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A CASE STUDY OF DIESEL ENGINE PISTONS MANUFACTURING AND OPERATION – COMPARATIVE ENVIRONMENTAL ASSESSMENT

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ABSTRACT: The main aim of the study was to compare two technologies of diesel engine piston manufacturing. Additionally, a simplified analysis was also made for the operation stage. The environmental impact was determined using a life cycle assessment. The research was conducted in four phases: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation. From the perspective of production itself, the aluminium pistons have been revealed to be a better option. However, differing emission characteristics and lower impact while in operation have compensated for the differences resulting from production and equalised the environmental impact of both solutions. Despite less environmentally friendly production, the fact that steel pistons are used in newer generations of engines means that, in terms of the two analysed life cycle stages, both solutions are environmentally comparable. The environmental hot spots of the production processes turned out to be different, although in both cases, they are associated with energy consumption. The research is of an applied nature with reference to real production processes and with highlights of the importance of factoring in the perspective of life cycle.

KEYWORDS: environmental impact, life cycle assessment, aluminium pistons, steel pistons

Introduction

The evolution of the automotive industry has been focused on reducing environmental impact for many years. According to reports, 25% of global CO2 emissions come from transport and 13% from passenger cars (Topics European Parliament, 2019). Therefore, issues related to changing levels of permissible emissions, the use of recycled materials, or the elimination of certain chemicals largely determine the development of production technologies for this industry. The engine is one of the key elements that have a direct impact on the vehicle's operating phase and air emissions. An engine is made up of many small, seemingly insignificant components. A number of studies show the importance of life cycle analysis in improving this product, with a strong emphasis on the potential to reduce the environmental impact of the life cycle of a vehicle. This article is part of the discussion on the environmental efficiency of engine component production technology. Meeting the requirements of each successive "EURO" directive, which safeguards the maximum thresholds of pollutant emission from the operation phase, is becoming more and more difficult and results in an increase in the diversity of production processes. The study covered pistons for internal combustion engines, which are essential components in generating engine power. The article provides a detailed analysis of aluminium and steel pistons, enabling the evaluation of the environmental performance of technological changes within the products, taking into account, to a selected extent, the stage of vehicle operation. Comparatively evaluating the environmental aspects of the manufacturing of aluminium pistons (intended for EURO 5 motors) and steel pistons (intended for EURO 6 motors) was the primary goal of the study. In addition, an analysis of environmental impacts was carried out in a simplified way, accounting for the operating stage of vehicles containing engines with the examined pistons. For comparison purposes, the diesel-powered configurations of the Honda Civic (IX and X generation) were used, outfitted with engines housing the desired pistons (IX generation car – aluminium pistons; X generation car – steel pistons). The research questions were defined as follows: (1) Are there differences in the environmental impact of the analysed steel and aluminium piston manufacturing processes? (2) What are the main drivers of this impact? (3) Does taking into account the operation stage affect the results? The research carried out is part of the area of environmental management and eco-design. This article is addressed to specialists in environmental management systems, production management, eco-design, and car users.

It should be emphasised that, because of no access to primary data on the bill of materials for entire engines, the pistons were analysed solely. In order to check the potential relevance of elements made of aluminium and steel, a screening Life Cycle Assessment (LCA) was made using a secondary dataset for the production of an internal combustion engine used in a passenger car. The results showed that it is justified to consider the components manufactured from aluminium and steel as potential main drivers of the environmental impact of the entire engine. In the screening analysis, these components were responsible for more than half of the impact within the most relevant impact categories.

An overview of the literature

In recent years, an increasing share of electric cars in the European Union market has been observed (ACEA, 2023). Despite the ambitious targets that countries and cities have set for themselves in terms of reducing CO_2 emissions by completely moving away from internal combustion vehicles to electric ones (e.g., Norway: 100% electric cars by 2025, France: 100% electric cars by 2040), there are no enforcement mechanisms, which may undermine the feasibility of these ambitions (Plötz et al., 2019). As some studies show, there are places where the trend of "replacing" combustion vehicles with electric ones will be difficult to maintain, because already, current users of electric cars do not want to buy another electric vehicle but are considering returning to an internal combustion equivalent.

