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Evaluation of the End of Life performance of a hybrid scooter with the application of Recyclability and Recoverability assessment methods

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Abstract

The waste treatment related to the End of Life phase of durable goods such as Electric and Electronic Equipment and road vehicles is increasingly regulated both from an European and a Worldwide point of view. Regarding the transport sector, most L-class vehicles, (mopeds, motorcycles, tricycles, quadricycles as defined in Regulation 168/2013/EU) are not fully subjected to the Directive 2000/53/EC, which is the reference for other light vehicle categories. The recent introduction of novel archetypes and innovative powertrains for L-vehicles suggests that such products represent an actual alternative to full conventional vehicles for urban mobility; however only limited data are available regarding their their Recyclability and Recoverability. In order to cover such gap, a comprehensive view of L-class vehicle characteristics from End of Life perspective is proposed. The objectives of the study are the definition and the critical analysis of the context in which L-class vehicles are supposed to be treated, the identification of End of Life assessment methodologies and the application on a case study. Two different methodologies are compared; both come from other transport sectors. The methodologies differ in terms of performance assessment of recycling and recovery processes.

The treatment of the vehicle has been reproduced in controlled condition to obtain a detailed inventory of parts. Furthermore, four different hypotheses regarding the accuracy of the treatment have been formulated. The data have been used to estimate vehicle Recyclability and Recoverability rates under the proposed scenarios. The results demonstrate the compliance of Recyclability and Recoverability rates according to the most demanding regulation adopted for automotive products, even if such characteristics are not type approval requirements. The comparison between the two assessment methods shows that

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satisfactory Recyclability and Recoverability values can be achieved also considering technological limitations, at the cost of increased dismantling effort. The variability of results on the basis of external conditions is calculated, estimating four cases from "worst" to "best" case. The discrepances between the results of the two assessments methods and the relation to realistic limitations are discussed.
Using the first assessment method – ISO22628 - it is calculated that the dismantling of the bodywork is sufficient to achieve a 85% Recyclability result, and higher values are obtained in case of favorable scenario; Recoverability is also assessed to be above 95%. Using a method taking into account technological limitations – UNIFE assessment, adapted from railway sector –lower values are calculated, the reduction being from 1% to 3% for Recyclability and from 3% to 15% for Recoverability, depending on the boundary conditions considered.
Further research should be done to improve the assessment methods and to estimate the effective waste production arising from vehicle treatment, thus identifying physical and technological limits in relation to the product and to the context under study. For the sector of L-class vehicles, the study should be extended to a range of products, validating data through on-field trials.

Keywords: End of Life; Scooter; Motorcycle; Three wheeler; Recyclability; Recoverability; Dismantling.

Acronyms

3R	3R rates - used in the article to indicate RR and RRR rates toghether
ASR	Automotive Shredder Residue
ATF	Authorized Tratment Facility
CAE	Computer Aided Engineering
CNG	Compressed Natural Gas
ELV	End of Life Vehicle
ELV-L	End of Life Vehicle - L class
EoL	End of Life
EPD	Environmental Product Declaration
EPR	Extended Producer Responsibility
ERF	Energy Recovery Factor
EV	Electric Vehicle
GF	Glass Fiber
GHG	Green House Gas
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IDIS	International Dismantling Information System
IMDS	International Material Data System
LCA	Life Cycle Assessment
LPG	Liquified Petroleum Gas

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MRF	Material Recycling Factor
PCB	PolyChlorinated Biphenyl (pollutants, e.g. fluids)
PCB	Printed Circuit Boards (components)
PCR	Product Category Rules
PST	Post Shredder Technologies
PTW	Powered Two Wheeler
RR	Reuse and Recycling
RRR	Reuse, Recycling and Recovery
WEEE	Waste Electrical and Electronics Equipment

Plastic material acronyms	please refer to ISO 1043:1998, Plastics - Symbols and abbreviated terms

1 - Introduction

From citizens to industry, from local authorities and governments to international organization, nowadays there is a growing interest on environmental topics. Industry at any level has to deal with environmental impact estimation and reduction. To achieve these targets, a number of methods have been developed to measure or to assess the impact of any product or process in terms of degradation of air, water, soil; to assess the depletion of natural resources and to analyze the influence on human life (Klinglmair et al., 2013). The evaluation of environmental impact from the production to EoL is then called LCA; a framework for the application of LCA methodology have also been formalized through the ratification of ISO 14000 technical notes (Mayyas et al., 2012). Considering the whole life cycle of a generic product, at least four main phases can be recognized (Delogu et al., 2015): raw material extraction, manufacturing, use and EoL; transportations also have to be considered. The present paper is focused on the analysis of waste production during the EoL phase.

The attention of Authorities has been increasingly focusing on the transport sector, that is responsible for a significant environmental impact at worldwide level. Assuming GHG emissions as main indicator, the global transport system accounts for about 23% of total emissions (Saboori et al., 2014); more in detail, approximately 10% of global energy consumption (amongst all sectors, including industry, transportations, residential consumptions etc.) and a similar rate of GHG emissions are related to light duty vehicles (Hawkins et al., 2012). It has been demonstrated through a number of researches that Use phase is responsible for the main impact, but that considering the externality of waste production EoL phase is also relevant (Schmidt et al., 2004). The management of the final waste is also an open issue both due to practical issues and economic factors; landfilling is a frequent destination, even if viable technological solutions for material separation and energy recovery have been identified (Cossu et al., 2014).

In relation to waste criticality, The European Union set ambitious Reuse, Recycling and Recovery targets for some categories of ELV through the definition of the Directive 2000/53/EC. The final target defined by such "ELV Directive" is in force: from 1 January 2015, the RRR rate percentage has to be a minimum of 95% by an average weight per vehicle and year, while the RR rate has to be a minimum of 85% by an average weight per vehicle and year.

The 2000/53/EC does not only describe the treatments to be applied on ELVs to protect the environment from contamination, but also indicates main criteria to be met during vehicle design to enable the achievability of RRR target, that is a challenging technological issue. In addition, the 2000/53/EC aims at reducing the hazardousness of final waste through a number of restrictions on the use of some substances (e.g. heavy metals). EPR criteria are introduced: according to the "polluter pays" principle, the producer should meet all or a relevant part of the costs related to take-back measures implementation. Therefore, the ELV Directive has been a significant improvement driver for vehicle manufacturers and for their supplier, since new alternatives for banned substances have been introduced and since the Recyclability and Recoverability characteristics became a requirement for vehicle homologation. It also has to be highlighted that RRR results are affected not only by the material used for components, but also by the manufacturing solutions adopted by the vehicle. The achievement of good Recyclability is therefore a design issue, so that specific methodologies to include EoL requirements in the design process and to analyze the interdependency of any choice on all life cycle phases have been proposed (Grujicic et al., 2008; Witik et al., 2011). Such methodologies are usually defined as "ecodesign" or "Design for X" (X being EoL, Recycling, Dismantling) procedures (Go et al., 2011).

The most restrictive prescriptions of the ELV Directive currently only applies to two vehicle categories:

- Passenger cars and light freight transport vehicles whose maximum mass does not exceed 3.5t; they are defined as M1 or N1
- three wheel motor vehicles, but motor tricycles are explicitly excluded.

A summary of the vehicle categories subjected to 2000/53/EC is illustrated in Table 1.

One of the reasons for the exclusion of other vehicles is certainly that M1 and N1 vehicles are by far the most relevant in Europe in terms of total circulating fleet and yearly renewal. However, as explained in next paragraphs, other categories of vehicles are usually subjected to EoL treatments which are very similar to those applied on N1 and M1 ELVs. In addition, recent market trends highlight the request for pure urban-commuting vehicles, and new architectures have been proposed in the latest decade.

Starting from this observation, an activity focused on the EoL treatment L vehicles, with particular regard to a tilting motor tricycle vehicle (L3e or L5e category depending on the version, according to Regulation 168/2013) is presented. The aim of the proposed study is to offer an overview on EoL scenarios for these kind of vehicles, defined as ELV-L, assessing the potential impact in case of full extension of ELV Directive to such vehicles through the calculation of Recyclability and Recoverability indexes. The activity has been performed through an approach that takes into account both the typical EoL vehicle management and the application and comparison of two existing and suitable calculation methods. The selected case study is an L-vehicle which is representative of recent design trends for urban mobility and includes electric traction components.

The paper is structured as follows. Section 2 describes the relevance of the topic and offers a brief literature review; general EoL topics and Recyclability/Recoverability assessment methods are introduced. Section 3 describes the methodologies to be applied for 3R rates estimation, including the boundary conditions of the activity. Section 4 illustrates the application on the selected case study and shows detailed results. Concluding observations are finally presented.

Category	Short description	Covered by 2000/53/EC targets	Type Approval
M1	Light Four wheels vehicles up to 3.5t, passengers	Yes	Directive 70/156/EEC Directive 2007/46/EC
N1	Light Four wheels vehicles up to 3.5t, freight	Yes	Directive 70/156/EEC Directive 2007/46/EC
L1e	Light two-wheel powered vehicle	No	Directive 92/61/EEC Reg. 168/2013/EC
L2e	Three-wheel moped	Yes	Directive 92/61/EEC Reg. 168/2013/EC
L3e	Two-wheel motorcycle	No	Directive 92/61/EEC Reg. 168/2013/EC
L4e	Two-wheel motorcycle with side-car	No	Directive 92/61/EEC Reg. 168/2013/EC
L5e	Powered tricycle	No	Directive 92/61/EEC Reg. 168/2013/EC
L6e	Light quadricycle	No	Directive 92/61/EEC Reg. 168/2013/EC
L7e	Heavy quadricycles	No	Directive 92/61/EEC Reg. 168/2013/EC

Table 1 – Summary of motor vehicle coverage by 2000/53/EC.

2 - End of Life L-vehicles

By today, the general prescriptions of 2000/53/CE (excluding those regarding binding RR and RRR targets) apply to all the road vehicles in most national transposition, but restrictions in terms of Recyclability and Recoverability until today have not affected the field of motorcycles, mopeds and L-class vehicles.
According to the growing environmental sensibility, the scope of the study is to assess the potential results of the full application of 2000/53/EC to ELV-L; in case of unsatisfactory RR and RRR targets, new measures could be needed in order to respect the limits. Improvements can be in terms of management of the ELV treatment processes or, if these were not sufficient, in terms of vehicle innovation. It has been demonstrated that the application of Eco-Design criteria such as design-for-disassembly precautions, in fact, have a large potential for waste reduction; however, they also imply the modification of the product (Schiavone et al., 2008) and the use of environmental impact assessment tools.

