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ORIGINAL PAPER

Recycled high impact polypropylene in the automotive industry - mechanical and environmental properties

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Abstract The use of recycled plastics remains an open issue. The common opinion being that recycled plastics have better environmental profile but worse mechanical properties. But is it really so? Various studies show no significant deterioration of the plastics qualities up to five or six reprocessing cycles and the environmental impacts have to be considered for the product whole lifecycle. If we take into account the increasing transports and impacts of recycling technologies, the advantages of recycled High Impact Polypropylene (HIPP) become less clear. In this study we take a closer look on recycling of HIPP, the most common polymer in car body parts, such as bumpers. To verify its advantages and drawbacks we combined two methods: test of mechanical and rheological properties depending on the number of reprocessing and Lifecycle Assessment (LCA) to verify environmental friendliness of the HIPP recycling. On one hand, our findings reveal that unlike Polypropylene (PP), HIPP mechanical properties start to deteriorate from the first reprocessing. On the other hand, like in the case of PP, we have not observed a significant deterioration before the 6th reprocessing. The LCA shows that road transports have a very small impact on simple HIPP product whole lifecycle. The main difference between virgin and recycled HIPP is based on the production process itself and electricity consumption for recycling. Our model proved decreasing impacts with any addition of recycled content, except for the ionizing irradiation potential category, which is typical for the French power grid mix.

Keywords High impact polypropylene (HIPP) · Recycling · Mechanical properties · LCA · Environmental impacts

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1 Introduction

Today, the European automotive industry is under pressure to ensure the vehicle price, safety, energy efficiency and increasing mandatory recycling ratio [1,2]. Already existing demand for smaller fuel consumption is intensified by obligations from the European regulation No. 443/2009. The regulation allows the average CO_2 emissions of an average passenger car to be 130 g CO_2/km by 2015 and 95 g CO_2/km by 2020 [3]. The car producers response to this regulation is based on developing more efficient engines and lightening the new car models weight.

Weight reducing leads to increasing use of plastics for cars production. The less load-bearing metal parts are replaced by plastic ones. Plastic injection is also an easy way of getting a complicated shape for new parts. The quantity of plastic parts is growing as well for the sake of users' comfort and to reach better aerodynamics. The part of plastics in an average car's weight has risen from 6% in 1970 to 16% in 2010 and it is expected to increase up to 18% in 2020 [4].

In the meantime, car producers are to keep an eye on the new cars recycling capacity. The European directive 2000/53/EC does not allow introducing a new car on the market, unless it can be considered reusable and/or recyclable to a minimum of 85% by mass. By "recyclable" it is understood, that closed or open loop recycling is possible and it is up to the manufacturer to prescribe the most suitable recycling technology [1,5]. This is the case of the High Impact Polypropylene (HIPP) which is common in bumpers and body panels. We can even find producers who use recycled HIPP in the new parts, such as Faurecia who participated in this study.

Car industries suffer from a lack of information on HIPP from the mechanical point of view as well as the environmental perspective. The mechanical properties are important for designing new parts, especially to decide whether the recycled plastic is suitable or not. From an environmental perspective, it is important to apply the good practices in ecodesign and verify whether the recycled plastic is environmentally friendlier than the virgin one or not. Since, It is usually considered that recycled matter is environmentally friendlier than virgin material [1,5,6]. However, this statement is less obvious if we take a closer look at recycling technologies and related infrastructures. If a plastic part is not recycled, it is landfilled or incinerated in a local waste treatment center, producing a small amount of electricity or energy for district heating [6,7]; whereas recycling involves additional transports and energy-consuming recycling technologies. Therefore, one cannot state without a closer study whether recycling really is the best solution.

Several studies deal with Polypropylene (PP) reprocessing from a mechanical point of view [8]. Such as Da Costa et al. [9] who demonstrated that HIPP rheological and physical properties deteriorated slightly after every reprocessing. While most studies conclude that five different reprocessing cycles are necessary to observe a significant degradation [9–14]. One should bear in mind that the mechanical properties evolution vary considerably depending on the chosen polymer or mix of polymers.

If there is little literature on recycled HIPP's mechanical aspects, there is a real lack regarding its environmental properties. We can find information about polypropylene in general [14] or even in the automotive industry [15] but these polymers are not exactly the same. Presence of Ethylene–propylene rubber can change not only mechanical but also environmental qualities of the final plastic.

Hence the choice to carry out this study by combining tests on recycled HIPP mechanical and rheological properties along with tests on recycling impacts on its environmental profile.

2 Methodology

Using the current technology, plastics cannot be recycled endlessly without changing their properties unlike glass or metals. Even though their reprocessing looks alike: the material is melted and reshaped in a new product. But plastic structure has one important particular aspect: polymerisation does not create crystals, it is made of long fibres. And just as paper recycling, these fibres are cut during the recycling process which affects the recovered material properties.

In literature we can find two ways of dealing with the analysis of recycling impacts. Either change the reprocessing number or modify the ratio between virgin and recycled material. Each approach answers a different question and can be applied in several situations.

When searching for recycled granulate, one cannot find any material with clear recycling history. Tracing back every part would be much more complicated than useful, so one can only estimate if and how many times the material has already been recycled. Besides, mixing virgin material with recycled one is very common.

From a practical standpoint, it seems more suitable to test different ratios of virgin/recycled material, as it is closer to reality. Indeed, it hides the influence of recycling itself. If we want to know what happens to the material due to recycling process, we need to study a homogeneous material while keeping other variations to a minimum.

But since various studies demonstrate that plastics deterioration regarding the number of reprocessing cycles is a result of the scission of the polymer chain, we wanted to confirm and explore furthermore their potential interdependence. That's why we chose to study the recycling impacts on mechanical and rheological properties following the first approach based on how many times reprocessing happens.

Regarding the environmental impacts study we chose the other approach since the study's goal definition would not even allow us to choose the number of reprocessing as a parameter. We need to know if recycling can be an environmentally friendlier option compared to using virgin HIPP. Therefore, we must study a scenario corresponding to the industry current practices. As a matter of fact, this very approach can be found in existing plastics recycling studies.

2.1 Impacts on material behaviour

Reprocessing consists in shredding off a product at the end of its life, granulating it and then re-injecting it into a new one. Except for possible pollution, all these processes does not change the chemical structure at all but they do imply mechanical tensions on the material that cause breaking of the polymer fibres. Reprocessing not only influences the length of the fibres themselves but also the material micro-structure.

According to previous studies about recycling of different plastics, we are supposed to witness a significant degradation starting from the 5th reprocessing [11–14]. In order to explore the modifications' impacts caused by multiple reprocessing, we chose to recycle the HIPP 0, 3, 6, 9 and 12 times in a row without adding any virgin material. The 12th time should ensure getting a significant recycling impact and linear scale could help us uncover potential mathematical sequence of impacts base on the number of reprocessing cycles. Each time, we observed the evolution of two parameters. First, on the material level, we assessed the molecular weight and rheological characteristics. Secondly, on the mechanical level we measured the tensile behaviour in low and high stress spectres. For the study, we chose the HIPP referenced as SABIC ®PP, grade 108MF97, composed by a PP matrix containing 22% of ethylene propylene rubber (EPR) particles. A small amount of talc was also detected (<0.5%), thus the material was assumed to be two-phase. This particular polymer is used by a car bumpers and plastic body panels manufacturer who collaborated on the study.