An insufficient access to charging infrastructure may be another reason for a limited interest in the use of electric cars (Hardman & Tal, 2021). Although many studies indicate electric vehicles as an ecological option, their environmental efficiency is strongly dependent on energy origin and electricity mix (e.g., Burchart-Korol et al., 2018; Das et al., 2014). Research on hydrogen-based solutions

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seems to be a promising area of environmental improvement for internal combustion engines. In press reports, Toyota informs that it is working intensively on the modification of the technology already offered on the market based on hydrogen fuel cells, generating electricity (Fuel Cell Electric Vehicle). This modification involves the direct combustion of hydrogen in an engine structurally similar to an internal combustion engine, but unlike them, it does not generate CO_2 during its operation (Toyota newsroom, 2021). Other companies are also working on hydrogen-powered internal combustion engines, including BMW and Ford (Wodorowyświat.pl, 2023). The new EU regulations provide for a gradual reduction of CO_2 emissions from vehicles by 2030 (Regulation, 2023). Manufacturers have been required to reduce CO_2 emissions by 55% for passenger cars and 50% for vans. This regulation sets new directions for the automotive industry and ultimately does not introduce a total ban on the production of combustion cars. In practice, this means the parallel production of vehicles with traditional gasoline and diesel engines next to those powered by hydrogen or electricity. Intensive research and development work is underway on internal combustion engines powered by e-fuel, an emission-free synthetic fuel that is nothing new, but it is to be an ecological fuel obtained and processed in a chemical process, e.g., from carbon dioxide from the atmosphere and green hydrogen obtained from the electrolysis of water, hence the name Electrofuel. Vehicles equipped with these engines could constitute the future of the automotive industry. The examples cited illustrate how ambiguous the rapid decline of combustion vehicles can be. This makes the development of these products require a more in-depth analysis that takes into account the role of the manufacturers of individual components and determines their part in shaping the environmental aspects of the vehicle's life cycle. LCA is gaining importance in this field. The scope of application of LCA studies in the automotive industry is wide. Although most attention is paid to the issue of emissions, other issues are also being analysed. It is worth noting the environmental reports of numerous manufacturers and scientific publications.

For many years, Daimler AG have been issuing verified LCA reports. They provide an assessment of the environmental impact of the first hybrid models and car models containing recycled materials (e.g. Life Cycle Environmental Certificate Mercedes-Benz B-Class Electric Drive, 2014; Life Cycle Environmental Certificate Mercedes-Benz S-Class including S 500 PLUG-IN HYBRID, 2015). LCA reports have also been prepared by other manufacturers: BMW (e.g. Environmental Report BMW X5 xDrive45e, 2019), Volkswagen (e.g. The Golf. Environmental Commendation – Background Report, 2010), Audi (e.g. The new Audi TT Coupé – Life Cycle Assessment, 2014), Kia (e.g. Kia EV6 achieves product carbon footprint certification from the Carbon Trust – Press Release, 2021), and Honda (e.g. Honda North American Environmental Report, 2017). An interesting study was conducted in 2017 on the material consumption of the Volkswagen Golf across six generations of the car (MK1-MK6) and the associated greenhouse gas emissions (Danilecki et al., 2017). Over the space of years, specific vehicle components have also been subjected to LCA analyses: the metal structures of the body (Warsen & Krinke, 2013; Zhang & Xu, 2022), the material composition of the engine portions (Sun et al., 2017), and much smaller parts like engine blocks (Bonollo et al., 2006), and engine valves (Silva et al., 2018).

Materials and methods

The study was carried out using the Life Cycle Assessment (LCA) methodology based on ISO 14040 standards (International Organisation for Standardisation, 2006a; International Organisation for Standardisation, 2006b). Four phases of LCA study were completed: a goal and scope definition; a life cycle inventory; a life cycle impact assessment; and an interpretation (International Organization for Standardization, 2006a). In the first step, the purpose of the study, function, functional unit, and system boundaries were defined. In the next phase, inventory data was collected on inputs (e.g., consumption of raw materials, energy) and outputs (emissions to the air, water, soil, and waste). The inventory results were assessed for the quality of the data. Next, the environmental impact assessment using the Impact 2002+ method was carried out (Jolliet et al., 2003). The following 15 impact categories were included: Aquatic acidification, Aquatic ecotoxicity, Aquatic eutrophication, Carcinogens, Global Warming, Ionizing radiation, Land occupation, Mineral extraction, Non-carcinogens, Non-renewable energy, Ozone layer depletion, Respiratory inorganics, Respiratory organics,

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Terrestrial acidification/nutrification, Terrestrial ecotoxicity. As part of the interpretation, an identification of the most relevant issues, a sensitivity analysis and an uncertainty analysis were carried out.