2.1 - Relevance of the problem

Although ELV-L are not covered by RRR binding targets, a certain attention on their EoL impact analysis can be found in applied research. Communications by motorcycle manufacturers association (ACEM, 2015a) state that the problem is not critical due to a number of reasons; two relevant ones are the existence of a well-established business of reused spare parts from ELV-L and the small amount of waste generated by the category. The market of L-vehicles and the related circulating fleet in Europe is, in fact, about one order of magnitude smaller than the one of M1 and N1 vehicles. To confirm such data an estimation through hypotheses is needed, since ELV-L waste flows are not included in Eurostat database. As shown in Table 2, the data related to M1 class vehicles registrations and deregistrations (Eurostat, 2014a, 2014b) have been used to calculate a yearly deregistration rate. The number of expected ELV-L is then calculated assuming that a similar rate applies to L-vehicle; statistics for L-class sales are provided by Manufacturers' Association (ACEM, 2015b). The average mass for L-vehicles shown in Table 3 is based on the technical data of a number of models which represents about 10% of the market sales, according to recent data for the EU28 countries (ACEM, 2015c). The final results confirm the predominance of other vehicles waste flows in comparison with ELV-L ones.

Such elements are still not sufficient to exclude the need for a specific analysis on ELV-L. According to the literature data presented in this paragraph, a few relevant reasons arise, main being:

- on a world basis, the number related to the EU context do not apply; the amount of waste material coming from L-sector is therefore absolutely relevant also in comparison with other vehicle classes, especially for the Asian area (Naomoto et al., 2004)
- the need to improve the environmental profile of any product is motivated not only by the amount of waste produced, but also from other drivers such as the sensitiveness of the customers; this element has been highlighted by the existence of voluntary recycling programs
- certain L-class vehicles have been identified as possible alternatives to other passenger vehicles categories, thus having a large market increase potential.

Early research on the topic of ELV-L in EU date behind the introduction of the 2000/53/CE Directive (Corso et al., 1999). An assessment of waste quantities arising from the EoL treatment of all kinds of vehicles circulating has also been proposed (Giannouli et al., 2007); such very complete work therefore represents main reference for any kind of analysis on motorcycle treatment activities, but the mass values for ELV-L appears to be overestimated and significantly differ from the assessment performed in the present study (see Table 3). Former analysis of waste input-output flows in the Asian context (Japan and Thailand) includes Trucks and Motorcycle waste together with automotive ones, thus highlighting the need to take into account all the possible sources and categories of ELVs (Fuse and Kashima, 2008). In relation to the European context, it has been highlighted that some EoL operators (dismantlers and shredders) can handle M1 and N1 together with other kinds of vehicles such as scooters and motorcycles, so that the final RRR rate is also influenced by the presence of such similar, but differently regulated scraps (Berzi et al., 2013). In specific contexts (e.g. large Italian cities) the amount of ELV-L waste is a significant share of the total amount processed by the plants: the estimation is about 10% in mass. Only a limited number of studies have been analyzing the Recyclability of a whole ELV-L; however, particular waste flows such as motorcycle tire have been considered (Rofiqul Islam et al., 2008).

According to the fact that the corporate image has been found as a relevant driver for the improvement of product environmental impact (Mathieux et al., 2008), EoL scenarios for motorcycles have been presented on the basis of voluntary activities, thus testifying the interest of the industry to the problem. The assessment of vehicle Recyclability is in fact proposed on manufacturer sustainability communications (HD, 2012; Piaggio&C, 2012); industrial initiatives regarding the improvement of the environmental profile of motorcycle products have also been described in scientific literature (Simboli et al., 2014).

Looking at the initiatives at a world level and, in particular, in relation to the Asian context, JAMA association introduced a voluntary recycling program in Japan since 2004 (Hiratsuka et al., 2013; JAMA, 2008) involving motorcycle manufacturers in a take back system for motorcycle and three-wheel commercial vehicles. ELV-L are also included in the Taiwan recycling program since the early 90s years, which implies that they are subjected to a mandatory recycling target; the system is based on a payback supply chain funded by manufacturers (Lee, 1997). The Taiwanese ELV-L recycling program is still under application (EPA-TW, 2015; Fan et al., 2005) and recent assessments claim that the number of recycled motorcycles overpasses the number of recycled cars (Cheng et al., 2012). In recent years the L-vehicle supply chain reorganization for the achievement of satisfactory EoL performances has been proposed using scientific approaches (Kuo et al., 2012; Phornprapha et al., 2010)

The evidence coming from such brief review is that a few scenarios for waste production from motorcycle sector have been proposed, thus highlighting the interest on the topic. However, it can also be said that a common method for the description of ELV-L characteristics is missing. As an example, a work focused on ELV-L issues (Simboli et al., 2011) shows a material inventory table for a large diffusion scooter, but material classification differs from the ISO22628 standard (ISO, 2002), that is the reference method for the calculation of RR and RRR rates of M1 and N1 vehicles.

Regarding the choice of the vehicle to be studied, the Piaggio MP3 tilting three-vehicle is particularly interesting due to its technical characteristics and due to its potential growth on the market, since it can be considered an alternative both to conventional PTWs and, partly, to passenger cars. PTWs vehicles are an interesting option for urban and inter-urban personal mobility in comparison with full-size M1 vehicles due to the possibility to limit surface use for parking, to reduce congestion, energy consumption and air pollution (Will et al., 2011). Main known drawbacks are related to their protection and comfort characteristics in comparison with cars (Festini et al., 2011). The proposal of "alternative" vehicles such as tilting ones (three and four wheelers) is therefore gaining interest at a European level; their safety and comfort capabilities have the potential to be more satisfactory in comparison to PTWs. The ability to tilt is a feature that enhances dynamic performances in comparison with rigid, very "narrow" vehicles, whose maximum lateral acceleration is limited by the risk of roll-over (Barker et al., 2009); different architectures have been proposed in the last decade (Bertoluzzo et al., 2008; Edelmann et al., 2011; Kidane et al., 2007). A recent work (Cahill et al., 2013) also highlights a large growth potential for L-vehicles in megacities within emerging markets.

In the context described above, the Piaggio MP3 scooter is one of the few market available products representative of the new sector. In particular, the MP3 hybrid powertrain is the one example of commercial hybrid system for L-vehicles (Hutchinson et al., 2014); its complexity is beyond the typical technology of ICE PTWs, but it is also proposed as a pure ICE. Furthermore, the Piaggio MP3 vehicle is available both as L3e or L5e version; the difference between the two models is related to small technical changes. Thus, the platform is representative of a wide range of similar products. For these reason, the vehicle has been used for a Recyclability analysis, aiming to find a reference value for the almost new category of the vehicle. The powertrain under examination is representative of a possible evolution path for L-vehicles; its technological content implies additional effort during EoL treatment, since the removal of parts such as batteries, power electronics and rare-earth motors is needed. The curb mass is relevant in comparison with other PTW products, but the vehicle adopts the same technology of most scooters and PTWs, using a plastic bodywork over a metallic frame. Such bodywork, differently from typical M1 vehicles, has an high potential for the production of ASR if not properly treated. The achievement of high recycling rate is conditioned by such complexity; specific dismantling phases are therefore needed to encourage material recycling.

Year	2006	2007	2008	2009	2010	2011	2012
EU - Countries considered	**20**	**23**	**23**	**21**	**21**	**22**	**19**
M1class registrations n.°	11,177,368	14,429,385	15,686,046	14,486,027	13,366,112	13,108,573	9,304,788
M1 class ELV n.°	3,537,032	5,218,748	5,973,404	8,419,040	6,584,018	6,270,691	4,308,098
M1 class ELV (t)	3,296,389	4,804,156	5,654,533	7,778,404	6,384,308	6,228,507	4,236,727
Ratio M1 ELV/registrations	32%	36%	38%	58%	49%	48%	46%
L class registration (EU28) n.°	2,300,382	2,460,440	2,328,215	1,934,874	1,669,777	1,510,320	1,313,260
ELV-L estimated n.°	727,946	889,880	886,608	1,124,517	822,516	722,485	608,037
ELV-L estimated mass (t)	129,611	158,443	157,860	200,220	146,449	128,638	108,261

Table 2 – Estimation of total waste flow related to L-vehicles. Due to lack of data for some countries, the numbers do not refer to the whole EU-28 market (ACEM, 2015b; Eurostat, 2014a).

Size	Stroke (cc)	Estimated mass (kg)	Estimated market share
Moped	0 to 50	102	20%
Light	50 to 250	141	25%
Average	250 to 750	199	30%
Large	750 and more	235	25%
Average	all	174	-

Table 3 - Estimation of the average mass for different size of L-class vehicles (all categories, excluding quadricycles) sold in EU-28. Adapted from ACEM data (ACEM, 2015c).

2.2 - Vehicle End of Life treatment

The recycling of road vehicles is performed in ATFs, which have to comply to specific regulation for environmental protection. The treatment, according to 2000/53/EC and to good practices, is based on three main steps: depollution, dismantling and shredding, this latter being followed by material separation. The depollution phase deals with the removal of main pollutants and hazardous materials, while the dismantling phase includes the separation of all those components suitable for reuse. Direct reuse without remanufacturing often occurs. The removal of parts in order to promote the recycling of the material is encouraged by the 2000/53/EC; a certain arbitrariness is permitted to the operator also depending on the subsequent treatments. The shredding of the vehicle is performed to comminute the body and all the remaining parts in small fragments, which can be segregated and successfully recycled. In general, almost all the metal content is separated with widespread available technologies, while the other materials (e.g. organics) are going to constitute the so-called ASR. Such mixed material waste can be addressed to various form of material and energy recovery if PSTs are available, but most shredding plants still do not perform material separation due to the complexity of the process and to the heterogeneity of the waste. Many studies regarding the evaluation of ASR characteristics and their variability are available in literature (Boughton and Horvath, 2006; Cossu et al., 2014; Vermeulen et al., 2011). Most suitable process often include thermal treatments (Sakai et al., 2007; Taylor et al., 2013; Vermeulen et al., 2012) and the economic sustainability of such PST has been verified for certain applications, but it still depends on the context (Ruffino et al., 2014). It can be stated that the achievement of satisfactory RRR rates depends on the successful reduction of the final amount of ASR produced and of any residual that has to be landfilled. If PSTs are not applied, the dismantling phase has to be highly accurate in order to promote the recycling of all the materials, most critical being non-metal ones. A general ELV treatment process is synthetized in the Figure 1, which has been adapted from previous work (Berzi et al., 2013) and comes from on-field observation. The main phases have to be performed for all the road vehicles, but the accuracy and the detail level of each sub-phase depend on vehicle type.

