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Life cycle assessment (LCA) of heavy vehicles used in the mining industry

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Abstract
The environmental problems are constantly worsening. This is visible as a result of increased production and use of means of transport. Although environmental impact assessment is practised in this sector, there is a lack of research dedicated to heavy vehicles. Therefore, the objective was to perform a life cycle assessment (LCA) of heavy vehicles used in mining (extractive industry) to determine which vehicles have the lowest environmental impact. A life cycle assessment of battery and diesel trucks used in mining was performed. The results of the analysis indicated that electric trucks have a lower environmental impact. However, the method is applicable to the analysis of any vehicle. It can be used by an entity (expert) to select vehicles with the lowest environmental impact in LCA. At the same time, it will be useful in assessing the environmental impact of heavy vehicles, including mining vehicles used in mining. The originality of the article is the method presented, which improves the calculation process as part of the vehicle life cycle assessment.

Keywords
LCA, environmental impact, vehicle, truck, mining industry, mechanical engineering

Introduction

Currently, environmental issues are becoming increasingly important (Siwiec & Pacana, 2021a), mainly in the area of transport. Therefore, newer methods are being developed to support the assessment of environmental impact in the transport sector (Folęga & Burchart-Korol, 2017). Electric and hybrid drive systems are considered promising technologies for vehicle drive. At the same time, they can reduce greenhouse gas and other emissions from road transport (Siwiec & Pacana, 2021b; Wang & Tang, 2022; Gavurova et al. 2023). This is due to the fact that electric drive systems are more energy efficient compared to conventional combustion engines (e.g., fueled by gasoline or diesel) and do not emit exhaust emissions (Nordelöf, Messagie, Tillman, Ljunggren Söderman, & Van Mierlo, 2014a). The trade-off between the benefits of operating vehicles with different types of drives can be estimated using life cycle assessment (LCA) (Pacana, Siwiec, Bednárová, & Petrovský, 2023; Proske & Finkbeiner, 2020; Siwiec & Pacana, 2021c; Turner, Oyekan, Garn, Duggan, & Abdou, 2022).

For example, in the article (Zheng & Peng, 2021), the authors analyzed vehicle life cycle emissions, comparing battery electric vehicles and vehicles with internal combustion engines, including vehicles with hybrid or diesel engines. For this purpose, a new measure of analysis was proposed, i.e., the square root of power and range (reflecting the main performance of the powertrain). However, the authors of the article (Liu et al., 2022) assessed the life cycle of light vehicles. The analysis was aimed at demonstrating the impact of the recycling effect on the choice of materials in such a vehicle. Another example is the article (Pell, Wall, Yan, Li, & Zeng, 2019; Pacana et al., 2014), in which the authors focused on the raw material extraction phase in the context of vehicle LCA. Research covered the nature of the impact of raw materials on the environment. The authors of the article also carried out research that included the assessment of the environmental impact of batteries in the recycling phase (Beaudet, Larouche, Amouzegar, Bouchard, & Zaghib, 2020). They also analyzed the economic factors for battery recycling as well as the financial and technological challenges involved in recycling. In turn, the study (Aichberger & Jungmeier, 2020) presented an analysis of lithium-ion batteries that were assessed for their environmental impacts within the LCA phases. Research on batteries used in vehicles in the context of LCA was also carried out by authors of works, e.g. (Chordia, Nordelöf, & Ellingsen, 2021; Davidson, Binks, & Gediga, 2016).

As reported by the study authors (Song, Pettersen, Pedersen, & Røberg, 2017), LCA is widely used to assess the environmental impact of transport modes. However, its use to analyze vehicles from the mining industry is still limited. This is an important issue because the global mining industry is responsible for approximately 8% of global carbon dioxide emissions (Hawkins, Singh, Majeau-Bettez, & Strømman, 2013a). Studies that included LCA of vehicles used in mining were conducted, for example, by the authors of the article (Song et al., 2017; Kelemen et al. 2021). The analysis concerned an underground copper ore mine. However, in studies, for example, Chàfer, Sole-Mauri, Solé, Boer, & Cabeza, 2019; van den Oever, Costa, & Messagie, 2023, life cycle assessments of heavy vehicles, e.g. trucks, were carried out. Analyses of the environmental impact of heavy vehicles with respect to their impact throughout their entire life cycle have also been presented in studies, for example (Fries & Hellweg, 2014; Jahangir Samet, Liimatainen, & van Vliet, 2023; Lyu, Pons, & Zhang, 2023; Tayarani & Ramji, 2022). Nevertheless, the research area of the use of LCA analysis in the mining industry is still limited.

Therefore, the aim of the article was to assess the life cycle of heavy vehicles used in mining (extractive industry) to determine the vehicle with the lowest environmental impact. As part of the research, a method was proposed to support the LCA assessment of this type of vehicle. The method was tested for trucks with electric and diesel engines.