2.1.1 Rheological properties

As seen earlier, plastics microstructure can be modified by reprocessing, that's why we performed micrographs to observe modifications on morphological aspects. We evaluated the molar weight, polydispersity index and melt flow index. HIPP is a two-phase material so it is important to understand the role of both phases in the reprocessing-induced microstructure changes. Therefore, we measured the rubber component state of dispersion and the interfacial adhesion using the SEM technique [16]. The liquid nitrogen-cooled samples were fractured by percussive fracture (Split Hopkinson Pressure Bar).

2.1.2 Mechanical properties

We used the Videotraction © system [17] in order to measure the elastic modulus (Young's modulus: E), yield strength (σy) and failure properties (failure stress: σr and failure strain: εr), as well as the volume strain response. The mechanical tensile parameters are defined as shown on (Fig. 1). The elastic modulus (Young's Modulus) is the initial slope of the stress-strain curve; Yield strength (sy) is assumed to be the maximum stress observed in each stress-strain curve at the beginning of yielding and the yield strain is the corresponding strain value. We defined all these parameters from stress-strain curves at a strain rate of 10^{-3} $s^{-1}$and at a 25 °C temperature.

2.2 Environmental impacts

Regarding the environmental impacts assessment we opted in favor of the Lifecycle Assessment (LCA) [18,19]. As one of the techniques of interactive design LCA allows to model the product's larger environment throughout its whole lifecycle. The purpose of the study is to satisfy the customer by reducing the product's environmental impacts and consequently also the customer's responsibility of the environmental issues [20]. The Lifecycle assessment is considered to be the most complete methodology to evaluate a product or technology environmental impacts, which makes it an excellent knowledge engineering tool [21,22]. It covers the whole product's lifecycle, preventing any impact transfer. This can be seen as an anti-error approach which is especially important in assessing recycling environmental friendliness. The assessment is not limited only to the common point of view that recycling save part of the material. It considers also the parts usual users don't think about, such as transport of the material to be recycled or compensation of the impacts of the end-of-life by use of heat from incineration for household heating and production of electricity.

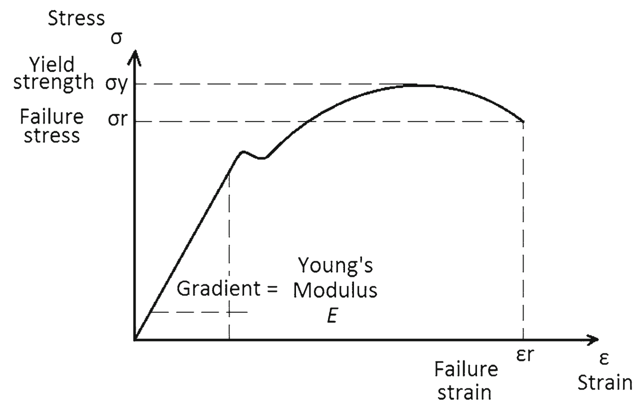

Fig. 1 Typical stress–strain curve

LCA offers the possibility of expression of environmental impacts in various categories of environmental impacts, preventing unfair comparisons, such as petrol versus electricity consuming process, evaluated only by their carbon footprint.

2.2.1 Goal and scope definition

The goal and scope definition is an essential part of the LCA. It defines the purpose of the study and the way of dealing with it. Outside of the comparison oriented platforms like Product Environmental Footprint/Organization Environmental Footprint (PEF/OEF) or Environmental Product Declaration (EPD® International), the results of different LCAs are not comparable and the goal and scope definitions usually explain the differences in results of products that should be otherwise alike. The goal was to identify the differences between virgin and recycled HIPP in term of environmental impacts. The situation is slightly different from the mechanical impacts study. The current recycling and use model does not distinguish once or more times recycled

HIPP. The recovered HIPP is mixed with the virgin one to become a product. Financially the recycled granulate has the same value no matter how many times it was recycled. It is the ratio between virgin and recycled HIPP that changes the price, quality and impacts of the whole product. Our aim is not to explore different ways of how the market could work. In this study we try to give the environmental impacts of an existing way of HIPP recycling and use. Therefore, instead of the number of reprocessing, we analyzed impacts of virgin and recycled HIPP on different ratios.

For Lifecycle Impact Assessment (LCIA) we chose the CML methodology. It is well adapted to the production industry [19] and widely used in the automotive industry [23–25].

The intended studied products are car parts, typically bumpers and panels or covers. Some plastic parts may be part of mechanisms, other parts may have influence on aerodynamics of the car. Yet any influence on friction is neglected in this study and we consider that the main function of the final products consists in their simple existence. As the core of our study is the material, we defined the reference flow as 1 kg of HIPP, which in case of need can be easily extrapolated to any precise number of real parts.

2.2.2 Lifecycle inventory (LCI)

For the study we used the LCA software GaBi version 4 with Lifecycle inventory (LCI) databases from PE-International and european ELCD. For virgin HIPP we took Polypropylene-EPDM granulate mix (at customer, located to Germany) from PE-International database. It shall be noted that contrary to the general belief, choice of the LCA software may have influence on the quantitative results [26]. Unfortunately we had not enough resources for verification of our results using other existing softwares.

To be consistent with other LCAs in the automotive industry and the Product category rule (PCR) describing studies within the EPD® International platform, we considered the processes and flows relevant to the product's manufacture, use phase and additionally the end of life [27].

We didn't have access to the precise data from the car parts production. The cooperating car parts producer gave us only the general model of production and lifecycle of a bumper. For the precise data we used a known product: a testing rod that we produced with the very same technologies. With the help of our automotive parts producer we expanded the scenario to three versions in order to get more information relevant to the real production. The first scenario is the real lifecycle of a testing rod. The second one replaces an unusual air transport by a truck and the third scenario simulates a hypothetical serial production.

The scenarios correspond to a closed loop recycling, where the recovered material from a product is used to produce the same new product. This scenario reflects the reality thanks to a relative cleanness of the used material and to the dimensions of bumpers and body panels. In other words, the parts to recycle are easy to recognize and dismantle and they make a big volume. Separation is easy and makes recycling economically viable. The main life cycle of the product is represented on the Fig. 2.

The main lifecycle consists of production-injection, followed by finishing of the new product, than transport to the use phase, separation at the end of life and finally transport to a recycling unit, where the old product is shredded and granulated in order to make a new entry for the injection. In our model there is always an entry of some virgin material. There are always some minor or bigger losses in the production and recycling processes, which exclude the possibility of recycling 100% of the original material. The inputs are energies and virgin material - Polypropylene-EPDM granulate mix (at customer, located to Germany) from PE-International database. Unfortunately the supplier wouldn't reveal the source of material, which is a common problem in LCA—some retailers consider it as confidential information. Therefore the transport was estimated to be 600 km with a truck. The outcome is, besides the modeled recycling, the French average of landfill and incineration. We considered the production of heat and electricity in both of them in order to avoid giving any unnecessary advantage to recycling. Parallel to the lifecycle of the product is the lifecycle of its packaging. The packaging is represented by a carton boxes, corresponding to those of the testing rod. Its quantity does not change in function of ratio between the virgin and recycled HIPP. It has therefore no effect at all on the goal of the study. It only places the results in the scale of the real use.

