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Environmental Loads Resulting from Manufacturing Technology

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Abstract: The study of environmental loads resulting from manufacturing technology is of great importance for environmental protection. Applying the principles of sustainable development means "a way of farming in which meeting the needs of the present generation will not reduce the chances of meeting the needs of future generations." Faced with such a challenge, the product must be assessed throughout its entire life cycle (LCA). From the available technologies and materials, one should choose those that are least harmful to the environment. In order to make a correct choice, it is necessary to know and understand the technological processes and phenomena that take place in them. Using *off-the-shelf* LCA applications, without knowing basic knowledge of manufacturing technology, can bias the results. The aim of the article is to present benefits resulting from the environmental assessment of manufacturing processes.

Keywords: Fe-C alloys, technological process, environmental assessment

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1. Introduction

Iron alloys are materials with versatile applications. Products from the steel, metallurgy and foundry industries are indispensable in the automotive sector, in construction, for the production of household appliances and in many other industries.

Until some time ago, it was only possible to invent a new substance or technology and the choice was based on operational, technical and economic criteria (Filipiak et al. 2018, Gabryelewicz et al. 2021). No environmental consequences were presented, for example with asbestos, freon or leaded naphtha. Technical progress and the progress in civilization were understood as an increase in production. The concept of quality did not include ecological standards, but technical and utility standards only (Adamczyk 2004). This situation is changing radically today. Assessing innovation from an ecological point of view is becoming the standard (Loucanova & Olsiakova 2020).

The production technology used has the greatest impact on the environment and determines what happens to the product after its useful life, vis-à-vis recovery, recycling, disposal and storage (Wędrychowicz et al. 2019, Wędrychowicz et al. 2021, Chamier-Gliszczynski & Krzyzynski 2005, Chamier-Gliszczyński 2011a, Chamier-Gliszczyński 2011b, Czwajda et al. 2019, Jajczyk et al. 2020, Straka et al. 2020). The choice of production technology and methodology for its optimization, taking into account ecological aspects, is made intuitively or based on the experience of the designer and technologist. (Adamczyk 2004, Sabadka et al. 2017). Commercial software, such as SimaPro, can be used to assess sustainable development and life-cycle (Burchart-Korol et al. 2020). This software has quantitative and qualitative databases on environmental pressures. In order to use them correctly, it is necessary to know the course of the technological process of the product assessed. Without knowledge of the manufacturing technology, it is easy to make a mistake in assessing environmental loads. Environmental research should be concerned with (Adamczyk 2004):

- achieving a certain quality of product – the level of individual features in the analysis of ecological effects in the entire or defined part of the product life cycle;
- and selection of manufacturing methods to meet the assumptions with a minimal negative environmental impact.

One method to motivate entrepreneurs to protect the environment is the introduction of environmental fees. Since 1 January 2018, the obligation to pay fees for polluting the environment under Environmental Protection Legislation applies only to the fees for the release of gases or dust into the air and the storage of waste. On the other hand, the rules for paying fees for discharging sewage into water or soil and water uptake are regulated by the provisions of the

Water Legislation and of the Regulation of the Council of Ministers of 22nd. December 2017 on Unit Rates of Charges for Water Services.

Fee rates for polluting the environment are getting higher every year, as shown in Table 1 with knowledge of the impact of a given technology on the environment seeming to be all the more beneficial for enterprises (Announcement of the Minister of Climate of 9 September 2020, Announcement of the Minister of the Environment of 18 August 2009, Announcement of the Minister of the Environment of 3 October 2018).

Table 1. Fees for selected iron and steel waste in 2010, 2019 and 2021

Type of substance	Fee in [PLN/Mg]		
	2010	2019	2021
Waste from tools used for turning and sawing and its alloys	10.94	12.92	13.43
Emission of CO_2	0.25	0.30	0.31
Waste from the iron and steel industries:			
Slag from smelting processes (blast furnaces, steel production)	16.95	20.03	20.82
Untreated slag from other processes	16.95	20.03	20.82
Solid waste from gas treatment containing hazardous substances	54.40	64.29	66.82
Rolling scale	16.95	20.03	20.82
Waste from cooling-water treatment containing oils	54.40	64.29	66.82
Dribbles from iron metallurgy	16.95	20.03	20.82
Waste ferrous sulphate	16.95	20.03	20.82

2. Environmental assessment method

The application of value analysis to the environmental assessment of production technology is aimed at finding the optimal solution from the ecological point of view, while maintaining quality, efficiency and low own costs.