Material and Method

As part of the research, a method was developed to support the life cycle assessment (LCA) of vehicles. LCA is an environmental impact assessment method that covers any industrial activity (Frischknecht, Wyss, Büsser Knöpfel, Lützkendorf, & Balouktsi, 2015; Lagerstedt, Luttropp, & Lindfors, 2003). It concerns the analysis of products or services from raw material extraction to the processing of waste (Saadé et al., 2022; Varun, Bhat, & Prakash, 2009). The method was developed in five main stages. The algorithm of the method is presented in Fig. 1.

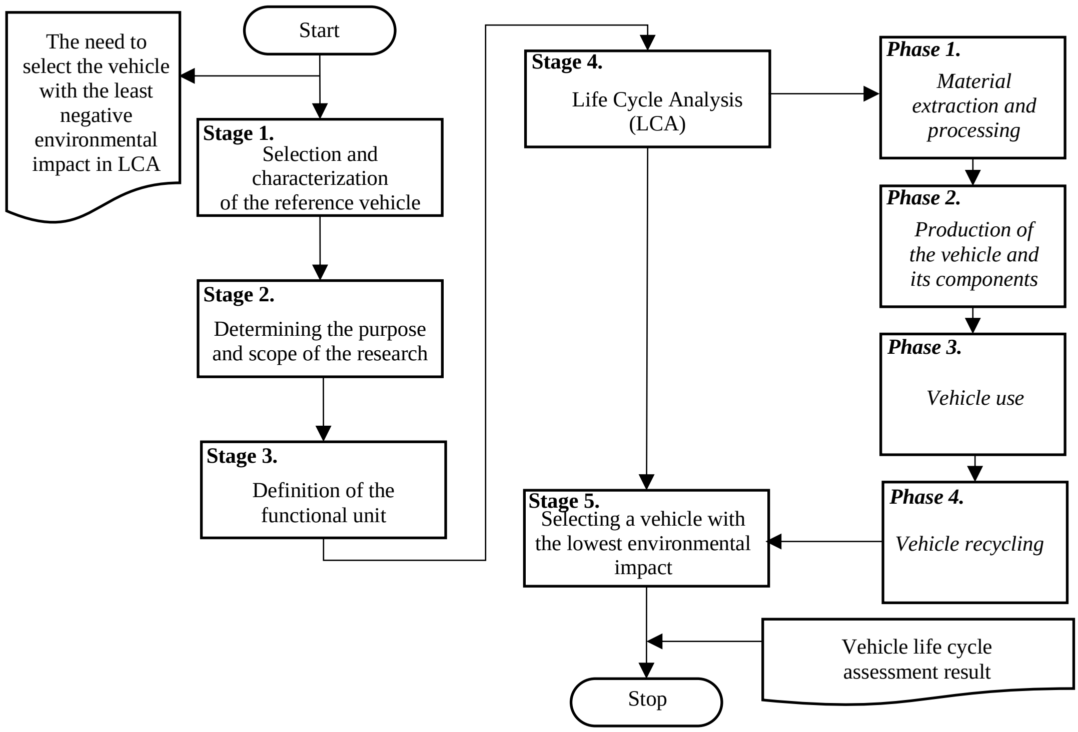

Fig. 1. Algorithm of a method supporting the vehicle life cycle assessment.

The characteristics of the procedure at individual stages of the method are presented later in the article.

Stage 1. Selection and characterization of the reference vehicle

The analysis is performed for the reference vehicle, which is the vehicle selected for analysis. It is a generalization of vehicles of a similar type. Depending on the needs of the entity (expert, dealer, manufacturer), it is possible to select one or more vehicles that will be compared to each other. This decision is made by the entity using the proposed method. The reference vehicle can be any. In the case of a larger number of vehicles, you should select vehicles that differ in an important feature (criterion), e.g. type of drive. As part of the proposed approach, it is assumed that the vehicles will belong to the group of heavy vehicles used in mining and the extractive industry. Vehicles selected for analysis should be characterized according to the main parameters that are most often provided in the specifications. According to the GREET v1.3.0.13991 model and based on the literature on the subject (Nordelöf, Messagie, Tillman, Ljunggren Söderman, & Van Mierlo, 2014b; Wong, Ho, So, Tsang, & Chan, 2021; Pacana et all., 2014), it was assumed that the main components of vehicles are: body, chassis, drive system, traction engine, electronics and battery. However, the main materials used to produce mining vehicle components are steel, aluminium, natural, rubber, and others.