All the energies, transports and end of life scenarios are located to the target country—France. Although, French processes were unavailable for the processes of truck transports, incineration, injection and recycling processes. According to the practices recommended in the Product category rules (PCR) of a car, for the process of truck transports we chose the closest available average—global [27,28]. For the other processes we chose the closest location—Germany. In incineration we changed the average trash composition for the French one and in the process of injection we were able to change the energy consumption according to the data from the producer of the injection press, used for production of our testing rod. The machine is well adapted for a mass serial production and therefore perfectly suitable for the two complementary hypothetical scenarios.

2.2.3 Lifecycle impact assessment (LCIA)

For Lifecycle Impact Assessment (LCIA) we chose the CML methodology. It is well adapted to the production industry [19] and widely used in the automotive industry [23–25].

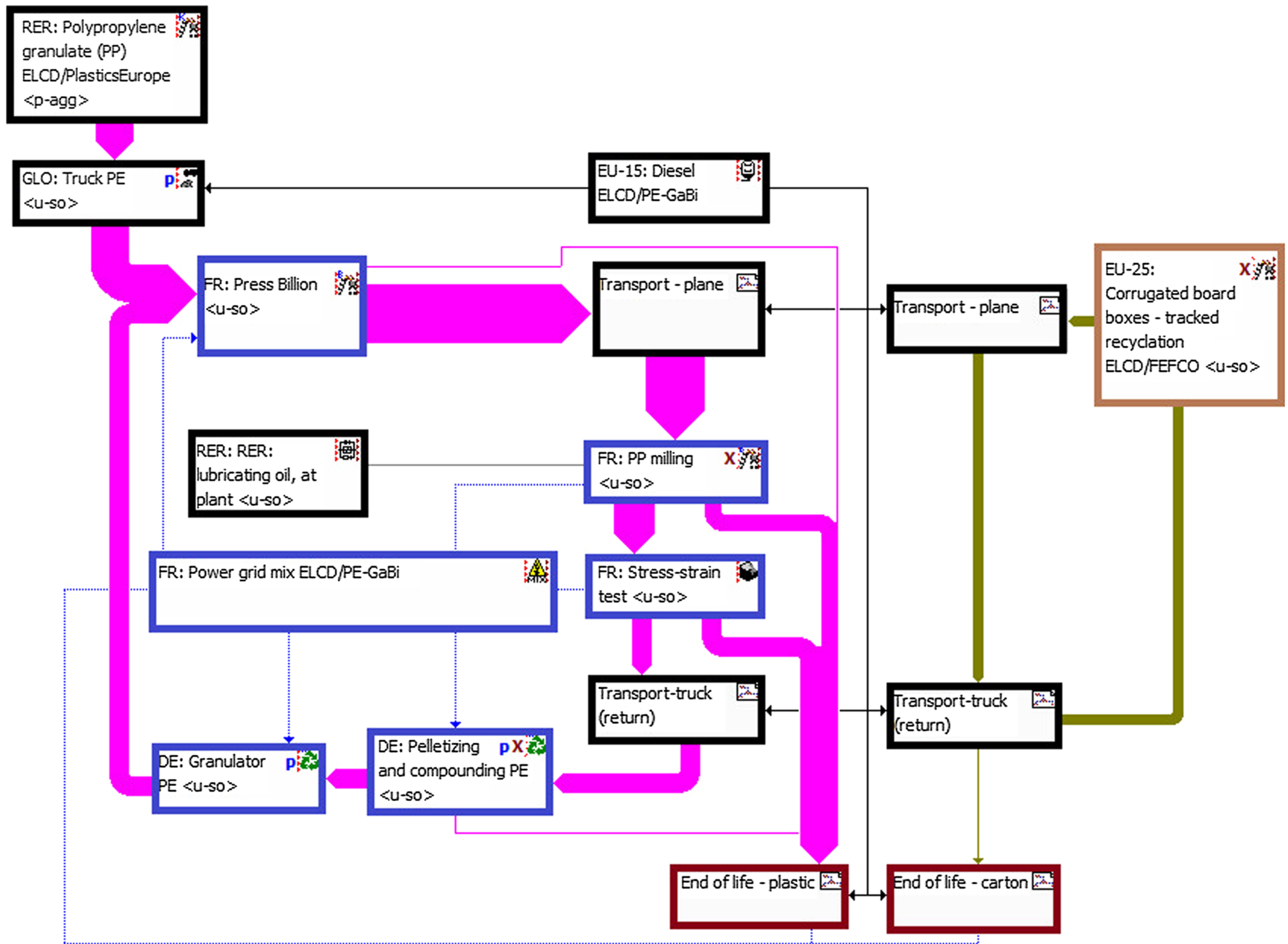

Fig. 2 Lifecycle model—initial scenario and 50% ratio of recycling. Thickness of the flashes represents weight of the concerned flows. *Colors* of flows are: *Rose* for HIPP, *black* for petrol and petrol products, *blue* for electricity and *green* for packaging

We have found two disadvantages of this characterization and impact assessment method. Firstly, the latest update we have used dates from 2009. CML is often replaced by newer ReCiPe and especially for the toxicity and at present, eco-toxicity impact categories USEtox® is mostly recommended [29]. Although it still remains a valid choice as the most LCAs in the automotive industry uses CML and we want to present the results in the same categories as those the industries are used to.

We verified the choice of CML methodology in comparison with several other available methodologies, ReCiPe (midpoint and endpoint approach), I02+ v2.1 and EDIP 2003/1997.

We found a very good coherence between the LCIA methodologies in most impact categories. On the other hand, in the categories of abiotic or metal depletion and freshwater ecotoxicity, the LCIA methodologies does not even agree whether the use of recycled HIPP has a positive or negative impact. The reason of non-coherence is mostly in the differences in characterization factors [30]. We decided to keep the CML, which does not exceed the lowest and highest results, with exception of human toxicity (Fig. 16).

The second inconvenient is lack of an impact category for the potential of ionizing irradiation, which may be important in the light of a major part of nuclear power in the French power grid mix.

We decided to present the results of this impact category separately, using the ReCiPe LCIA method.

3 Results

3.1 Rheological properties

As a consequence of the polymer chains rupture, the average molar weight and polydispersity index decreases significantly with the number of extrusion runs. Viscosity versus the shear rate is also decreasing significantly. The trend is confirmed by the evolution of melt flow index, represented on Fig. 3.

