Analysis of recycling effect on degree of environmental impact at VW cars production

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Abstract. The economic system of a modern state requires efficient road transport, which plays an essential role in communication and freight transport. Such dynamic development of the automotive industry entails a number of negative effects, above all for the natural environment, causing pollution of air, soil and water as well as an increase in the amount of waste products generated during operation and disposal of motor vehicles. Mainly due to the threat to the natural environment, it is necessary to fully utilize waste products in the process of recycling and recovery. The aim of the article is to present the recycling effect on changes in the environmental impact during the production process of a vehicle.

1. Introduction
One of the problems of the 21st century is the increasing threat to the natural environment and the use of raw materials. Automotive industry has a major impact on the overall level of environmental degradation as it plays a key role in communication and transport of goods. Its development entails a number of negative effects on the natural environment, causing pollution of air, soil and water [3, 4]. It is a source of waste products created during operation and disposal of vehicles withdrawn from use. Currently, the world car park has about 500 million passenger cars and about 150 million trucks [3, 4, 5]. Every year there are 35 million cars more, it is estimated that by 2020 there will be a billion vehicles in the world [5]. Means of transport are one of the main causes of atmospheric pollution. Mainly due to the threat to the natural environment, it is necessary to fully develop the process of recycling or recovery. The management of products from used vehicles is also necessary due to the increasing costs of storage as well as material and energy savings. Processed materials from end-of-life vehicles can be used in a variety of ways, mainly for the production of new products, but also as a substitute fuel or in special applications. No possibility to use waste products forces to store or dispose them. Full and efficient management of waste products generated in road transport requires action in the design and production period [1, 2, 6].

2. Process of a vehicle withdrawal
The development of the automotive industry entails an increase in the amount of waste products created during the operation and disposal of motor vehicles. Environmental considerations also require proper management of such products in the processes of recycling and recovery. The processing of products from used vehicles is also necessary due to the increasing costs of storage and savings, especially in materials and energy. Processed materials from exploited cars can be used in a variety of ways, mainly for the production of new products, but also as a substitute fuel or in special applications. No possibility to use waste products forces to store or dispose them. Full and efficient
management of waste products generated in road transport requires action in the period of their design and manufacturing. And the rational use of a vehicle has a decisive impact on the durability of its components.

One of the ways of limiting the harmful impact of vehicles on the natural environment is recycling, which due to the large amount of waste from end-of-life vehicles and the greatest threat to the environment is the most developed in the automotive industry. No consumer product has such a high recovery rate of materials as motorization. Recycling is therefore a field that includes technical, technological and organizational activities aiming at the maximum recovery of assemblies, parts and subassemblies as well as materials from end-of-life (used and damaged) means of transport [8, 9, 10].

In general, four forms of recycling can be distinguished [8, 9]:

- re-use for the same purpose (e.g. removing an efficient part from an end-of-life vehicle and mounting it in another vehicle),
- re-use for other purposes (e.g. using car tires as bumpers in the port),
- re-use in the same production process (use of plastic granules as a raw material),
- re-use in another manufacturing process (e.g. plastic waste for the production of thermal insulation of clothing).

Currently, the world car park has about 500 million passenger cars and about 150 million trucks. Every year there are 35 million cars more, it is estimated that by 2020 there will be a billion vehicles in the world. Means of transport are one of the main causes of atmospheric pollution. Mainly due to the threat to the natural environment, it is necessary to fully develop the process of recycling or recovery. The management of products from used vehicles is also necessary due to the increasing costs of storage as well as material and energy savings. Processed materials from end-of-life vehicles can be used in a variety of ways, mainly for the production of new products that can be re-used. Full and efficient management of waste products generated in road transport requires action in the design and production period.

Necessity to manage waste products in transport is also increasing material and energy costs. The processing of used materials, the regeneration of parts and their re-use allows for significant savings. The essence of the withdrawal phase of a vehicle is now a possibility to recover used materials to build passenger cars. This is essential both for reducing the volume of waste irretrievably stored in landfills, and for reducing the consumption of natural resources, because there is no need to satisfy all demand for these materials based only on primary production. Another advantageous environmental aspect of using the same materials and parts is the reduction of energy consumption and emission levels associated with the production phase and the operation of the car.