The subject of the analysis were the production processes of two types of pistons: aluminium pistons, intended for the internal combustion diesel engine in the EURO 5 class (piston weight 0.352 kg/pcs), and steel pistons, used for the internal combustion diesel engine in the EURO 6 class (piston weight 0.486 kg/pcs). Pistons made from aluminium contained secondary raw material from internal recycling (less than 10% of the input). According to the manufacturer's declaration, the steel pistons were made from virgin raw material. The use of a particular metal in the piston determines a number of engine parameters. For this reason, the same material cannot be used in both types of engine. The use of steel, a material with much greater strength than the commonly used aluminium, allowed the size and construction of the piston to be changed. The use of steel construction affects, for example, the height of the piston and the length of the connecting rods (reducing the height of the piston by 30% has made it possible to use a longer connecting rod, resulting in a 10% reduction in lateral forces).

In this study, production is understood as "materials" and "manufacturing". This means that both the construction materials that are part of the finished products and the materials that are not part of the pistons (e.g., water, salt cores, detergents, etc.) were taken into account in the analysis. For example, the inputs to the "melting and casting" process include both aluminium ingots (primary and secondary), electrolytic copper, alloy additives, and electricity needed to power the furnaces. The outputs cover aluminium castings, pollutant emissions, and waste (dross and foundry slag). In the case of "forging" process (steel pistons), the inputs include the steel casting (cast iron, chromium steel, alloy additives) and the electricity necessary to carry out this process. The results of the environmental impact will therefore be shown for all inputs and outputs assigned to unit processes within materials and manufacturing.

The main objective of the study was to compare in detail the environmental impacts associated with the production of pistons and to estimate, on the basis of selected operating parameters, how the environmental impact of vehicles equipped with engines with the analysed pistons differs. The function of the manufacturing system is to produce finished pistons, and the production of 160,000 pieces is assumed to be a functional unit. This production volume allowed for the production of 40,000 engines, included in the simplified analysis covering the operation stage. The production processes are divided into basic (main) processes and supporting (auxiliary) processes.

For the analysed production processes, inventory data was obtained directly from the manufacturer. In total, as part of the data inventory, about 100 inputs and outputs were identified. The quality of the data was evaluated by applying a semi-quantitative approach based on Pedigree Matrix (Weidema & Wesnaes, 1996). The results of the data quality assessment were used to perform uncertainty analysis with the use of a Monte Carlo simulation. The obtained values for the variation coefficients are at a similar level, which indicates a comparable data quality. The basic processes for the production of aluminium (Figure 1) and steel (Figure 2) pistons are presented below.

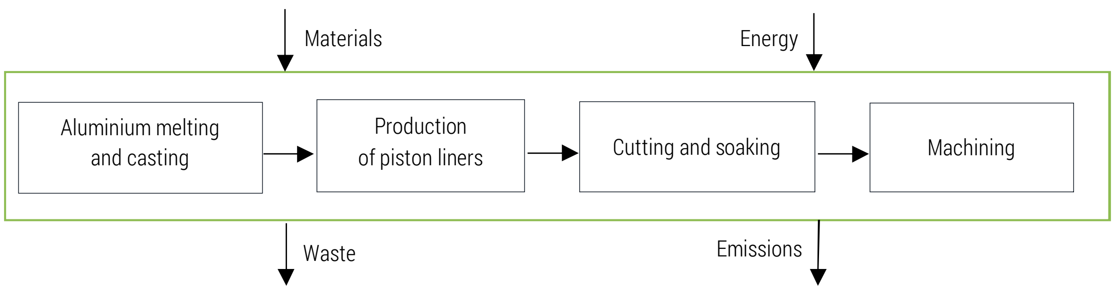

Figure 1. Basic processes of aluminium piston production

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The supporting processes of the production of aluminium pistons included:

- Manufacturing of salt cores on a hydraulic press, and then heating in a furnace to harden their structure,
- production of demineralised water, later used in galvanic processes,
- production of machining coolants by mixing water with emulsion concentrates of appropriate concentration,
- refining of liquid aluminium to purify it,
- cooling of foundry furnaces by means of water circuits,
- preparation for surface treatment processes (washing with dedicated detergents),
- inspections of the final product or semi-finished product at the casting stage,
- keeping processes running,
- neutralisation of wastewater generated as a result of galvanic processes, product washing, waste gas treatment, and emulsion ultrafiltration.

