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ASSESSING OF VARIOUS METHODS OF CAST-OFF TYRE DISPOSAL

Production of cast-off tyres and ways of dealing with this waste have been analysed. Possible ways of processing cast-off tyres such as "use as fuel" and "tyre crushing" have been compared in terms of their environmental impacts. The presented research is ecobalance and despite using the knowledge of LCA method, the method itself according to ISO standards is not applied. Use for energy ("use as fuel" process) was assessed as more environmentally efficient, i.e. with lower environmental impacts than "tyre crushing".

1. INTRODUCTION

Motor vehicles are manufactured products of the highest value. They roll on rubber tyres that wear out several times over the average vehicle's lifetime [1]. Tyres represent an important component of our everyday lives. We use them almost all the time – driving our cars or riding public transport vehicles, as passengers on air flights, and one must not forget the truck tyres that transport various materials, products or equipment. The global demand for tyres has been increasing in the recent years, which is caused by the developing society; this also leads to an increase in cast-off tyre production.

More than 3.3×10^6 tonnes of end-of-life tyres (ELTs) are generated annually in the European Union (EU), of which 2.6 million tonnes are either recycled or recovered [2]. The disposal of ELTs in landfills is banned in the EU (Directive 1993/31/EC); their disposal is therefore mainly managed via: (i) integrated management systems (IMS) run by non-profit companies (a system used in 18 countries); (ii) the free mar-

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ket (e.g., in the United Kingdom, Ireland, Germany, Switzerland, Austria, Bulgaria and Croatia), and (iii) a system of taxes paid by the manufacturers (Denmark, Slovenia and Slovakia). In 2010, about 3.3×10^6 tonnes of used tyres were managed in an environmentally sound manner. This represents a 2% increase in arisings compared to 2009. After sorting out the data of tyres going for reuse or retreading, an estimated 2.7×10^6 tonnes of ELTs were left to be treated. This material flow went into a variety of recycling applications, public works and civil engineering or was used as a fuel substitute in cement kilns, boilers and power plants [2].

An interesting observation in 2010 is the shift in trend, i.e. growth in material recovery (by 10%) and a reduction in energy recovery (by 3%). In numbers, this means that 1.3×10^6 tonnes of ELTs went to material recovery and 1.2×10^6 tonnes into energy recovery. Within material recovery, recycling of ELTs as tyre rubber granulate and powder in various applications is the main recovery route (80%), followed by the use of ELTs in civil engineering applications and public works (18%), dock fenders, blasting mats (<2%) and reducing agent in steel mills and foundries (<1%). As regards energy recovery, the main user of ELTs shreds or whole tyres remains the cement industry (92% in volume), whilst district heating and power plants absorb the remainder [2].

Alternative fates for ELTs, including their retreading [3], de-vulcanization [4], their use in the steel industry [5], the manufacturing of rubber-modified asphalt [6], their use as road bases [7], and their use as fillers for the tread and sidewalls of new tyres [8] have been the subject of study for years. Ground rubber products are also used for athletic and recreational materials, such as running tracks and playground surfaces [1]. Currently, there is much interest in using these materials for energy generation. Tyre-derived fuels (TDFs) are used as substitutes of fossil fuels in the concrete industry [9–11] and in combustion processes for the generation of electric power, e.g., by boilers in the paper manufacturing industry, by industrial boilers and by power stations, etc. [12]. In Europe, nearly 40% of ELTs are used as TDF, whereas in USA and Japan this percentage reaches 53% and 70%, respectively [2].

The goal of this study was to provide an analysis of the production of cast-off tyres and ways of dealing with this waste. The practical part compares possible ways of processing cast-off tyres: "use as fuel" and "tyre crushing" in terms of their environmental impacts.