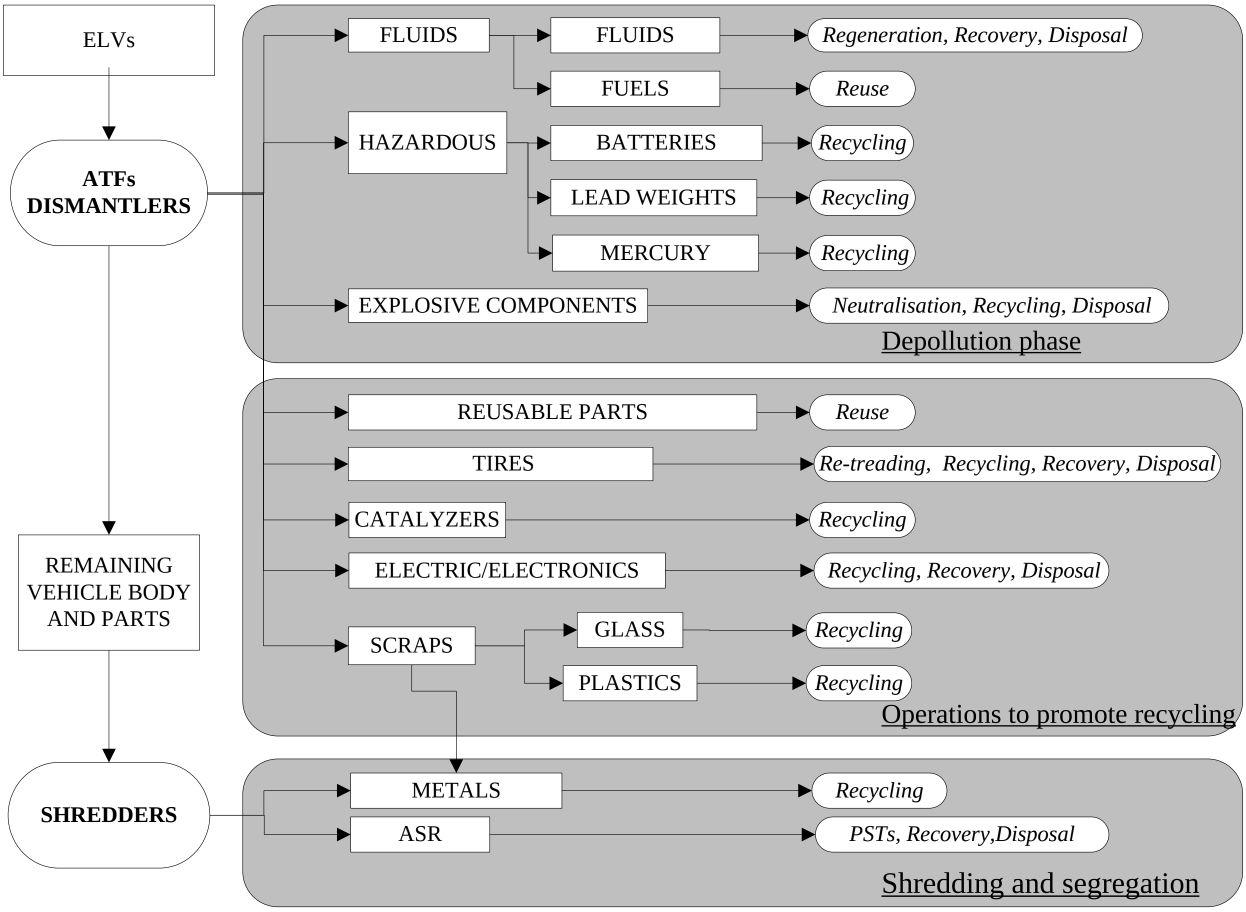

Figure 1 – General EoL treatment for vehicles; upgraded and adapted from (Berzi et al., 2013).

The evidence coming from the on field investigation is that the material flows coming from M1, N1, L and heavy vehicles are frequently mixed together; such activity is not in contrast with the regulation, but can cause inaccuracy in terms of the calculation of final rates. The presence of other type of waste (e.g. urban waste residuals, WEEE) is one of the reasons that can cause contamination of automotive waste, such as PCB pollutants presence (Mancini et al., 2010). Regarding ELV-L, they are subjected to a treatment procedure that is conceptually similar to the one applied to any other ELV; however, since binding RR and RRR rates and not requested, the dismantling operations to promote material recycling can be neglected.

2.3 - The need for a disassembly procedure

In case of automotive products covered by the Directive 2000/53/EC, a list of parts to be removed and of their constituting material is usually suggested to the operators through the IDIS (IDIS, 2015), whose information come from the manufacturers. For the class of the vehicle under study, such documentation is not available and it is therefore necessary to build up an appropriate treatment sequence. This task has been performed on the three wheeler taking into account the suggestions coming from the experiences and the information acquired during an investigation conducted on ATFs on the Italian territory; the scenarios are described in detail in Section 4. Considering that the dismantling of vehicle parts is labor consuming, various analysis have been proposed in literature to estimate the effort (in terms of cost and time) needed for such phase; however, it can be highlighted that for most products a standardized EoL assessment method is still missing (Mathieux et al., 2014). For main automotive categories parts, for example, empirical time estimation procedure have been proposed in literature (Coates and Rahimifard, 2007; Fang et al., 2014). Other analysis are based on the dismantling time estimation through the build-up of a precise disassembly sequence. Data describing the type and number of fastenings, the tools needed, the mass of the parts are needed; specific CAE tools are available (Santini et al., 2010).
The cited analyses, however, do not seem to take into account the occurrence of "destructive" operations in case of dismantling for recycling, in which the parts can be cut or broken. In case of recycling, the occurrence of damage (e.g. cracks) of plastic parts is irrelevant; however, a certain material loss in comparison with accurate part dismantling is possible. The consequence of such practices will be shown in the results of the present study.

2.4 - Reference standard and approaches for the assessment of 3R rates

Considering that a mandatory regulation for the achievement of any 3R target does not exist for L-vehicles, a methodology for the assessment of expected value has to be defined from the ones used in other transport sectors. The two existing methods in the land transport field are:

- The ISO 22628:2002 standard for road vehicles

- The UNIFE method for Railway vehicles characterization.

The ISO22628:2002 method (ISO, 2002) is the only method currently included within existing technical regulation for road vehicles, since it is part of type approval for class N1 and M1 (Directive 2005/64/EC). A reason for the use of this method is the evident analogy between PTWs and automobiles in terms of technology and materials; such similarity is also highlighted by the habit of mixing motorcycle and automotive scraps in ATFs, as described in previous paragraph. The ISO22628 has been already used for the Recyclability assessment of PTW products within the industry, resulting, for the specific manufacturer (Honda motors, 2011), in an overall RR rate of 86.1% and 87.8% for scooter and motorcycles respectively, aggregated result being 86.9%. A case study for the application of this methodology has also been presented in scientific literature (Millet et al., 2012). According to recent studies (Maris and Froelich, 2013) the methodology defined by ISO22628 is affected by a number of deficiencies; amongst others, three main criticalities emerged:

- Recyclability indicators should take into account the preservation of the mass of secondary raw materials in respect of primary ones
- the treatment should be described in accordance with the reference recycling network for a certain product; in particular, the geographical context, the existence of regulation and the product category can cause different results for parts made of the same materials
- the scope of the calculation itself is not clarified in detail.

Taking into account the whole context of vehicles for inland transport, the other relevant method for the 3R rates calculation is the one proposed for railway rolling stock by the Association of Railway Manufacturers UNIFE. The method has been prepared by an expert committee within the proposal of PCR for railway vehicles (EPD Consortium, 2009; UNIFE, 2013) and has to be applied for the proposal of a realistic EoL scenario while performing LCA analysis (Del Pero et al., 2015). Its application, however, is currently not mandatory according to the legislation. Nevertheless, this second choice is particularly interesting for a number of reasons. First of all, it is supposed to be applied by railway vehicles manufacturers on a voluntary basis, in order to satisfy the need of their customers about environmental certification beyond the requirements of regulations. The scopes of the assessment are therefore strongly similar to those of the case study here presented. As a second point, the UNIFE method is related to the performances of industrial recycling and recovery processes.

RecyclabilityUNIFE calculation method assumes the ISO22628 as his basis (Merkisz-Guranowska et al., 2014) but it has been defined in recent years, so that it can be considered as a possible evolution of the ISO22628 standard . In particular, the description of material inventory is more detailed (16 classes are used instead of 7) and it takes into account a number of technological limitations through the definition of appropriate Material Recycling and Energy Recovery Factors (MRF and ERF). A simple example clarifies such difference: the ISO22628 considers that metal parts are 100% recyclable, while the UNIFE method introduces 98% MRF. The factors are defined according to process losses, that are almost unavoidable due to thermodynamics and technological limits; a description of main causes for the phenomena (e.g.

inaccuracy in material separation, slag production during recycling, quality loss due to contamination) can be found on literature (Froelich et al., 2007a; Graedel et al., 2011; Passarini et al., 2013). Topics related to the assessment of metal recyclability are also gaining interest due to recent trends in vehicle manufacturing, which lead to a different use of aluminum alloys (Hatayama et al., 2012) and to the increased use of steels containing elements such as manganese, chromium, nickel, and molybdenum (Diener and Tillman, 2015; Ohno et al., 2015). A RRR rate of 100% is not achievable in any case according to the UNIFE method, since it sets an upper limit for the value that cannot be exceeded even in case of optimal vehicle treatment; the practical occurrence of such limitation is well known in literature (Reuter et al., 2006; Schmid et al., 2013). The UNIFE method also takes into account the peculiarities of Electric and Electronic components, whose quantity is relevant on EVs and HEVs. In this study, the factor used to assess the Recyclability of power electronics and mechatronics is the one suggested by UNIFE method, even if the assessment of such value is still an open issue and specific dismantling methods are currently under development (Li et al., 2014); the assessment of battery Recyclability is also a topic under discussion in applied research (Richa et al., 2014).

The formalization of loss factors focuses the approach on the calculation of realistically achievable 3R rates instead of theoretical ones; such assessment is in accordance with latest trends in the sector of recycling. The use of loss factors to estimate effective Recyclability, in fact, has also been applied in studies related to other kind of durable goods, relevant ones being WEEE. The factors can also vary depending on the local context in which the item is supposed to be dismantled (Mizuno et al., 2012), demonstrating the flexibility of the approach and its applicability to different contexts.