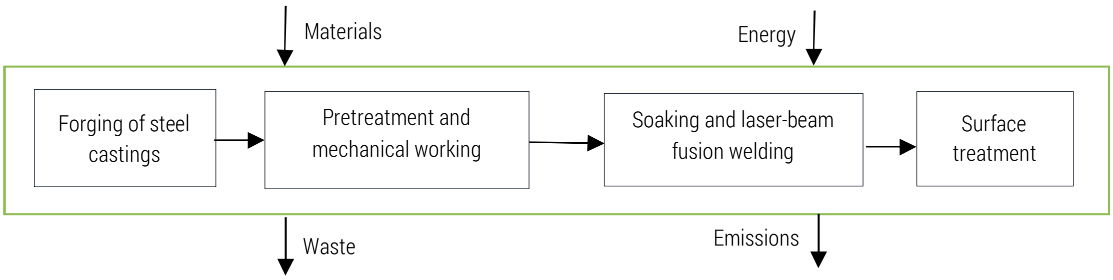


Figure 2. Basic processes of steel piston production

In addition, in the production of steel pistons, the following supporting processes were distinguished:

- Production of technological cold for the needs of production,
- production of protective gas in the form of a mixture of nitrogen and hydrogen for heating and laser welding,
- production of liquid carbon dioxide, used to wash specific areas of the product.

Both aluminium and steel pistons were considered unarmed (sealing rings, wiper rings, piston pins, and piston pin retaining protection were not included in the analysis).

As mentioned, the usage stage-was analysed in a simplified way – only through fuel consumption (diesel) and carbon dioxide and nitrogen oxide emissions for a distance of 150,000 km (this distance is considered representative in many LCA reports). The simplified approach used for the use phase was related to the availability of comparable operating data for vehicles with the analysed pistons (available emission and fuel consumption data for the use phase constitute the most significant influence of this phase). Selected parameters taken into account during operation are presented below (Table 1).

Table 1. Selected aspects of vehicle operation included in the comparative analysis

Parameter	Engine with aluminium pistons (X3WA RZ0) – EURO 5	Engine with steel pistons (XL5B) – EURO 6
Fuel consumption (diesel) – combined (NEDC) [l/100 km]	3.58	3.53
CO_2 emission [g/km]	94	93
NO_x emission [g/km]	0.139	0.052

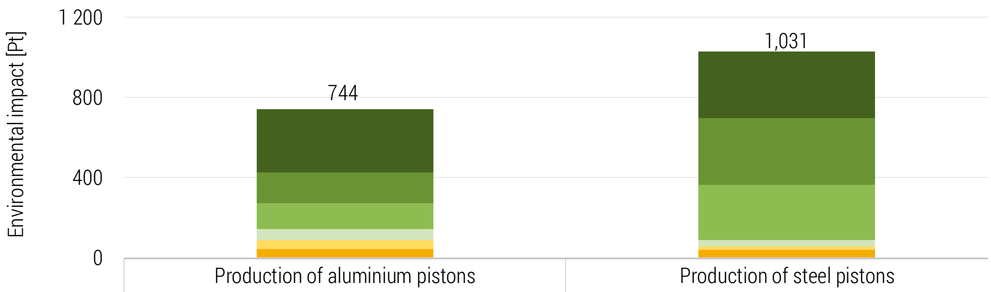
Source: authors' work based on engine manufacturer's data (measurements made in accordance with the New European Driving Cycle, NEDC methodology).

Results of the research

In LCA studies, the results of the environmental impact assessment can be analysed at different levels. In the case of the Impact 2002+ method used, the most aggregated level is obtained after weighing, of which the results are expressed in Points [Pt]. The least aggregated level presents characterised results, of which the results of the environmental impact for each of the impact categories are expressed in a different unit (e.g., for global warming in kg CO_2 eq., for respiratory inorganic in kg PM 2.5 eq.). Regardless of the level, the same interpretative principle always applies: the higher the positive result, the greater the negative impact. In this chapter, both weighed and characterised results will be presented. They will be the basis for answering the research questions presented in the introduction. First, the weighed and characterised results for the production stage will be presented, and then for both stages together: production and use.

Results of the research – production stage

The total potential impact on the environment of the manufacturing of 160,000 aluminium pistons is 744 Pt. The production of the same number of steel pistons achieved a result 39% higher (1,031 Pt). This means that, from an aggregate single score point of view, making aluminium pistons is an environmentally better option. By analysing the results broken down into 15 impact categories, the three most relevant environmental problems were identified: "respiratory inorganics," "global warming," and "non-renewable energy." This means that at least 80% of the total cumulative impact falls into these three impact categories. As shown in Figure 3, this applies to both of the production processes analysed.