Stage 2. Determining the purpose and scope of the research

The purpose of the research is determined by the entity (expert). It was assumed that the aim was to assess the environmental impact of heavy vehicles used in mining and the extractive industry. Depending on the needs, the detailed aim of the analysis may be to compare various heavy vehicles that differ significantly from each other. For this study, two reference vehicles with a diesel engine and an electric motor were analyzed. The environmental impact of vehicles mainly concerns the consumption of energy, materials, carbon dioxide (CO_2), emissions of pollutants into the air, and waste generated. The research included analyzing the environmental impact of vehicles throughout their entire life cycle (LCA). Therefore, the scope of the research includes LCA phases, i.e., 1) material extraction and processing, i.e. processes of obtaining raw materials necessary for the production of the vehicle, 2) production of the vehicle and its components, i.e. production of the necessary vehicle components, 3) vehicle use, including all indirect impacts that are related to the use of the vehicle, e.g. fuel consumption, tyre or oil wear, 4) vehicle recycling, concerns the recycling of recyclable components, including battery recycling (if present in the vehicle) (Pacana et al., 2023). These phases are characterized in detail in the fourth stage of the method.

Stage 3. Definition of the functional unit

A functional unit allows you to normalize a database (Hawkins, Singh, Majeau-Bettez, & Strømman, 2013b; Wong et al., 2021), in this case, in terms of the reference vehicles analyzed. Therefore, it is necessary to define this unit as part of the research carried out. Based on the literature on the subject (Balboa-Espinoza, Segura-Salazar, Hunt, Aitken & Campos, 2023; Hawkins et al., 2013a; Van Mierlo, Messagie & Rangaraju, 2017), it is assumed that this unit is defined according to the estimated period of vehicle use. In the case of heavy mining vehicles and those used in the extractive industry, this is 21,500 effective working hours. Following the authors of the studies

(Balboa-Espinoza et al., 2023; de Souza et al., 2018), environmental impact is determined for one ton of material transported per 1 km.

Stage 4. Life Cycle Analysis (LCA)

Life cycle analysis (LCA) of vehicles is a quantitative method that allows you to determine the potential impact on the environment. This impact is related to the vehicle's life cycle and mainly concerns the analysis of energy and material consumption, carbon dioxide (CO_2) consumption, air pollution emissions, and waste (Figure 2).

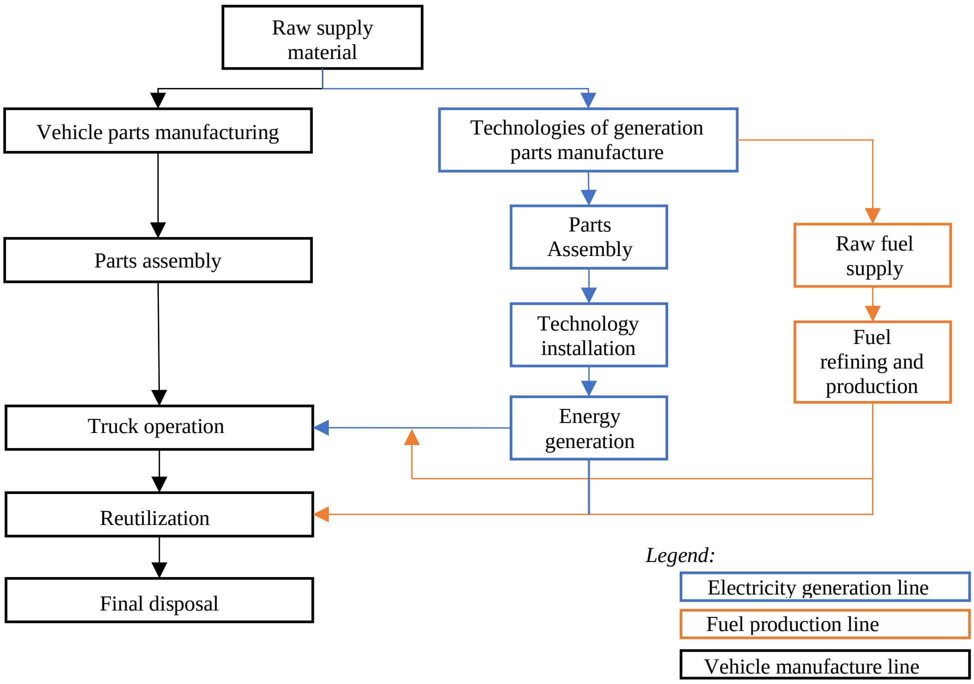

Fig. 2. Life cycle of heavy vehicles used in mining. Own studies based on (Balboa-Espinoza et al., 2023).