As a final observation, it has to be noted that the assessment of both methods are affected by a strong uncertainty level; the reason is that the decision to dismantle certain vehicles parts is defined through qualitative or arbitrary estimations (e.g. accessibility of the part, availability of recyclers on the local market). The coefficients proposed by the UNIFE document are representative of current technological context in Europe; however, it is not excluded that an update could be necessary depending on the area of application and the technological improvement in next years. Literature studies highlighted the need for the manufacturer to investigate on the recycling industry to define their own guidelines (Froelich et al., 2007b), and, consequently, the need to compare different contexts (Camañes et al., 2014).

In the present study both the methods will be applied; the ISO22628 is needed to get an index to be compared with existing experiences, while the UNIFE methodology and its corrective factors will be used to calculate an improved index that is expected to be more realistic and, in any case, more restrictive.

The study presents a set of different hypotheses regarding the accuracy of the treatment; the results therefore include a range of values instead of a unique RRR rate.

3 - Method for vehicle dismantling and 3R rates assessment

This section describes all the phases performed to analyze the three wheeler and perform 3R rates calculation. The topics include the definition of main treatment steps according to the selected methodologies; after that, the vehicle has been fully dismantled and analyzed, as described in next section.
According both to ISO22628 and UNIFE method, the process has to be described through the list of those parts and materials removed during main treatment steps, in accordance with the sequence usually adopted in ATFs:

a) pretreatment
b) dismantling
c) separation of metals
d) processing of non-metallic residue

The material breakdown is also described through the use of pre-defined classes. The methodology, as described by the standards, is formulated in such a way that it can deal with the EoL process of different types of land vehicles.

3.1 - Material breakdown phase

Both the methods propose a list of material classes which include all the typical ones for automotive and railway components. The two methods use different material classes, the UNIFE proposal being more detailed. Table 4 illustrates the two proposed approaches; regarding UNIFE one, the coefficients MRF and ERF have to be used as described in Table 5. MRF and ERF values are based on the know-how on current technological limitations. Notably, a low ERF (less than 20%) is used for the non-metal materials mixed in ASR; such value can be justified by the high ash production related to thermal valorization, that has been demonstrated even considering the significant organic content of the ASR (Vermeulen et al., 2011).

ISO22628		UNIFE method				
Class	Description	Class	Description	MRF	ERF	Residue
1	Metals	1	FE Metals	98%	0%	2%
2	Polymers	2	Non-FE Metals	98%	0%	2%
3	Elastomers	3	Elastomers	80%	20%	0%
4	Glass	4	Thermoplastics (unfilled)	100%	0%	0%
5	Fluids	5	Thermoplastics (GF filled)	67%	33%	0%
6	Modified Organic Natural Materials (MONM)	6	Thermosets	100%	0%	0%

7	Others (Compounds, Electric, etc.)	7	Thermosets (GF filled)	67%	33%	0%
		8	Carbon or natural fiber reinforced polymers	67%	33%	0%
		9	Glass	100%	0%	0%
		10	Safety Glass	94%	0%	6%
		11	Lubricants	0%	100%	0%
		12	Other service Fluids	83%	0%	17%
		13	Modified Organic Natural Material (MONM)	95%	5%	0%
		14	Electric and electronics	79%	19%	2%
		15	Ceramics	43%	0%	57%
		16	Mineral wool	97%	0%	3%
		All non-metal	Mixed non-metal materials in ASR	14%	19%	67%

Table 4 – Material categories for both considered methods and material factors to be used for UNIFE calculations. Considering those parts that are not dismantled, MRF and ERF for ASR have to be used.

3.2 - Pretreatment phase

The pretreatment of the vehicle is mainly determined by safety reasons and implies the removal from the vehicle of all the potentially harmful substances. When the substance cannot be extracted, whole parts are removed. The pretreatment step is extremely critical because the accuracy of its execution affects the subsequent stages. In particular, an inappropriate pretreatment may involve the presence of pollutants recognized as dangerous in the residue obtained after vehicle shredding; hydrocarbons contamination is a typical example. All the removed elements usually need other treatment processes such as neutralization, reuse, recycling or recovery, depending on their characteristics; such operations are most time performed by specialized operators different from the ATF.
Components prescribed to be removed include:

- batteries
- all vehicle fluids
    - engine oil, fuels, coolant, service fluids
- gas tanks (LPG, CNG), if present
- oil filters
- tyres
- catalytic converters

In addition, it is mandatory to remove any other component containing hazardous substances or materials. Typical examples are lead weights, mercury switches, electric parts containing PCB fluids; however, all this parts are typical of old production vehicles. The ISO22628 describes the pretreatment phase in such a way that the operations to be done are almost univocally determined.
The sum of the masses of the components, materials and fluids removed at this stage is considered to be reusable or recyclable; according to ISO22628, the abbreviation is conventionally m_P. According to UNIFE

method, no relevant differences arise; m_P has to include other parts typical of rolling stock vehicles (e.g. fire extinguisher).

3.3 - Dismantling phase

According to both the ISO 22628 and the Directive 2000/53/EC, the manufacturer has to identify the vehicle components that have to be disassembled for the purpose of their reuse and/or recycling as material. None of the two prescribe exactly which components have to be disassembled, but only the criteria for the selection are declared. In the ISO22628 the first criterion of selection is based on the easiness of dismantling, which depends on the accessibility of the part, on the type of fastening used and on the existence of proven dismantling technologies. As a second element, the part can be selected if a proven recycling technology is available according to its material composition.
The use of indicators to quantify "easiness of dismantling" is still under discussion and this characteristics is therefore subjected to qualitative estimations or, in any case, it is related to the know-how of the manufacturer rather than to public standards. Also, the availability of technologies for dismantling and recycling depends on the local context on which the dismantling phase is performed and could vary with the progress of technological status; it has already been highlighted that it is up to the manufacturer to be aware about the suitable options (Millet et al., 2012). As a conclusion, these evaluations are partially arbitrary and different choices are possible.
The Directive 2000/53/EC contains additional information since it includes in its Annex I the categories of components to be considered for dismantling, such as:

- Catalysts
- Metal components containing copper, aluminum and magnesium if these metals are not segregated in the shredding process
- Glass
- Tyres and large plastic components (bumpers, dashboard, fluid containers, etc) *if these materials are segregated in the shredding process in such a way that they can be effectively recycled as materials*

A few observation are necessary to understand the consequence of the notes declared in this list for the calculation of RR and RRR rates. The prescription regarding the catalyst is coherent with ISO 22628, which indicates its removal during the pretreatment phase; in practice this is always done due to the high economic value of the scrap resulting from such component.
The removal of metal parts is not critical due to the fact that post-shredding segregation methods for metals are technologically mature. In any case, the ISO 22628 always includes metal parts in the list of mass to be recycled, so that the occurrence of metal parts dismantling does not influence the calculation of RR and RRR rates; next paragraphs clarify this point. In any case, operators usually dismantle metal parts if they can recognize the presence of an alloy having an high economic value.

The removal of glass parts is usually performed due to their accessibility, but this material is not used in the vehicle under examination, as usual for ELV-L.

The last elements of the list include organic materials; in this case, the occurrence of dismantling is critical for recycling. Considering the large number of existing families (elastomer, thermoplastic and thermoset polymers), only a few of them are suitable for recycling. In addition, polymers can be effectively recycled if the purity of the scrap is high, that means low presence of contaminants and high level of separation of each polymer from the others. Even if post-shredding segregation technologies are available at an industrial level, the amount and the quality of processed material can be lower in comparison with those obtained by manual dismantling of the parts. Since a large number of plastic parts are usually installed on vehicles (up to a few hundreds, considering also small mass parts), the 100% removal is not feasible and a compromise is necessary (Tian and Chen, 2014). It is therefore evident that the choice of the plastic components to be dismantled is critical for the achievement of satisfactory 3R rates. In the application phase of this study different scenarios are proposed depending on the amount of dismantled plastics.

The ISO 22628 indicates the sum of the masses of the components disassembled at this stage with the symbol m_D. The same approach is proposed by to the UNIFE method; in addition, this latter introduces additional guidelines to suggest to the operator which components are best candidates for dismantling.

3.4 - Metals separation

After the disassembly phase, all the ferrous and non-ferrous metals that were not removed in the previous phases are considered as recyclable. These mass is mainly constituted by vehicle body and powertrain; it is identified by the symbol m_M. The metal parts included in m_M are therefore considered recyclable as well as those manually removed and included in m_D. In practice, the dismantling of metal parts is not really influencing the final 3R rates. As said before, however, the manual dismantling can avoid the mixture of special alloys with other metal scraps and it is certainly a good option to preserve the characteristics of the material. Nevertheless, the RR rate calculation is not conceived to distinguish between different quality levels of recycling.

3.5 - Non-metals residues treatment

All the materials remaining from previous steps are subjected to shredding together with the metal part of the vehicle and are therefore constituting the ASR. The ISO22628, and similarly the UNIFE method, identifies for this residuals the following destinations:

- additional treatment with separation and recycling: the mass subjected to this selection is identified by the symbol m_{Tr}
- use for energy recovery: the mass potentially usable for this purpose is indicated by the symbol m_{Te}.

The determination of m_{Tr} is, again, dependent on existing technologies and therefore it is estimated on the basis of the available know-how. According to the notes in ISO22628, polymers, elastomers and MONM are considered *potentially* usable for the recovery of energy. Within the present activity such materials are supposed to be always subjected to thermal recovery if not included in m_D or m_{Tr}. As a consequence, the sum of m_D, m_{Tr} and m_{Te} is constant and the choices determining m_D and m_{Tr} are not influencing the final RRR rate. In addition, since m_{Te} is based on the amount of material addressed to recovery processes, the effective performances of such technology (e.g. production of waste residuals such as bottom ashes) are not explicitly considered.

On the contrary, the UNIFE method uses two constant parameters for the evaluation of m_{Tr} and m_{Te}; these are calculated as 14% and 19% (MRF and ERF, respectively) of the mass of non-metal materials not included in m_D. Due to the use of such factors, within the UNIFE method the RRR rate is expected to vary and to be dependent on the assumptions regarding dismantling effort.