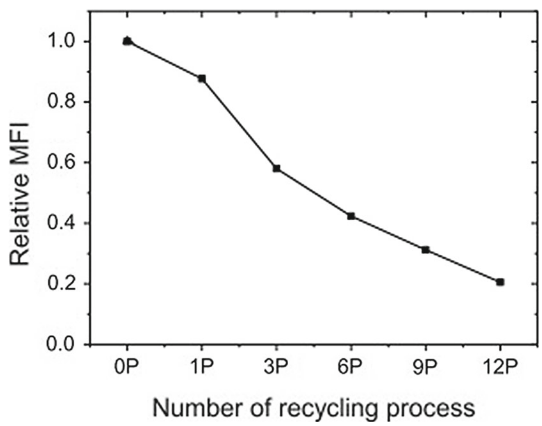

Fig. 3 Relative melt flow index (MFI) based on number of recycling

Table 1 Average number molar mass, average weight molar mass and polydispersity index for the two different phases of virgin HIPP and 6 times reprocessed HIPP

Phase	Mn (g/mol)	Mw (g/mol)	IP = Mw/ Mn
PP phase -virgin HIPP	31000	166000	5.35
EPR phase-virgin HIPP	24000	92000	3.80
PP phase -6P HIPP	21000	69000	3.30
EPR phase -6P HIPP	24000	95000	3.95

In order to understand the principle of HIPP deterioration as a two-phase material, we separated the PP fibres from the rubber parts using selective dissolution in trichlorbenzene (TCB). We analyzed the two phases by Size Exclusion Chromatography (SEC). Table 1 shows the results. We can see a deterioration of the PP matrix while the rubber parts remain intact.

Cavitation is typical for polymers exposed to critical constraint. This phenomenon is due to shorter chains and embrittlement of the amorpheous matrix due to reprocessing, as explained by Fayolle et al. [31]. Figure 4 shows the difference between virgin HIPP and 6th recycled HIPP.

3.2 Mechanical properties

The material exhibits classical mechanical behaviour under tensile loading [32] after a linear elastic response, a small viscoelastic response appears before the yielding point. From this point on, the material deforms plastically with non-linear response (Fig. 5).

In the small domain stress strain, the difference is less obvious. We observed that the variation in the Young Modulus values was of the same magnitude order as the experimental errors. Thus, it can be concluded that a slight difference may be detected between the virgin material and its respective derivatives (12 times recycled) (Fig. 6). The failure stress decreases linearly, with degradation after several cycles. At the same time, the failure strain decreases also significantly and linearly depending on the number of reprocessing (Figs. 7, 8).

We did not observe any neckling on any sample. However, a white zone appeared at the sample's centre since relatively low strain. This zone grew until the specimen failure. This is characteristic for significant amount of cavitation, caused by the plastic deformation of polymers near the yield point. Growth of cavitation with reprocessing is confirmed by micrographs on Fig. 4.

We noticed that the recycling process decreases the yield stress and yield strain respectively. It seems from the results obtained that the mechanical recycling process has no effect on the Poisson ratio.

3.3 Environmental impacts

3.3.1 Basic results of the LCA

In coherence with the goal of the study, we present the differences between virgin and recycled HIPP first. Before publishing the quantitative results it should be noted that we have found one non-negligible impact outside of CML

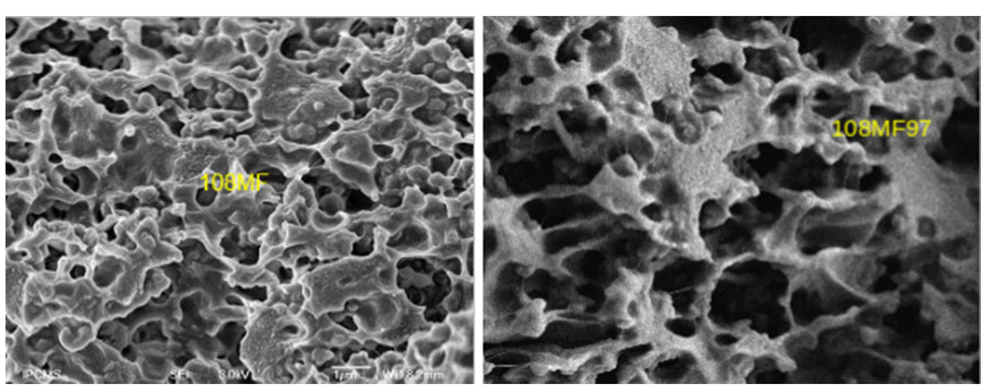

Fig. 4 Growth of cavitation with recycling. On the *left*—virgin HIPP 108MF97, on the right the same material 6 times recycled. Scale is identical on both sides

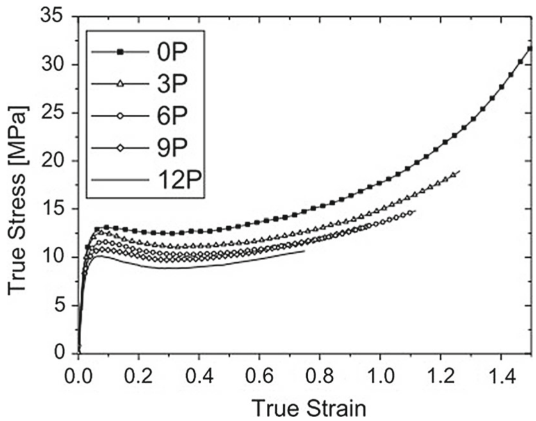

Fig. 5 Large domain stress strain

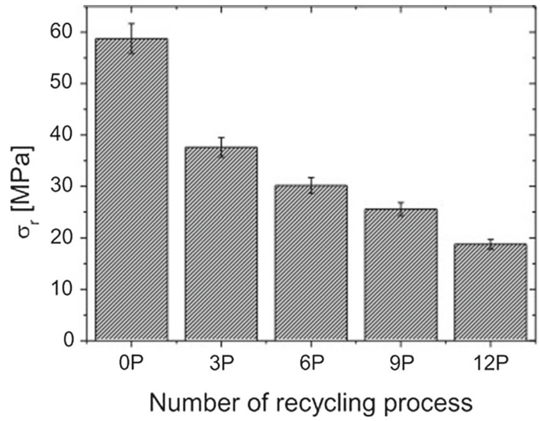

Fig. 7 Failure stress

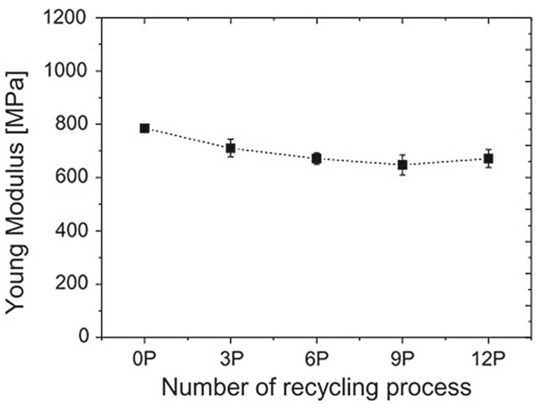

Fig. 6 Young modulus

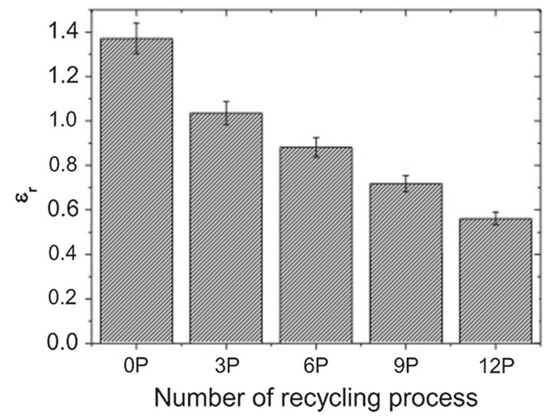

Fig. 8 Failure strain

impact categories. It is the ionising irradiation potential category and it is discussed in *chapter 3.3.3 – sensitivity analysis*.