Value analysis is (Crum 1973) a planned procedure aimed at achieving the necessary functionality of a product at the lowest cost without compromising the level of quality, reliability and without compromising the operating and delivery conditions. It is a procedure which gradually attains its goal by means of tried and tested techniques and new methods combined into one logical ensemble.

It is possible to evaluate the entire technological process as well as individual stages of its life (Chamier-Gliszczyński 2010, Chamier-Gliszczyński 2011) or its fragments (Clift 1997). The assessment is facilitated by comparing a given technology with similar ones, distinguished by a high level of environmental friendliness and proven in industrial conditions (Ekvall et al. 2005, Guinee et al. 2001). Often, there is a need to evaluate and select the optimal manufacturing technology from among several possibilities. (Hochschorner & Finnveden 2003, Jajczyk 2016). In order to conduct a reliable assessment of manufacturing technology, extensive experience, along with a complete knowledge, thereof, based on the manufacturing technology being assessed, as well as appropriate knowledge about possible solutions, are necessary. Value analysis can be applied to products at any stage of their development, such as in the design, production and use). This method can be used to test design or operating systems.

3. Environmental assessment of a manufacturing technology

The manufacture of the product involves the choice of material and technology. Generally, there is a choice between different materials and manufacturing technologies. The shape and / or dimensions of the product may vary, but the function and quality of the product remain unchanged (Ashby 1998).

In the case of the environmental assessment of iron alloy products, a difference analysis can be applied. Only those production stages that differ from the analysed products are analysed and assessed (Nielsen & Weidema 2001). In the case of products made of iron alloys, the stage under analysis is the manufacturing process. This means that acquisition of the raw material, its use and its disposal are omitted. It was assumed that these stages have an equal effect on the environment. Such a simplification can be accepted because these products are made of the same, or very similar, raw materials. The stage of use of machine parts does not affect the environment and the utilisation stage, in the case of iron-alloy products, in most cases, consists of landfilling or recycling, which is the same for all the above-mentioned groups of products. Graphically, the concept of defining a system's boundaries is shown in Figure 1.

The manufacturing process has been divided into three main stages:

– preparation stage for the input material, i.e. the amount of input material,
– preparation stage of a semi-finished product,
– completion stage.

Only processes influencing further unit processes are included in a system's boundaries. When determining a system's boundaries, attention should be paid to the availability and validity of the data assigned to each production stage (Weidema 1993). All the data used for environmental assessment in this study was obtained and compiled on the basis of the literature, primarily the data from the Reference Document on Best Available Techniques (BREF) and the literature on environmental problems in machining were used (Pieńkowski 2005, Srinivasan & Sheng 1999, Schulz & Schiefer 1986). The method for analysing the manufacturing process reflects the sequence of successive technological operations leading to the production of the product tested (Fig. 1).