LCA results may vary depending on the type and specificity of the vehicle. The general formula for vehicle life cycle assessment is as follows (1) (Tang, Xu, & Wang, 2022):

$$C_{V_{ref}} = C_M + C_{VA} + C_{VU} + C_{RE} \tag{1}$$

where: C_V – total carbon dioxide emissions in the vehicle life cycle, C_M – carbon emissions from material extraction and processing, C_{VA} – carbon dioxide emissions from the production of the vehicle and components, C_{VU} – carbon dioxide emissions from vehicle use, C_{RE} – carbon dioxide emissions in recycling vehicle, i - ith vehicle alternative, *ref* - reference vehicle.

Phase 1. Material extraction and processing

This phase includes obtaining and processing raw materials that are used to build vehicle components. Therefore, this phase includes processes such as mining, enrichment, smelting, refining, etc. Carbon emissions resulting from the extraction and processing of vehicle material are calculated using formula (2) (Tang et al., 2022):

$$\begin{cases} C_M = \sum_x \left(C_{x,f} + C_{x,e}\right) \\ C_{x,f} = m_x \sum_n \left[E_{x,n} \sum_k \omega_{x,n,k}\alpha_k\right] \\ C_{x,e} = m_x \sum_n \left(\frac{E_{x,n}\omega_{x,n,e}}{3600}\right) \end{cases} \tag{2}$$

where: $C_{x,f}$ – carbon dioxide emissions from fuel consumption during material production, $C_{x,e}$ – carbon dioxide emissions from electricity consumption during material production, x – material, m – mass (kg), n – production process, $E_{x,n}$ – energy consumption per unit of material in its production process (kJ/kg), k – fuel, $\omega_{x,n,k}$ – share of fuel consumption in $E_{x,n}$, $\omega_{x,n,e}$ – share of electricity consumption in $E_{x,n}$, α_k – fuel carbon emission factor ($\mathrm{CO_2 kg/kJ}$).

Phase 2. Production of the vehicle and its components

The production of a vehicle and its components involves the storage of vehicle parts necessary to create the vehicle. In this phase, the analysis involves calculating the emissions generated during the processing and assembly of the vehicle's main components. Assembly includes, for example, stamping, welding and painting. It is also possible to take into account the distribution of the vehicle, i.e. transport (Yang et al., 2021a). To calculate carbon dioxide emissions from the production of a vehicle and its components, formula (3) is used (Tang et al., 2022):

$$\begin{cases} C_{VA} = \sum_x \left(C_{y,f} + C_{y,e}\right) + \frac{E_{VA}}{3600} \\ C_{y,f} = \sum_q \left[E_{y,q} \sum_k \omega_{y,q,k}\alpha_k\right] \\ C_{y,e,} = \sum_q \left(\frac{E_{y,q}\omega_{y,q,e}}{3600}\right) \end{cases} \tag{3}$$

where: $C_{y,f}$ – carbon dioxide emissions from fuel consumption by the production of the component, $C_{y,e}$ – carbon dioxide emissions from electricity consumption in the production of the component, y – component (part) of vehicle, E_{VA} – electricity consumption during vehicle assembly, q – production process, $E_{y,q}$ – energy consumption of a component in the production process (kJ), $\omega_{y,q,k}$ – share of fuel consumption in $E_{y,q}$, $\omega_{y,q,e}$ – share of electricity in $E_{y,q}$, α_k – fuel carbon emission factor ($\mathrm{CO_2 kg/kJ}$).

Phase 3. Vehicle use

The vehicle use phase concerns energy consumption and carbon emissions during the operation of the vehicle. It mainly covers fuel consumption, use of vehicle components and maintenance (Yang et al., 2021a). Calculations for carbon dioxide emissions during vehicle use are made according to formula (4) (Tang et al., 2022):

$$\begin{cases} C_{VU,EV} = \frac{dP_E}{100C_E} & - \quad for\ electric\ vehicles \\ C_{VU,ICEV} = \frac{dF_k}{100}\left(\rho_k\alpha_k LHV_k + C_k\right) & - \quad for\ vehicles\ with\ other\ engine \end{cases} \tag{4}$$

where: P_E – electricity consumption per 100 km by an electric vehicle (kWh/km), C_E – charging efficiency, d – total driving distance of the electric vehicle (km), F_k – fuel consumption per 100 km of a vehicle with an internal combustion engine or diesel engine (l), ρ_k – fuel density, k – fuel, LHV_k – a lower thermal value of the fuel (kJ/kg), C_k – carbon emissions per unit k in fuel production.