Figures 9, 10, 11 shows evolution of environmental impacts based on the recycled matter ratio. We can observe nearly linear decrease of most impacts. An exception is the ozone depletion category. The increasing impact corresponds to use of R-11 and R-114 as a cooling medium in French nuclear power plants. Since year 2000, both R-11 and R-114 are forbidden in the new structures and their impacts are constantly decreasing [33].

The results' linear evolution is only approximate but it shows how important production of the virgin HIPP is compared to transports and electricity consumption for recycling.

The three graphs differ in the relative recycling impact. Whereas the difference between 0 and 100% recycling represents around 25% of most impacts in the initial scenario, it does make a difference exceeding 50% in the scenario of a hypothetical serial production. This information is important in the decision making process for eventual extrapolation to a real product. Again it confirms a big difference between the virgin HIPP impacts and its transports or recycling technologies.

3.3.2 Contribution and dominance analysis

We performed the contribution analysis following the approach proposed by Bauman ant Tillmann [19]. We divided the studied product's lifecycle into seven lifecycle stages: virgin material production, product manufacture, transports, packaging, use, recycling and end of life.

Virgin material transport is associated to the virgin material stage as their impacts are inseparable. Following the same reasoning, transports of separated material to the recycling unit and then to the producer are accounted for in the recycling stage. Figures 12, 13, 14 show the results of the contribution analysis.

The graphs show relative distribution of impacts in all the impact categories according to the different lifecycle stages. The scale is relative to 100% of potential impacts in each impact category. For example, in the initial scenario 50% of the fossil fuel depletion potential has its origin in the first lifecycle stage—Virgin material.

Figure 15 shows the processes in the lifecycle scenario, which does not influence the difference between virgin and recycled HIPP. These processes have constant incoming and

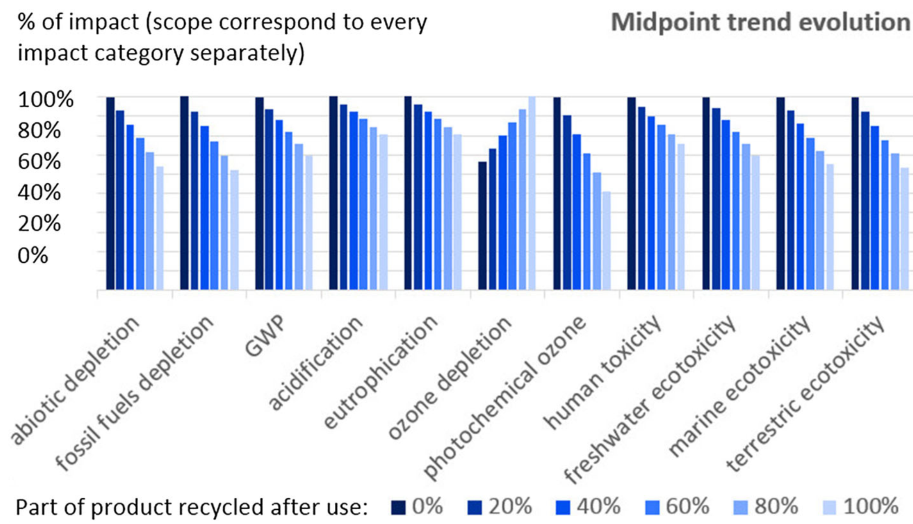

Fig. 9 Midpoint evolution based on % of recycled matter—initial testing rod scenario

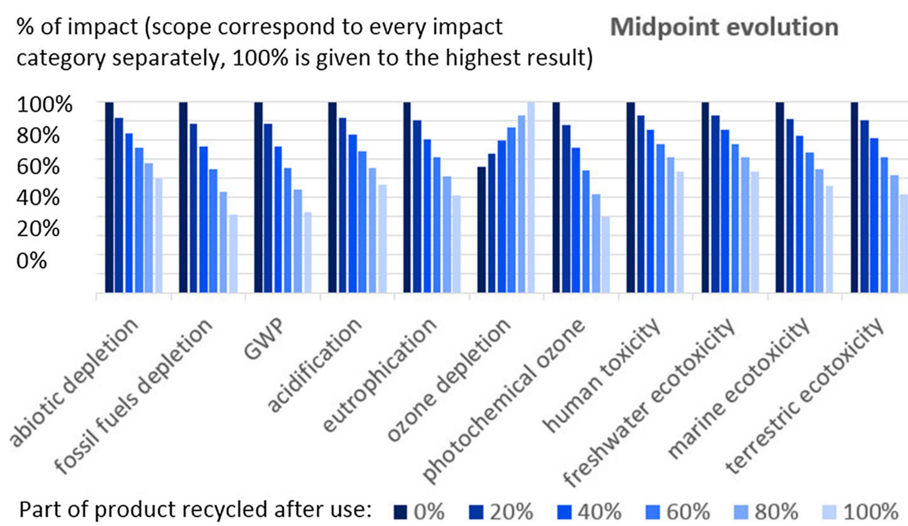

Fig. 10 Midpoint evolution based on % of recycled matter—scenario replacing aircraft by road transports

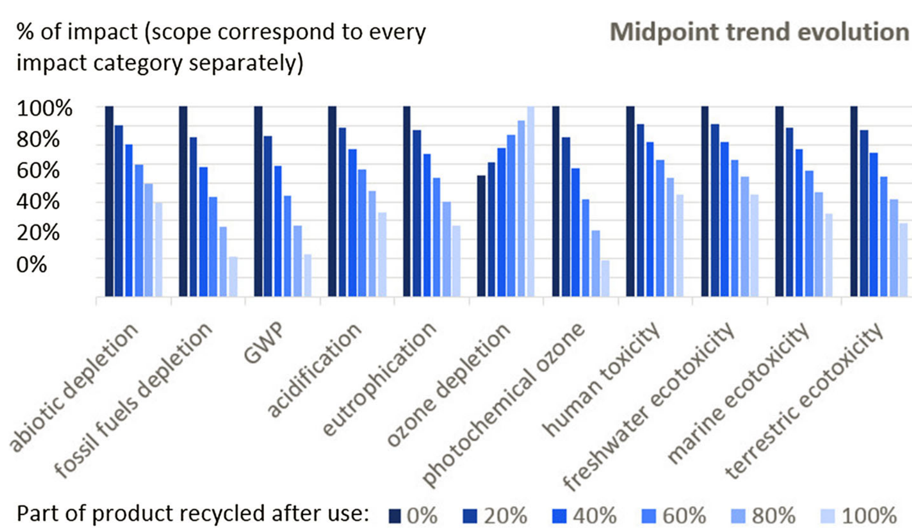

Fig. 11 Midpoint evolution based on % of recycled matter—hypothetical scenario for a bigger serial production