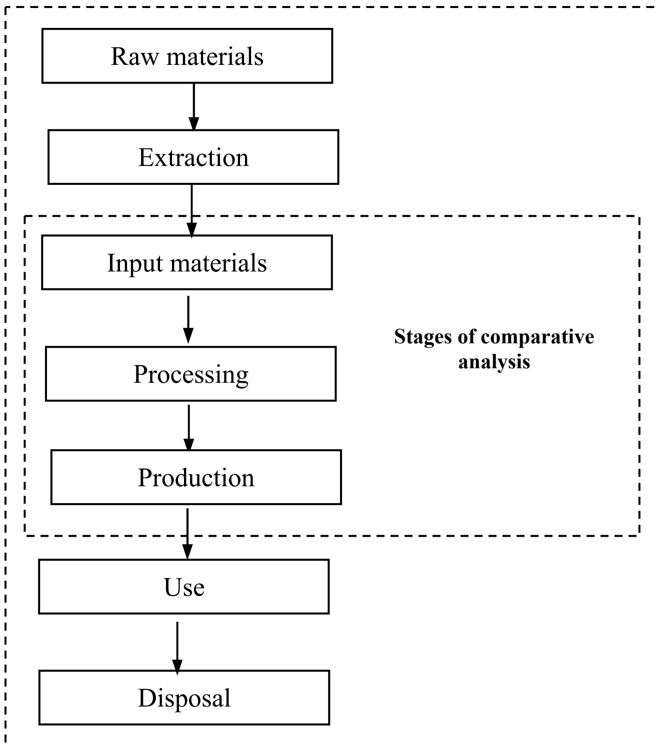

Fig. 1. Graphical concept illustrating the scope of the analysis

Numerical data used for calculations i.e., data on energy inputs, the number of pollutants emitted, water used and the amount of sewage, the amount of waste, the amount of raw materials, the semi-finished products and materials used, can be presented in two ways (Sala 1986, 1996, Sheng & Munoz 1995, Gabryelewicz et al. 2020). Firstly, they can be given either in a natural, physical form, i.e., in units of energy, mass and volume and so on; this type of calculation is 'technological'; or it can be given in the form of value, as in economic value, in terms of cost or price; this type of calculation is 'economic'. In order to analyse the impact on the environment of the technology of manufacturing products from iron alloys, the methodology based on the value analysis was followed, that is:

- determination of the object of the test,
- determination of the system's boundaries, i.e. the stages of the manufacturing process,
- determination of the unit processes, that is, the links between them and the assignment of quantitative data related to the functional unit, which will be the pulley,
- data analysis.

3.1. Determination of the object of the test

This analysis concerns the environmental assessment of two production technologies: machining and die forging. The manufacturing technology was assessed using, as an example, a pulley treated as a functional unit (Fig. 2) and made as:

− a pulley, machined from a cylindrical bar,
− a die-forged and machined pulley.

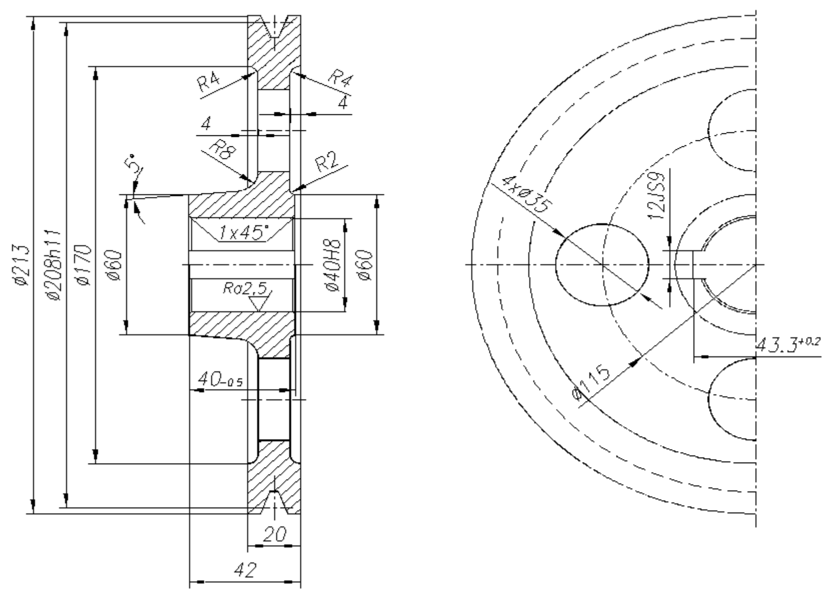

Fig. 2. Pulley – a functional unit

Due to the needs of the analysis of manufacturing technology, the same concept regarding the pulley structure was adopted, despite knowing about the possibility of giving different shapes to a given part, fulfilling the same function but made with different technologies. However, for the sake of comparability, the possibility of obtaining the same shape for a given pulley, obtained by different manufacturing techniques, was taken into account.

3.2. Definition of a system's boundaries

The boundaries of the system being tested are the technological processes that make up the production of a given pulley. The processes that make up the analysis are shown in Fig. 3 for a pulley produced by machining from a steel bar and Fig. 4 for a drop-forged and machined pulley.