Phase 4. Vehicle recycling

The analysis of emissions generated during recycling, but also the disposal and reuse of selected vehicle components concerns the fourth phase of LCA (Yang et al., 2021a). This phase also includes the process of dismantling vehicles. Then, metal and non-metallic materials are separated from these components and properly cleaned. The metal is recycled (no batteries). In turn, non-metallic materials (plastic, glass, etc.) are usually landfilled or incinerated. In the case of vehicles with a battery, battery recycling should also be analyzed. The formula (5) is used for this purpose (Tang et al., 2022):

$$\begin{cases} C_{RE} = C_{re,f} + C_{re,e} \\ C_{re,f} = \sum_x \left[m_x E_{re,x} \sum_k \left(\omega_{re,x,k}\alpha_k\right)\right] \\ C_{re,e} = \left[\frac{E_{vd}}{3600} + \sum_x \left(m_x \frac{E_{re,x}\omega_{re,x,e}}{3600}\right)\right] \end{cases} \tag{5}$$

where: $C_{re,f}$ – carbon dioxide emissions from fuel consumption in vehicle recycling, $C_{re,e}$ – carbon dioxide emissions from electricity consumption in vehicle recycling, $E_{re,x}$ – energy consumption per unit of material x in the recycling phase (kJ/kg), x – recycled material, $\omega_{re,x,k}$ – share of fuel consumption in $E_{re,x}$, $\omega_{re,x,k}$ – share of electricity consumption in $E_{re,x}$, m – mass (kg), E_{vd} – energy consumption when dismantling the vehicle.

Once all indicators for the LCA phases have been calculated, it is possible to calculate the total carbon dioxide emissions over the life cycle of the reference vehicle. The previously indicated formula (1) is used for this purpose. Next, the obtained results are interpreted. On their basis, the entity (expert) can decide to choose the most advantageous vehicle (with the lowest negative environmental impact throughout its life cycle).

Stage 5. Selecting a vehicle with the lowest environmental impact

The entity (expert) using the proposed method selects a vehicle. The selection is made according to the LCA results. The vehicle with the lowest whole life cycle index ($C_{V_{ref}}$) is the most advantageous vehicle. This vehicle has the lowest environmental impact throughout its life cycle. This is the last stage of the proposed method.

Results

The proposed method was tested for trucks used in mining and extractive industries. The analysis of the results is presented in five main stages of the method.

In the first stage, reference vehicles were selected. The selection was made by the entity (expert) using the method. These vehicles were two trucks used in mining (extractive industry). The first one was a truck with an electric (battery) drive. The second one was a truck with a conventional drive (diesel engine). These were vehicles manufactured in Europe. Then, they were characterized according to the composition of the main materials. It was based on data from the model GREET v1.3.0.13991 and on a review of the literature on the subject (de Souza et al., 2018; Nordelöf et al., 2014b; Wong et al., 2021), as shown in Table 1.

Tab. 1. Approximate material composition of trucks

Material	Electric vehicle		Diesel Vehicle	
	Mass (kg)	Composition (%)	Mass (kg)	Composition (%)
Steel	33596	69.8	22494	78.4
Aluminium	5516	11.4	2976	8.5
Rubber	1143	2.4	1066	3.0
Other	7893	16.4	3555	10.1

The analysis included only the main materials, i.e. those having a significant share of use in the vehicle. These were steel, aluminium, natural rubber, and others. The predominant material in trucks is steel. In turn, materials whose share was negligible were omitted from this study.

In the second stage, the purpose and scope of the research were determined. The aim was to assess the life cycle of battery and conventional (Diesel) trucks used in mining (extractive industry). This assessment was intended to support the selection of the truck with the lowest environmental impact. Then, the scope of the research was determined. According to the assumptions, the research covers four phases of LCA, i.e., extraction and processing of materials, production of the vehicle and its components, use of the vehicle, and recycling of the vehicle (Pacana et al., 2023).

In the third step, the functional unit is determined. Heavy vehicles (trucks) were analyzed according to the assumptions. Hence, the functional unit is 21,500 effective working hours, as stated by the authors (Balboa-Espinoza et al., 2023; de Souza et al., 2018). The environmental impact is calculated for one ton of material transported per 1 km.

Then, the fourth stage of the method was implemented, i.e., life cycle assessment (LCA) of trucks. In the first phase, the extraction and processing of materials from these vehicles were analyzed. For this purpose, the emission factor during this process was determined. For this purpose, data from the GREET model and data from a literature review were used, e.g., (Yang et al., 2021b). The result is presented in Table 2.

Tab. 2. Emission factor of material production for mining trucks.

Material	Emission factor of material production (kg/kg)
Steel	2.00
Cast aluminium	2.62
Wrought aluminium	5.92
Rubber	3.62

Then, it was necessary to determine the energy consumption factor for the production of materials and the CO2 emission factor in LCA. Again, it was based on data from the GREET model and data from the literature review (Tang et al., 2022; Yang et al., 2021b). Coefficients with negligible values were omitted from the analysis. The collected data is presented in Table 3.

Tab. 3. Energy consumption rate for material production and CO_2 emission rate.

