Energy and environmental evaluation of construction materials used for VW cars production

M Orzechowski and M Mrozik
West Pomeranian University of Technology Szczecin, Faculty of Mechanical Engineering and Mechatronics, Al. Piastów 19, 70-310 Szczecin
E-mail: miron.orzechowski@zut.edu.pl; malgorzata.mrozik@zut.edu.pl

Abstract. Production and operation of vehicles currently has a significant impact on the environment. The choice of more environmentally friendly construction materials which a car is made from can significantly reduce its environmental impact. The main aim of this article was to compare the environmental impact assessment of changes in the design of passenger cars by using the life cycle assessment analysis (LCA). The paper presents a simplified LCA method of a car, which in specific cases can be used to analyse environmental impacts associated with the manufacturing process to assess the ecological performance of new passenger cars. In the adopted LCA simplification, the carbon dioxide equivalent emission CO2eq was used to assess the impact. The values of these variables were determined based on the mass of materials used to build the car. A practical example of using the simplified LCA method for a comparative assessment of the ecological efficiency of Volkswagen Group passenger cars manufactured over the last 30 years is presented.

1. Introduction
Automotive industry is one of the very important elements of economic and social life. Its development is accompanied, above all, by greater use of means of transport, in particular passenger cars. This significant increase in the number of produced cars can only be realized through the increasing global consumption of production raw materials as well as energy carriers. The exploitation of more and more vehicles is also connected with the pollution of the natural environment, which is growing more and more quickly, not only by the emission of harmful substances resulting from fuel combustion or production processes in the automotive industry, but also due to the increasing number of parts and subassemblies of the vehicle to be replaced, and, above all, the rapidly increasing number of vehicles withdrawn from traffic and subjected to the scrapping process. All this has an impact on sustainable development and, above all, on the quality of the natural environment [1, 2, 3].

The global automotive industry is currently undergoing changes related to the global problems of the ongoing degradation of the natural environment. This forces car manufacturers to improve their design constantly in order to meet the requirements of customers for whom the environmental impact of the car is an increasingly important criterion when choosing a new model. In addition, consumer markets of highly developed countries expect more and more comfortable and safe vehicles. This leads to the increasing use of elastomers, plastics, aluminum and other non-ferrous metals in car equipment components and in electronic driver assistance systems. The use of these materials, apart from increasing energy consumption and CO2 emissions in the production process, also complicates the recycling and reuse processes. The mass of cars is systematically increasing. The results of our research show that in
the last 25 years the mass of compact passenger cars from the so-called C-segment has increased by approx. 43% [1, 7]. In order to counteract this unfavorable trend, manufacturers are forced to introduce changes in the material structure and production technology, which are increasingly more often optimized in terms of the car impact on the natural environment.

The paper presents a simplified model of the Car Life Cycle Assessment, in which the total CO\textsubscript{2} emission is determined on the basis of the mass of materials. This model was used to assess the eco-efficiency of the design of passenger cars manufactured over the last 30 years. It was analyzed how, as a result of technological progress, the consumption and the use of materials from which new cars are produced have been changing. It was also examined which of these changes have the greatest impact on increasing the level of emissions in the production process. The obtained results have reflected changes in the emissivity of the VW Golf car structure since 1984. An interesting issue, among others, was the statement what benefits resulted in the introduction of an environmental management system and a design oriented to environmental optimization of a car construction (DfE – Design for Environment) [8, 9].

2. Purpose and scope of the analysis
The automotive industry and the public administration authorities take a lot of efforts to improve the energy 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. Since 2006, recovery and re-use must be 85% and recycling and re-use 80% in relation to the weight of the car. Only in the case of vehicles manufactured until the end of 1979, 75% recovery and 70% for reuse and recycling was allowed. The goal was to achieve at the beginning of 2015 a level of 95% for reuse and recovery and 85% for reuse and recycling for all vehicles. Obtaining recovery and recycling levels in Poland, which has been increased since 1st January 2015, was possible by increasing the level of disassembling vehicles withdrawn from service. It required improving the profitability of disassembly - that is, modifying the method of dismantling subsidies treated as a reimbursement of expenses incurred for dismantling. 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 in 90%. The problem is the re-use of plastics. The biggest obstacle is the loss of the initial properties of the recycled elements [4, 5, 6]. The requirements imposed by the legislators regarding the management of cars withdrawn from use forced manufacturers to environmental optimization of car construction, taking into account the selection of materials and recycling at the design stage. Selection of construction materials used in the car construction has a significant impact on the level of its environmental impact throughout the life cycle of the car, including the production phase. Therefore, there is a need for a detailed analysis to identify materials (components) of the car that generate the highest level of the environmental impact [1, 7]. The results obtained relate to the six design generations of the Volkswagen Golf car with a petrol engine, with similar operating characteristics, produced from 1976 to 2012 (Table. 1). 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.
Table. 1. Basic technical data of Volkswagen cars [7]

