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Original Citation:

End-of-Life in the railway sector: Analysis of recyclability and recoverability for different vehicle case studies / Delogu, Massimo; Del Pero, Francesco; Berzi, Lorenzo; Pierini, Marco; Bonaffini, Davide. - In: WASTE MANAGEMENT. - ISSN 0956-053X. - ELETTRONICO. - 60:(2017), pp. 439-450. [10.1016/j.wasman.2016.09.034]

Availability:

The webpage https://hdl.handle.net/2158/1057541 of the repository was last updated on 2020-11-06T18:48:23Z

Published version:

DOI: 10.1016/j.wasman.2016.09.034

End-of-Life in the railway sector: analysis of recoverability and recyclability for different vehicle case studies

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ABSTRACT

The railway system represents one of the most resource-efficient answer to our ever-growing demand for transport service and the development trends for the following years forecast a substantial increase in this sector. Considering the European Union, rolling stock realizes a significant share of both goods and passengers carriage while it is responsible for a derisory quota of environmental impact and energy consumption involved by transportation. Contrary to the low environmental impact, the amount of End-of-Life (EoL) waste generated by rolling stocks in relation to the number of vehicles is notable, much greater than in the case of road vehicles. As railway vehicles are built from many heterogeneous components, the EoL rolling stock is a precious source of materials, whose recycling brings measurable economic benefits and needs to be appropriately debated. The paper performs the calculation of recoverability/recyclability rate for different typologies of representative railway vehicles on the basis of primary data and according to the recyclability and recoverability calculation method issued by UNIFE in the context of Product category Rules (PCR). The typologies of railway vehicles taken into account are electric metro, diesel commuter train and high-speed electric train. The analysis envisages also to repeat the calculation in case innovative materials and manufacturing technologies are adopted in the construction of car-body structure. Results show that recyclability/recoverability rates are abundantly over the quota of 90% for each one of the three trains, these latter being made in major part of metals which benefit from very efficient recovery processes. The adoption of innovative materials and manufacturing technologies for car-body structure involves a scarce reduction of recyclability and recoverability rates (about 2% and 0.2% respectively) due to the introduction of components and materials characterized by critical dismantlability and low efficiency recovery processes; recoverability results less affected by lightweighting because post-shredding thermal recovery treatments are roughly independent with respect to dismantlability. A sensitivity analysis based on different dismantling scenarios reveals that the effectiveness of dismantling has a moderate influence on recyclability/recoverability rate (the variation does not exceed 3%). The low variability of recyclability/recoverability rate can be explained by the following reasons: material composition of trains shows a predominance of metals; the efficiency of metals separation processes is close to 100%; post-shredding recycling processes of metals are characterized by recovery factors equal to the ones of post-dismantling recycling processes.

Keywords:

Train, Railway, Rolling stock, Recyclability, Recoverability, End-of-Life, Dismantling

Highlights:

Overview on railway vehicles End-of-Life;

Assessment of recyclability and recoverability for three trains representative of current railway vehicle categories "urban, high-speed and commuter" within European area;

Recyclability and recoverability rate of railway vehicles are abundantly over the quota of 90%;

The introduction of innovative materials and manufacturing technologies involves a scarce reduction of recyclability and recoverability rate;

Contrary to the automotive context, design for dismantling has a negligible influence on recyclability and recoverability of railway vehicles.

1. Introduction

Our global society is strongly dependent on transportation with development trends indicating a substantial growth in this sector over the coming decades (Hawkins at al., 2012). Currently the transportation industry is the second largest contributor to anthropogenic GreenHouse Gas (GHG) emissions within the European Union and around 20% of these emissions are generated by road transportation (Witik et al., 2011; Solomon et al., 2007). More specifically light-duty vehicles ownership could increase from roughly 700 million to 2 billion over the period 2000-2050 (World Business Council for Sustainable Development, 2004), forecasting a dramatic increase in fuel demand with inevitable implications on energy security, climate change and urban air quality (Hawkins at al., 2012).

To date, environmental analyses and eco-design solutions have been applied in depth to all Life-Cycle (LC) stages of automotive vehicles and components (Berzi et al., 2013, 2016; Cappelli et al., 2007; Delogu et al., 2015; Mayyas et al., 2012). In this context, many Life Cycle Assessments (LCAs) (Chanaron, 2007; Finnveden et al., 2009; ISO 14040, 2006; ISO 14044, 2006) of both conventional (Finkbeiner et al., 2006; Schmidt et al., 2004; Spielmann and Althaus, 2006) and innovative (Alves et al., 2010; Du JD et al., 2010; Duflou et al., 2009; Luz et al., 2010; Mayyas et al., 2011; Vinodh and Jayakrishna, 2011; Zah et al., 2006, Zanchi et. Al., 2106) alternatives for personal transportation have been performed. On the other hand, less interest has been paid to the transportation by railway. Considering the European Union (EU-28), rail transport contributes for 11% of the goods carriage and 8% for passengers one (European Commission, 2015); in absolute terms the total number of passenger vehicles is slightly lower than 100.000 while it exceeds 400.000 for the goods wagons. Despite the notable significance of railway in the global pictures of transportation, rolling stock (both passengers and freight) is responsible for merely 0.6% of Green-House Gas emissions (GHG) and 2% of energy consumption in transport (Merkisz-Guranowska et al., 2014; Stodolsky et al., 1998; Rozycki et al., 2003; Chester et al., 2009; Chester and Horvath, 2010). Contrary to the low environmental impact of railway transport with respect to other transport modes, the amount of End-of-Life (EoL) waste generated by rolling stocks in relation to the number of vehicles is notable; to give an example of this, it is much greater (1-2 order of magnitude higher) than in the case of road vehicles. This is confirmed by Merkisz-Guranowska et al., (2014) who state that the disposal of a passenger railcar in terms of weight of the obtained waste corresponds to the same of 36-42 passenger vehicles. As railway vehicles are built from many components which include ferrous and non-ferrous metals, elastomers, polymers, glass, fluids, modified organic natural materials, compounds, electronics and electrics, the EoL rolling stock is a precious source of materials, whose recycling brings measurable economic benefits. The possibility to recover the highest amount of these materials presents two beneficial effects with respect to the environmental aspects: on one hand it involves the reduction of the demand for primary raw materials, on the other hand it reduces the environmental perils of improper management such as contamination of ground and ground waters with hazardous substances used for their production. Materials recover leads also notable economic benefits: reduction of costs involved by raw materials extraction, production, decrease of capital consumption/energy production and avoidance of expensive waste landfilling.