Fuel	Energy consumption for the production of materials (MJ/kg)					
	Coal	Natural Gas	Crude oil	Coke	Gasoline	Electricity
Emission factor CO_2	0.10	0.06	0.11	0.08	0.09	0.19

Steel	2.13	0.83	1.21	0.03	0.00	0.20
Aluminum	5.04	0.80	0.00	0.00	0.00	1.54
Rubber	0.04	1.98	0.00	0.36	0.01	0.15

According to the prepared data, carbon dioxide emissions from the extraction and processing of materials were calculated for a truck with a diesel engine and a battery. Formula (2) was used for this purpose. The result is presented in Table 4.

Tab. 4. Carbon dioxide emissions from the extraction and processing of truck materials.

Material	Electric vehicle			Diesel Vehicle		
	$C_{x,f}$	$C_{x,e}$	C_M	$C_{x,f}$	$C_{x,e}$	C_M
Steel	26449.10	3.73	26452.84	17708.84	2.50	17711.34
Aluminum	7852.37	6.17	7858.54	4236.52	3.33	4239.85
Rubber	1259.28	0.09	1259.36	1174.44	0.08	1174.52

where: $C_{x,f}$ – carbon dioxide emissions from fuel consumption during material production, $C_{x,e}$ – carbon dioxide emissions from electricity consumption during material production, C_M – carbon emissions from extraction and processing of the material.

The total carbon dioxide emissions in the first phase of LCA for the analyzed electric truck were C_M = 35570.74 [kWh]. However, for a truck with a diesel engine it was C_M = 23125.71 [kWh]. It was observed that the electric truck had higher CO_2 emissions in the material extraction and processing phase.

Then, the analysis was carried out for the production phase. Emissions during the processing and assembly of the main components of the trucks were estimated. According to data from the GREET model and based on a review of the literature on the subject (Sullivan, Burnham, & Wang, 2010; Tang et al., 2022), energy consumption and CO_2 emissions were determined for the main vehicle production processes, as shown in Table 5.

Tab. 5. Energy consumption and carbon dioxide emissions for vehicle production processes.

Components	Electric vehicle			Diesel Vehicle		
	Electricity (kWh)	Natural Gas (MJ)	Diesel (kg)	Electricity (kWh)	Natural Gas (MJ)	Diesel (kg)
Body and chassis	9306	-	-	8809	-	-
Motor	189	147	0.47	-	-	-
Power electronics	60	-	-	-	-	-
Engine	-	-	-	429	-	-
Engine accessory	-	-	-	109	-	-
Transmission	98	163	0.09	197	423	0.21
Vehicle assembly	3039	-		2672	-	-

According to formula (3), emissions generated during the processing and assembly of the main components of the truck were estimated. In the case of a diesel truck, these emissions amounted to C_{VA}= 9967.95 [kWh]. However, for a truck with an electric drive (not including the battery), it was C_{VA}= 9964.40 [kWh]. Emissions during the production of a lithium-ion battery (LiFePO4/graphite type) were estimated separately. According to (Balboa-Espinoza et al., 2023), energy consumption for this type of battery was determined, as shown in Table 6.

Tab. 6. Energy consumption production of acumulator.

Battery elements	Electricity	Coal	Crude Oil	Natural Gas
Cathode	0.02	0.14	0.02	0.44
Anode	0.00	0.10	0.02	0.54
Separator	0.00	0.02	0.00	0.02
Electrolyte	112.34	0.00	0.00	0.00
Packaging	2.40	23.40	0.56	33.20
BMS	5.74	0.00	0.00	0.00
Battery package	147	0.00	0.00	0.00

According to the authors of the article (Balboa-Espinoza et al., 2023), battery installation was assumed to be 2.67 MJ/kg. Using the formula (3), the emissions of the battery production processes were estimated to be 326.20. Therefore, the emissions of the production process of an electric truck (including battery production) were estimated as C_{VA}= 10290.36 [kWh].

Subsequently, calculations were performed for the third phase of LCA. It covers the use (operation) of trucks. For this purpose, reference vehicles were characterized, as shown in Table 7.

Tab. 7. Characteristics for analyzing the use of reference vehicles.

Characteristic	Electric vehicle	Diesel Vehicle
P_E – electricity consumption per 100 km by an electric vehicle (kWh/km)	468	-
C_E – charging efficiency (%)	90	-
d – total driving distance of the electric vehicle (km)	280	-
F_k – fuel consumption per 100 km of a diesel vehicle (l)	-	35
ρ_k – fuel density	-	0.85
d – total driving distance of diesel vehicle (km)	-	100
LHV_k – lower thermal value of fuel (kJ/kg)	-	37
α_k – fuel carbon emission factor	-	0.83
C_k – carbon emissions per unit k in fuel production	-	0.64

Then, using formula (4), the emissions generated during the use of the analyzed vehicles were estimated. According to the authors (Bakhtyar, Qi, Azam, & Rashid, 2023; De Wolf & Smeers, 2023; Li et al., 2023), it was assumed that the effective use of trucks is 150,000 km. In accordance with the adopted assumptions, it was estimated that emissions generated during the use of trucks with batteries are approximately $C_{VU,EV}$ = 780000 [kWh]. However, emissions generated when using diesel trucks are approximately $C_{VU,ICEV}$ = 1404034 [kWh]. It has been shown that in the use phase, diesel trucks have a significantly greater environmental impact.