3. Purpose and scope of the analysis

The automotive industry and the public administration authorities take a lot of efforts to improve the environmental efficiency of cars. However, this does not solve the basic environmental problems associated with the development of transport. The increasing needs of societies for mobility, preferring the use of individual transport, are contradictory to the actions of legislative bodies that strive for a more sustainable development of transport. According to OICA statistics in 2017, only in EU countries, about 17 million passenger cars were produced. Every year, about 9 million cars go to scrap yards. The rules for dealing with cars withdrawn from use in EU countries are regulated by Directive 2000/53/EC [9], later 2005/64/EC. They impose indicators of mandatory recovery of cars withdrawn from use. Since 2006, recovery and re-use must be 85%, and recycling and re-use 80% for the weight of the car. Only in the case of vehicles produced by the end of 1979 75% for recovery and 70% for reuse and recycling is allowed. The goal is to achieve at the beginning of 2015 a level of 95% for reuse and recovery and 85% for reuse and recycling for all vehicles.

The recycling possibilities depend on the type of material. It is now believed that cast iron, cast steel and steel can be re-used in 100%, and non-ferrous metals can be re-used in 90%. The problem is the re-use of plastics. The biggest obstacle is the loss of the initial properties of recycled elements. The obtained results relate to the six design generations of the Volkswagen Golf car with
a petrol engine, with similar operating characteristics, produced from 1976 to 2012. Inventory of materials was carried out on the basis of data obtained from the dismantling station in Szczecin (Poland) and data from the IDIS database. In order to estimate the energy contained in the materials and the emission of carbon dioxide related to the production of the car, information from the following databases was used: Ecoinvent v2.0, Eco-Indicator EI99 E/A Europe and Gemis 2.7.

4. Characteristics of energy inputs and environmental loads occurring in the scrapping phase of a passenger vehicle

Analysis of the energy inputs and environmental burdens were performed for the selected material groups of the passenger vehicle obtained during primary production and including recycling at a predetermined degree of the material recovery.

The degree of recovery of recycled materials in the vehicle production phase was determined on the basis of the applicable recovery rates for selected materials, which are presented in Table 1.

Table 1. Material recovery rates [3, 4]

| Material                        | Material recovery rate |
|---------------------------------|------------------------|
| Steel, cast iron                | 0.70-1.00              |
| Aluminum                        | 0.70-0.90              |
| Plastics                        | 0.05-0.30              |
| Tires and elastomers            | 0.30-0.50              |
| Consumables                     | 0.05-0.85              |
| Glass                           | 1.00                   |
| Non-ferrous metals              | 0.05-0.15              |

4.1. Characteristics of energy inputs occurring in the scrapping phase of a passenger vehicle

For the minimum and maximum values of these coefficients, appropriate levels of material recovery from the end-of-life vehicle were determined taking into account changes in its material structure.

Table 2. Energy inputs in [MJ] for various VW Golf models with varying degrees of material recovery

| NE [MJ] | VW Golf |
|---------|---------|
|         | Mk1     | Mk2     | Mk3     | Mk4     | Mk5     | Mk6     |
|         | production |        |        |        |        |        |
| Entire vehicle | min. | 44831 | 47706 | 59059 | 67900 | 65918 | 72643 |
|            | max.   | 50007 | 50094 | 67900 | 72643 | 65918 | 72643 |
| M1         | min.   | 33138 | 34958 | 44084 | 50560 | 49158 | 54006 |
|            | max.   | 38525 | 41345 | 51421 | 58697 | 55287 | 60833 |
| M2         | min.   | 23187 | 24338 | 26925 | 30015 | 28391 | 30111 |
|            | max.   | 29469 | 31333 | 35048 | 38133 | 35522 | 37344 |
| M3         | min.   | 9127  | 11980 | 13815 | 15620 | 14193 | 15620 |
|            | max.   | 9127  | 11980 | 13815 | 15620 | 14193 | 15620 |
| M4         | min.   | 4346  | 5237  | 5237  | 5237  | 5237  | 5237  |
|            | max.   | 4346  | 5237  | 5237  | 5237  | 5237  | 5237  |
4.1.1. Energy inputs for the entire vehicle. The energy inputs for the entire vehicle when recycled with the minimum and maximum recovery rates for different versions of VW Golf are lower than the inputs incurred during primary production.

