Design features of comminution disc and their relation with CO₂ emission in disc life cycle

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Abstract. The structure of the comminution discs has the greatest impact on the comminution process efficiency and energy consumption and on the product fragmentation degree. Manufacturing, use and utilization of machine components carries environmental burdens in the form of emissions and energy consumption. The purpose of the work was to analyze the impact of the design features of the comminution disc (the construction material, the number and diameter of disk holes) on the amount of CO₂ emissions in their life cycle. The 3D model of discs was made in SolidWorks and then an analysis of CO₂ emission was made in Solid Works on the basis of the LCA and CM method. Sustainability was performed as well. It was found that energy consumption and CO₂ emissions were higher for the life cycle of steel discs than those made of HDPE. Emissions of carbon dioxide during the life cycle of the working disk decrease along with an increase in the diameter and the number of holes. Regression equations describing the relationship between the diameter, number of holes in the disc and the amount of CO₂ emissions in the life cycle were obtained on the basis of multiple regression analysis.

1. Introduction

Comminution disc is one of the elements of a grinding machine, whose main goal is the size reduction [1]. During the design process of comminution machines and elements one should pay attention to criteria such as: safety, efficiency and environmental impact, controllability and high quality [2–4].

To achieve the postulated states of high quality, high efficiency and high environmental harmlessness some eco-innovative concepts have to be introduced as well as optimization procedures providing a choice of the best performance and design parameters. Relations between the process indicators, materials parameters and design features should also be included in the designing process (Figure 1) [5–10].

It is connected with the concept of green growth and circular economy promoted by European Union [11], [12]. The main assumptions of the designs, products and the processes states imply that they should be resource-efficient, use green technologies, be competitive and characterized by low-carbon design. Products are required to be easy to repair, re-usable, re-manufacturable and then recyclable, so that nothing is wasted [12–16]. Hence, there is a necessity to study the environmental impact of designs and the relations between design features and emissions.

Despite the ever-growing popularity of environmental analyses in the design of machinery and equipment, not many research works address the relationship between structural and material parameters and the environmental impacts. In the case of comminution machines and equipment, environmental assessments mainly focus on assessing the comminution process as a constituent
process of mineral processing/extraction [17–21]. The presented analyses are mainly concerned with energy aspects [17, 20, 21] and greenhouse gas emissions [18, 21]. Landfield and Karra carried out LCA for a rock crusher, however they did not take into account the processes of the crusher manufacturing or the materials from which the crusher was made [22]. The research conducted for various processes, machines and technologies show, however, that these are stages of production and raw materials acquisition that are characterized by the largest negative environmental consequences [23–26]. Therefore, in order to reduce environmental impacts, it is necessary to assess machine elements already at the design stage, in accordance with the idea of green designing and eco-designing [27–29]. This can be done with the use of CAD tools, thanks to which the designer can choose the structural and material features during designing that will cause the lowest possible environmental damage [30–35].

![Image](https://i.imgur.com/3.png)

**Figure 1.** Scheme of relations between different parameters in the design process of comminution disc

In the light of the above and according to the state-of-art, the purpose of the work was to investigate and analyze the relations between the design features of a comminution disc and CO₂ emissions in its life cycle. The research problem was formulated as a question: how does the amount of CO₂ emission depend on a comminution disc design features?

In order to find the answer to the research problem posed, an analysis of the life cycle emissivity of a multi-disc mill working disc was carried out, assuming as a variables: the type of material from which the disc was made and the number and diameter of holes in the disc. Then, using the statistical analysis tools, the relationships between the design features and CO₂ emissions in the life cycle of a working disk were determined.

2. Materials and methods

The research focuses on the relations between design features of grinding disc and CO₂ emissions in their life cycle. The discs with diameter of 274 mm made from steel 1.2210 (115CrV3) and high-density polyethylene (HDPE) were analysed (Figure 2). Each disc had a different number of holes with different diameters, according to Table 1. It was assumed that the manufacturing process of the disc is milling. To determine the relationship between the structural features and CO₂ emissions, first 3D models of discs with various design features were developed (Table 1) and an analysis of environmental impacts was performed for them in accordance with the life cycle assessment (LCA) methodology. LCA is a methodology for assessing the environmental effect caused by the life cycle of a given process or product, which takes into account the environmental load from the moment of
The analysis was to determine the environmental impact of the introduced loads, 3) proposed changes and solutions resulting in the reduction of harmful impacts [36], [37].