| Brand          | Model | Production year | Bodywork type | Complete vehicle kerb weight [kg] | Engine capacity [cm$^3$] | Fuel consumption in the city [l/100 km] | Fuel consumption outside the city [l/100 km] | Average fuel consumption [l/100 km] |
|----------------|-------|-----------------|---------------|-----------------------------------|--------------------------|------------------------------------------|----------------------------------------|-----------------------------------|
| Volkswagen     | Golf MK 1 | 1976-1983       | hatchback      | 830                               | 1272                     | 10,5                                     | 7,9                                     | 7,8                               |
|                | Golf MK 2 | 1983-1987       | hatchback      | 875                               | 1272                     | 7,9                                      | 5,5                                     | 6,1                               |
|                | Golf MK 3 | 1991-1997       | hatchback      | 1030                              | 1391                     | 9,0                                      | 5,5                                     | 6,8                               |
|                | Golf MK 4 | 1997-2003       | hatchback      | 1174                              | 1390                     | 8,4                                      | 5,5                                     | 6,4                               |
|                | Golf MK 5 | 2006-2008       | hatchback      | 1153                              | 1390                     | 9,1                                      | 5,4                                     | 6,8                               |
|                | Golf MK 6 | 2008-2012       | hatchback      | 1215                              | 1390                     | 8,5                                      | 5,1                                     | 6,4                               |

To assess the impact on the basis of the inventory results, a set of environmental variables in the form of pollutant emissions, such as CO$_2$, CO, SO$_2$, NO$_x$, CH$_4$, N$_2$O, NMVOC have been used. The emission values of these pollutants (for the whole car and its assemblies) were determined on the basis of the mass of materials used to build the car, using the commercial database Ecoinvent v 2.0. According to the accepted simplification of the LCA phase, the environmental impact of these variables has been converted to carbon dioxide emissions CO$_2$eq. The Eco-Indicator EI99 E/A Europe model, available in the commercial SimaPro 7.1 software, was used for conversion. In the adopted LCA simplification, consistent with the objective of the environmental tests, the emission of CO$_2$eq was treated as a category of the environmental impact. It has been shown that the selection of construction materials used in the construction of vehicles has a significant impact on the total CO$_2$eq emission over the whole life cycle.

3. Material car model

The analysis presented in the article is based on the model of the life cycle of a passenger vehicle, which was based on LCA analysis according to the requirements of ISO 14040 and ISO 14044. The basic assumption of the model is the analytical modeling of the production phase of the passenger vehicle shown in Figure 1, which includes in the first stage its division into systems (U), which are then divided into units (Z) consisting of individual materials (M) with a given mass. These materials were grouped into five basic groups: ferrous metals, aluminum and its alloys, plastics, non-ferrous metals and other materials. Determining the material structure of a motor vehicle is the basis for determining the amount of energy inputs for particular types of materials.
Figure 1. Analytical model of passenger vehicle decomposition

It was proposed to divide the structure of the car into five systems, which correspond to the basic functional systems:

- vehicle body – (U₁),
- vehicle chassis – (U₂),
- motor with accessories – (U₃),
- electric and electronic components of the vehicle – (U₄),
- fluid – (U₅).

The diagram of such a car division into systems is shown in Figure 1. Each system (U₁ ... U₅) consists of units (Zᵢ), and the unit consists of parts with specific masses (mᵢ), made of different materials (Mᵢ). The identification of the mass and material type of each part was carried out during the inventory. A set of 27 types of materials Mᵢ = {M₁, M₂...M₂₇} has been separated (Table 2). These materials were assigned to five material groups:

- materials M₁,
- materials M₂,
- materials M₃÷M₁₃, M₁₆,
- materials M₁₇,
- other materials.