![Figure 1. Energy inputs for entire car vehicle with various levels of material recovery](image)

With a minimum recovery rate, energy inputs range from 33138 MJ for Mk1 to 54006 MJ for Mk6 and are lower from 25.4% to 26.7% than the inputs incurred during primary production. However, at the maximum recovery rate, the energy inputs amount from 28008 MJ for Mk1 to 45938 MJ for Mk6 and are lower from 36.5% to 38.2% than the inputs incurred during primary production, and lower from 14.8% to 15.7% than the inputs incurred when recycling for a minimum recovery rate.

4.1.2. Energy inputs for steel, cast steel and cast iron in a vehicle. The energy inputs for steel, cast steel and cast iron in a vehicle with recycling with the minimum and maximum recovery rates for different VW Golf versions are lower than the inputs incurred during primary production. With a minimum recovery rate, the energy inputs are from 15652 MJ for Mk1 to 20313 MJ for Mk6 and are lower by 32.5% than the inputs incurred during primary production. However, at the maximum recovery rate, the energy inputs amount from 12408 MJ for Mk1 to 16113 MJ for Mk6 and are lower by 46.5% than the inputs incurred during primary production, and are lower by 20.7% than the inputs incurred when recycling for a minimum recovery rate.

![Figure 2. Energy inputs for steel, cast steel and cast iron in a vehicle with varying degrees of material recovery](image)
4.1.3. Energy inputs for aluminium and its alloys in a vehicle. The energy inputs for aluminium and its alloys in a vehicle with recycling, with the minimum and maximum recovery rates for various VW Golf versions, are lower than the inputs incurred during primary production. With a minimum recovery rate, the energy inputs are from 3056 MJ for Mk1 to 6033 MJ for Mk6 and are lower by 62.7% than the inputs incurred during primary production. However, at the maximum recovery rate, the energy inputs amount from 1587 MJ for Mk1 to 3133 MJ for Mk6 and are lower by 80.6% than the inputs incurred during primary production, and lower by 48.1% than the inputs incurred when recycling for a minimum recovery rate.

![Figure 3. Energy inputs for aluminium and its alloys in a vehicle with varying degrees of material recovery](image)

4.2. Characteristics of environmental loads occurring in the scrapping phase of a passenger vehicle

4.2.1. CO$_2$ emission

Table 3. CO$_2$ emission in [kg] for various VW Golf models with varying degrees of material recovery

| CO$_2$ [kg] | Mk1 | Mk2 | Mk3 | Mk4 | Mk5 | Mk6 |
|------------|-----|-----|-----|-----|-----|-----|
| Entire vehicle production | 3971 | 4219 | 4996 | 5674 | 5447 | 5926 |
| min. | 2470 | 2612 | 3165 | 3593 | 3456 | 3761 |
| max. | 1831 | 1936 | 2388 | 2715 | 2618 | 2853 |
| production | 2601 | 2730 | 3020 | 3367 | 3185 | 3377 |
| M1 min. | 1375 | 1443 | 1596 | 1779 | 1683 | 1785 |
| max. | 849 | 891 | 986 | 1099 | 1040 | 1103 |
| production | 522 | 581 | 762 | 894 | 876 | 1030 |
| M2 min. | 194 | 216 | 283 | 332 | 325 | 382 |
| max. | 100 | 111 | 146 | 171 | 168 | 197 |

4.2.2. CO$_2$ emission for the entire car vehicle. CO$_2$ emission for the entire vehicle when recycling with the minimum and maximum recovery rates for different versions of VW Golf is lower than the
CO₂ emission produced during primary production. With a minimum recovery rate, CO₂ emission ranges from 2470 kg for Mk1 to 3761 kg for Mk6 and is lower from 36.5% to 38.1% than the CO₂ emission produced during primary production. However, at the maximum recovery rate, CO₂ emission ranges from 1831 kg for Mk1 to 2853 kg for Mk6 and is lower from 51.9% to 54.1% than the CO₂ emission produced during primary production, and lower from 24.1% to 25.9% than the CO₂ emission produced when recycling for a minimum recovery rate.

