke and quicklime. It is also important to pay attention to the environmental burdens associated with the development and modernisation of the area, where a similar amount of these burdens is associated with forest management. In turn, when analysing the consumption of material resources, it is necessary to undertake improvement actions within the production of chromite ore concentrate and the operation of copper mines. Taking action to address the main environmental burdens can significantly contribute to reducing the negative impact of complex heavy machinery on the environment during its life cycle.

Conclusions

In order to meet the contemporary challenges facing the construction industry, the concept of sustainable development is increasingly being promoted. Sustainable construction is an approach that aims to minimise the negative impact on the environment while ensuring the efficiency and quality of construction processes. As part of this idea, it is crucial to select appropriate building materials that not only meet strength and aesthetic requirements but also have a smaller carbon footprint and can be recycled. Another important element is the development of appropriate energy use patterns during construction and during the operation of facilities, including the implementation of energy-saving technologies and systems that reduce energy demand.

A sustainable approach to construction also includes the increasingly widespread use of green technologies that support environmental protection, such as renewable energy sources or rainwater management systems. The implementation of solutions that support the reduction of harmful substance emissions, such as building materials with low volatile organic compound emissions, is also key in this context.

However, in addition to the selection of materials and technologies, an equally important element in the process of sustainable construction is the use of environmentally friendly construction equipment, especially when it comes to complex machines that are necessary for construction work. In the case of these machines, such as cranes or excavators, the key challenge is to reduce their impact on the environment, including both during production and use. The production of heavy equipment is associated with the acquisition and processing of large amounts of raw materials, as well as CO_2 emissions and energy consumption throughout the life cycle of these devices, including in the process of their disposal or recycling.

Therefore, the search for solutions supporting the development of ecological technologies in the design, production and use of construction machines is becoming a key task in the process of striving for sustainable development in construction. Thanks to innovative solutions, it is possible to significantly reduce the negative impact of these machines on the environment, as well as improve energy efficiency, which in the long term leads to savings and lower consumption of resources.

Due to the significant amount of materials used in this type of machine, it was considered crucial to analyse the environmental burdens from the first phase of the life cycle, which is extraction and processing. The main environmental burdens were analysed, taking into account carbon footprint (CO_2) emissions, land occupation, and material consumption. Analyses were carried out using the OpenLCA programme with the Ecoinvent 3.10 database. The main environmental burdens were identified for the mentioned categories, thus proposing the sequence of improvement actions.

In the case of CO_2 emissions, the largest negative impact is from pig iron production (1.22E+05 m^2a). Subsequently, similar impacts are associated with heat production at hard coal industrial furnaces and iron sinter production. Next, emissions resulting from land occupation were considered. The largest share was from hardwood forestry, beech, and sustainable forest management (1.81E+03 m^2a). When analysing emissions from nuclear energy, similar impacts were found for uranium production, in yellowcake, in-situ leaching, and underground.

Taking action that focuses on the greatest environmental burdens can contribute to a noticeable minimisation of negative environmental impacts not only in the phase of material extraction and processing but also in terms of the entire life cycle. The results of the analysis can support managers, designers, and other interested parties in their efforts to promote sustainable construction development.

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