2. EXPERIMENTAL

Methods of handling cast-off tyres or end-of-life tyres (ELTs) generate various environmental impacts. Each of these methods is specific in some way; therefore it is necessary to consider the impact of the relevant methods of handling this type of waste on the environment. The objective of the work was to carry out research on the possibilities of utilising waste from the communal sphere, specifically cast-off tyres, to find out and assess the potential impacts of using "tyres as fuel" and of "crushing tyres". The main method used to assess these two ways of utilisation is the ecobalance method which uses the knowledge of LCA method. Similar problem was the focus of the paper by Corti and Lombardi [13], who also dealt with the assessment of methods for disposing of cast-off tyres but using the LCA method. Their findings cannot be used for comparing with the gained results because they set different system of boundaries for the assessment in their work. Our research uses the knowledge of LCA method but the method of LCA according to ISO standards has not been applied. Two ways of dealing with cast-off tyres were analyzed and compared. For both methods environmental impacts were evaluated.

The methods used for the work included: the comparative method, analytic-synthetic method, methods of induction and deduction, the qualified estimate method. It was necessary to assess the studied technologies upon a generated set of criteria (i.e. recognised negative environmental impacts). This was achieved by means of multiple criteria assessment of alternatives (further referred to as MAA). The general procedure of using MAA is based on the following algorithm. The role of MAA is characterised by the so-called criterion matrix where columns represent criteria A_j, where $j = 1, 2, ..., k$ and lines represent the assessed alternatives X_i, where $i = 1, 2, ..., n$. The constituents of the matrix express the rating of the i-alternative according to the j-criterion. Consequently it is necessary to define the ideal and basal alternative. The ideal alternative is understood as a hypothetic or real alternative which reaches the best possible values in all the criteria. Similarly, basal alternative is an alternative that has all the criteria values on the lowest level. The next step is the consolidation of the entered criteria. If some of the criteria are entered as maximising and some as minimising, they need to be converted to maximising criteria. These values of the multiple criteria matrix are expressed in different units, therefore it is necessary to normalise these values according to relation $r_{ij} = (y'_{ij} - D_j)/(H_j - D_j)$, where D_j represents the lowest value of the j-criterion and H_j represents its highest value. There are several methods of solving the MAA tasks. For the purposes of this work, the method of weighted total, which represents the determination of weights of the relevant criteria, was used. In order to maintain the objectivity of the weight definition, information from people involved in the studied problem was used. The point method was applied to determine the weights [14].

3. RESULTS

3.1. DETERMINING THE SUBJECT OF THE ANALYSIS

The subject of the analysis is utilisation of tyres as fuel in cement works (referred to as cement works fuel) and crushing of tyres (referred to as crushing). The aim was to compare which of the two methods of utilising cast-off tyres produces lowest environmental impacts. Table 1 lists the advantages and disadvantages of these two methods.

Table 1

Advantages and disadvantages of the examined disposal methods

	Cement works fuel	Crushing
Advantages	replacement of fossil fuels by an alternative fuel	minimum waste production
	lower emissions	volume reduction
	no ash production	
	minimum waste production	
	sulphur binding into cement clinker	
	material use of iron	
Disadvantages	release of toxic substances during imperfect incineration.	production of dust
	emissions may contain dioxins and furans	noise
	risk of fire	high energy demand
	interest of public in emissions	high investment costs – price of final product

3.2. DESCRIPTION OF TECHNOLOGICAL OPERATIONS

Transport is a specific factor therefore this work does not deal with the primary transport but deals specifically with the transport (relations) between the individual operations (phases) for the above listed disposal methods. The stated technological operations describe the situation in concrete plants specialising in handling cast-off tyres.

Technological operations during the tyre utilisation as fuel in cement works are:

1. Unloading (delivery from warehouse) – there are two options:

a) unloading by tipping from truck,

b) unloading by high dumper.

2. Sorting of tyres by size: larger tyres are separated from smaller sizes.

3. Storage bin – space for tyre storage.

4. Conveyor – automated device transporting the tyres.

5. Rotating furnace – tyre incineration.

The last two operations are fully automated without the need for direct presence of personnel. Technological relationships (operations) during tyre crushing are:

1. Unloading (delivery from warehouse).

2. Initial crushing – roughly crushed tyre parts.

3. Entry of material onto the processing line.

4. Crushing:

a) primary mill circuit,

b) secondary mill circuit.