3.6 - Recyclability and Recoverability rates

The calculation of the RR and RRR rates takes into account the masses defined in the previous steps. The RR and RRR rates are respectively indicated by the R_{cyc} and R_{cov} coefficients. Different definitions are possible for the initial mass of the vehicle $m_{V;}$ in this application it is constituted by the total shipping mass of the vehicle as defined by ISO1176 - Standard on road vehicles masses (ISO, 1990). The mass m_V includes the masses of lubricants, service fluids, fuel (it is assumed that the reservoir is filled at least 90% of the capacity specified by the manufacturer) and equipment such as spare wheels, standard accessories, tool kits. Such definition is in accordance with ISO22628.

The two methods differ on the basis of the use of loss factors (MRF and ERF for the UNIFE), as described in Table 5; the final RR and RRR values have to be rounded to the unit, but in the present document a one decimal approximation is used for enhanced precision.

As already discussed, the consequence of the use of the UNIFE factors is that the 100% result is not achievable in any case.

ISO22628	UNIFE method
$R_{cyc} = \frac{m_P + m_D + m_M + m_{Tr}}{m_V} * 100$	$R_{cyc} = \frac{\sum m_i * MRF_i}{m_V} * 100$
$R_{cov} = \frac{m_P + m_D + m_M + m_{Tr} + m_{Te}}{m_V} * 100$	$R_{cov} = \frac{\sum m_i * MRF_i + \sum m_i * ERF_i}{m_V} * 100$ Where m_i corresponds to the partial masses coming from main steps (m_P, m_D, m_M, m_{Tr}, m_{Te})

Table 5 – Comparison between calculation criteria for the two methods (ISO22628 Vs. UNIFE method).

3.7 - Scenario definition

The application of the ISO standard in order to calculate the RR and RRR rates implies the definition of a dismantling scenario for EoL; it should be as consistent as possible with the actual treatment in the ATFs. Dismantling operations, in fact, are subjected to an uncertainty which depends, amongst others, on the technology available for post-shredding operations. As described in paragraph 3.4 -Metals separation, the dismantling of metal parts is not influencing the RR and RRR rates; also, the pretreatment phase is prescribed in detail both by ISO 22628 and Directive 2000/53/EC and is therefore completely defined. As a consequence, the element that differentiate final results for a realistic scenario is the amount of organic materials dismantled, since only this choice has a significant impact on the calculation results.
Therefore, the proposal of a list of parts to be dismantled by the manufacturer is partly based on arbitrary considerations, which are aimed at the achievement of satisfactory recycling indexes; it is possible that other recyclable parts are excluded, if not strictly necessary to achieve the binding threshold. During dismantling in plants, the choice suggested by the manufacturer can therefore vary depending on operators' attitude. In order to consider the variability of the process, different scenarios are considered in the present work. Assuming the point of view of the manufacturer, the analysis can be used to identify the parts of the vehicle to be listed in the ISO22628 which are essential for the achievement of RR and RRR targets, while the non-priority ones could be considered only for post-shredding treatments.
Assuming the point of view of the Authority, the analysis estimates what is going to happen in terms of waste production in case of inappropriate or incomplete treatment of the vehicle in the ATFs. This can occur due to the heterogeneity of such plants, which are mostly using craft-type dismantling methods.

4 - Application on the three wheeler case study

This section describes the approach followed for the evaluation of the 3R rates for the case study and compares the outcomes obtained from the application of the two different standards. The vehicle under study has been fully dismantled and analyzed to obtain the parts and materials inventory; documentation such as workshop manual has also been used. Starting from such data, the material breakdown has been expressed according to the two different classification proposed by ISO22628 and UNIFE standards. Then, a typical treatment sequence – including pretreatment and dismantling – is formulated. On the subsequent step, four scenarios have been identified considering different dismantling effort and the context of the ATFs. This phase generates the list of parts to be dismantled and to the estimation of RR and RRR rates for the two methods.

The last step introduces additional hypotheses to the scenarios (i.e. increased ERF coefficient for ASR and loss of material in case of destructive dismantling) in order to calculate the variability of the RR and RRR rates.

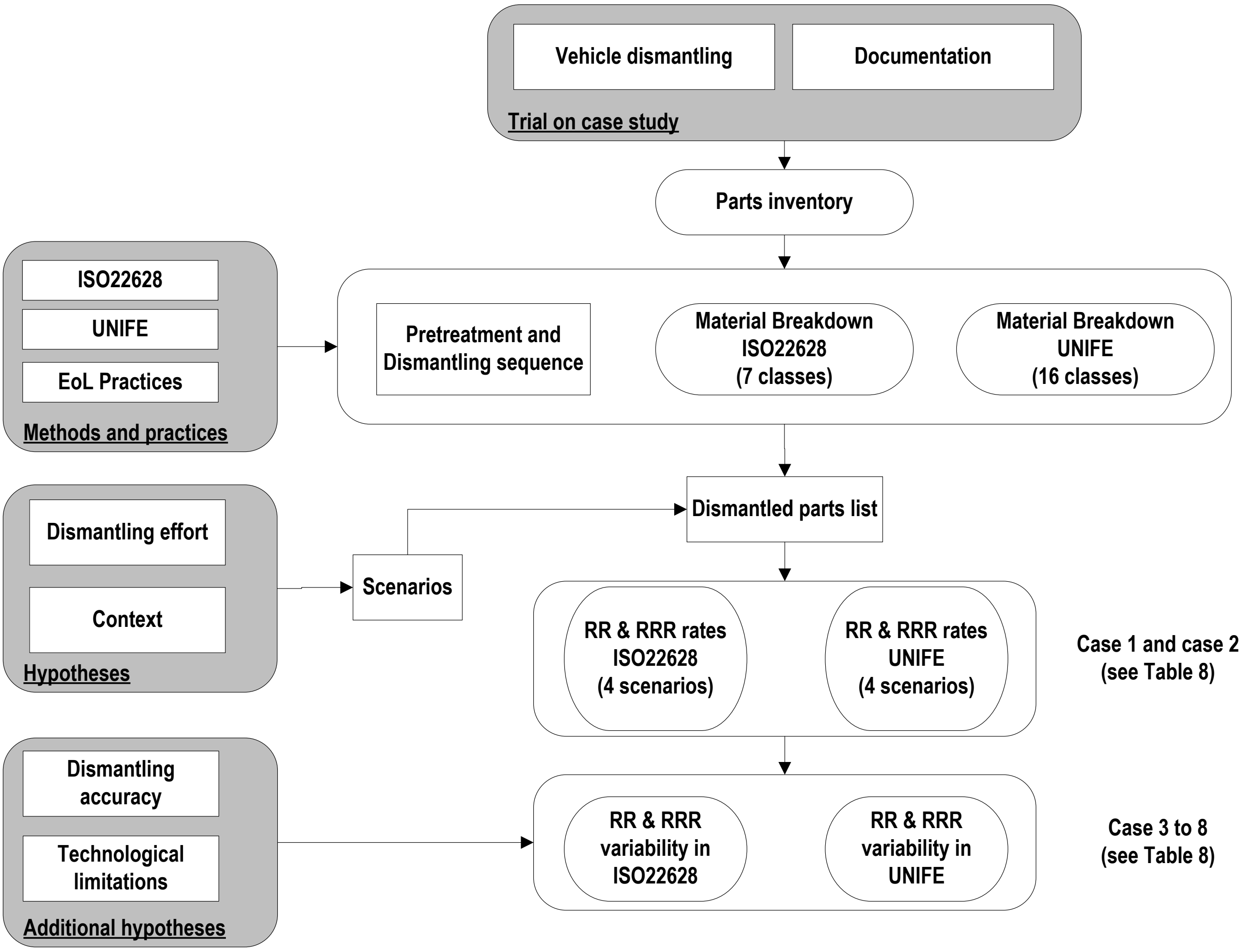

Figure 2 – **Methodology adopted for the EoL analysis of the three wheeler.**

4.1 - Vehicle description

The vehicle used for the case study is an L-class three wheeler; depending on technical details, it is assimilated to L3e type (motorcycle vehicles) or L5e type, while most part of the model remain the same. The layout of the vehicle is typical of scooters: the engine is rear and integrated with the swingarm, the central part of the frame is structured as a foot platform and the rider is protected by a large front shield. The structural part is composed by a steel frame, while the bodywork is constituted by plastic covers. The vehicle is equipped with a tilting system on the front part that significantly increases its curb weight (about 279kg) in comparison with scooters having similar displacement. The powertrain includes a gasoline-electric hybrid unit. After the removal of harmful substances, the three wheeler has been disassembled obtaining the complete separation of body parts, fittings, chassis and engine. Complex subsystems (shock adsorbers, engine, bearings) have not been further dismantled, since such detail is not needed at the dismantling stage. Finally, the inventory of parts included 178 elements , which have been singularly weighted.

Figure 3 – Vehicle "Piaggio MP3 125 Hybrid" exploded components

As shown in Figure 4, the total vehicle mass is constituted by about 70% of metals (mainly frame and engine), followed by a 19% of plastic parts, particularly used for the bodywork. The 5% is then constituted by rubber parts (tires, pipes, transmission belt, seals, etc.) and followed by 4% of fluids (fuel, coolant, engine oil and brakes fluid); 2% is constituted by electronic parts (small PCB used in control units). High voltage electric parts such as the battery and the power converters have been further dismantled to list their constituting materials (plastic, metals and others). As illustrated in Figure 6, steel is the predominant metal (80%), followed by aluminum (about 16%); these fraction are supposed to be separated at the end of the process, consequently to the shredding phase.

The classification according to the material categories proposed by the UNIFE method is shown in Figure 5; in this subdivision, electric parts include all batteries and power converters; further classification is not necessary since the method proposes a specific MRF for electrical compounds.

Focusing the attention to the plastic components (mainly thermoplastic, with the exception of PU foam used for the seat), the most used polymers are constituted by polypropylene-based compounds (PP sometimes including fillers such as glass fibers and glass dust), representing 65% of the total mass of plastics. Within other polymers, the most used is ABS, that is about 12% of total polymers.

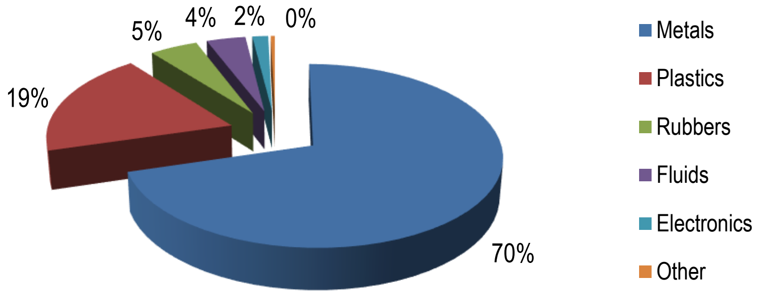

Figure 4 – Vehicle "Piaggio MP3 125 Hybrid" mass composition according to ISO22628.