As part of the last phase of LCA, emissions from truck recycling were analyzed. Since the verification involved a truck powered by an LFP battery, it was necessary to separate the emissions released during battery recycling from those released during the recycling of other truck components (Yang et al., 2021a). The emission characteristics for recycled vehicle components are presented in Table 8.

Tab. 8. Characteristics for analyzing the use of reference vehicles.

Phases	Electric vehicle			Diesel Vehicle		
	Electricity (kWh)	Natural Gas (m^3)	Coal (kg)	Electricity (kWh)	Natural Gas (m^3)	Coal (kg)
Vehicle assembly	627.3	-	-	618.08	-	-
Non-battery components	1114	9.13	9.79	1170.8	11.19	20.64

According to formula (5), it was calculated that the emissions during recycling of an electric truck (without battery recycling) are C_{RE}=1760 [kWh]. In contrast, emissions when recycling a diesel truck are C_{RE}= 1821 [kWh]. According to the authors of the article (Balboa-Espinoza et al., 2023; de Souza et al., 2018; Nordelöf et al., 2014b), Li-on battery recycling can be expected to involve 113,017 MJ/t, 1641 kg- CO2eq/t (Aichberger & Jungmeier, 2020). Therefore, recycling a truck with a battery involves much more emissions (approximately C_{RE}=33154 [kWh]).

Once all indicators for the LCA phases have been calculated, it is possible to calculate the total carbon dioxide emissions over the life cycle of the reference vehicle. Formula (1) is used for this purpose. Based on the calculations performed, it was shown that the overall environmental impact of LCA for a truck with a battery is $C_{V_{ref}}$ = 859 015.10 [kWh]. However, for a truck with a Diesel engine, it is $C_{V_{ref}}$ = 1438 945.11 [kWh]. The results are summarized in Fig. 3.

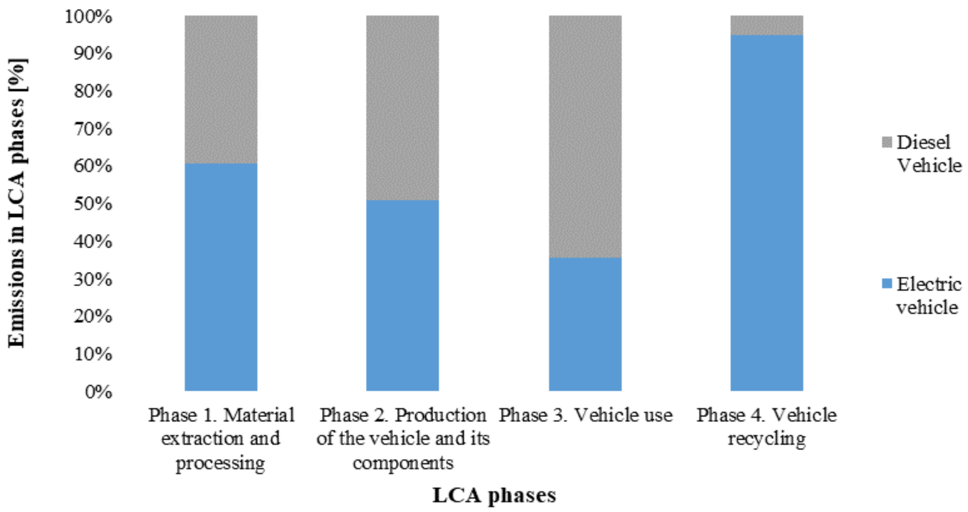

Fig. 3. Analysis of LCA results for trucks used in mining (extractive industry).

In phase one of the LCA, the battery truck had a slightly greater environmental impact. In turn, the diesel truck had a slightly greater environmental impact in the second phase. Significant differences between the analyzed truck types were observed in the third and fourth phases. It has been shown that a diesel truck has a much greater environmental impact in the use phase. However, these impacts were relatively similar for the recycling phase, excluding battery recycling. However, considering the truck and battery recycling, it has a much greater environmental impact than a diesel truck.

Based on the analysis, it was shown that a truck with a battery is the most advantageous in terms of the environment. Therefore, the entity (expert) should first consider its choice. However, the final decision rests on the entity, which may also be based on other aspects, e.g., purchase price or truck efficiency. Still, from an environmental perspective, an electric truck proved to be more advantageous than a diesel truck.