The objectives of the study are the following:

- providing an organic overview regarding the dismantling of EoL vehicles and related current practices in the railway sector;
- analyzing in detail methods and legal regulations currently adopted by railway vehicles manufacturers for calculating the recoverability rate of rolling stock;
- performing a comparison between recoverability/recyclability rate of different typologies of railway vehicles;
- assessing the effects on recoverability/recyclability that implementing innovative lightweight solutions have on different typologies of railway vehicles.

The paper is organized as follows. Section 2 reports an overview related to the EoL of railway vehicles in terms of contextualization of the problem (i.e. numbers of circulating vehicles and estimation of EoL numbers), treatment practices and guidelines, literature and studies in LCA and EPD perspective. The section 3 deals with the assessment of recoverability and recyclability rate of three representative railway vehicles according to the calculation method developed by European Rail Industry (UNIFE) in the context of Product category Rules (PCR). In section 4 the outcomes of the application are reported and discussed; the recyclability/recoverability rates are analyzed, the influence of lightweighting on recyclability/recoverability is treated and a sensitivity analysis for different dismantling scenarios is performed. Finally, concluding observations are presented.

2. Overview on railway vehicles End of Life

2.1 Estimation of circulating vehicles and expected EoL numbers

The estimation of the amount of waste materials and scraps related to railway sector is affected by a number of uncertainties due to the variability of the typology, the lack of precise statistics about vehicles going out-of-service and their mass. However, a rough estimation on the basis of available data and on authors' guess is exposed in Table 1, which demonstrates that the mass of railway vehicles to be scrapped is about one order of magnitude smaller than the mass of ELVs such as passenger cars, total amount being about 600000t, and therefore being quite a noticeable amount on European basis.

	Locomotives and railcars	**Passenger Transpor Vehicles**	**Goods Transpor Wagons**	**All railway vehicles**	**Passenger cars**
Circulating (number)	58054	96206	427236		204802250
Expected for EoL (number)	1935	3207	14241		6250000
Average Mass per unit (t)	60	40	25		1.03
Total Mass to be treated (t)	116108	128275	356030	600413	6460000
Data sources for circulating Railway vehicles: European Commission, 2015; referring to 2013 year.					
Data sources for mass of Railway vehicles and expected EoL numbers: Authors' guess based; lifespan based on 30 years					
Data sources for circulating and EoL masses of Passenger Road cars : Eurostat, 2016; referring to 2012 year.					

Table 1. Estimation of EoL masses for railway vehicles in comparison with passenger cars; all numbers are based on EU-28 countries data.

The order of magnitude is in line with former estimation provided in literature. Melo, 1999, describes train as responsible for 4% aluminum consumption in Germany, road vehicles being 75%, and it is one of the few examples of disaggregated data available in literature, since most data are still available by sector (Ciacci et al., 2013). Railway vehicles have been also recognized as a non-negligible source for Copper materials (Ruhrberg, 2006).

At the same time the municipalized companies around the world increasingly require that rolling stock manufacturers develop policies and methods for vehicles EoL management; the selection of materials and their recoverability are two key factors in order to implement such a typology of policies. Therefore, the low environmental footprint represents a necessary requirement in order to be competitive in the market and green policies are becoming a proper element of market strategy. At this regard manufacturers are taking environmental initiatives themselves without awaiting legal regulations: an example of this is represented by the development of rolling stock recycling standards from European Rail Industry (UNIFE), the association that gathers rail vehicles manufacturers and stakeholders.

2.2. EoL treatment practices and regulations

When a rolling stock reaches its EoL it should be treated to recover as much as possible its constituent materials and to minimize the overall environmental impact of this Life Cycle (LC) stage.

Most road End if Life Vehicles (ELVs) are treated in specific workshops called Authorized Treatment Facilities (ATFs), able to manage with waste treatment and storage (Simic, 2016). Regarding railway sector, it is not possible at the moment to identify if the EoL trains are treated in the same workshops where repair and maintenance occur, or in dedicated plants, or in generic scrapyards. Probably, all the alternatives coexist across Europe depending on the context and on local regulation.

The recycling process of a railway vehicle involves four typical steps:

- Pre-treatment;
- Dismantling;
- Metals separation;
- Treatment of non-metallic residues.