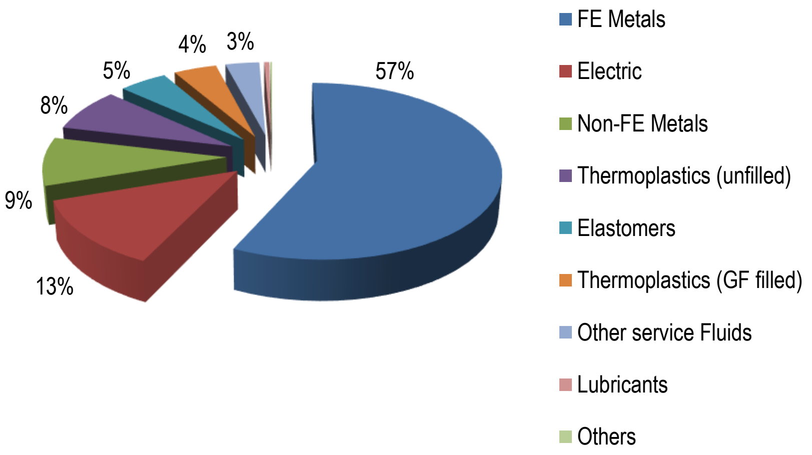

Figure 5 – Vehicle mass composition according to UNIFE categories. Only most representative categories are shown (8 out of 16), while the remaining (thermosets, glass, MONM etc.) are included in "others".

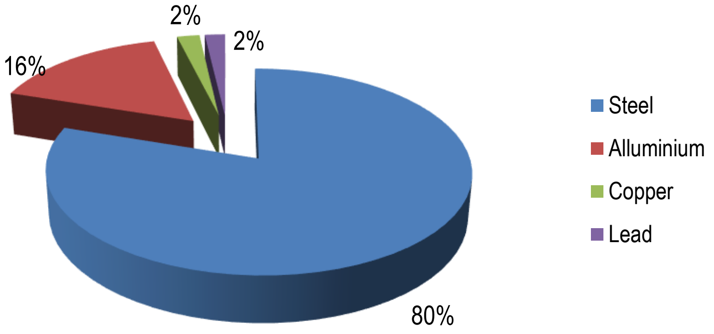

Figure 6 – Metals contributions to the whole metal fraction. Lead is used for the low-voltage battery.

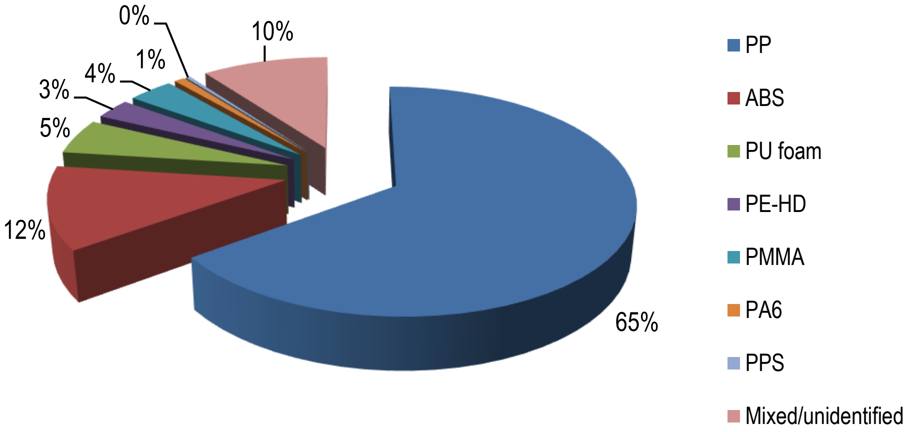

Figure 7 – Contribution of each plastic polymer to the whole plastic mass composition.

4.2 - Dismantling scenarios

According to the possibility of process variability, 4 different End of Life scenarios have been proposed: for each of them, the same depollution operations have been considered, but then the accuracy level of dismantling is varied, as described in paragraph 3.7 -Scenario definition.
The 4 scenarios have been hypothesized as follows:

- scenario n° 1: in this case no dismantling is considered, so after the pretreatment, the whole remaining vehicle is directly subjected to the shredding operation. Consequently, at the end of the whole EoL process, all plastic components will be included in the ASR fraction. This scenario represents the *"worst case"* and is representative of an inappropriate treatment

- scenario n° 2: the dismantling of PP-based components has been considered in addition to the treatment provided in the scenario n° 1. PP-based materials are the most used plastics in the vehicle, accounting for 34.3 kg (12.3% of total vehicle mass); the availability of recycling technologies for PP is proven (Froelich et al., 2007b). The removal of the parts, according to the structure of the vehicle, also implies the disassembly of some additional parts (mainly metal-based, e.g. aluminum radiator, front supports, etc.). Most PP is localized on the bodyworks, that is directly accessible. This case is defined as the *"PP dismantling scenario"*.
- scenario n° 3: the treatment includes the dismantling of plastic parts made with the two most used thermoplastic polymers, namely PP and ABS, in addition to the treatment provided in scenario n° 1. ABS parts account for 6.3 kg (2.3% of total vehicle mass); this second material has been chosen because it is mostly localized on the exterior body of the vehicle, thus being accessible. It is named *"PP & ABS scenario".*
- scenario n° 4: in this last case, it has been considered the dismantling of all the components made with other thermoplastic polymers or recyclable ones in addition to the treatment provided in scenario n° 1. This case represents the best scenario, called *"Accurate dismantling"*.

Concerning the scenario from 2 to 4, few assumptions are necessary. The removal of some components has been considered unfeasible due to their accessibility difficulties, which imply high disassembly time, or instead for its low mass. It was therefore assumed that they are left on the vehicle and subject to shredding together with the metal parts, thus contributing to the formation of ASR. The list of these components is summarized in the Table 6.

Table 7 includes the components made of polymeric materials that have not been disassembled in the scenario 2 and 3. This components are included in the dismantling list for the scenario 4. The PP and ABS components to be removed, as expected in the scenario 2 and 3, are described in the graphical summary presented in Figure 8.

In addition to the four main scenarios, a few additional boundary conditions have also been formulated. The disassembly of plastic parts is usually partially destructive (e.g. through cutting, breaking, ripping), allowing the removal of only a portion of the mass of the components. In the present work, all the scenarios are therefore also presented including the possibility of such partial removal; the hypothesized removed mass percentage is 95%. In this way, the remaining amount (5%) is intended to contribute to the formation of the ASR. Regarding ASR, two ERF factors are used for comparison: the standard UNIFE one, that is 19%, and an enhanced one, that is 50%; such value is used in order to evaluate which improvement should be necessary to the PST process to achieve the 95% RRR target. Another variation has been done considering the reduction of MRF to 0%, that is still a probable option in some contexts.

Reasonable assumptions are also necessary for those parts made of more than one material which are closely bonded; for these, it was assumed that the organic part is thermally recoverable and that the remaining part is recyclable as metal. The ratio between organic and inorganic was obtained by weighting (see Table 8). It should be noted that wire harness is about 2.5% of total vehicle mass, that is quite remarkable; a relevant contribution comes from the hybrid powertrain system. According to ISO22628, the mass of complex components that are supposed to be dismantled in the pretreatment (e.g. high voltage battery) is considered recyclable, even if such hypothesis is almost unrealistic.

PP or ABS components	Mass [kg]
Lower helmet compartment	4.260
Rear cover helmet compartment	1.140
RH passenger grab handle	0.322
LH passenger grab handle	0.315
Closure backrest support	0.288
Rear luggage closure	0.178
Central part front wheels compartment	0.135
Electric fan bracket	0.101
RH switch support	0.087
LH switch support	0.084
Radiator fan	0.047
RH side front suspension cover	0.029
LH side front suspension cover	0.029
Closure passage wiring helmet comp.	0.028
Licence plate light	0.017
Bracket wiring helmet comp.	0.010

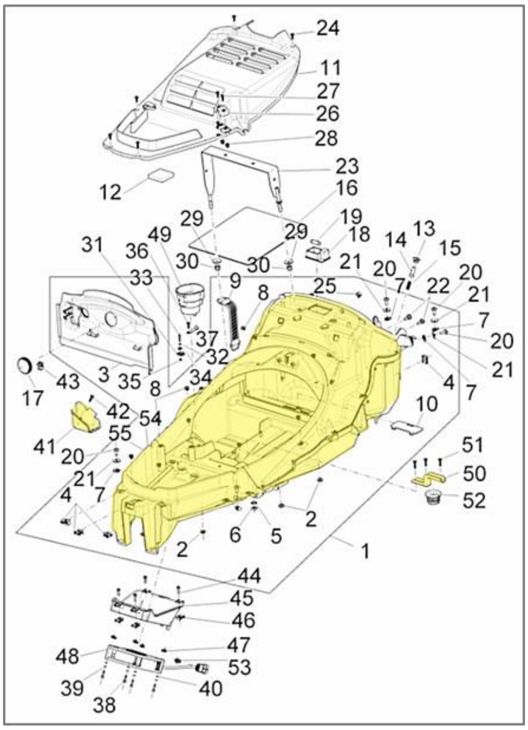

Table 6 – List of PP and ABS components that have been evaluated unsuitable for disassembly. On the right column, an example of underseat ones (n° 1, 41 and 50). Source: Piaggio Spare Parts Catalogue.

Component	Material	Mass [kg]
Seat foam	PU foam	1.55
Fuel tank	PE-HD	1.53
Headlamp	PPT40, PA66, PES PC, EPDM	1.48
Windshield	PMMA	1.20
Rubber pipes (various)	Rubber n.d.	1.11
Passenger backrest	PU foam, PVC	1.11
Meter combination	PC	0.93
Seat cover	PVC	0.49
Plastic bands, rubber seals and caps	Various rubbers and plastics	0.35
Cooling fan	Plastic n.d.	0.34
Ignition coil cover	PBT 30GF	0.32
Muffler protection	PA66 30SV	0.28

Table 7 – List of components not disassembled, and thus considered only for energy recovery (m_{Te} mass contribution) in the EOL scenario 2 and 3. Small parts (below 0.25kg) are not reported.

Component	Total Mass on vehicle (kg)	Ratio
Wire harness (plastic/copper), (plastic/steel)	5.5	Organics 45%; Copper 55%
Bowden flexible cables	1.3	Organics 15%; Steel 85%

Table 8 – Components constituted by closely bonded materials and therefore not easy to separe. Such data have been used to estimate m_{Tr} and m_M contributions for the ISO22628 calculation.