5. Granulation.

6. Separation of fractions.

7. Material output.

Crushing, granulation and separation of fractions all run with parallel suction. Most of the operations are fully automated but presence of personnel is necessary in some of the phases. Determination of the functional unit is an important step in the LCA method. For the purposes of this work the functional unit was determined as the volume of 10^3 kg of tyre waste.

Definition of the scope of studied technological processes. This part is concerned with processes which are characteristic of the relevant disposal methods. These processes are highly important and closely monitored by the subjects processing this type of waste. The individual operations including corresponding activities are described below (Tables 2 and 3).

Table 2

List of operations "cement works fuel"

Operation	Activity
Unloading into storage bin	technical equipment work
Unloading onto storage area	employee and technical equipment work
Sorting	employee work
Storage	–
Transport to storage bin	employee and technical equipment work
Transport from storage bin to conveyor	automated equipment
Weighing	automated equipment- scale
Batching	automated equipment
Transport on conveyor	automated equipment
Rotating furnace	automated equipment

Table 3

List of operations "crushing"

Operation	Activity
Unloading	technical equipment (truck)
Storage	–
Transport for crushing	employee work and technical equipment work (manitou loader)
Crushing	automated equipment and employee work
Transport for crushing	technical equipment and employee work (lugli and desta loaders)
Crushing	automated equipment and employee work
Granulation	automated equipment
Separation of fractions	automated equipment
Suction	automated equipment
Filling in Big Bags	technology
Weighing	technology
Pickup and hauling of Big Bags	technical equipment and employee work (lugli and desta loaders)

Activities were specified for the individual operations. Energy and material flows that are defined for the individual methods are shown in Figs. 1 and 2.

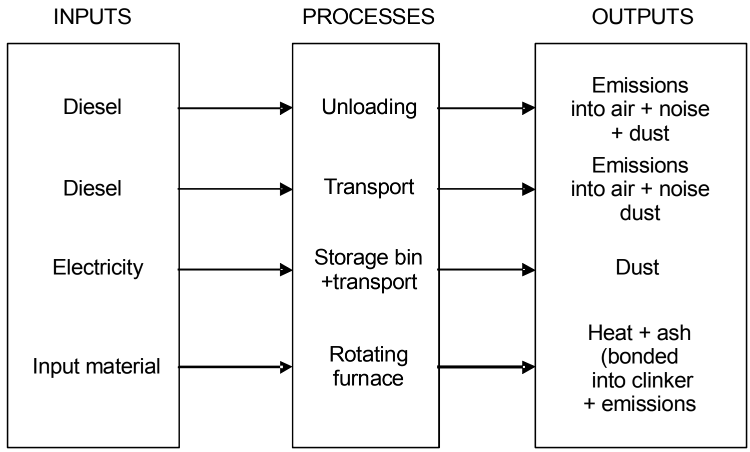

Fig. 1. Processes, energy and material flows
related to utilisation of tyres as fuel in cement works