**Figure 4.** CO₂ emission for entire vehicle with different levels of material recovery

4.2.3. **CO₂ emission for steel, cast steel and cast iron in a motor vehicle.** CO₂ emissions for steel, cast steel and cast iron in a motor vehicle with recycling with the minimum and maximum recovery rates for different VW Golf versions are lower than the CO₂ emissions produced during primary production. With a minimum recovery rate, CO₂ emissions range from 1375 kg for Mk1 to 1785 kg for Mk6 and is lower by 47.1% than the CO₂ emission produced during primary production. However, at the maximum recovery rate, CO₂ emission ranges from 849 kg for Mk1 to 1103 kg for Mk6 and is lower by 67.41% than the CO₂ emission produced during primary production, and lower by 38.29% than the CO₂ emission produced when recycling for a minimum recovery rate.

**Figure 5.** CO₂ emission for steel, cast steel and cast iron with varying degrees of material recovery
4.2.4. CO\(_2\) emission for aluminium and its alloys in a motor vehicle. CO\(_2\) emissions for aluminium and its alloys in a motor vehicle with recycling with the minimum and maximum recovery rates for different VW Golf versions are lower than the CO\(_2\) emissions produced during primary production. With a minimum recovery rate, CO\(_2\) emissions range from 194 kg for Mk1 to 382 kg for Mk6 and is lower by 62.9% than the CO\(_2\) emission produced during primary production. However, at the maximum recovery rate, CO\(_2\) emission ranges from 100 kg for Mk1 to 197 kg for Mk6 and is lower by 80.8% than the CO\(_2\) emission produced during primary production, and lower by 48.4% than the CO\(_2\) emission produced when recycling for a minimum recovery rate.

![Figure 6. CO\(_2\) emission for aluminium and its alloys in a vehicle with varying degrees of material recovery](image)

4.2.5. SO\(_2\) emission

Table 4. SO\(_2\) emission in [kg] for various VW Golf models with varying degrees of material recovery

| SO\(_2\) [kg] | Mk1  | Mk2  | Mk3  | Mk4  | Mk5  | Mk6  |
|--------------|------|------|------|------|------|------|
| Entire vehicle production | 6,05 | 6,62 | 9,59 | 11,02| 10,98| 12,48|
| min.         | 6,01 | 6,49 | 9,22 | 10,48| 10,40| 11,65|
| max.         | 6,07 | 6,53 | 9,17 | 10,40| 10,30| 11,48|
| production   | 1,13 | 1,18 | 1,31 | 1,46 | 1,38 | 1,46 |
| M1 min.      | 2,11 | 2,22 | 2,46 | 2,74 | 2,59 | 2,75 |
| max.         | 2,54 | 2,66 | 2,95 | 3,29 | 3,11 | 3,30 |
| production   | 1,69 | 1,89 | 2,48 | 2,90 | 2,84 | 3,34 |
| M2 min.      | 0,55 | 0,61 | 0,80 | 0,94 | 0,92 | 1,08 |
| max.         | 0,22 | 0,25 | 0,32 | 0,38 | 0,37 | 0,44 |

4.2.6. SO\(_2\) emission for the entire vehicle. SO\(_2\) emissions for the entire vehicle when recycled with the minimum and maximum recovery rates for different versions of VW Golf are lower than the SO\(_2\) emissions produced during primary production. Only in the case of Mk1, SO\(_2\) emission when
recycled with maximum recovery rates, is slightly higher than the emission generated during primary production. With a minimum recovery rate, SO\textsubscript{2} emission is from 6.01 kg for Mk1 to 11.65 kg for Mk6 and is lower from 0.7% to 4.9% than the SO\textsubscript{2} emission produced during primary production. However, at the maximum recovery rate, the SO\textsubscript{2} emission ranges from 6.01 kg for Mk1 to 11.65 kg for Mk6. SO\textsubscript{2} emission is lower from 1.4% to 8.1% than the SO\textsubscript{2} emission produced during primary production for the versions from Mk2 to Mk6. In the case of Mk1 it is higher by 0.3%. Compared to SO\textsubscript{2} emission produced when recycling with the minimum recovery rate it is lower from 0.5% to 1.5% for the versions from Mk3 to Mk6 and is higher from 0.6% to 1.0% for versions Mk2 and Mk1, respectively.