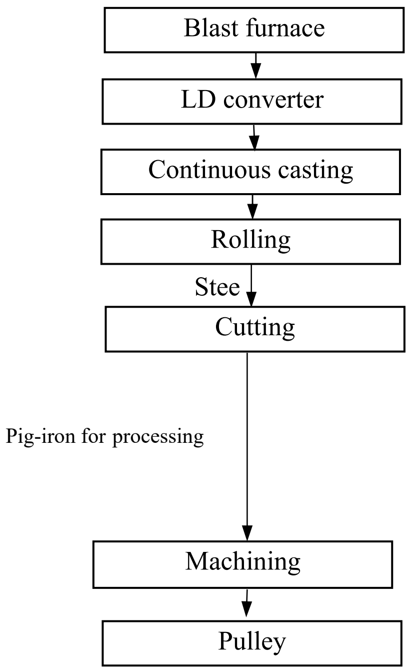

Fig. 3. System boundaries for the environmental analysis of a pulley; steel rod

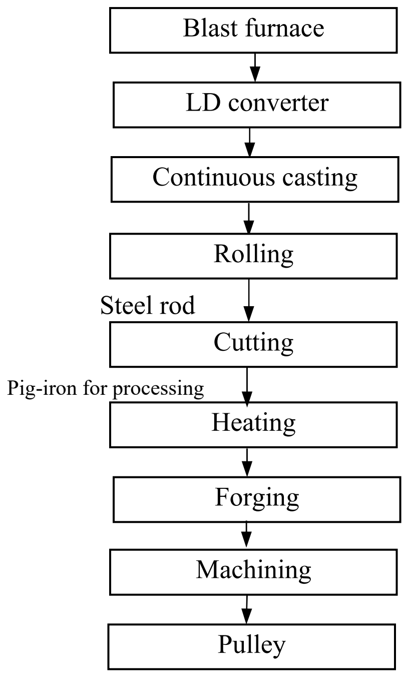

Fig. 4. System boundaries for the environmental analysis of a pulley; drop-forged

3.3. Environmental loads – a pulley machined from a cylindrical rod

The starting material for the production of the pulley is a steel rod: ∅225 x 45 mm.

Table 2. Data for analysing a pulley produced by the machining method

	Pulley	Pig-iron for making the pulley. Steel rod ∅225 by 45 mm
Volume	481,823.4 mm^3	1,788,328.0 mm^3
Mass	3.782 kg	14.038 kg

The mass is calculated by assuming the density of steel: g = 0.00785 g/mm^3

Table 3. Physical quantities of environmental aspects per functional unit

Process	Energy consumption MJ/pc.	Emissions generated into the atmosphere kg/pc.		Waste kg/pc.	Sewage dm^3/pc.
		total	in that CO_2		
Pig-iron production	192.450	11.824	11.467	10.661	58.64
Melting of cast steel in the LD converter	11.764	2.817	2.807	1.9772	7.440
Continuous casting	3.875	0.222	0.218	0.0296	1.196
Rolling	109.398	10.578	10.449	2.076	98.266
Cutting	0.282	–	–	1.3	no data
Machining	22.21	–	–	10.256	no data
Total:	339.979	25.441	24.941	26.2998	165.542

In figures 12 to 15 the environmental unit assessment is shown as bars while the cumulative environmental load is shown as a curve.

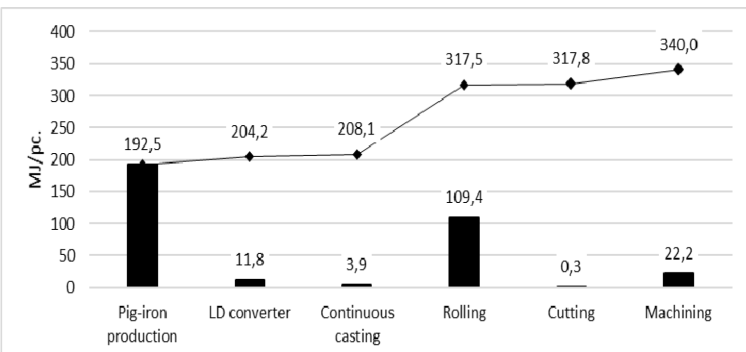

Fig. 5. Energy consumption in the production of a pulley made by machining a cylindrical rod [MJ/pc.]

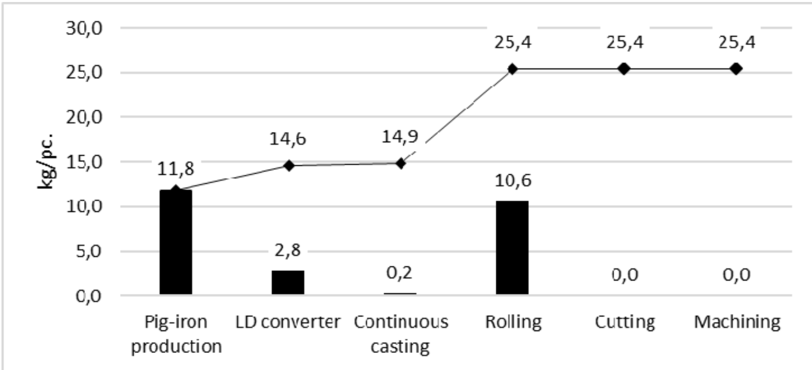

Fig. 6. Emissions generated into the atmosphere, in the production of a pulley made by cutting a cylindrical rod [kg/pc.]