Pretreatment. The pretreatment is mainly determined by safety reasons and implies the removal from the vehicle of all the potentially harmful substances. During this step all toxic and explosive substances/gases which can be harmful to human and environment are removed and stored in appropriate containers. The average rolling stock contains an wide variety of operating fluids, including brake fluid, antifreeze, gear oil, etc. First of all, the rolling stock must be taken to a safe place which is suitable to perform the drainage and removal of all kinds of fluids. This operation is extremely critical because the accuracy of its execution affects the subsequent stages. In particular, an inappropriate pretreatment may involve the contamination of the environment by dangerous pollutants in the residue obtained after vehicle shredding. The extracted substances, materials and components usually need other treatment processes such as neutralization, reuse, recycling or recovery, depending on their characteristics; such operations are performed by specialized operators. Substances that are to be reused as spares are not drained. Materials, substances and parts like oil, fluids, batteries, fire extinguishers and catalytic capacitors are examples of components recommended to be handled in the pre-treatment stage.

Dismantling. At the dismantling step the components available for reuse and recycling are individually removed from vehicle along with materials and parts for material recycling. The objective of the dismantling stage is to extract as much material as possible from rolling stock before entering it into the shredding process. During dismantling, parts and materials are separated and sorted and then forwarded to dedicated recycling facilities where further segregation and processing take place. First of all, parts and components that are to be reused (i.e. bogies, bogie frames, wheel sets, couplings, buffers, springs, doors) are dismantled; some of them are directly installed on other vehicles without any modifications while the others need interventions in order to be suitable for reuse. In a subsequent stage parts and components that are to be recovered (i.e. windows, seats, floors, cables and electronic parts, Heating, Ventilation and Air Conditioning (HVAC) units) are dismantled; electronic parts should be handled as electronic and electrical scrap with specific treatment processes and sorting technologies. These parts and components are forwarded to specialized recycling facilities. All the elements that are not treated in the dismantling step are processed in the next phase, the shredding and metals separation.

The greater the amount of materials treated in the dismantling stage, the most effective the recycling process and the higher the recycling rate. On the other hand, the time used for dismantling the vehicle represents a key factor for the cost effectiveness of the entire operation. Therefore, a balance between effectiveness of recycling and time consuming must be found and components for which dismantling is particularly time-consuming are not dismantled.

Shredding and metals separation. After the pre-treatment and dismantling steps, the vehicle is mechanically treated sharing it in more parts and, where possible, baling it in pressed in order to reduce the space needed for its transport to other locations and to prepare it for the separation of specific materials. Later, the remaining parts and materials are forwarded to the shredding process, where the materials are milled and grinded into small pieces for further processing. After the shredding the small pieces are sorted into two different material fractions by using magnetic properties and eddy current separators. These material fractions are:

- Shredder Heavy Fraction (SHF), comprising pure ferrous materials (i.e. steel, iron and its alloys) and non-ferromagnetic materials (i.e. Aluminum, Copper, Brass);
- Shredder Light Fraction (SLF), a mix of different materials and substances such as plastics, fibers, glass, elastomers and residue.

Materials considered for the shredding process cannot be classified as reusable. SHF is treated to be recycled. SLF may be further segregated for recycling, combusted with energy recovery or at least landfilled. Technologies that enable sorting and using up to two thirds of the mass of the shredder residue exist (Krinke et al., 2006) but they are very rare; in practice large part of the remains after shredding is still landfilled (Cossu et al., 2014).

Treatment of non-metallic residues. With the exception of parts and components which are to be reused, all dismantled elements at the stage of dismantling are forwarded to specialized recycling facilities where they are treated with the use of appropriate technologies. Similarly, the materials separated in the shredding process are forwarded to recycling facilities.

Taking into account the existing regulations about EoL transportation vehicles, the issues of recycling have been legally regulated only for the road transport modes, both passenger cars and light duty trucks (European Parliament, 2000). Considering the railway sector, international authorities and national governments have not yet implemented any specific legislation. On the other hand both original equipment manufacturers are looking for more sustainable vehicles and special attention is paid to EoL environmental impact; this is mainly due to the demand expressed by their customers about environmental certification beyond the requirements of regulations. In confirmation of this, the existing actions related to recycling of rolling stock result from voluntary regulations as well as individual strategies realized by stakeholders. At the European level, the Association of the European Rail Industry (UNIFE) developed standards for recycling of EoL rolling stock vehicles; currently the reference guideline from UNIFE is the “Recyclability and Recoverability Calculation Method – Railway Rolling Stock” (UNIFE, 2013a). The method was defined by an expert committee within the development process of Product Category Rules (PCR) for railway vehicles (EPD Consortium, 2009; UNIFE, 2014). The aim of the PCR is representing a reference guideline for the OEMs in developing Environmental Product Declarations (EPD) of their vehicles according to the ISO 14025 standard. Representatives of the different parts of the rail transport sector (such as system integrators, rolling stock manufacturers, sub-system suppliers and operators) have took part in the development process (EPD Consortium, 2009) and some of the main OEMs worldwide have been involved (Alstom Transport, AnsaldoBreda – today Hitachi Rail Italy -, Bombardier Transportation, Siemens Mobility, Knorr-Bremse and Saft Batteries). The development of the UNIFE calculation method has been performed starting from ISO22628 (2002) for the automotive industry through an adaptation to the specificity of the rolling stock vehicles; therefore, it can be considered as an evolution of the ISO22628 standard. Similarly to the ISO22628, the UNIFE calculation method determines the recoverability/recyclability rate as the ratio between the masses of materials involved in the four typical EoL steps and the total mass of the vehicle; it has to be noted that the guideline specifies exclusively the calculation method without indicating the rates to be achieved. The element of innovation, with respect to the ISO22628, is the fact that the UNIFE standard takes into account various technological limitations through the definition of multipliers indexes for both material and energy recovery processes. Such indexes are defined for specific material classes and they take into account typical process losses, usually unavoidable due to thermodynamics and technological limits even in case of optimal material treatment. A description of main causes for the phenomena (e.g., cross contamination during material separation, slag formation during recycling, and overall quality loss) and the occurrence of such limitations is well known in literature (Froelich et al., 2007a; Graedel et al., 2011; Passarini et al., 2013). The aim of the formalization of loss factors focuses the approach on the calculation of realistically recoverability/recyclability rates instead of theoretical ones. Such an assessment is in accordance with the latest trends in the sector of preliminary recyclability assessment (Garcia et al., 2015) and it has also been applied in studies related to other kinds of durable goods, such as Waste Electrical and Electronic Equipment (WEEE; see Mizuno et al., 2012). A point of criticism that affects the method proposed by UNIFE is the limited knowledge of recovery/recycling processes that effectively are performed at vehicle EoL; more particularly, the selection of