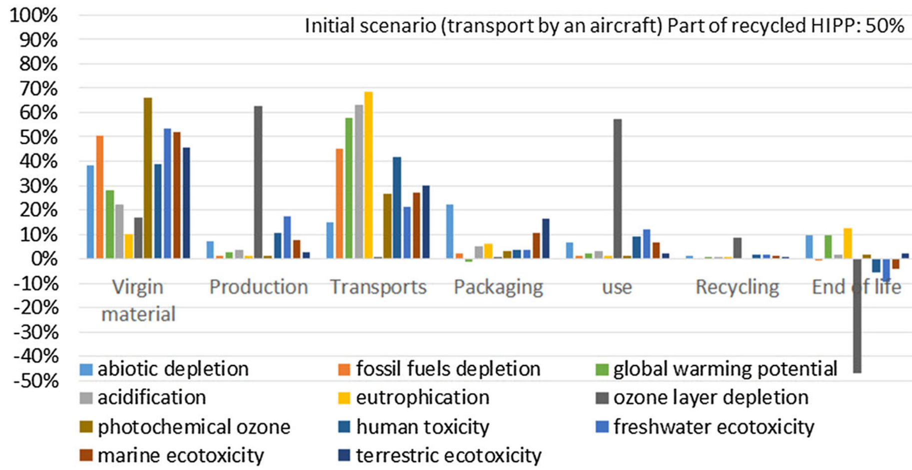

Fig. 12 Contribution of lifecycle stages in the initial scenario, ratio of recycling: 50%

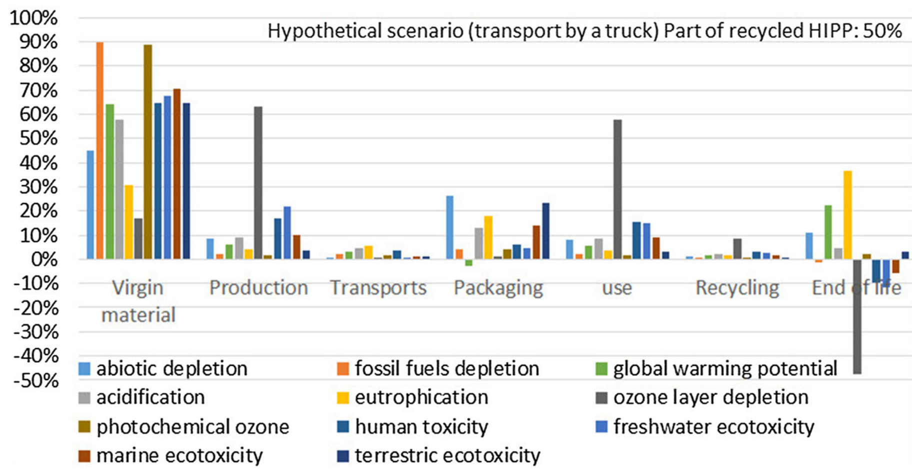

Fig. 13 Contribution of lifecycle stages in the road transports scenario, ratio of recycling: 50%

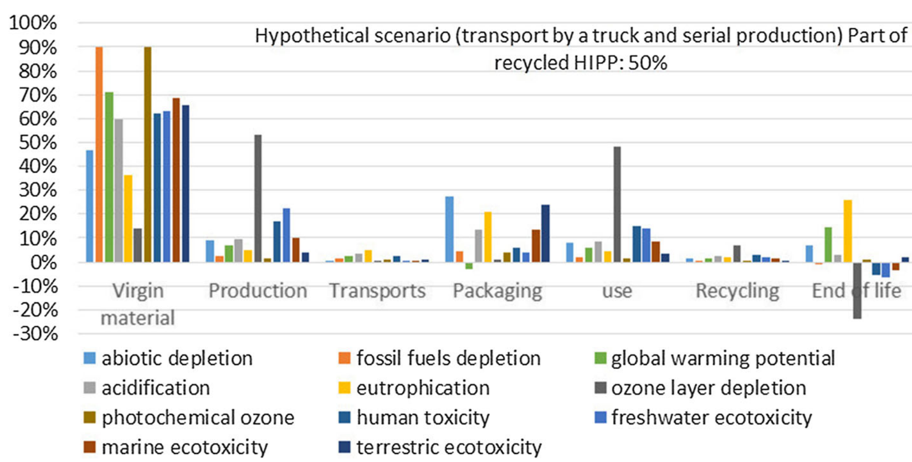

Fig. 14 Contribution of lifecycle stages in the estimated serial production, ratio of recycling: 50%

outgoing flows no matter the ratio between virgin and recycled HIPP.

We can see that the use phase is constant through the three scenarios. Therefore absolute values of its impacts are always the same and they can be used as scale for comparison within the three scenarios.

Most of the impacts can be attributed to the virgin material production. Comparison to a small contribution of recycling technologies and road transports explains the apparent linearity of the whole scenario absolute results. It also explains growing importance of recycling throughout the three studied scenarios. Most of the first stage's impacts are linked to