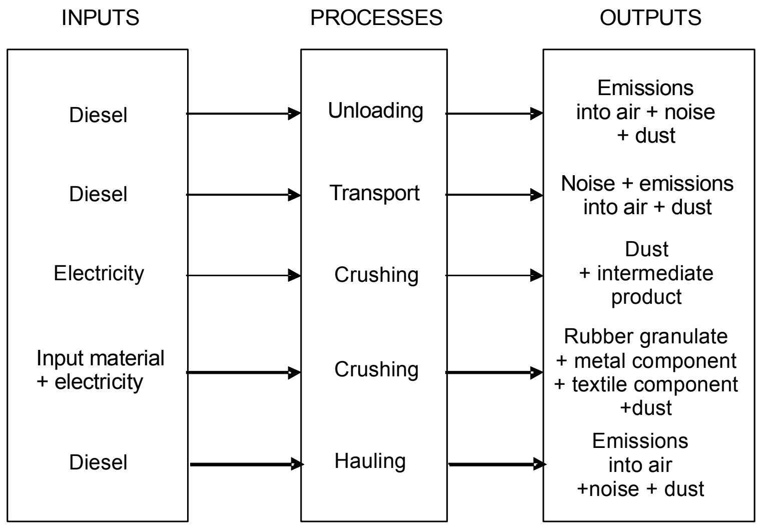

Fig. 2. Processes, energy and material flows related to tyre crushing

3.3. CONDITIONS DEFINED FOR THE ASSESSMENT OF DISPOSAL METHODS

The aim of the inventory analysis was to make a summary of all the flows, i.e. materials and energies, which enter into and come out in the individual phases of the process. The inventory matrces (Tables 4, 5) were divided into a part relating to inputs

Table 4

Inventory matrix for "use as fuel" [15]

Technological operation	Inputs		Outputs			
	Diesel [dm^3]	Electricity [kWh]	Heat [MJ]	Noise [dB]	CO_2 emissions [10^{-3} kg]	Emissions from parallel waste incineration
Unloading into storage bin	0.25	–	–	80	634.26	–
Unloading onto storage area	0.37	–	–	80	945.14	–
Sorting	–	–	–	–	–	–
Storage	–	–	–	–	–	–
Transport to conveyor	0.02	–	–	80	46.44	–
Transport from storage bin to a conveyor	–		–		–	–
Weighing	–	7.77	–	–	–	–
Batching	–		–		–	–
Transport via conveyor	–		–		–	–
Rotating furnace	–	–	25×10^3	–	837 194	[1]
Weighed average	–	–	–	80	–	–
Total	0.64	7.77	25×10^3	–	838819.84	–

[1]TZL, SO_2, NO_x, HCl, HF, TOC, Tl, Cd, Hg, dioxins and furans, Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V.

Table 5

Inventory matrix for "crushing"

Technological operations	Inputs		Outputs				
	Diesel [dm^3]	Electricity [kWh]	Noise [dB]	Rubber granulate [10^3 kg]	Textiles [10^3 kg]	Metals [10^3 kg]	CO_2 emissions [10^{-3}kg]
Unloading	0.29	–	80	–	–	–	745.71
Storage	–	–	–	–	–	–	–
Transport for crushing	0.38	–	80	–	–	–	977.14
Crushing	–	[1]	85	–	–	–	–
Transport for crushing	0.49	–	81	–	–	–	1992.67
Crushing							
Granulation							
Separation of fractions	–	65.63[1]	89.7	0.78	0.07	0.15	–
Suction							
Filling in Big Bags							
Weighing							
Hauling of Big Bags	0.33	–	81	–	–	–	1342
Weighted average	–	–	82.78	–	–	–	–
Total	1.49	65.63	–	0.78	0.08	0.15	5057.52

[1]The value 65.63 kWh is the sum of electrical energy needed the following operations: crushing, granulation, separation of fractions, suction, filling in Big Bags, and weighing. The crushing operation represents approximately 8% (5.25 kWh) share of the total amount of electrical energy.

and a part relating to outputs. The first part contained: fuel consumption (diesel) and energy consumption for the individual technological operations. The outputs included: CO_2 emissions, noise, and other emissions (Table 4) or rubber granulate, textile component, metal component, CO_2 emissions, noise (Table 5).

Further actions included quantitative and qualitative assessment of the potential impacts on the environment. One of the key steps was determination and defining of relevant impact categories that will be assessed in four steps: classification, specification, evaluation, interpretation.

Primary effects stated in the inventory analysis are sorted and grouped into categories by their character of environmental impact. This relates to the consumption of energy gained through the transformation of primary non-renewable resources, which can be described as energy demand assessment (Table 6).