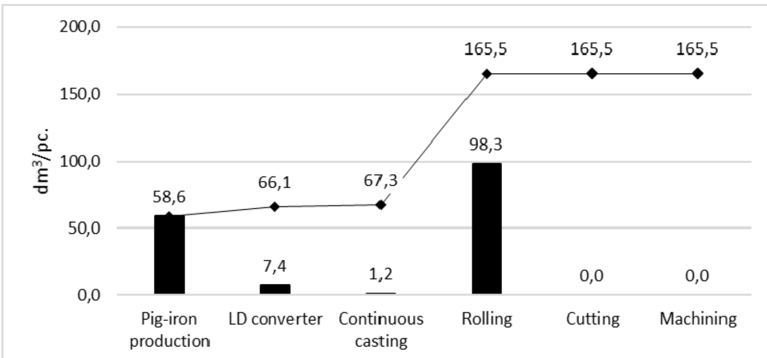

Fig. 7. Waste water generated in the production of a pulley made by machining from a steel bar [dm^3/pc.]

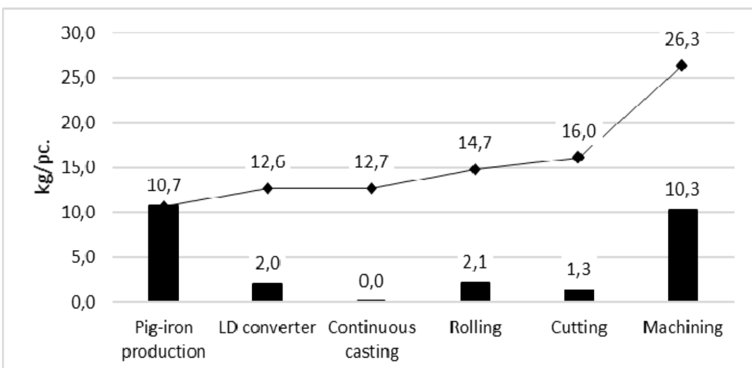

Fig. 8. Waste generated in the production of a pulley made by cutting from a steel bar (in kg/piece)

3.4. Environmental assessment – forged and machined pulley

As starting material, we take 68 rods, 161 mm long.

Table 4. Data for the environmental analysis of a drop-forged pulley

	Pulley	Pig-iron for making the pulley. Steel rod ∅ 68 to 161 mm	Forging
Volume	V = 481.823 cm^3	V = 74,446.4 mm^3	V = 592.9 cm^3
Mass	m = 3.782 kg	m = 5.844 kg	m = 4.654 kg

The mass is calculated by assuming the density of steel: g = 0.00785 g/mm^3.

Table 5. Levels of environmental aspects for the technology of manufacturing a die-forged pulley

Process	Energy consump-tion MJ/pc.	Emissions generated into the atmosphere kg/pc.		Waste kg/pc.	Sewage dm^3/pc.
		total	in that CO_2		
Pig-iron production	80.111	4.918	4.770	4.435	24.413
LD converter	5.425	1.172	1.168	0.823	3.097
Continuous casting	1.788	0.092	0.091	0.0123	0.498
Rolling	14.181	4.400	4.346	0.864	40.91
Cutting	0.258	no changes	no changes	0.546	no data
Heating	1.377	no data	no data	–	–
Forging	2.152	no data	no data	2.062	no data
Machining	1.482	no data	no data	0.872	no data
Total:	106.774	10.582	10.375	9.6143	68.918

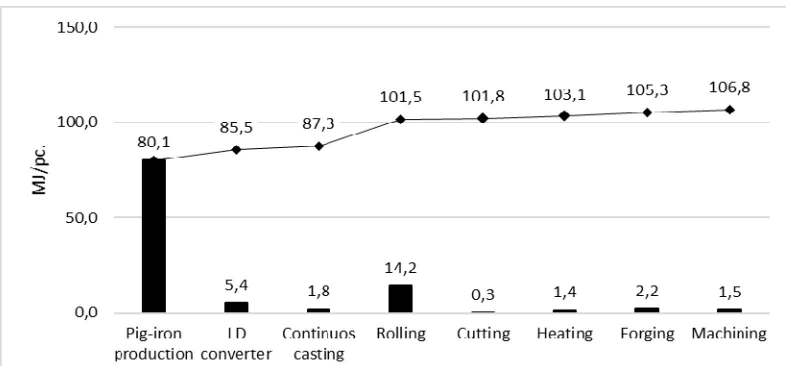

Fig. 9. Energy consumption in the production of a die-forged pulley [MJ/pc.]