- which parts are processed within the different EoL steps
- which typology of treatment has to be applied to the specific component and material

is performed through qualitative or arbitrary estimations (e.g., accessibility of the part and availability of recyclers on the local market) and, therefore, it is affected by a notable margin of uncertainty. Another element which introduces approximation is represented by the efficiency indexes of recovery/recycling processes. The coefficients proposed by the UNIFE method are representative of current technological context in Europe; however, these factors vary depending on the local context in which the item is supposed to be dismantled (Mizuno et al., 2012) and, therefore, it is not excluded that an update could be necessary depending on the area of application and on the technological improvement in next years. The knowledge of technological contexts (Camanes et al., 2014) and the implications for the definition of design guidelines (Froelich et al., 2007b) are, in general, delegated to the manufacturer itself (Millet et al., 2012) of assessment methods.

As it was highlighted above, the application of the method proposed by UNIFE is currently not mandatory according to the legislation; in contrast, it is adopted by several rolling stock manufacturers on a voluntary basis for determining the recovery/recycling indexes of their vehicles.

2.3. EoL of railway vehicles in LCA and EPD perspective

Starting from the work by Vandermeulen et al., 2003, the estimation of Possible Material Recycling (PMR) coming from trains has been suggested as one of the indicators representative of environmental performance, potentially being a driver since vehicle design phase. However, a methodology for PMR assessment was not described in the study. Other existing works examine EoL topics related to the railway sector mainly focusing on specific case studies, without proposing general methods to be applied as guidelines for the sector. As an example, focusing on issues related to stainless steel vehicles (Matsuoka, 2003), or on composite materials (Lee et al., 2010), or on material degradation analyses for specific components (Ito and Nagai, 2008, 2007). No studies dealing with on-board electric and electronic devices, which are quite critical in trains, have been found, while the topic is gaining interest and is currently under study for road vehicles (Barwood et al., 2015; Cucchiella et al., 2016).

Merkisz-Guranowska et al. (2014) is one of the few literature works that deals with the EoL treatment of railway vehicles from a general and multi comprehensive point of view. The authors describe the rules related to the EoL treatment and the procedure for the disposal of rolling stock. Despite there are no regulations related to the recovery and recycling in the railway sector, the paper states that rolling stock manufacturers and its users should support the European policy on waste management; in this context they list a plethora of examples of such actions based on social responsibility and possible economic benefits. The recovery rate of selected rail vehicles as declared by the manufacturers is also presented.

Literature provides also some Life Cycle Assessment (LCA) studies of railway vehicles. In this case EoL does not represent the focus of the study but it is assessed as part of an holistic approach including also the other stages of vehicle LC, (i.e. production and use). All these studies show that for a rolling stock the use stage is definitely the greatest contributor to environmental impacts while the EoL involves a minimal portion of it (Stodolsky et al., 1998; Struckl and Wimmer, 2007; Rozycki et al., 2003; Chester et al., 2009, 2013; Chester and Horvath, 2009, 2010, 2012). To give an example of this, Del Pero et al. (2015) presents a LCA of a heavy metro train for operation in the urban area of Rome. The study assesses all LC stages of the vehicle (production, use and EoL) basing on a broad range of impacts to human and ecosystem health and includes also a predictive analysis of recyclability/recoverability at EoL according to ISO 22628 (2002). The authors show that:

- the use stage is largely the most influential stage for its high energy intensity with respect to the other stages (for the Global Warming Potential – GWP - the use amounts to almost 85% of total impact);
- production is on the whole the second most influential stage based on resource consumption and emissions during raw materials extraction (for Abiotic Depletion Potential elements – ADPe - it amounts to 68% of total, while for GWP it does not exceed 7%);
- the impacts associated with EoL are low compared to the other stages (definitely under the quota of 10% for all the considered impact categories).
- the projected recyclability and recoverability rates amount respectively to 87.4% and 92.1%.

A sensitivity analysis of the LCA results stresses the influence of vehicle occupancy on electricity consumption during operation and the overall outcomes. The authors identify major improvement potential in the reduction of use stage electricity consumption; at this scope the key recommendations are the decrease of vehicle mass by application of lightweight materials and the improvement of efficiency of the heating system.