Table 6

Assessment of energy demand [kWh]

Operation	Use as fuel	Tyre crushing
Transport from storage bin to conveyor Weighing Batching Conveyor transport	7.77	–
Initial crushing Crushing Granulation Separation of fractions Suction Filling in Big Bags Weighing	–	65.63
Total	7.77	65.63

For both methods of cast-off tyre utilisation, consumption of electrical energy does not cause direct negative impacts on the environment. However, the high consumption of primary resources needed to produce the electricity must be considered. Processes using these primary resources produce a number of emissions that negatively influence the environment. Electricity is necessary for most of the operations involved in both assessed processes. Consequently, the consumption of primary non-renewable resources was also included (volume of fuel – diesel per 10^3 kg of tyres used (Table 7).

The task was to assess the overall impact of the studied processes on the environment in terms of quantity [15]. This is based on data contained in the inventory analysis. A necessary step that must be taken is to transform the data defined in the relevant classification groups to a common standard in such a way that allows assessing negative impacts of the entire category of detected influences. This is standardisation. Another step in the specification phase is normalisation that helps to evaluate the defined adverse impacts related to the area where they occur.

Table 7

Consumption of primary non-renewable resources [dm^3]

Material	Use as fuel	Tyre crushing
Diesel	0.64	1.49
Total	0.64	1.49

Emissions are described upon their contribution to the greenhouse effect. Determination of contribution to the greenhouse effect is performed using CO_2 equivalent, although there are also other emissions generated through the "use as fuel" method. These emissions will be listed in the overview of process outputs and will be assessed in a separate category.

Table 8 states the amount and types of outputs that were defined for processing of 10^3 kg of cast-off tyres under "use as fuel" method and "tyre crushing" method.

Table 8

Overview of outputs

Output	Use as fuel	Tyre crushing
CO_2 emissions, 10^{-3} kg	838819.84	5057.52
Noise [dB][1]	80	82.78
Emissions from parallel waste incineration	–	–
Textile component, 10^{-3} kg	–	0.07
Metal components, 10^{-3} kg	–	0.15

[1]Average noise level was determined as weighted average in which the scales represented average time of operation of the individual technologies (machines).

During the "use as fuel" process, heat is generated on the output part but as all this heat is then used up in the rotating furnace it shall not be assessed in terms of its negative impact on the environment. During crushing of tyres rubber granulate is produced on the output part, but this output was listed under products as it is eventually recycled and used as material to make various products. This output shall not be assessed in terms of its negative impacts on the environment either.

Consumption of energy gained through transformation of primary non-renewable resources is the first classified group, the second is consumption of primary non-renewable resources, and the third is contribution to the greenhouse effect. The fourth group includes noise, which impacts by its excessive intensity. Excessive noise intensity harms workers' health and also negatively influences the citizens' quality of life. The fifth group includes production of waste, which significantly influences the environmental aspect of the enterprise as well as its economic aspects (high costs of waste disposal or its dumping). Sixth group included emissions generated during the parallel incineration of tyres, which relates only to the "use as fuel" process.

No uniform method is prescribed for this phase. The evaluation issued mostly from the subjective approach of the researchers and the opinions of experts. The experts are university – educated individuals with specialized knowledge, therefore a reliable source of skill, experience and training, who deal with cast-off tyres or other kinds of waste. The evaluation was directed at influences, which were divided into six classified groups. The overall negative impact on the environment is stated in the relevant units regardless of the importance of the individual influences.

For the purposes of general environmental impact assessment the studied methods of cast-off tyre disposal were marked as follows: X_1 – use as fuel and X_2 – tyre crushing. Multiple alternative assessment method was used for evaluation. Selection of criteria issues from the following classification groups:

A_1. Consumption of energy gained through the transformation of primary non-renewable resources (electricity consumption).

A_2. Consumption of primary non-renewable resources (fuel consumption).

A_3. Contribution to the greenhouse effect.

A_4. Noise.

A_5. Production of waste.

A_6. Emissions generated during parallel incineration of waste.

Table 9

Point evaluation of criteria

Criterion	Person 1	Person 2	Person 3	Person 4
A_1	5	5	4	4
A_2	4	5	5	3
A_3	4	3	3	3
A_4	4	2	3	2
A_5	5	4	4	4
A_6	3	3	3	5
Total	25	22	22	21

Point method was used to determine weights. The weights of the individual criteria were gained as weighted average of point values provided by four persons. These involved persons providing point evaluation for each of the criteria. Point evaluation was selected from interval ⟨1; 5⟩ of natural numbers where the higher value of the point evaluation represents that the criterion is of higher value for that particular person. Table 9 shows an overview of the result achieved through the point method.