![Figure 2. View of comminution discs subjected to analysis](image)

**Table 1. Configurations of structural features of the comminution disc analyzed**

| Diameter | Number of holes |
|----------|-----------------|
|          | 14              | 22  | 27  | 33  | 39  |
| 33 mm    | x               | x   | x   | -   | -   |
| 30 mm    | x               | x   | x   | x   | -   |
| 27 mm    | x               | x   | x   | x   | x   |
| 23 mm    | x               | x   | x   | x   | x   |
| 21 mm    | x               | x   | x   | x   | x   |
| 17.5 mm  | x               | x   | x   | x   | x   |

For assessment of the carbon footprint in the life cycle of a disc the CML method was used, which is one of the methods used in LCA. CML method is a problem-oriented LCA method developed by the Institute of Environmental Sciences of the University of Leiden (CML). It focuses on a series of environmental impact categories expressed in terms of emissions to the environment or use of natural resources. It includes eight impact category groups: acidification, climate change, depletion of abiotic resources, ecotoxicity, eutrophication, human toxicity, ozone layer depletion, photochemical oxidation [23], [38]. In this work, the impact of the comminution disc life cycle in the area of climate change, which corresponds to CO₂eq emissions in the life cycle, has been analyzed.

The analysis was carried out in the Solidworks Sustainability during the disc designing. The material, number of holes and their diameters were changed for each disc. The purpose of the LCA analysis was to determine the comminution disc life cycle stages with the highest and lowest emissions and to compare the emissivity of discs with different design parameters. The life cycle of the comminution disc included raw material acquisition, production, transport and the end-of-life stage (Figure 3). Storage and distribution stages were omitted due to a negligible amount of materials and energy involved in these stages.

Disc 1 was the functional unit of analysis. The geographical border of data collection was Europe. It was assumed that the life time of a disc will last 3 years. The disc will be transported over about 300 km by a truck. For the end-of-life phase, it was assumed that 70% of the material is recycled, 24% is incinerated and 6% goes to a landfill. The number of raw materials, the amount of energy and fuel to be used was accepted to be the analysis input. Table 2 presents an example of an inventory of inputs in the system for a disc made of steel and HDPE.
After receiving the results of the LCA analysis for twenty four structural variants and two disc materials, the relationships between the disc design features and the value of CO₂eq emissions in its life cycle were examined. Pearson's correlation analysis was performed, followed by a multiple regression analysis. A significance level of $p < 0.05$ was adopted.

### 3. Results

In the first stage, the results of the environmental impact assessment were analyzed for the examined structural variants of the comminution disc. Based on the results it was found that the highest CO₂ emissions appeared for steel disc (Figure 4) in all tested variants, which is associated primarily with the large amount of steel used to make the disc. To make a steel disc, much more material was used than for HDPE to make a polymer disc (Table 2). It was also found that, the highest contribution in CO₂ emissions had the raw material acquisition stage, and then the production stage, which results from the use of materials and electricity at the production stage. It should be clearly indicated that at the design stage it is possible to assess the environmental impacts of the product, as well as control the life cycle and selection of materials so as to minimize negative effects. Moreover, among others, optimization tools including environmental analyses have been created, which have been adapted to construction of support programs.

Then, relationships between variable design features and the life cycle of CO₂ emissions were analyzed. First, Pearson's correlation analysis was performed. The correlation analysis showed that there was a very high negative dependence between CO₂ emissions and the number of holes for both discs: these made of steel ($R = -0.975$) and these made of HDPE ($R = -0.96$) (Figure 5). Similar dependence was found between CO₂ emissions and diameter of holes (steel disc: $R = -0.989$, HDPE disc: $R = -0.973$) (Figure 6). In both cases, the correlations were statistically significant ($p < 0.05$). A
A larger number of holes in a disc involves a smaller amount of material used for its construction, as does an increase in the disc hole diameters. Due to the largest potential of negative impacts at the stage of raw material acquisition, any reduction in the weight of a structural element will result in a significant impact reduction. It can be said that the highest negative impact is observed for discs with a smaller number of holes with small diameters.

![Carbon footprint](image)

**Figure 4.** Example results of carbon footprint assessment for one disc (22 holes, 22 mm diameter)

![Comparison of CO₂ emissions](image)

**Figure 5.** CO₂ emissions in the life cycle of the comminution disc depending on the number of holes in the disc together with the results of correlation analysis

**Correlation coefficient**

Steel: $R = -0.975$, $p = 0.005$

PE HD: $R = -0.960$, $p = 0.01$

![Comparison of CO₂ emissions](image)

**Figure 6.** CO₂ emissions in the life cycle of the comminution disc depending on the diameter of the holes in the disc together with the results of correlation analysis

**Correlation coefficient**

Steel: $R = -0.989$, $p = 0.001$

PE HD: $R = -0.973$, $p = 0.001$

In the next step, multiple regression analysis was performed, taking into account two variables affecting the value of CO₂eq emissions over the life cycle of the grinding disc. The dependence
between CO₂ emissions and these two variables is presented on the 3D Surface chart (Figure 7, Figure 8). The highest potential CO₂ eq emission in the life cycle of a steel disc (> 20 kg CO₂ eq) is predicted for discs with 14 to 33 holes with diameters of 17.5-27 mm, and the lowest (<7.6 kg CO₂ eq) for discs with the number of holes was above 35 and diameters larger than 35 mm.