Considering the non-scientific field, recently great attention was paid to the development of Environmental Product Declarations (EPDs) (International EPD System, 2013a) in the railway sector. An EPD is a certified environmental declaration based on LCA in accordance with the ISO 14040 standards (ISO 14040, 2006). More specifically, ISO 14025 (2010) defines EPD as “quantified environmental data for a product with preset categories of parameters, but not excluding additional environmental information”. The interest in environmental declarations can be explained by the continuously growing demand from customers and public authorities for sustainability policies and initiatives; at this regard it can be stated that ecological modes are becoming a method to gain competitive advantage and an important element of market strategy. In this perspective worldwide manufacturers deal with LCA analyses in order to collect data for EPDs of their vehicles. To date, examples of published EPDs exist for a large variety of vehicles like trams, metros, regional and intercity trains (AnsaldoBreda, 2010, 2011; Bombardier, 2010a, 2010b, 2010c, 2012a, 2012b; CAF Construcciones y Auxiliar de Ferrocarriles, 2011a, 2011b; SIEMENS, 2005).

In conclusion, the State of the Art (SoA) analysis regarding railway vehicles EoL leads to the following considerations:

- Merkisz-Guranowska et al. (2014) describes the rules related to the EoL railway vehicles and the procedure of the disposal of rolling stock. On the other hand a few papers perform the LCA of rolling stock. In these cases the EoL is not assessed singularly but it is evaluated at the same level of other stages of vehicle LC; the contribution of EoL to vehicle impact is evaluated and compared to the one of other stages;
- the existing studies simply present the legal regulations concerning the EoL of rolling stock and the actions undertaken by the producers. In particular, no study calculates itself the recovery rate of EoL railway vehicles on the basis of legal regulations and using primary data.

In the light of critical analysis of existing literature regarding rolling stock EoL, the objectives of the study are the following:

- providing an organic overview regarding the dismantling of EoL vehicles and related current practices in the railway sector;
- analyzing in detail methods and legal regulations currently adopted by railway vehicles manufacturers for calculating the recoverability rate of rolling stock;
- performing a comparison between recoverability/recyclability rate of different typologies of rolling stock;
- assessing the effects on recoverability/recyclability that implementing innovative lightweight solutions have on different typologies of railway vehicles.

3. Calculation of recoverability and recyclability rate of three representative railway vehicles

In the section it is presented the calculation of recoverability/recyclability rate for different typologies of railway vehicles on the basis of affordable data directly provided by an OEM and according to the recyclability and recoverability calculation method issued by UNIFE in the context of Product category Rules (PCR) (UNIFE, 2013). The typologies of railway vehicles taken into account are the following: electric metro for urban mobility; an intercity diesel train and an high-speed electric train. The calculation of recyclability/recoverability rate is performed also in case innovative materials and manufacturing technologies are involved in realization of car-body structure.

3.1. Calculation method

The calculation of recyclability and recoverability rate is based on the guideline proposed by UNIFE “Recyclability and Recoverability Calculation Method - Railway Rolling Stock” (UNIFE, 2013). As recyclability is influenced by many factors (such as availability of EoL processes/technologies and time/cost for dismantling) that strongly vary over time and life-span of a railway vehicle normally lasts some decades, it is not possible to give an accurate figure of EoL processes. In the light of these considerations, the calculation of Recyclability/Recoverability Rate (RRR) is performed adopting the following assumptions regarding materials and EoL treatments:

- for each material category prescribed by UNIFE (2013) the percentage by mass involved in each EoL process is determined by the mean value of the intervals proposed in Appendix B “General material recycling figures and common EoL treatment methods” of PCR 1.0. (International EPD System, 2009); for each material class a percentage on a mass basis is proposed by analyzing in detail dismantlability and peculiarities of each component. By way of example, within the family of thermoplastic polymers the intended use of each material class (Polypropylene, Polyethylene, Polycarbonate, etc) is examined and quantities associated to not-removable components (i.e. sealants, coatings and paints) are not included in the recoverability rate.

- efficiency of recycling/recovery processes is assumed from PCR 2.0. (International EPD System, 2013b) which refers to UNIFE (2013).

For the calculation of recyclability/recoverability rate as well as mass of material destined to landfilling, following relations, based on the method proposed by UNIFE (2013), are used:

$$R_{cyc_i} = \frac{\sum\left(m_{P_i} * MRF_{P_i} + m_{D_i} * MRF_{D_i} + m_{M_i} * MRF_{M_i} + m_{T_i} * MRF_{T_i}\right)}{m_V}$$

$$R_{cov_i} = \frac{\sum\left(m_{P_i}\ (MRF_{P_i} + ERF_{P_i}) + m_{D_i}\left(MRF_{D_i} + ERF_{D_i}\right) + m_{M_i}\left(MRF_{M_i} + ERF_{M_i}\right) + m_{T_i}\ (MRF_{T_i} + ERF_{T_i})\ \right)}{m_V}$$

$$m_L = m_V - \left(\frac{\sum\left(m_{P_i}\ (MRF_{P_i} + ERF_{P_i}) + m_{D_i}\left(MRF_{D_i} + ERF_{D_i}\right) + m_{M_i}\left(MRF_{M_i} + ERF_{M_i}\right) + m_{T_i}\ (MRF_{T_i} + ERF_{T_i})\ \right)}{100}\right)$$

Where:
R_{cyc} = recyclability rate of the vehicle [%];
R_{cov} = recoverability rate of the vehicle [%];
m_P = mass of material taken into account at the pre-treatment [kg];
m_D = mass of material taken into account at the dismantling [kg];
m_M = mass of material taken into account at the shredding and metals separation [kg];
m_T = mass of material taken into account at the treatment of non-metallic residue [kg];
m_L = mass of material destined to landfilling [kg];
m_V = total mass of the vehicle [kg];
MRF = Mass Recovery Factor [%];
ERF = Energy Recovery Factor [%];
i = material subscript;
P, D, M, T = EoL treatments subscript.