Upon data listed in Table 9 the weights for the individual criteria were calculated according to the evaluation provided by the relevant persons. The value of the criterion was divided by the sum of evaluations, separately for each of the persons [14]. Results were rounded off to two decimal positions. The total weight for each criterion was determined as arithmetic average of the respective values, i.e. by quotient $\sum v_{ij}/4$, where $i = 1, ..., 6$ represent criteria values, $j = 1, ..., 5$ represent criteria evaluation by the involved persons. The resulting value for each of the criteria was rounded off to two decimal positions. The results are listed in Table 10.

Table 10

Weights of determined criteria

Criterion (v_{ij})	Person 1	Person 2	Person 3	Person 4	$\sum v_{ij}$	Total weight (v_j)
A_1	0.20	0.23	0.18	0.19	0.80	0.20
A_2	0.16	0.23	0.23	0.14	0.76	0.19
A_3	0.16	0.14	0.14	0.14	0.58	0.15
A_4	0.16	0.09	0.14	0.10	0.49	0.12
A_5	0.20	0.18	0.18	0.19	0.75	0.19
A_6	0.12	0.14	0.14	0.24	0.64	0.16

Upon data listed in Table 10 the vector of the weights (**V**) was determined.

$$\mathbf{V} = (0.20, 0.19, 0.15, 0.12, 0.19, 0.16)$$

The so-called criterion matrix was created where matrix columns represent the criteria, i.e. A_1–A_6. The lines of this matrix represent the assessed alternatives (methods of cast-off tyre management). In particular, these are the "use as fuel"– X_1 and "tyre crushing" – X_2 methods. The a_{ij} components of the matrix represent the evaluation of the i-alternative according j-criterion. The final criterion matrix:

$$\mathbf{Y} = \begin{bmatrix} A_1 & A_2 & A_3 & A_4 & A_5 & A_6 \\ 7.77 & 0.64 & 838\,819.84 & 66.40 & 0 & 16\,169.12 \\ 65.63 & 1.49 & 5057.52 & 82.78 & 0.22 & 0 \end{bmatrix} \begin{matrix} \\ X_1 \\ X_2 \end{matrix}$$

After setting up the criterion matrix it is necessary to determine the ideal and basic alternative (ideal alternative was marked as *H* and basic as *D*). The ideal alternative is the hypothetic or real alternative that receives best possible values in all the criteria. Basic alternative is such that has all the criteria values on the lowest level (i.e. highest values).

$$\mathbf{H} = (7.77, 0.64, 5057.52, 66.40, 0, 0)$$

$$\mathbf{D} = (65.63, 1.49, 838819.84, 82.78, 0.22, 16169.12)$$

After setting up the ideal and basic alternatives it is necessary to use the individual components y_{ij} of matrix **Y** to calculate components z_{ij} of normalised matrix **Z** using the basic D_j and ideal H_j alternatives according to the relation

$$z_{ij} = \left(y_{ij} - D_{ij}\right)\left(D_j - H_j\right) \tag{1}$$

$$\mathbf{Z} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 \end{bmatrix} \begin{matrix} X_1 \\ X_2 \end{matrix}$$

After setting up the normalised matrix **Z**, the weights of the individual criteria v_j (Table 10) and components z_{ij} (normalised matrix **Z**) are used to calculate the values of the weighted sum $u(x_i)$ for individual alternatives x_i, where $i \in \langle 1; 2\rangle$ of natural numbers upon equation:

$$u\left(x_i\right) = \sum_{j=1}^{u} z_{ij} v_j \tag{2}$$

The results of the weighted sum calculation $u(x_i)$ produce the following values:

$$u(x_1) = 0.31, \qquad u(x_2) = 0.50$$

The method of processing cast-off tyres with lower environmental impact will be the method producing the lowest value of the weighted sum as minimising criteria were applied. The first, upon the weighted sum method and the above stated criteria, placed the “use as fuel” process. Second, using the same method and stated criteria, was “tyre crushing”. The aim was to combine knowledge, information, and data from the inventory analysis that are used to assess environmental impacts of the compared processes and to make conclusions. Operations causing serious negative impacts on the environment were defined.