	Production of aluminium pistons	Production of steel pistons
Respiratory inorganics	316	333
Global warming	156	333
Non-renewable energy	127	273
Land occupation	54	34
Non-carcinogens	46	14
Remaining impact categories	44	43

Figure 3. Environmental impacts of aluminium and steel pistons at the production stage – weighed results of impact category indicators [Pt]

Source: authors' work based on Grygiel (2023).

The vast majority of environmental impacts are attributable to the implementation of basic processes: more than 90% for two types of pistons. In the production of aluminium pistons, the highest value of the index (473 Pt) was obtained for "melting and casting,". In the case of steel piston manufacturing, the most important process turned out to be "forging" (525 Pt). The results are presented in Table 2.

Table 2. Environmental impact of piston manufacturing processes

Production of aluminium pistons						
Aluminium melting and casting	Production of piston liners	Cutting, soaking, and machining processes	Supporting processes	Transport	Total	Unit
473	117	108	43	2	744	Pt
64	16	15	6	0,3	100	%

Production of steel pistons							
Forging of steel castings	Pretreatment and mechanical working	Soaking and laser-beam fusion welding	Surface treatment	Supporting processes	Transport	Total	Unit
525	84	164	184	68	6	1,031	Pt
51%	8%	16%	18%	7%	1%	100	%

Source: authors' work based on Grygiel (2023).

Next, the characterised results for the three most relevant impact categories were analysed. In the case of "respiratory inorganics," the environmental impact of producing steel pistons is larger, with a total PM 2.5 eq. of 3,077 kg. For aluminium pistons, the total PM 2.5 eq. is 2,983 kg. In the case of this category, it should be noted that the environmental influence of aluminium pistons is linked with the "melting and casting" (65.37% share in the value of the indicator of this category). When it comes to steel pistons, the impact is associated with the "forging" process (56.13% share in the value of the indicator of this category). In the case of another key category, which is the "global warming" category, the environmental influence of steel pistons is also larger (GWP is 3,053 Mg CO_2 eq., where for aluminium pistons it amounts to 1,333 Mg CO_2 eq.). The main source of impact in this category are the processes that are most responsible for the "respiratory inorganic" category. For the third relevant category ("non-renewable energy"), a higher indicator value was also obtained for the production of steel pistons. This amounts to 37,998 GJ of primary energy and is more than twice as high as the result for aluminium pistons. Table 3 presents the characterised results for the most significant processes.

Table 3. Environmental impact of the most relevant unit processes within the most significant impact categories – characterised results

The most relevant impact category	Production of aluminium pistons		Production of steel pistons		Unit
	The most relevant process	Environmental impact (characterized)	The most relevant process	Environmental impact (characterized)	
Respiratory inorganics	Aluminium melting and casting	1,950	Forging of steel castings	1,727	kg PM2.5 eq.
		65.37		56.13	%
Global warming	Aluminium melting and casting	866	Forging of steel castings	1,570	Mg CO2 eq.
		64.97		51.42	%
Non-renewable energy	Aluminium melting and casting	10,928	Forging of steel castings	19,637	GJ
		65.32		51.67	%

Source: authors' work based on Grygiel (2023).

When considering the impact on the environment, differences between the analysed processes are apparent (Figure 4). In the case of aluminium pistons, material consumption has the greatest impact (562 Pt in total), followed by energy consumption in production processes (196 Pt in total).

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In the case of steel piston production, material consumption generates significantly lower impacts than energy consumption. Other aspects (waste, air emissions, sewage) have a similar influence.

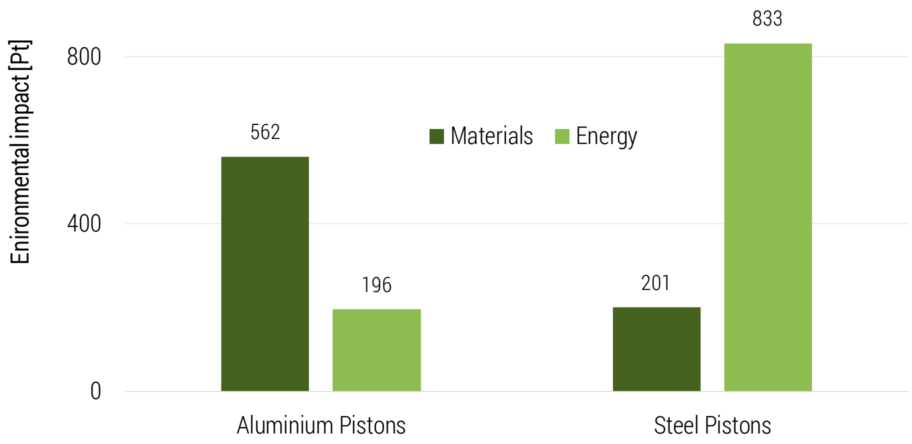

Figure 4. Environmental impacts of aluminium and steel pistons from the point of view of the most relevant environmental aspects [Pt]
Source: authors' work based on Grygiel (2023).