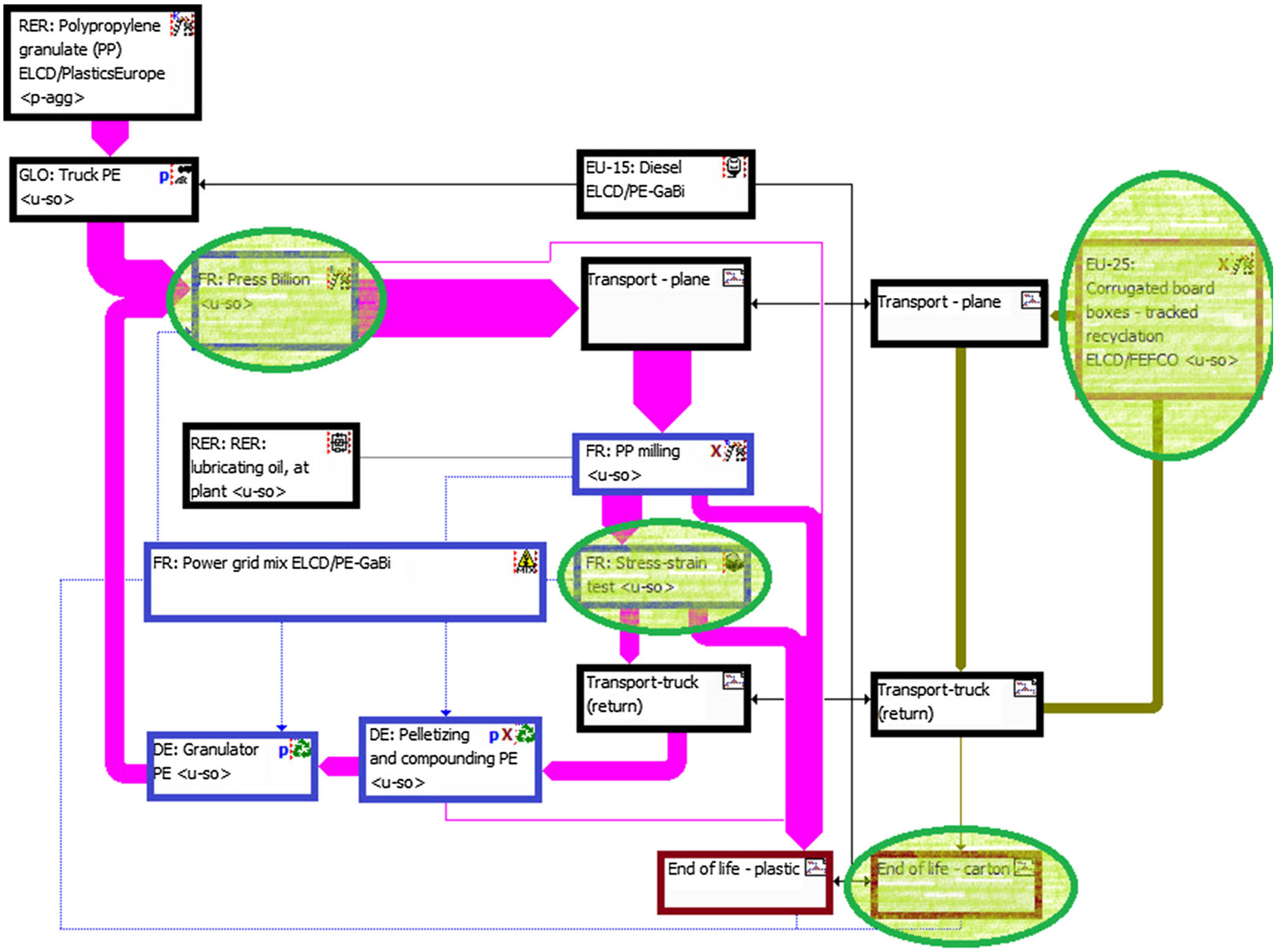

Fig. 15 Processes with constant flows no matter the scenario

extraction of oil and use of fossil fuels. HIPP production is also the main contributor to the abiotic depletion category. These potential impacts are based mostly on use of metals, particularly led and zinc. These metals are not directly used for polymer production but in the secondary processes [34]. Their high contribution is not due to high consumption. It is a projection of low consumption of other processes in the scenario.

In the initial scenario, next to virgin material production, transports are important contributors. More than 90% of these impacts are coming from combustion of kerosene in the plane's engines or from fuel production.

In the second and third scenarios, road transports impacts are very different. Their contribution is also mostly based on fuel extraction but the transports stage does not reach more than 6% of the scenario's impact in any impact category.

The biggest impact of the use phase, production phase and recycling phase is in ozone layer depletion potential category. 90% of impacts in this category comes from the use of CFCs (refrigerants R11 and R114). All of them are emitted from one process: Power from nuclear power plant, global average. Use of CFCs is forbidden in European Union since 31th December 2000 [33]. Since then, consumption and emissions in power plants in EU decreased significantly. In the latest PE-International database the emissions of CFCs are smaller by order of 1E11 for R11 and 1E6 for R114. Two more categories exceed 10% contribution to the scenario's impact - human toxicity and terrestric ecotoxicity, both of them mainly due to the emissions of heavy metals. We would expect them to be caused mainly by lubricating oil consumption during the machining process, but it is mostly coming from the electric energy conversion. However, the lubricating oil extraction and elimination process is incomplete and some important impacts may be missing. If it was the case, it wouldn't compromise the goals of this study since the production flows remain constant no matter the recycled content ratio.

The packaging phase consists in production, recycling, transports and end of life. Packaging does not represent any objective in this study and its consumption is the same no matter the scenario. Its lifecycle impacts are represented only by the overall results. Mostly, the impacts are consequence of paper production and recycling. 71% of impacts in the abiotic depletion category are due to the adhesive production for the cardboard boxes [35]. Packaging contributes significantly to the terrestric and marine ecotoxicity. 80% of potential impacts in these two impact categories are cause by Cr3+ emissions. Like in the case of HIPP production, we did not find any direct link between the paper production and chromium. Thus, we supposed that these emissions their source in secondary processes [36,37].

The profile of use phase, recycling phase and production phase are alike as they all are mostly defined by electric energy conversion and comparison between these three lifecycle stages is given mostly by the differences of electric energy consumption. Still, they remain different: production is influenced by lubricating oil consumption, recycling implies transports from separation to recycling unit and use phase is defined by electric energy pure consumption.

The end of life is characterized by several negative results. We chose to give a credit to end of life for thermal and electric energy conversion. The produced energy replaces otherwise produced electricity and heat. This approach eliminates the risk of giving any unnecessary advantage to the scenarios with a higher recycling ratio. Otherwise, the end of life contributes significantly to eutrophication, GWP and abiotic depletion. 76% of impacts in the eutrophication category are caused by phosphorus emissions and ammonia at landfill and 21% of emissions are nitrogen oxides from incineration. GWP is caused by CO_2emissions during incineration and methane escaping from landfill biological processes [38]. The abiotic depletion category is caused by adding $MgCL_2$ into the smoke depollution process inside incinerators which improves its efficiency [39].

3.3.3 Sensitivity analysis

The choice of LCIA methodology is a very sensitive issue in LCA. Characterization factors influence directly the quantitative results and the characterization factors assignment of the different impact categories vary from one LCIA method to another [30].

Therefore, we compared our results coming from the LCIA methodology CML 2001—nov. 09 to all the other LCIA methodologies we had available. Next to CML, we had ReCiPe and Impact 2002 with midpoint and endpoint approach. Both initially based on CML and they are well adapted to the production industry. Both would be a valid choice to our study. Between the two we would have preference for ReCiPe, because it is newer [19]. To complete the comparison we also included EDIP, even though we wouldn't choose it because it is designed for data concerning Northern America [30].

Figure 16 shows the comparisons of the five available LCIA methodologies. In order to place all the methodologies at one scale, we used proportional results. The column in black shows virgin HIPP impacts. It is fixed at 100% for all the methodologies. The other columns show the results of HIPP with 50% of recycled content. For example: I02 abiotic depletion potential of the recycled HIPP is compared again but only to the I02 abiotic depletion potential of the virgin HIPP. This approach allowed us to put all the LCIA methodologies on one (proportional) scale and compare the difference they make between the virgin and recycled HIPP. In this comparison the impact categories correspond to CML. The differences are noted in the legend. For instance in EDIP the category of human toxicity has three subcategories. We did not do any averages, the subcategories are standing in the comparison one next to another.

The graph on Fig. 16 shows a very good consistency between all LCIA methodologies in most impact categories. Surprisingly, the results are consistent even for human toxicity, terrestric and marine ecotoxicity, which are very difficult to account for. In the categories of freshwater ecotoxicity and abiotoc depletion the LCIA methods do not agree whether recycling is friendlier than virgin HIPP or not. The non-consistency in the abiotic depletion category can easily be explained by the choice of characterization factors. ReCiPe, which indicates higher impact for recycling, accounts only for metals, whether the other two methodologies takes into account all the available non-renewable resources. The non-consistency of freshwater ecotoxicity category can be explained by the issues of all ecotoxicity categories. If ecotoxicity had solid bases, it could be a universal indicator for all the environmental aspects. Unfortunately it is very difficult to measure and even more difficult to interpret. Ecotoxicity can be measured only on a limited quantity of species in an exactly defined environment but in reality every local environment is different and contains hundreds to thousands of species. Representation' uncertainty is very high and influence the quantitative results. In our study, we considered the good consistency in terrestric and marine ecotoxicity as a matter of coincidence and we supposed one can not make a clear conclusion whether or not in these categories recycling increases or decreases the impacts.