Figure 1 illustrates the rail vehicle EoL treatment steps as prescribed by UNIFE (2013).

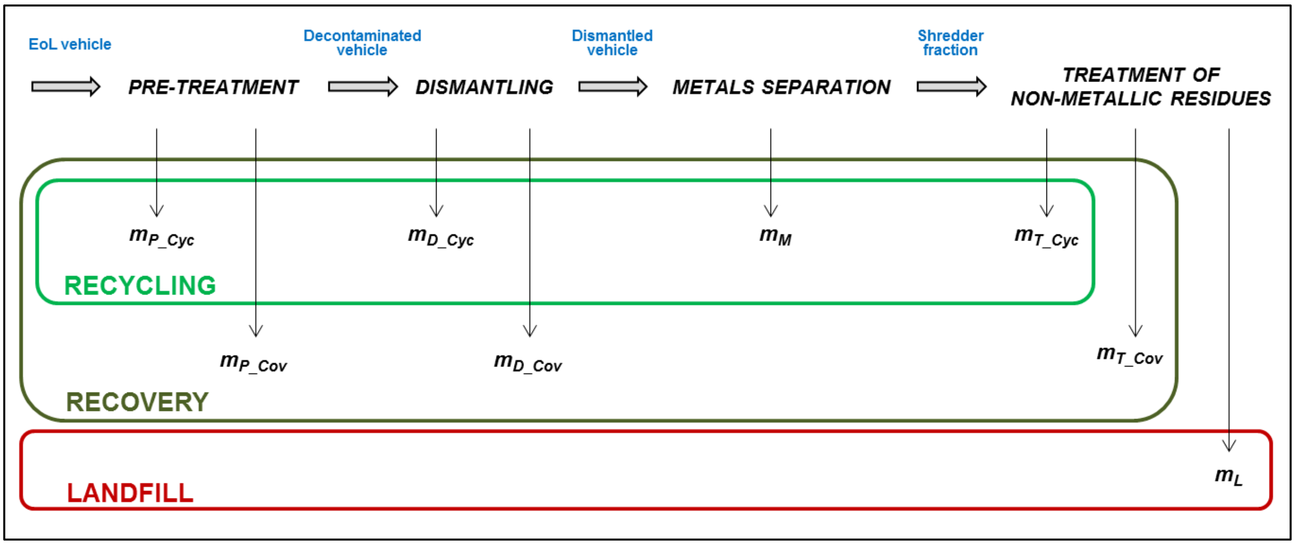


Figure 1. Rail vehicle end-of-life treatment steps

Table 2 sums up the resulting set of percentages regarding mass allocation to EoL treatments and partial masses assumed in the study.

	UNIFE material category	**Allocation to EoL treatments [% in mass]**				**Recovery factor [%]**		
			MetroRomaC	**ETR1000**	**IC4**	**Mass (MRF)**	**Energy (ERF)**	**Total**
Metals	1. Fe metals	Dismantling (m_D)	0	0	0	98.0	0.0	100.0
		Metals separation (m_M)	100	100	100	98.0	0.0	100.0
	2. Non-Fe metals	Dismantling (m_D)	0	0	0	98.0	0.0	100.0
		Metals separation (m_M)	100	100	100	98.0	0.0	100.0
Polymers	3. Thermoplastics (GF)	Dismantling (m_D)	48	46	48	100.0	0.0	100.0
		Treatment of non-metallic residues (m_T)	52	54	52	14.0	19.0	33.0
	4. Thermoplastics (GF)	Dismantling (m_D)	59	60	60	66.7	33.3	100
		Treatment of non-metallic residues (m_T)	41	40	40	14.0	19.0	33.0
	5. Thermosets (unfilled)	Dismantling (m_D)	12	9	40	100.0	0.0	100.0
		Treatment of non-metallic residues (m_T)	88	91	60	14.0	19.0	33.0
	6. Thermosets (GF)	Dismantling (m_D)	60	60	60	66.7	33.3	100.0
		Treatment of non-metallic residues (m_T)	40	40	40	14.0	19.0	33.0
	7. Carbon or natural fiber reinforced polymers	Dismantling (m_D)	14	40	40	66.7	33.3	100.0
		Treatment of non-metallic residues (m_T)	76	60	60	14.0	19.0	33.0
Elastomers	8. Elastomers	Dismantling (m_D)	65	64	61	80.0	20.0	100.0
		Treatment of non-metallic residues (m_T)	35	36	39	14.0	19.0	33.0
Glass	9. Glass	Dismantling (m_D)	100	100	0	100.0	0.0	100.0
		Treatment of non-metallic residues (m_T)	0	0	100	0.0	0.0	0.0
	10. Safety glass	Dismantling (m_D)	89	94	94	94.0	0.0	94.0
		Treatment of non-metallic residues (m_T)	11	6	6	0.0	0.0	0.0
Fluids	11. Oil, grease	Pre-treatment (m_P)	0	0	0	0.0	100.0	100.0
		Treatment of non-metallic residues (m_T)	100	100	100	14.0	19.0	33.0
	12. Acids and cooling	Pre-treatment (m_P)	50	79	83	0.0	83.0	83.0
		Treatment of non-metallic residues (m_T)	50	21	17	14.0	19.0	33.0
MONM	13. MONM	Dismantling (m_D)	94	38	57	95.0	5.0	100.0
		Treatment of non-metallic residues (m_T)	6	62	43	14.0	19.0	33.0
Electrics / Electronics	14. Electrics / Electronics	Dismantling (m_D)	54	79	79	79.0	19.0	98.0
		Treatment of non-metallic residues (m_T)	46	21	21	14.0	19.0	33.0
Ceramics / Mineral wood	15. Ceramics	Dismantling (m_D)	15	37	43	43.0	0.0	43.0
		Treatment of non-metallic residues (m_T)	85	23	57	14.0	19.0	33.0
	16. Mineral wool	Dismantling (m_D)	0	0	0	97.0	0.0	97.0
		Treatment of non-metallic residues (m_T)	100	100	100	14.0	19.0	33.0