![Figure 7. CO₂ eq emissivity in the life cycle of a steel disc depending on the diameter and number of holes in the disc](image)

For HDPE discs, the highest potential CO₂ eq emission over the life cycle (> 3.2 kg CO₂ eq) is predicted for discs with 14 to 31 holes with diameters of 17.5-27 mm, and the lowest (<1.4 kg CO₂ eq) for discs the number of holes was above 37 and diameters larger than 32 mm.

On the basis of the multiple linear regression the values of coefficients of the regression equation (1) was obtained (Table 3). The coefficient as well as the regression equation were statistically significant (Table 3, Table 4).
\[ E_{\text{CO}_2\text{eq}} = an + bd \]  

where: \( E_{\text{CO}_2\text{eq}} \) – life cycle \( \text{CO}_2\text{eq} \) emissions, kg \( \text{CO}_2\text{eq} \), \( a, b \) – coefficients of the regression equation, \( n \) – number of holes, \( d \) – hole diameter, mm.

**Table 3.** Multiple regression analysis results

| Coefficient | Standard Error | t-Value | Prob>|t| | 95% LCL\(^1\) | 95% UCL\(^2\) |
|-------------|----------------|---------|-------|----------------|----------------|
| Steel disc  | a 0.27 0.12 2.30 0.03 0.26 0.508 | | | | |
|             | b 0.46 0.12 3.82 9.46 \( \times \) \( 10^4 \) 0.210 0.709 | | | | |
| HDPE disc   | a 0.039 0.016 2.44 0.02 0.006 0.071 | | | | |
|             | b 0.065 0.016 3.99 6.19 \( \times \) \( 10^4 \) 0.031 0.099 | | | | |

\(^1\) – lower confidence limit for 95% confidence level  
\(^2\) – upper confidence limit for 95% confidence level

The regression equations were characterized by a high fit (Table 4). In the case of a steel disc, the regression equation describing \( \text{CO}_2\text{eq} \) emissivity over the life cycle of the disc explained 90% of the variability of this parameter, in the case of the HDPE disc it was 91% (Table 4). The presented regression equations can be successfully used by designers involved in the design of comminution assemblies of plant material shredders to optimize the structure in terms of emissivity without the need for time-consuming life cycle analyses.

**Table 4.** The results of the significance test of the multiple regression equation

|                 | F Value | Prob>|F| | R\(^2\) | Adj. R\(^2\) |
|----------------|---------|-------|------|--------|-----------|
| Steel disc      | 108.75  | 3.93 \( \times \) \( 10^{12} \) | 0.91  | 0.90   |
| HDPE disc       | 120.37  | 1.42 \( \times \) \( 10^{12} \) | 0.92  | 0.91   |

4. Conclusions
The aim of the work was achieved by analyzing the relationship between \( \text{CO}_2\text{eq} \) emissions occurring in the comminution disc life cycle and its design features, i.e. the type of material, the number and diameter of holes in the disc. Based on the LCA results, it is concluded that \( \text{CO}_2\text{eq} \) emissions were higher in the life cycle of steel discs. The disc made of polymer material (HDPE) causes lower environmental loads in its life cycle than the disc made of steel. It was also found that, the highest contribution in \( \text{CO}_2 \) emissions is attributed to the raw material acquisition stage, and then the production phase, which results from the use of materials and electricity at the production stage. Due to the largest potential negative impacts in the raw material acquisition phase, any reduction in the weight of a structural element will result in a significant reduction in impacts.  
Based on the results of correlation and regression analyses it was found that \( \text{CO}_2 \) emissions in the life cycle of the disc decrease along with an increase in the diameter and number of the holes drilled in it. The highest potential \( \text{CO}_2\text{eq} \) emission in the life cycle of a steel disc (> 20 kg \( \text{CO}_2\text{eq} \)) is predicted for discs with 14 to 33 holes with diameters of 17.5-27 mm, and the lowest (< 7.6 kg \( \text{CO}_2\text{eq} \)) for discs with the number of holes above 35 and diameters larger than 35 mm. For HDPE discs, the highest potential \( \text{CO}_2\text{eq} \) emission over the life cycle (> 3.2 kg \( \text{CO}_2\text{eq} \)) is predicted for discs with 14 to 31 holes with diameters of 17.5-27 mm, and the lowest (< 1.4 kg \( \text{CO}_2\text{eq} \)) for discs the number of holes above 37 and diameters larger than 32 mm. Environmental design of machine components is crucial for sustainable product development. The results presented are guidelines for the designers of multi-disc mills in the selection of optimal design
features of comminution discs. The work deals only with the aspect of construction of comminution disc assemblies and environmental impacts depending on changes in the number of holes and their diameters. The listed design features of the discs will, however, also affect the course of the comminution process, including: efficiency, fragmentation degree, energy consumption. Further analysis is needed to determine the relationship between the number and diameter of the holes and the comminution process, in order to determine the interrelationships between construction parameters - grinding process and environmental impacts, and find among them optimal solutions.

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