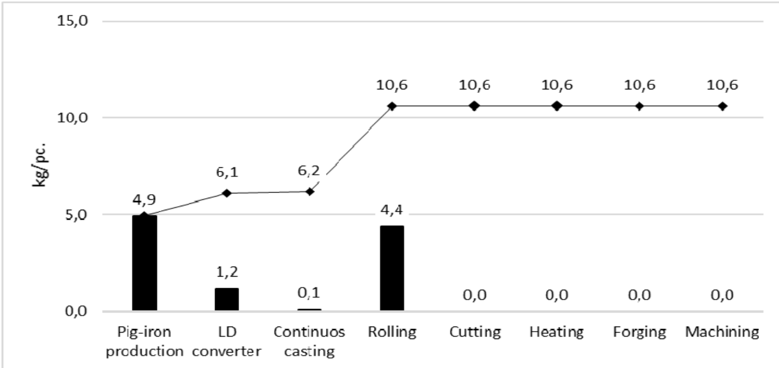

Fig. 10. Emissions generated into the atmosphere, in the die-forging of a pulley [kg/pc.]

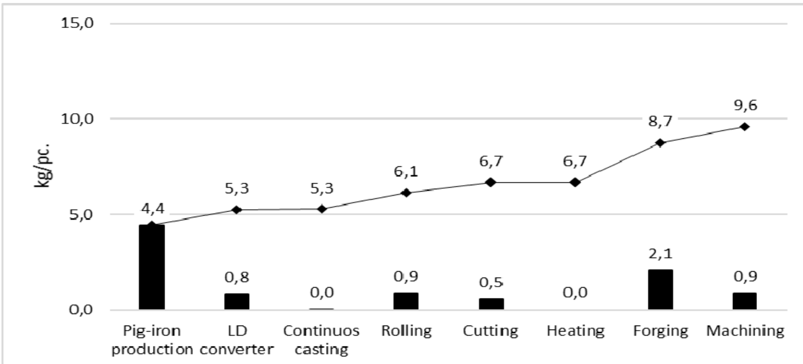

Fig. 11. Waste generated in the die-forging of a pulley [kg/pc.]

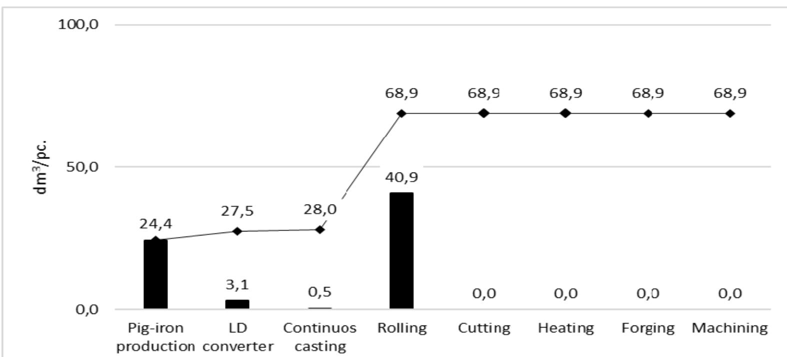

Fig. 12. Waste water generated in the die-forging of a pulley [dm^3/pc.]

4. Analysis of environmental data for selected production technologies

The compilation of environmental aspects, together with the physical quantities relating to individual manufacturing technologies, allows the impact of individual technologies on the environment to be analysed. The results obtained are summarised in the Table 6 and in the graphs from 13 to 16.