One interesting result is the ionising radiation potential category which does not appear in CML and according to other methodologies, recycling increases the potential radiation impacts. According to the dominance analysis, most of this category's impacts are due to nuclear power plants of the French national power grid mix. If the French power grid mix is switched to hydraulic power plant, the ionising radiation potential indicator is decreasing proportionally to the recycled HIPP ratio.

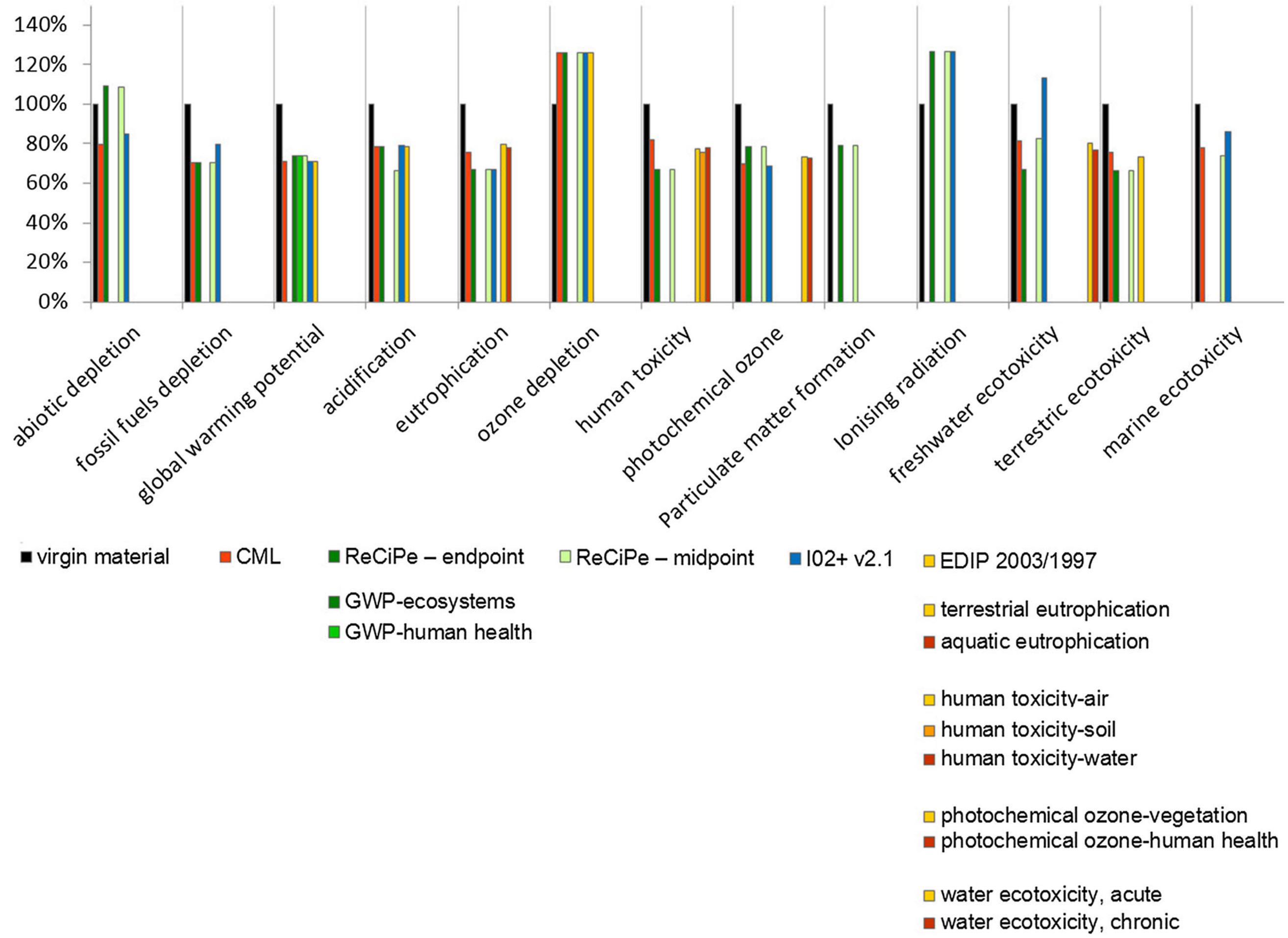

Fig. 16 Comparison of LCIA methodologies: Impacts of HIPP with 50% ratio of recycling in each impact category for each LCIA methodology are compared relatively to the impact of virgin HIPP, represented as 100% in every impact category

4 Conclusions and perspectives

The study proved deterioration of HIPP with recycling. It is the polypropylene matrix that looses its qualities with shortening of its polymer chains when rubber parts seem to remain intact. The material becomes more brittle because of the decreasing length of polymer chains.

From the mechanical point of view our findings agree with other studies [9–14] showing first significant deterioration after five reprocessings. This concerns melt flow index and traction resistance in large stress domain. The deterioration is mostly linear. Young modulus and yield stress do not seem to show significant deterioration even after the 12th reprocessing.

Changes of melt flow index implies that recycled HIPP has an impact on injection and the material behaviour inside the mold. The final product would behave more or less the same no matter if it is made of virgin or recycled HIPP. The difference comes under large constraint, where the recycled HIPP is more brittle. This is important information for parts with programmed distortion. Distortion of virgin bumper would accept more energy than distortion of slightly more brittle recycled bumper.

However, practice in the automotive industry, where recycled HIPP granulate is mixed with virgin HIPP granulate should enlarge the average length of the polymer fibers and compensate the deterioration of the mechanical properties.

Our LCA confirmed the common opinion about recycled plastics. In most impact categories, recycled HIPP shows less impact than the virgin HIPP.

From the environmental point of view, recycling of HIPP has a positive effect on most environmental impact categories except two. In France and other countries with high proportion of nuclear power plants, recycling has a negative influence on the ionizing radiation potential category. But, the increase in electric energy consumption for recycling is in the scale of units of kWh per kg of HIPP. This is negligible compared to the rest of the automotive industry consumption.

The second rising impact category is ozone depletion. The contribution analysis showed the origin of 90% of the impact in this category is the use of CFCs (refrigerants R11 and R114) in nuclear power plants. Use of CFCs is forbidden in European Union since 31th December 2000 [33]. We can suppose that up to now, if not eliminated completely, consumption and emissions in power plants in EU decreased significantly.

Whereas production, transport to client, use phase, and packaging remain constant, the difference lies in saving virgin material on one side and transports and electric energy for reprocessing on the other side. The end of life is also influenced by recycling but its role is more complicated. It participates to pollution while also producing energy and preventing other pollution from energy consumption for electricity production and heating.

The results are even more convincing in the case of estimated serial production (Fig. 11), where the difference between virgin and recycled HIPP gets bigger thanks to eliminating air transport impact from the scale.

Further studies could clarify the influences of mix ratio between virgin and recycled HIPP as an additional parameter.

From the point of view of LCA, further studies could explore deeper the origin of the virgin material and details on the HIPP parts production and transport.

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