For the “use as fuel” method two parameters were evaluated for the technological operations. They were the consumption of fuel (diesel) and electricity. The total fuel consumption was 0.64 $dm^3/10^3$ kg of used tyre. In terms of technological operations the most fuel-demanding was the “unloading onto storage area” operation where fuel consumption was 0.37 dm^3, which represented approximately 58% of the total fuel consumption. The total consumption of electricity needed to perform this operation was 7.77 kWh per 10^3 kg of used tyre. 10^3kg of used tyre, incinerated parallel in a rotating furnace, produces 25×10^3 MJ of heat.

Another of the monitored parameters was noise. Weighted average noise for this process was 80.00 dB. The highest intensity of noise was produced during transport to storage bin (80 dB), unloading into storage bin and unloading onto storage area (80 dB). The semi-final output was the value of CO_2 emissions of 10^{-3} kg per 10^3 kg of used tyres. These emissions include CO_2 emissions generated during the burning of fuel and CO_2 emissions from parallel incineration of the used tyres in the rotating furnace. The highest share of 99% was represented by CO_2 emissions from incineration the rotating furnace. The last of the monitored outputs were emissions generated during parallel incineration (NO_x, SO_2).

For "tyre crushing", two parameters were assessed for inputs in technological operations. With regard to fuel consumption – diesel, the total fuel consumption was 1.49 $dm^3/10^3$ kg of used tyre. The most demanding of the technological operations were: transport for crushing where diesel consumption was 0.49 $dm^3/10^{3}$ kg, which represent approximately 33% of total fuel consumption and transport for primary crushing where diesel consumption represented 0.38 $dm^3/10^3$ kg, which was 26% of the total fuel consumption. The second assessed parameter was electricity, which represented 65.63 kWh per 10^3 kg of used tyre.

Outputs were represented by: noise, waste (textile and metal components) and CO_2 emissions. The first studied parameter was noise. Weighted average of noise for this process was 82.78 dB. The highest noise intensity was recorded during the series of operations that run parallel: crushing, separation of fractions, suction, filling in Big Bags and weighing; the value was 89.70 dB. Waste generated during this process contains textile component (0.07×10^3 kg) and metal component (0.15×10^3 kg). Textile component represented approximately 8% and metal component approximately 15% of 10^3 kg of used tyre. Rubber granulate was produced during the crushing of the cast-off tyres (0.78×10^3 kg/10^3 kg of used tyre). Rubber granulate is not treated as waste in this study but is considered a product which is consequently processed into various types of final products (sound insulation panels, rubber flooring, safety flooring for horses, etc.). Processing of rubber granulate takes place in another plant that was not subject to study. The last studied output were CO_2 emissions 10^{-3} kg per 10^3 kg of used tyres. These are CO_2 emissions that were generated from several operations during the studied process: unloading, transport for primary crushing, and hauling of Big Bags. These emissions were generated during fuel burning (diesel). The total amount of emissions produced was 5057.52×10^{-3} kg CO_2. The most CO_2 emissions were generated during transport for crushing – 39% of the total amount of produced emissions.

4. DISCUSSION OF RESULTS AND CONCLUSIONS

Comparison of the achieved results with other studies performed, e.g. with the paper by Corti and Lombardi [13] is difficult although the used methods are similar. The quoted study considered different impact categories and operations for the studied processes. These operations, machines and equipment naturally differ among individual facilities and proper comparison is therefore difficult if not impossible.

Another research for end of life tyre assessment has been made by Li et al. [16]. To assess the management methods of cast-off tyres they used GaBi 4 software whereas our study based on the multiple criteria alternative assessment method. Energetic use was assessed as more environmentally efficient, i.e. with lower environmental impacts. The same results were achieved in our research.