Discussion

Sustainable development has become a phenomenon, especially in the last two decades. Individuals and firms need to be aware of the importance of sustainability at a global level (Folgado-Fernández et al., 2023; Gavurova et al. 2022a). For instance, when individuals notice the importance of sustainability, they can show more participative behaviour in some activities, such as reducing waste and protecting energy (Devkota et al., 2023). The majority of businesses around the world also feel under pressure because of their customers' expectations for sustainability activities (Rozsa et al., 2022; Kristóf & Virág, 2022). Thus, they become active in the digital transformation process by using new technologies for their operations (Civelek et al., 2023a; Gavurova et al. 2022b). Although small firms have a fragile structure in the internationalization process (Civelek & Krajčík, 2022) and have lower-level financial assets compared to large enterprises (Ključnikov et al., 2022a), they have more flexible structure than large companies when adopting new technologies (Krajčík et al., 2023) to create more value-added goods and services (Ključnikov et al., 2022b). In this regard, owners of small businesses are motivated to use these innovative technologies when sustaining their businesses (Azman & Majid, 2023; Gavurova et al. 2020). Innovative policies (Rigelsky et al., 2022) and innovative capabilities also enable small firms to achieve financial sustainability (Civelek et al., 2023b) and to survive in the long term (Kliuchnikava, 2022; Kő et al. 2022).

The sustainable development concept has also greatly drawn the attention of many industries (Cheng et al., 2022; Mares et al. 2023). For instance, sustainable development (Ostasz, Siwiec, & Pacana, 2022; Pacana & Siwiec, 2022b; Ostasz, Czerwińska, & Pacana, 2020) in the transport sector makes it necessary to conduct vehicle life cycle assessment (LCA). This is due to the dynamics of introducing newer technologies and improvements to reduce the negative impact of vehicles on the environment (Pacana & Siwiec, 2022a; Siwiec & Pacana, 2022). However, LCA in the mining industry (extractive industry) is still not well developed (Song et al., 2017).

Therefore, the aim was to assess the life cycle of heavy vehicles used in mining (extractive industry) in order to determine the vehicle with the lowest environmental impact. Trucks with batteries and diesel engines were analyzed. As part of the analysis, a method was proposed to support the selection of a vehicle that will have the lowest negative environmental impact throughout its life cycle. The benefits of the proposed method include:

- ability to estimate environmental impact throughout the life cycle,
- supporting decisions about choosing a vehicle with the least impact on the natural environment,
- improvement of LCA analysis according to a specific method based on calculation formulas, which allows it to be carried out without additional resources (e.g., computer programs),
- low-cost method,
- the possibility of combining the results of the method with other analyses, e.g., assessment of vehicle purchase costs,
- providing analysis of any type of vehicle.

The limitations of the method are the need to obtain data to assess the life cycle of vehicles at individual LCA phases. The results from the method are approximate and include the analyzed reference vehicles. Therefore, it is impossible to interpret the results obtained for other types of vehicles.

Future research will be based on extending the proposed method by analyzing the quality level of vehicles. Additionally, an analysis of vehicle purchase costs is planned. Extending the method to additional aspects will allow its use in quality (Pacana &Siwiec, 2021) and cost analyses, including considering the environmental impact of vehicles throughout their life cycle.

The method is applicable to the analysis of vehicles. It can be used by an entity (expert) to select vehicles with the lowest environmental impact in LCA.

Conclusion

The drive to reduce global warming significantly involves the transport sector. It is important to assess the environmental impact of vehicles to meet the challenges of climate change. Although these issues are increasingly discussed for light vehicles, few studies assess the environmental impact of heavy vehicles (used in industry, e.g. mining).

The aim was to assess the life cycle of heavy vehicles used in mining (extractive industry) in order to determine the vehicle with the lowest environmental impact. For this purpose, a method was developed to analyze the environmental impact of trucks used in mining (extractive industry). These were trucks with a battery and a diesel engine.

In the first and second phases of LCA, slight differences in the environmental impact of the analyzed trucks were observed. However, significant differences between the analyzed truck types were observed in the third and fourth phases. A diesel truck has a greater environmental impact in the use phase. However, a battery truck has a much greater environmental impact on the recycling phase than a diesel truck. Nevertheless, the battery truck has proven to be more environmentally friendly over its entire life cycle. Hence, the choice of trucks should be focused on this type of truck. However, the final decision depends on the entity using the proposed method.

The proposed method can be used for LCA analysis of any vehicle. Using this method to analyze more than two vehicles can significantly improve the selection of vehicles in terms of their environmental impact. At the same time, such behaviour supports enterprises in their pursuit of sustainable development.

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