Taking into account the origin of pollutants within the category "respiratory inorganic" for the aspect with the strongest impact for aluminium pistons (materials in the melting and casting process, 1,875 kg PM 2.5 eq.), it was considered that it is largely related to the production of nickel. On the other hand, when analysing in detail the sources of contamination in this category for the element with the largest impact for steel pistons, it was assessed that it is primarily related to forging and energy consumption during this process (1,184 kg PM 2.5 eq.). For the other most relevant impact categories (global warming and non-renewable energy), the materials used for melting and casting are the most relevant aspects for aluminium piston manufacturing (mostly virgin aluminium). For the production of steel pistons, the energy consumed during forging is the most relevant aspect, given the problem of global warming and non-renewable energy.

Table 4. Environmental impact of the most relevant unit processes and their aspects within the most significant impact categories – characterised results

The most relevant impact category	Aluminium pistons manufacturing		Steel pistons manufacturing		Unit
	The most relevant process and its environmental impact	The most relevant aspect and its environmental impact	The most relevant process and its environmental impact	The most relevant aspect and its environmental impact	
Respiratory inorganics	Aluminium melting and casting	Materials (constituents)	Forging of steel castings	Energy	kg PM2.5 eq.
	1,950	1,875	1,727	1,184	
	65	63	56	38	%
Global warming	Aluminium melting and casting	Materials (constituents)	Forging of steel castings	Energy	Mg CO2 eq.
	866	794	1,570	1,306	
	65	60	51	43	%
Non-renewable energy	Aluminium melting and casting	Materials (constituents)	Forging of steel castings	Energy	GJ
	10,928	9,702	19,637	16,143	
	65	58	52	42	%

Source: authors' work based on Grygiel (2023).

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Results of the research – production and operation

After taking into account the stage of operation (mileage of 150 thousand km), the single score was obtained at a level of 142,110 Pt for aluminium pistons and 140,613 Pt for steel ones. Considering the production and operation stages of the analysed pistons together, the two most relevant impact categories have been identified: non-renewable energy and global warming. In both cases (both for aluminium and steel pistons), the most relevant impact categories collectively generate more than 90% of the environmental impact. For the production and operation stages of aluminium pistons, the weighted impact category indicator of non-renewable energy was 656, 29 Pt, while the weighted impact category indicator of global warming had a value of 646,34 Pt. For the production and operation stages of steel pistons, the above indicators were respectively 648,60 Pt and 641,00 Pt.

The burdens of the manufacturing along with the usage stage were then analysed, taking into account the increasing distance, starting from 5,000 kilometres up to 200,000 kilometres. The results are presented in Figure 5. Initially, the greater environmental impact of steel pistons can be observed. After a distance of 25,000 km, the environmental impact of steel pistons is lower than that of aluminium pistons (considering the production and operation stages). This difference increases with every kilometre in favour of steel pistons.