Table 2. Mass allocation to EoL partial masses and recovery factors for EoL treatments

3.2. Description of case studies

The calculation of recyclability and recoverability rate is performed for three vehicles manufactured by AnsaldoBreda (Today HRI – Hitachi Rail Italy):

- MetroRomaC: electric heavy metro train belonging to the passenger transportation category “Urban – High passenger capacity” (EPD System, 2013b);
- ETR1000: electric high-speed train belonging to the passenger transportation category “ High speed – Direct main city connections” (EPD System, 2013b);
- IC4: diesel commuter train belonging to the passenger transportation category “Regional – Mainline service” (EPD System, 2013b).

These trains have been chosen as reference because they are representative of current railway vehicle categories “urban, high-speed and commuter” within the European area, both in terms of technical features and fulfilled service. Table 3 summarizes the main technical/operational features of the three trains; in particular, the allocation of mass between vehicle systems is illustrated.

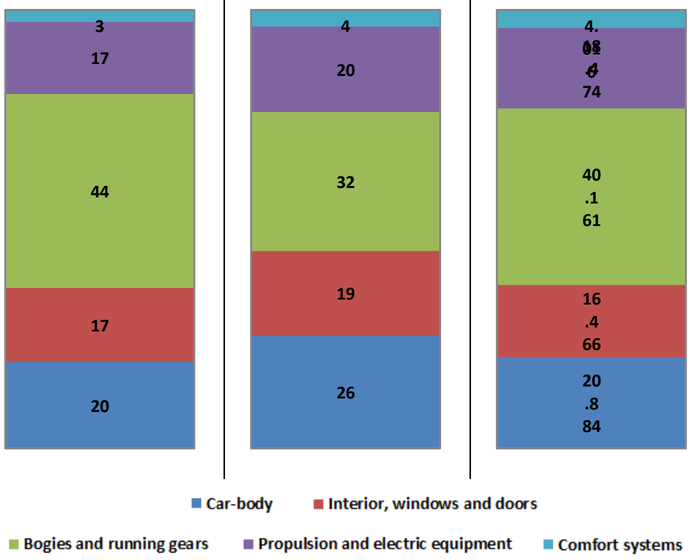
		MetroRomaC	**ETR1000**	**IC4**
N° coaches		6	8	4
Total length [m]		110	202	86
Width [m]		2.85	2.92	3.15
Max seated passenger		194	471	124
Traction		Electric	Electric	Diesel
Max. speed [km/h]		90	360	160
Mass	Car-body [t]	37.0	116.9	52.2
	Interior, windows and doors [t]	32.2	87.8	41.3
	Bogies and running gears [t]	84.8	143.4	100.4
	Propulsion and electric equipment [t]	30.9	88.5	46.1
	Comfort systems [t]	5.0	17.0	10.5
	Total [t]	189.9	453.6	249.7
	Contribution analysis by PG [%]			

Table 3. Main technical and operational features of vehicles

For each vehicle the calculation of RRR is performed for two distinct scenarios with respect to car-body design:

- Reference car-body: standard configuration of the train (Aluminum car-body);
- Lightweight car-body: substitution of aluminum car-body by full composite one, with a carbon fiber epoxy aluminum honeycomb sandwich structure and a stainless steel under-frame. This represents an ideal and extreme solution for the future, where all-metallic frame would be unnecessary.

Considering the switch from reference to lightweight car-body scenario, the comparative LCA and LCC study performed by Castella et al. (2009) on different design alternatives for car-bodies of the Korean Tilting Train eXpress (TTX) project is assumed as reference. More specifically aluminum car-body and full composite car-body scenarios are assumed as reference for:

- materials substitution in the switch from reference to lightweight scenario;
- percent mass reduction achieved through the lightweight scenario;
- percent mass allocation to materials in the lightweight scenario.

Table 4 reports materials and their composition for the two design alternatives assumed from Castella et al. (2009).