Figure 7. SO\textsubscript{2} emission for the entire motor vehicle with varying degrees of material recovery

4.2.7. SO\textsubscript{2} emission for steel, cast steel and cast iron in a motor vehicle. SO\textsubscript{2} emission for steel, cast steel and cast iron in a motor vehicle when recycled with the minimum and maximum recovery rates for different versions of VW Golf is higher than the SO\textsubscript{2} emission produced during primary production. With a minimum recovery rate, SO\textsubscript{2} emission is from 2.11 kg for Mk1 to 2.75 kg for Mk6 and is higher by 87.7% than the SO\textsubscript{2} emission produced during primary production. However, at the maximum recovery rate, the SO\textsubscript{2} emission ranges from 2.54 kg for Mk1 to 3.30 kg for Mk6 and is higher by 125.2% than the SO\textsubscript{2} emission produced during primary production and higher by 20% than the SO\textsubscript{2} emission produced when recycling with the minimum recovery rate.
4.2.8. SO$_2$ emission for aluminium and its alloys in a motor vehicle. SO$_2$ emission for aluminium and its alloys in a motor vehicle with recycling with the minimum and maximum recovery rates for different VW Golf versions is lower than the SO$_2$ emissions produced during primary production. With a minimum recovery rate, SO$_2$ emissions range from 0.55 kg for Mk1 to 1.08 kg for Mk6 and is lower by 67.6% than the SO$_2$ emission produced during primary production. However, at the maximum recovery rate, SO$_2$ emission ranges from 0.22 kg for Mk1 to 0.44 kg for Mk6 and is lower by 87% than the SO$_2$ emission produced during primary production, and lower by 59.7% than the SO$_2$ emission produced when recycling for a minimum recovery rate.

5. Conclusions

On the basis of the conducted research and its analysis, it can be clearly stated that the recycling of materials from end-of-life vehicles influences the reduction of energy inputs during the car production process. Recycling is thus an effective way to improve this impact. At the same time, it helps to
reduce CO$_2$eq emissions. For the maximum recovery rate, the energy inputs of VW Golf cars are smaller by an average of 37% than the inputs incurred during the primary production. In the case of VW Golf, recycling for the maximum recovery rate reduced CO$_2$ emissions by an average of 52.7% and reduced SO$_2$ emissions by an average of 4.3%.

Based on the results of the analysis, it can be concluded that the optimization of the selection of construction materials taking into account the processes of their recycling may constitute an effective method to reduce the environmental loads of the car. However, the scope of these activities, presented on the example of the VW Golf car, does not solve the problem of increasing energy consumption and emissivity of materials used in the production of subsequent car models, even at the maximum recycling rates. This could even lead to a thesis that the changes in the method of using construction materials are to a larger extent the result of the growing requirements of consumer markets, which expect more and more comfortable and safe vehicles, than the care for the natural environment. The activities undertaken by producers in this area focus on meeting the requirements for fuel consumption and permissible emission levels during the period of a car usage. However, from the point of view of the car impact on the environment throughout the life cycle, these activities prove to be insufficient. Changes in the selection of construction materials shown on the example of the VW Golf car, which consist in increasing the use of lightweight materials, are limited to compensating for the effects of the mass increase of newly produced cars. Such changes only allow for the maintenance of energy consumption and CO$_2$ emissions in the next car models when the car is used at an unchanged level. Reducing the level of environmental impact requires more radical action. One of the possibilities is a more decisive increase in the share of plastics and aluminium in the construction of the car.

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