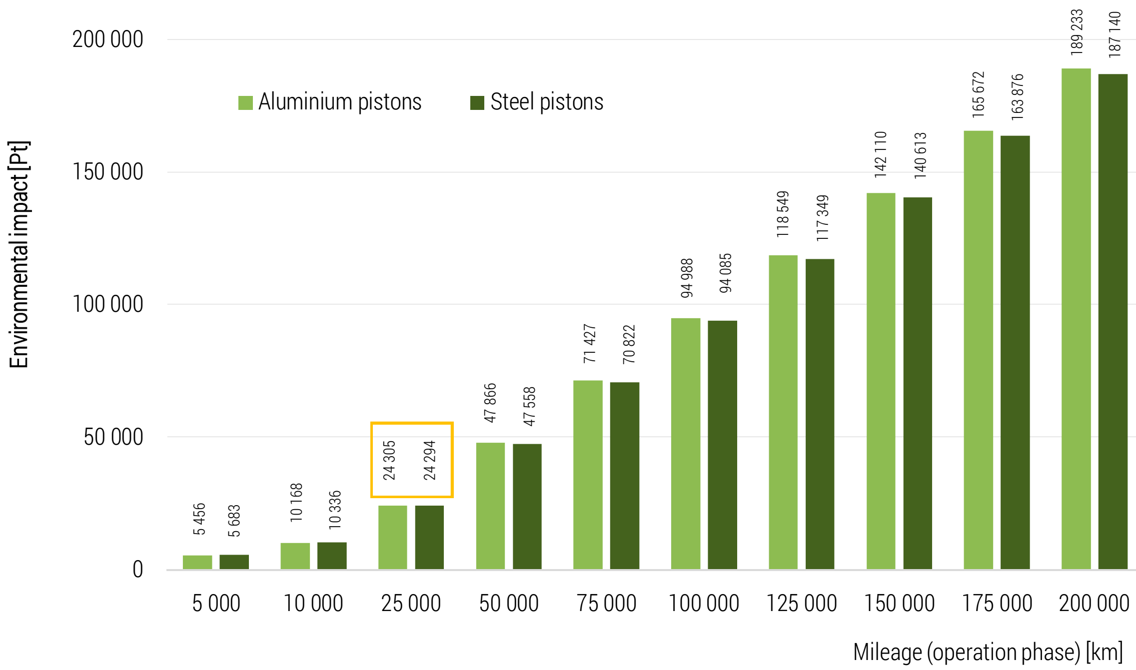

Figure 5. Cumulative environmental impact of the production and operation stages of aluminium and steel pistons given different vehicle mileages (40,000 engine variant) [Pt]

Source: authors' work based on Grygiel (2023).

Discussion

In the presented study, the starting point was the evaluation and comparison of two processes of piston production intended for use in the propulsion systems of internal combustion vehicles. The first research question was as follows: "Are there differences in the environmental impact of the analysed production processes of steel and aluminium pistons?" The results obtained allow us to conclude that the differences exist and are significant. From the point of view of the single score, the impact of the production of 160,000 steel pistons turned out to be 39% higher than the production of the same number of aluminium pistons. In both cases, the same most relevant environmental problems were identified, two of which are emission impact categories ("respiratory inorganic" and "global warming"), and one is a resource category ("non-renewable energy"). Respiratory disorders are associated with the emission of inorganic compounds into the air that contribute to the formation

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of the so-called London-type smog: particulate matter, nitrogen oxides, sulphur oxides, carbon monoxide, and ammonia. Compared to aluminium alternatives, the steel pistons manufacturing leads to a 3% higher environmental impact in this impact category (characterised results). This means that more of these pollutants are emitted in the supply chains of the materials used and in the production process of steel pistons themselves. In the case of "global warming," greenhouse gas emissions into the air are taken into account, and the impact of these emissions is calculated on the basis of the Global Warming Potential. The production of steel pistons has a carbon footprint that is more than twice as high as that of the production of aluminium alternatives. This means that, from the point of view of greenhouse gas emissions, the difference between the compared processes is significant. The situation is similar in the field of "non-renewable energy," where the characterised result of the indicator for the production of steel pistons is more than twice as high. In this case, the consumption of non-renewable energy carriers such as hard and brown coal, crude oil, natural gas, or uranium is taken into account. The assessment of the impact is based on the caloric value of these fuels. The analysed production process of steel pistons (from cradle to gate) requires more than twice as much energy stored in non-renewable carriers.

At this point, it is worth referring to the second research question: "What are the main drivers of environmental impact in the analysed production processes?" In both cases, the analysis was done from cradle to gate and included the processes of sourcing, processing, and metalworking. Figure 4 shows that the main source of environmental impact of the aluminium pistons manufacturing lies in the material consumption of this process, while for steel pistons, it lies in the energy consumption (understood as the energy demand of the production infrastructure). To produce 160 thousand pieces of aluminium pistons, about 136 tons of input materials are introduced into the foundry furnace, of which about 83% are primary aluminium ingots, 7% are secondary aluminium ingots, 4% are aluminium alloys, 1% are electrolytic copper, and 5% are other alloying additives (magnesium, silicon, and nickel). Among the materials mentioned, two are particularly associated with environmental impact: virgin aluminium and nickel. In both cases, it is not about the extraction of metal ores, because the category of impact "mineral exclusion" has not been identified as significant. Therefore, we should look for other aspects responsible for the emission of inorganic compounds, greenhouse gases, and the consumption of non-renewable energy carriers. First of all, it is the combustion of non-renewable fossil fuels to generate the energy needed to convert bauxite ore into a goose from primary aluminium (Bayer process, Hall-Heroult electrolysis, refining, and casting). Therefore, it can be said that the main driver of the environmental impact of aluminium piston manufacturing is the indirect aspect, which is the energy consumption (upstream) of the primary aluminium supply chain. In the case of steel pistons, the main source of impact is energy consumption directly related to the production infrastructure. In this case, the following should be perceived as the main sources of impact: emissions and consumption of non-renewable energy carriers in the supply chains of electricity and gas consumed in the factory, as well as the combustion of gas on site to generate heat.