4.3 - Results

The calculation of the RR and RRR rates for each of the four vehicle End of Life scenarios and for the different boundary conditions described in the previous paragraph generates the results summarized in Table 9 and Figure 8. The outcomes of both calculation methods are included, the UNIFE one being more conservative in comparison with ISO22628, as expected.

	Method	Boundary Conditions			RR				RRR			
		% dismantling	MRF ASR	ERF ASR	Worst	PP	PP+ABS	Accurate	Worst	PP	PP+ABS	Accurate
1	ISO22628	100%	-	-	79.3%	85.3%	87.4%	89.4%	98.1%	98.1%	98.1%	98.1%
2	UNIFE	100%	14%	19%	79.1%	83.9%	85.7%	87.2%	85.6%	89.6%	91.0%	92.3%
3	UNIFE	100%	14%	50%	79.1%	83.9%	85.7%	87.2%	91.3%	93.4%	94.2%	94.9%
4	UNIFE	100%	0%	19%	76.5%	82.2%	84.3%	86.0%	88.7%	91.7%	92.8%	93.7%
5	ISO22628	95%	-	-	79.3%	85.0%	87.1%	88.9%	98.1%	98.1%	98.1%	98.1%
6	UNIFE	95%	14%	19%	79.1%	83.7%	85.4%	86.8%	85.6%	89.4%	90.7%	92.0%
7	UNIFE	95%	14%	50%	79.1%	83.7%	85.4%	86.8%	91.3%	93.4%	94.1%	94.7%
8	UNIFE	95%	0%	19%	76.5%	81.9%	83.9%	85.6%	83.0%	87.6%	89.2%	90.7%

Table 9 – Final RR and RRR rates achieved in the different scenarios according to the described boundary conditions. Case 1: ISO22628 calculation on the four scenarios. Case 2: UNIFE calculation on the four scenarios. Case 3: UNIFE calculation, on the hypothesis of 50% ERF for ASR. Case 4: UNIFE calculation, on the hypothesis of 0% MRF for ASR. Case 5 to 8: same hypotheses of case 1 to 4, additional hypothesis being 95% dismantling rate for non-metal parts (e.g. due to destructive dismantling).

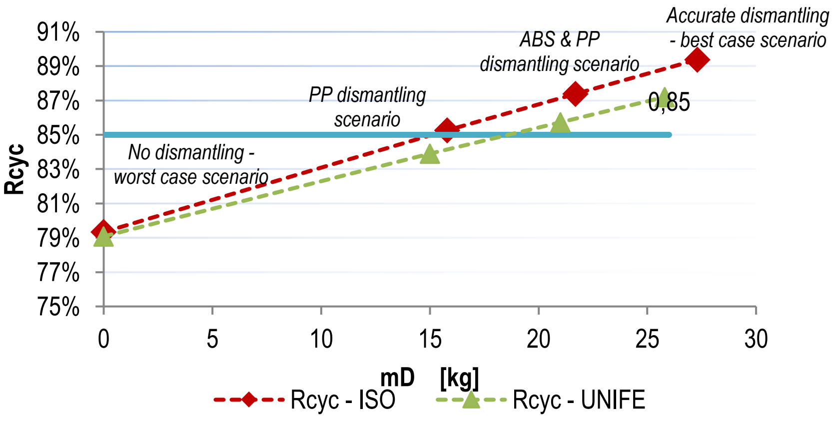

Figure 8 – RR rate in the four analyzed EoL scenarios, according with the different methodologies applied. Buondary conditions applied: 95% dismantling rate for plastic parts, standard UNIFE MRF and ERF factors for the ASR (case 5 and 6 in Table 7).

Looking at ISO22628 results, the RR rate changes significantly depending on the scenario considered. No dismantling intervention (scenario 1) produces a RR rate of 79.5%, while the hypothesis of dismantling only the PP components appears to be sufficient to comply with the 85% limit required by EoL Directive. In the cases of the scenario 3, where PP and ABS components are disassembled, and in the scenario 4, where an accurate dismantling phase has been hypothesized, the RR rate significantly exceeds the 85% limit, respectively being 87.4% and 89.4%. Figure 9 illustrates material flow for the different phases for the scenario 3 under the adoption of ISO22628 method.

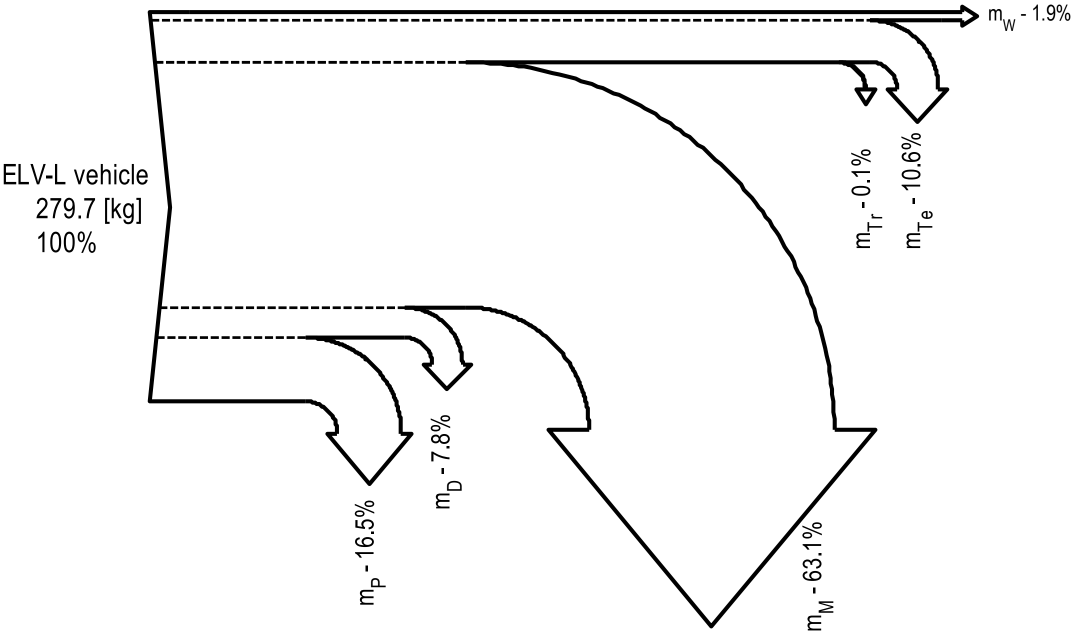

Figure 9 – Sankey diagram illustrating EoL material flow for the case study – method adopted: ISO22628, scenario PP+ABS dismantling. Masses corresponds to the symbols introduced in Table 5.

Looking at the Pareto chart in Figure 10, if the disassembly is conducted without breaking the plastic bodywork components, the target of RR=85% is obtained removing only the first n° 30 heaviest PP and ABS components (graphically, this scenario corresponds with the point of intersection between the green curve with the horizontal blue line). However, the experience suggests that a partially destructive dismantling can occur in certain ATFs. Such case is modeled assuming that 95% of material for each part is effectively removed, while 5% remains on the vehicle frame, thus becoming ASR after shredding. With this additional hypothesis, it is necessary to consider an higher number of PP and ABS components in order to achieve to the same Recyclability value.

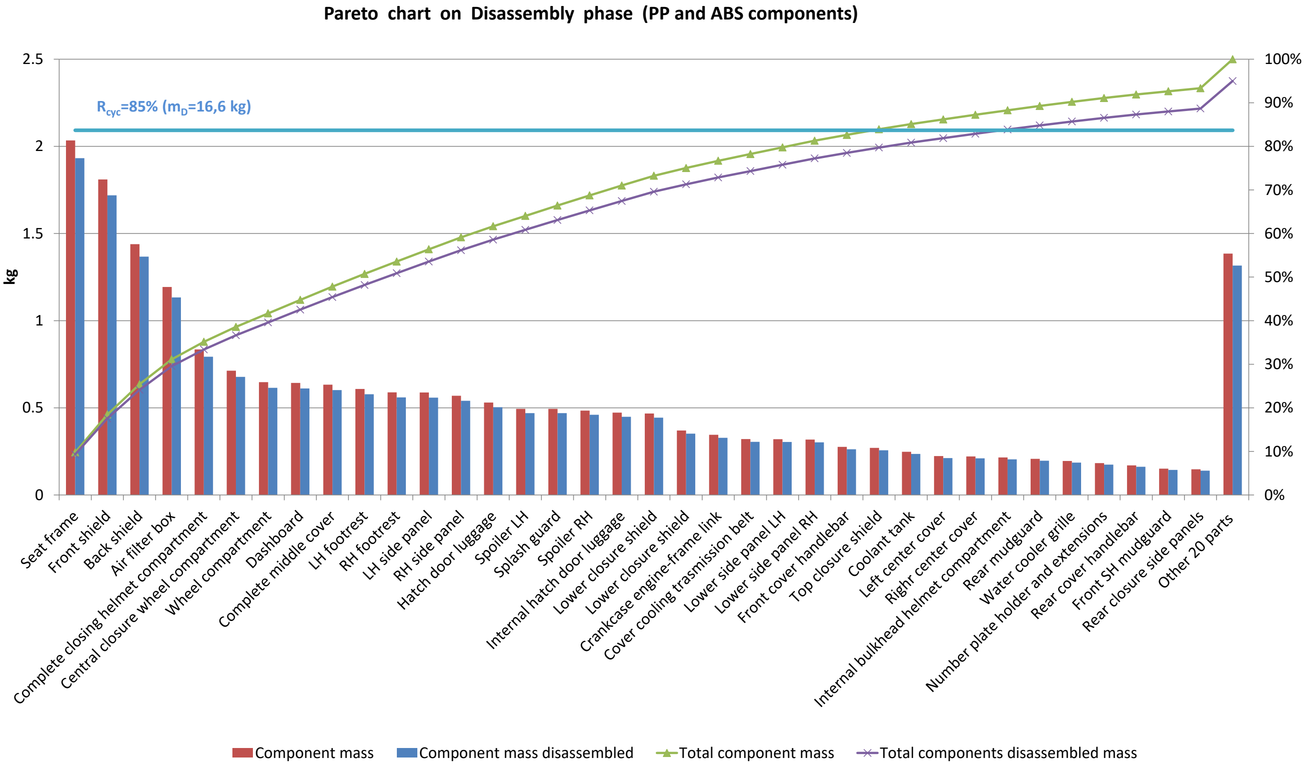

Figure 10 – List of all ABS and PP components suitable for dismantling (scenario 2, 3 and 4), showing their singular mass and the cumulated dismantled one. The plot include the minimum value to be reached for 85% RR rate using the ISO22628 approach (corresponding to at least 16.6 kg of dismantled plastic) and the effect of the application of a 95% effective dismantling rate.