Table 6. Environmental aspects for the pulley depending on the manufacturing technology employed

	Energy consumption [MJ/pc.]	Emissions generated into the atmosphere [kg/pc.]	Waste [kg/pc.]	Wastewater [dm^3/pc.]
Machining	339.98	25.44	26.3	165.54
Die forging	106.77	10.58	9.61	68.92

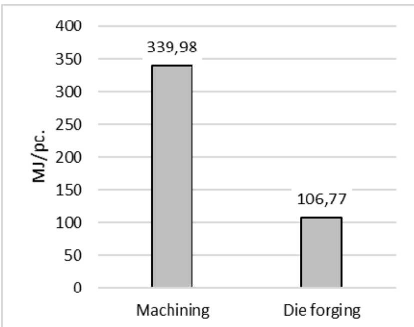

Fig. 13. Energy consumption for a pulley, depending on the technology employed in its construction

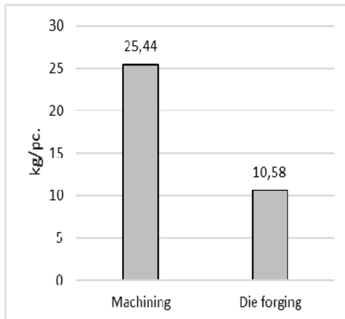

Fig. 14. Emissions generated into the atmosphere for a pulley, depending on the technology employed in its construction

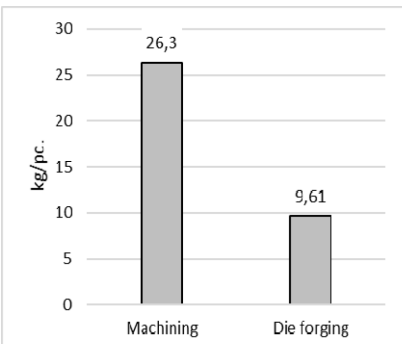

Fig. 15. Waste generated for a pulley depending on the technology employed in its construction

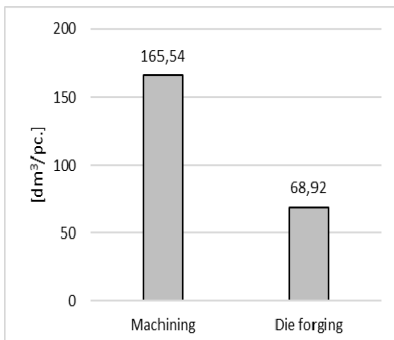

Fig. 16. Wastewater generated for a pulley depending on the technology employed in its construction

5. Conclusions

In an era of global environmental crisis, the overriding objective should be to meet the demand for products produced in balance with the environment, i.e., using renewable, non-hazardous materials and energy sources, while protecting biodiversity. Production systems should not be linear, but closed and cyclical, in order to consume fewer materials, less water and less energy. We should question the need for many products and look for other ways of meeting or reducing needs. A holistic and integrated product-centred approach to environmental issues should be implemented. Most environmental problems such as global warming, toxic contamination, or loss of biodiversity are caused by the way in which natural resources are produced and consumed and also at the pace at which natural resources are produced and consumed.

When analysing the environmental friendliness of the manufacturing technology of a machine part, account should be taken of the task it is intended to perform in the operation of the machine as well as the functionality, reliability and durability criteria thereof. All other considerations must be subordinated to these overriding objectives and therefore also to the environmental friendliness of the technology used in the manufacture of machine parts. Based on the analysis of the issue, the following conclusions were drawn:

- the end result for a given technology allows the environmental load to be tracked;
- knowledge of the unit size of environmental load allows the critical points of the process to be identified;
- the holistic process analysis makes it possible to avoid transferring environmental loads from one unit process to another;
- only when taking into account cumulative environmental loads is it possible the assess the full scope of environmental risks and then identify the most environmentally friendly technologies;
- the environmental burden can be reduced by changing the manufacturing technology, changing the material used or by changing the design of the product;
- the number of research methods for environmental analysis is extensive and there is a serious problem to be overcome in order to select them properly. There is a clear conflict between substantive and practical reasons when making a choice.
- new products and technologies should be brought to life on the basis of an analysis of the environmental costs of their entire life cycle.

Common sense requires energy and environmental protection to be managed rationally at every stage of a product's life. Various indicators can be used to assess the impact of human activity on the environment. By carrying out a variant evaluation of projects, it is possible to clearly identify a better or worse variant of the solution. The second recommendation for assessing the state of the environment is the use of quantitative indicators. Quantitative indicators, expressed in physical quantities *per* functional unit, seem to be more suited to the analysis of manufacturing technology. They give a picture of the actual impact of the technology under analysis on the environment. Having the actual data relating to a given unit process, can be converted into a monetary unit, for example.

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