As the research has shown, taking into account the use stage and fuel supply chain (from well-to-tank) and emissions from the vehicle's tailpipe (from tank-to-wheel) can change the relationship between results. Steel pistons with a less environmentally friendly production process are installed in newer generation engines, which results in lower fuel consumption and emission intensity at the operational stage. With a mileage of about 25 thousand kilometres (Figure 5), the combined impact of the production and use stages is equal for both variants. The advantage of the aluminium pistons production is offset by a greater impact of the operation. Taking into account steel pistons, the higher production impact is compensated by the environmental benefit resulting from the better parameters of EURO 6 engines. After exceeding 25,000 kilometres, the solution with steel pistons begins to achieve a lower environmental index score, although the difference is small. At 200 thousand kilometres, it is about 1%.

Conclusions

The compared production processes are equivalent in terms of function (in both cases, pistons are produced as components of diesel engines for passenger vehicles). From the point of view of the production stage, the production of aluminium pistons is a better option. However, the different emission characteristics of the engines and the lower impacts during use have compensated for the differences resulting from production and equalised the environmental impact of the two alternatives. Despite less environmentally friendly production, the fact that steel pistons are used in a newer generation of engines means that both solutions may be seen as environmentally comparable. The environmental hot spots of the two production processes are different, although in both cases, they are ultimately related to energy intensity. If recommendations were to be made for improving the environmental manufacturing process, in the case of aluminium pistons, they would primarily concern indirect environmental aspects and the environmental performance of aluminium ingots' supply chains. The recommended solution would be to increase the share of recycled content in the input materials and, at the same time, improve the energy efficiency of suppliers of primary aluminium ingots. In the case of steel piston production, the main recommendation would be to reduce the consumption of electricity and heat in the production process and to cover the energy demand using carriers and technologies with better environmental performance.

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The contribution of the authors

Conceptualization, J.G., Z.F. and K.J.L.; literature review, J.G., Z.F. and A.L.; methodology, J.G., K.J.L. and A.L.; formal analysis, J.G. and K.J.L; writing, J.G., K.J.L. and A.L.; conclusions and discussion, J.G., K.J.L. and A.L.

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STUDIUM PRZYPADKU PRODUKCJI I EKSPLOATACJI TŁOKÓW DO SILNIKÓW WYSOKOPRĘŻNYCH – PORÓWNAWCZA OCENA ŚRODOWISKOWA

STRESZCZENIE: Celem badań było porównanie oddziaływania na środowisko dwóch technologii produkcji tłoków przeznaczonych do silników wysokoprężnych. Wpływ na środowisko określono przy użyciu środowiskowej oceny cyklu życia. Badanie zrealizowano w czterech fazach: określenie celu i zakresu, analiza zbioru wejść i wyjść, ocena wpływu cyklu życia i interpretacja. Z punktu widzenia etapu produkcji, wytwarzanie tłoków aluminiowych okazało się lepszą środowiskowo opcją. Jednakże odmienne parametry emisyjne silników i mniejsze oddziaływania podczas użytkowania skompensowały różnice wynikające z produkcji i zrównały oddziaływanie obu alternatyw. Mimo mniej przyjaznego środowiskowo wytwarzania, fakt wykorzystywania tłoków stalowych w nowszej generacji silników powoduje, że w perspektywie dwóch analizowanych etapów cyklu życia oba rozwiązania są porównywalne. Środowiskowe punkty krytyczne obu procesów produkcyjnych okazały się różne, mimo, że w obu przypadkach ostatecznie wiążą się one z energochłonnością. Wartością badań jest ich walor aplikacyjny i odniesienie do rzeczywistych procesów produkcyjnych. Analiza uwidoczniła istotne znaczenie uwzględnienia perspektywy cyklu życia podczas oceny procesów technologicznych.

SŁOWA KLUCZOWE: oddziaływania na środowisko, ocena cyklu życia, tłoki aluminiowe, tłoki stalowe

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