The RRR rate remains constant in each scenario, equal to 98%, and thus satisfying the limit of 95% required by the 2000/53/EC Directive. An explanation is needed for such result. As already observed describing ISO22628 methodology, the RRR value is based on the material *potentially* recoverable, so that any organic material not considered in m_D and m_{Tr} is in any case included in m_{Te}; the sum of the three is constant. The same applies to metal materials; those parts not included in m_D are in any case included in m_M. Since m_P is unambiguously determined by the prescription, the final result is that RRR value does not depend on the treatment applied.

Such result are in line with those achieved by the products subjected to Directive 2000/53/EC and demonstrates that the vehicle can already satisfy 3R requirements provided for M1 and N1 classes. The analysis of all the vehicle components showed that even if Recyclability is not a legally binding target for this vehicle, the good prescriptions usually applied in automotive production to encourage recycling are respected, and in particular:

- most components are marked with the symbol or the acronym of the constituting material, that is fundamental to recognize and trace recyclable ones
- the number of polymeric families used in the vehicle are quite low, and most parts are made using PP and ABS, that can be recycled

- parts potentially containing hazardous materials can be separated quite easily, mainly being represented by the electronic components and electric accumulators.

The analysis, however, still suggests that the application of further Design for EoL criteria is necessary to increase the opportunities for recycling. Even if no criticalities emerged, a few improvement opportunities arised. In particular:

- a certain separation effort is necessary to dismantle from the bodywork panels those additional parts which are built using different polymers, e.g. the elastomer protectors linked to the PP footboard
- despite of the fact that most part are directly accessible for disassembly, a few components with relevant mass are not recommended for dismantling due the complexity of the operation. That is the case of helmet and luggage vane which is collocated under the seat; thus, even if its constituting material is recyclable, this part was excluded for disassembly, since it is not compatible with the time restrictions related to normal ATFs activities
- the number of different polymers and of their coatings used in the vehicle should be further reduced; the vehicle, however, already shows a remarkable homogeneity
- the participation to the IDIS platform, originally developed by the automotive industry to meet the legal obligations of the 2000/53/EC Directive; IDIS can be used to suggest to the operators the treatments to be performed on the basis of manufacturers know-how; this is mainly aimed to:
    - ensure that all the hazardous components are removed on the pretreatment phase, e.g. highlighting the presence of fluid in the shock adsorbers
    - identify the components, particularly the plastic ones, which have be to be dismantled to achieve the RR target with reasonable labor.

The collection of fluid from shock absorbers is time consuming and is often neglected from ATFs. Such practice, even if related to insufficient treatment rather than to manufacturer choice, should be discouraged, e.g. through proper component marking. However, sealed shock absorbers are used also on vehicle already subjected to 2000/53/EC, so that the three wheeler is, again, in line with those vehicle currently subjected to mandatory 3R targets.

The application of the UNIFE method leads to significantly lower RR rates. Considering that a market for secondary raw materials coming from plastic scraps are quite consolidated only for a few polymers (e.g. the painted PP constituting the bodywork can be treated together with bumpers coming from M1 and N1 vehicles), at the current moment the scenario 3 (which suggests the dismantling of PP and ABS parts) is likely to be the most feasible. In this case, the effective value estimated by the UNIFE method is slightly above the 85% limit, thus showing the feasibility of the achievement of the RR target even considering technological limitations. It should be noted, however, the relevant role of PST for ASR recycling: the modification of the MRF from 14% to 0% (a realistic scenario for current shredding facilities), in fact, implies that 85% target can be reached only in case of accurate dismantling.

Regarding the final RRR rate, the value assessed by the UNIFE method is significantly lower than the ISO22628 one and in general below the 95% target. The difference is due to the unfavourable MRF and ERF factors (14% and 19%, respectively) used for those parts which are not dismantled from the vehicle and are supposed to be recovered through ASR treatment. In case that more efficient PST techniques will be introduced, a value of 95% could be achievable; in the proposed example, an ERF of 50% could lead to an RRR value in line with the target considering the unit approximation (i.e., 94.9% is 95%). However, it cannot be said, on the basis of the present work, if the ERF has to be limited due to technological factors (i.e., new technologies could reach the needed 50% factor) or due to unavoidable limitations (i.e., the limit is related to the characteristics of the materials and 50% ERF is physically unfeasible). To respond to such question, a shredding trial of the three wheeler together with other L-class vehicles (similar three wheelers, two wheelers, scooters etc.) and a tailored ASR characterization would be needed.

It should be noted that the ELV-L under study, even if not currently subjected to the whole requirements of 2000/53/EC Directive, is designed in a way which enables the achievement of promising RR and RRR rates, so that according to the current automotive reference standard ISO22628 the target for 2015 can be fully satisfied. The consequence is that the mixing of the scraps coming from ELV-L with the ones coming from M1 and N1 ELVs does not modify significantly the overall recycling results, for which the M1 and N1 ELVs are certified.

5 - Conclusions

Market forecasts regarding urban mobility alternatives suggest that an increasing relevance of L-class vehicles in the European circulating fleet is possible. Main cause for such interest is based on the need for new personal and urban mobility solutions in the context of European and worldwide cities. However, the European ELV Directive does not set 3R objectives for most L-category vehicles. Not surprisingly, recycling programs are consolidated on those countries where L-vehicles are sold in relevant numbers, especially in Asian area.

The present study aims at estimate the EoL performances of one L-vehicle and has been conducted on the Piaggio MP3 125 Hybrid. It has been chosen due to the fact that it represents a niche market segment with a relevant potential for increase in the next years; the vehicle technology is also innovative and it is a candidate as personal urban mobility solution in the context of vehicle electrification. The analysis has been developed not only according to regulation-related standards, but also taking into account actual EoL issues. As a first assumption, former experiences have been used to define a proper EoL treatment for ELV-L category, the process being structured similarly to the one applied on full-size M1 and N1 vehicles. Two methods for the assessment of 3R performances have been chosen and compared, the first one being the ISO22628 standard, suitable for automotive products, and the second one being the UNIFE method. This latter is supposed to be used on the basis of voluntary agreements by railway manufacturers; it introduces effective Recyclability/Recoverability factors (MRF and ERF). Various hypotheses have been proposed, leading to four main dismantling scenarios.

The vehicle has been dismantled, obtaining a detailed inventory. The first results of the study is a full material breakdown which highlights the predominance of metallic materials, the value being above 70%, similarly to other regulated automotive products. The study showed that the vehicle is capable of satisfactory EoL performances. Precautions such as material marking permits the correct identification of all the components during dismantling and, in general, limited criticalities have been noted.

The analysis of the vehicle, according to the unavoidable arbitrariness of the existing methodologies, highlights that it can fully comply with the dictates of the Directive and with the type approval necessities if analyzed using ISO22628. In particular, the extensive use of PP suggests a possible market interest for the plastic scraps; in addition, the dismantling of the bodywork is also sufficient to achieve the 85% RR result, and higher values are obtained in case of favorable scenario.

Since the performances of the recycling system in each Country are evaluated on the basis of final scraps and ASR products, the adoption of a method which uses loss factors based on experience enhances the quality of preliminary calculation of RR and RRR rates. According to such observation, the use of the UNIFE methodology highlights that, even if it is still possible to achieve a satisfactory RR rate, the actual Recyclability differs from the theoretically calculated one, discrepancy being about 2% for typical scenarios. The analysis suggests that the ATFs should dismantle both PP and ABS parts (the most used plastics in the vehicle) in order to achieve an effective 85% RR rate. The UNIFE RR rate is further reduced adopting additional, restrictive hypotheses. In such case, the target of 85% can be reached only in case that considerable effort is spent for the accurate dismantling on the vehicle. However, average values are not far from the threshold, since RR rate below 82% are obtained only in case of improper treatment by ATFs (worst case scenario).

Regarding the RRR rates, the discrepancy between ISO22628 and UNIFE estimations is wider in comparison with RR rate. According to the first method, RRR rate overpasses 98% in every scenario, since the method itself is not able to estimate the sensitiveness of the results on the treatment variation. The UNIFE estimation, on the contrary, defines an upper limit that reduce the realistic, achievable value on the edge of 95%. The difference between ISO22628 and UNIFE RRR rate ranges from 3% to 15%, depending on the considered scenario.

It is not possible, in the present study, to determine if such limit can be overpassed improving the technology of the treatment or if it is unfeasible in any case. Such observation confirms that further work is necessary to verify MRF and ERF values and to improve the confidence on preliminary RR and RRR calculations. In particular, batteries and inverters are critical components for HEVs; further study is necessary to assess their Recyclability with dedicated factors rather than using average ones for electrical parts. MRF and ERF specific for context of application should be investigated through applied research, since such parameters are related not only to the component material but also to the technological level of demanufacturing operations.

From a manufacturer' point of view, the study demonstrates that the vehicle under study – structured as a plastic bodywork over metallic frame and adopting an hybrid powertrain - is able to achieve EoL performances which are comparable to conventional M1 and N1 vehicles if ISO22628 method is used. Good practices such as material marking and prevalent use of certain polymers are already adopted for the considered case study. Future work should examine the EoL performances of a range of L-class vehicles to confirm that the category, on average, is able to satisfy the requirements of Directive 2000/53/EC; on field trial for the production and examination of ASR should be performed. Since the ISO22628 leaves to the Manufacturer the responsibility to identify the available recycling technologies, the use of the UNIFE method or of similar ones represents a valuable information source, but it implies lower 3R results.

From an Authority point of view, two evidence arise: the limitations of the assessment method and the occurrence of physical 3R limitations, that is an open topic in literature. If UNIFE method is used, it is confirmed that current RR and RRR targets are approaching physical limitations. This point has many significant implications for future policy planning, main one being that the definition of eventual new EoL thresholds could be ineffective from a practical point of view if up-to-date assessment methods are not provided. The generic indications of the ISO22628, in fact, lead to a lack of sensitiveness in terms of the estimation of 3R results, an issue that is not depending on the class of the ELV. It is therefore possible that the 3R assessments using ISO22628 are based on the masses addressed to recycling and recovery rather than on those effectively valorized or discarded. The study estimates the potential discrepancy between theoretical assessment and practice and confirms that improved methods based on factors are able to catch the sensitiveness to the quality of the treatment.

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