Figure 2 presents quantitative changes in the total weight and mass of individual groups of materials in subsequent generations of VW Golf. These changes are a signal of technological progress that has been made in the car construction and car equipment over the last 30 years. The total weight of the Golf VI compared to the first generation model increased by approx. 46%. The basic structural material is still steel, cast steel and cast iron (M₁ materials). The weight of these materials increased by approx. 30%. The mass of other construction materials increased considerably faster. The mass of aluminum and its alloys (M₂ materials) increased by approx. 97%, a plastics (materials M₃...M₁₃, M₁₆) - about approx. 106%. Almost three times (about 174%) the mass of non-ferrous metals increased (materials M₁₇).
The greatest technological progress took place with the introduction of III generation model. In this model, a number of changes have been introduced to improve the comfort and safety of car use. The price of these changes was to increase the weight of the new car by approx. 18%. Technological progress was also reflected in the change of the designing way of the Golf III model, in which for the first time in the world the influence of introduced car modifications on the natural environment was taken into account. The effect of implementing life cycle engineering as the main principle of car development was the change in the way materials were used, which is shown in Figure 3. Starting from III generation model there is a clear reduction in the share of steel, cast steel and cast iron (M1) in the total weight of materials used to build the car. On the other hand, the share of light materials such as aluminum (M2) and plastics (M3…M13, M16) is increased. Such a strategy to reduce the weight of the car, aimed at compensating the increasing use of safety systems, comfort and electronic devices (M17, other materials), is used in the next generations of the VW Golf model. Since the appearance of the Golf III model, the share of lightweight materials has increased by 4%. This corresponds to an increase of their weight by approx. 80 kg.

![Figure 2](image1.png)

**Figure 2.** Changes in weight materials in subsequent generations of VW Golf

![Figure 3](image2.png)

**Figure 3.** Changes in the material composition in subsequent generations of VW Golf
4. Comparative analysis of energy inputs
A comparative analysis of the impact of VW golf cars on the environment was based on the level of energy contained in the materials used in the production of cars. In order to identify the materials and components of the car with the greatest impact on the environment, the levels of these impacts were determined both for the whole car and for separate groups of materials. Comparison of energy levels for the whole car and the division into individual materials is shown in Figure 4. The difference of these levels in VI and I generation cars is approx. 62%. The energy contained in the materials in subsequent models increases faster than the weight of the car, the increase of which is approx. 46% (Figure 2). This means that each of the components of this mass has a varied impact on such a trend of energy changes in the entire car. The level of this energy is primarily related to the mass of steel, cast steel and cast iron (M1). Starting from IV generation model, the energy level of M1 material is stabilized. The biggest influence on the increase in the overall energy level of the car has the increase in the weight of the other materials (Figure 3) such as plastics (M3…M13, M16), aluminum (M2) and other non-ferrous metals (M17), with a much greater level of energy contained, compared to steel, cast steel and cast iron. The impact of material (M2) increased by 97%, materials (M3…M13, M16) - by 122%, and material (M17) - by 174%.

Figure 4. Energy levels for the entire car and for individual materials in subsequent generations of VW Golf

Figure 5. Relative energy consumption for individual materials in subsequent generations of VW Golf
The effect of such changes is a systematic increase of the share of these materials in the total energy level of the car, while reducing the share of steel, cast steel and cast iron (M1).

5. Comparative analysis of CO₂eq emissions

In order to identify the materials and components of the car with the greatest environmental impact, the level of this emission was determined both for the whole car and for separate groups of materials and functional systems. The comparison of CO₂eq emissions for the entire car and the division into individual materials is shown in Figure 6. The difference in CO₂eq emission levels for the whole car in VI and I generation models is approx. 49%.

![Figure 6. CO₂eq emission levels for the entire car and for individual materials in subsequent generations of VW Golf](image)

Steel, cast steel and cast iron (M1) have the greatest impact on CO₂eq emissions. The share of (M1) material accounts for approx. 60% of the total CO₂eq emission of the car, showing a tendency to decrease (Figure 7). Such changes are related to the more widespread use of aluminum (M2) and metals (M17) having much larger, compared to steel, cast steel and cast iron, unit levels of CO₂eq emission in the production of subsequent car models. If to compare the changes in the material composition (Figure 6) with CO₂eq emission changes for individual materials (Figure 7), it can be concluded that among all materials the highest rate of increase in total CO₂eq emission is related to the increase in the mass of materials (M2) and (M17). However, the greatest potential for limiting the dynamics of the car CO₂eq emission is applied to plastics (M3…M13, M16).
6. Conclusions