In terms of consumption of fuel gained through transformation of primary non-renewable resources the "use as fuel" process scored better. This disposal method uses only approximately 12% of electricity needed for the "tyre crushing" process. The influence of consumption of primary non-renewable resources closely relates to fuel consumption. Diesel is used as fuel for many technological operations in both methods. Lower negative impacts on the environment were found in the "use as fuel" method. This method uses approximately 43% fuel of that for "tyre crushing". Another studied impact, which has been highly discussed in recent years, was the contribution to the greenhouse effect. Only CO_2 emissions were studied. Lower negative impacts related to CO_2 emissions occurred during the "tyre crushing" method. This method produces approximately 166 times (by 99.4%) less CO_2 emissions than the "use as fuel" process. The greatest share of the contribution to the greenhouse effect is represented by CO_2 emissions generated during processes taking place in rotating furnaces. However, thanks to the recently performed modernisation of the furnaces, the CO_2 production is much lower and the cement works meet all of the currently applicable limits and standards. In the "tyre crushing" process, contribution to the greenhouse effect is represented by CO_2 emissions generated during the burning of fuel. Another studied influence was the contribution to noise level. Noise occurred in both methods during various technological operations, especially those related to transport, handling, and operations involved in processing. Lower negative impact of this environmental influence occurred during "use as fuel". This method generates approximately 4% less noise than the crushing process. From the perspective of waste production better results were achieved by the "use as fuel" process.

According to Pořízek [17], this method of cast-off tyre processing leads to their safe disposal and parallel use of energy content. The process of "tyre crushing" produces 0.22×10^3 kg of waste, which represents 0.07×10^3 kg of textile component and 0.15×10^3 kg of metal component. Generated waste is handed over for further processing where their material and energy content is used. Textiles (chemlon fibres) are hauled to incinerator where the contained energy is utilised. The metals are hauled to scrap yard. Although the "tyre crushing" process generates waste, it is positive in the fact that this waste can be recycled in terms of material or energy. The product of the process is rubber granulate. Rubber granulate is used to make, e.g. rubber paving, non-slip surfaces for around swimming pools, rubber mats, filling of artificial lawns, sound insulation panels, stress-absorbers for bridge constructions, railway track shock absorbers, rubber granulate is used also to for safety mats on playgrounds and sport pitch grounds. The last assessed influence was the production of emissions generated during parallel waste incineration. In terms of this impact, the achieved results showed that "use as fuel" produces worse results. For "tyre crushing" this impact cannot be determined as these emissions are not monitored during this type of processing. Emissions monitored during the incineration of cast-off tyres at cement works include: TZL, SO_2, NO_x, HCL, HF, TOC, Tl, Cd, Hg, the volumes of Sb, As, Pb, Cr, Co, Mn, Ni, V, dioxins and furans. The volume of emissions generated during parallel incineration of waste (used tyres) meets all current legislative standards and limits set by the cement works. Modern, tried, and environment-friendly categories (modern furnaces, separating filters) help to meet the limits for these emissions with sufficient reserve. Both of the compared processes generated "dust" [18]. This influence was not studied in terms of its environmental impact due to data unavailability. However, this influence must be mentioned in the interpretation because dust occurs during many operations under both processes. More dust was generated during "tyre crushing" – this was found upon subjective assessment performed during a visit to the crushing plant.

It is also necessary to mention that processed data related to pollution leak, burden or impact the compared processes. To decide upon the selection of a process to handle this type of waste it is necessary to consider many aspects such as economic data, e.g. investment costs, operational costs, market potential, etc. although the economic aspect does play an important part in the selection of the process, this aspect was not studied in this work, especially due to the unavailability of required data relating to costs or investments and also due to higher general demands.

The results of this work can also provide recommendations to enterprises dealing with processing of cast-off tyres for "use as fuel in cement works" and "tyre crushing" in order to improve their processes (operations) in terms of environmental impacts.

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