The selection of construction materials used in the construction of cars has a significant impact on the total energy and CO\textsubscript{2}eq emissions throughout the life cycle. It was found that in six consecutive VW Golf models produced over the past 30 years, the CO\textsubscript{2}eq emission of construction materials has been systematically increasing. Increasing the total energy intensity of materials and CO\textsubscript{2}eq emissions in subsequent car models is the price of technological progress that has been made in the construction and equipment of VW Golf cars, especially with the introduction of III generation model. The manifestation of this progress is to increase the weight of the car by about 46%, which is accompanied by a change in the way the materials applied to its production are used. A detailed analysis made it possible to identify materials generating the highest level of environmental impact. The material with the highest energy consumption are ferrous metals. With their mass constituting over 60% of the total weight of the car with a slight tendency to reduce, the share of ferrous metals energy constitutes about half of the total energy level contained in the materials of the whole car. However, the greatest impact on the increase of the total energy level of the car has wider and wider use of other materials with a much higher level of cumulated energy compared to ferrous metals. These are mainly non-ferrous metals and plastics currently commonly used in car body and equipment components as well as in electronic driver assistance systems.

Compared to I generation models, the total weight of these materials in the Golf VI has doubled. The share of all non-ferrous metals in the total energy level of the Golf VI is only 13% smaller than the share of ferrous metals, although their weight is six times higher than the weight of non-ferrous metals. Smaller impact levels are associated with an increase in the weight of plastics. With four times less weight of plastics compared to ferrous metals, their share in the total energy level of the Golf VI materials accounts for almost half of the share of ferrous metals.

Similar trends in changes in the environmental impact of materials can also be observed in the carbon dioxide emission category CO\textsubscript{2}eq. The level of impact of ferrous metals as the basic construction material constitutes approx. 60% of the total level of impact of materials of the whole car with a slight tendency to decrease. The highest dynamics in increase of CO\textsubscript{2}eq emission characterized non-ferrous metals. Total level of this emission has increased more than twice, and in the Golf VI model it accounts for 40% of emissions of ferrous metals. The level of CO\textsubscript{2}eq emissions of plastics also doubled, however, their share in the total emissions of this car model is more than twice lower than that of ferrous metals, although their mass is 5% lower than the weight of plastics. Compared to ferrous metals, the share of CO\textsubscript{2}eq emissions of plastics is six times smaller with a four-fold difference in weight. With such changes
in CO₂eq emission levels of individual materials, the total emission level of the entire car increases by approx. 50%.

References

[1] Danilecki K., Mrozik M., Smurawski P.: Changes in the environmental profile of a popular passenger car over the last 30 years – Results of a simplified LCA study. Journal of Cleaner Production, Volume 141 (2017)

[2] Gollinger M.: Analiza wskaźnikowa w ocenie jakości ekologicznej procesów technologicznych. Akademia Ekonomiczna w Krakowie, Zeszyty Naukowe nr 508, Kraków 1998

[3] Gollinger M.: Ecological Factors of Technological Process Quality, 5th International Commodity Science Conference, Quality for European Integration, Poznań 1996

[4] Import używanych samochodów
http://www.pzpm.org.pl/pl/Rynek-motoryzacyjny/Import-uzywanych-samochodow

[5] Merkisz-Guranowska A.: Aspekty rozwoju recyklingu w Polsce. Instytut Technologii Eksploatacji w Radomiu, Państwowy Instytut Badawczy, Poznań-Radom 2005

[6] Merkisz-Guranowska A., Merkisz J.: Wybrane aspekty globalizacji w przemyśle motoryzacyjnym. Zeszyty Naukowe Politechniki Poznańskiej, Budowa Maszyn i Zarządzanie Produkcją, nr 6, Poznań 2007

[7] Mrozik M., Danilecki K., Smurawski P.: Ocena wpływu materiałów konstrukcyjnych pojazdu na jego efektywność energetyczną. Autobusy: Technika, Eksploatacja, Systemy transportowe, Nr 7/2016

[8] White Paper Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system
http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52011DC0144&from=EN

[9] World Vehicles in use,http://www.oica.net/category/vehicles-in-use/