	Materials and material composition for the car-body of TTX project (source: Castella et al. 2009)			
	Aluminum car-body scenario		Full composite car-body scenario	
	Mass [t]	Share of total mass [%]	Mass [t]	Share of total mass [%]
Aluminum	9.0	100.0	0.4	5.0
Stainless steel	0.0	0.0	5.3	70.0
Carbon Fiber Reinforced Plastic (CFRP)	0.0	0.0	1.7	22.0
Bondex	0.0	0.0	0.2	3.0
Total	**9.0**	**100.0**	**7.6**	**100.0**

Table 4. Materials and material composition for the two design alternatives assumed from Castella et al. (2009)

Table 5 reports the resulting material composition for MetroRomaC, ETR1000 and IC4 (both reference and lightweight scenarios).

	Material composition of car-body											
	MetroRomaC				ETR1000				IC4			
	Reference car-body		Lightweight car-body		Reference car-body		Lightweight car-body		Reference car-body		Lightweight car-body	
	Mass [t]	Share of total mass [%]	Mass [t]	Share of total mass [%]	Mass [t]	Share of total mass [%]	Mass [t]	Share of total mass [%]	Mass [t]	Share of total mass [%]	Mass [t]	Share of total mass [%]
Aluminum	32.4	100	1.4	5.0	111.5	100	4.4	5.0	34.6	100	1.5	5.0
Stainless steel	0.0	0.0	19.1	69.7	0.0	0.0	61.3	69.7	0.0	0	20.4	69.7
Carbon Fiber Reinforced Plastic (CFRP)	0.0	0.0	6.1	22.3	0.0	0.0	19.7	22.4	0.0	0	6.5	22.4
Bondex	0.0	0.0	0.8	3.0	0.0	0.0	2.5	2.9	0.0	0	0.8	2.9
Total	**32.4**	**100**	**27.3**	**100**	**104.1**	**100**	**87.9**	**100**	**34.6**	**100**	**29.2**	**100**

Table 5. Main technical and operational features of vehicles

4. Results and discussions

Following tables report the results of the study:

- Table 6: material composition of the trains with respect to material classes prescribed by UNIFE (2013);
- Table 7: Recyclability (R_{cyc}) and Recoverability (R_{cov}) Rate of the trains.

		Material composition [t]					
		MetroRomaC		**ETR1000**		**IC4**	
	UNIFE material class	**Reference car-body**	**Lightweight car-body**	**Reference car-body**	**Lightweight car-body**	**Reference car-body**	**Lightweight car-body**
Metals	1. Fe-metals	96.7	115.8	215.9	273.9	72.6	92.6
	2. Non-Fe metals	70.2	39.2	169.4	69.7	58.1	25.0
Polymers	3. Thermoplastics (unfilled)	2.3	2.3	7.9	7.9	3.0	3.0
	4. Thermoplastics (glass filled)	0.6	0.1	0.8	0.8	0.0	0.0
	5. Thermosets (unfilled)	0.1	0.9	3.5	6.1	1.1	1.1
	6. Thermosets (glass filled)	0.3	0.2	0.6	0.6	0.8	0.8
	7. Carbon or natural fiber reinforced polymers	0.0	6.6	3.3	23.0	1.7	8.2
Elastomers	8. Elastomers	7.1	7.1	12.5	12.5	7.0	4.7
Glass	9. Glass	3.2	3.2	7.5	7.5	0.0	0.0
	10. Safety glass	0.6	0.6	2.2	2.2	4.5	4.5
Fluids	11. Oil, grease or similar	2.0	2.0	1.4	1.4	3.5	3.5
	12. Acids and cooling agents or similar	2.6	2.6	4.3	4.3	1.1	1.1
MONM	13. Modified Organic Natural Materials (MONM)	2.6	2.6	5.6	5.6	2.4	2.4
Electrics	14. Electric/Electronic	0.7	0.8	9.6	9.6	0.6	0.6
Ceramics	15. Ceramics	0.6	0.5	8.5	8.5	0.1	0.1
	16. Mineral wool	0.0	0.0	0.0	0.0	0.0	0.0

Table 6. Material composition of the vehicles with respect to material classes prescribed by UNIFE (2013)

	Recyclability and Recoverability rate (R_{cyc}, R_{cov}) [%]					
	MetroRomaC		**ETR1000**		**IC4**	
	Reference car-body	**Lightweight car-body**	**Reference car-body**	**Lightweight car-body**	**Reference car-body**	**Lightweight car-body**
Recyclability rate (R_{cyc})	93.6	92.3	92.7	90.9	91.9	90.9
Recoverability rate (R_{cov})	95.2	95.1	94.5	94.4	95.1	94.9

Table 7. Recyclability and Recoverability rates (R_{cyc} and R_{cov}) of the vehicles

4.1. Analysis of recyclability/recoverability rate

RRRs of the three vehicles are abundantly over the quota of 90% for both the reference and lightweight scenarios. This is primarily due to the fact that material composition of the trains is definitely metals-oriented and metals are characterized by high efficiency recycling and recovery EoL processes. On the other hand plastics and polymeric materials, whose recycling/recovery processes present a relatively low efficiency, constitute a minority share of total. Figure 2 reports mass allocation for the three vehicles: metals represent a quota of at least 80% on a mass basis (the minimum is 83.5% for IC4) followed by elastomers, polymers and glass.

Despite the three trains are destined to different transport modalities (urban, intercity and long distance-high speed), the variability of R_{cyc} and R_{cov} is limited (within 2% for $\mathrm{R_{cyc}}$ and 1% for $\mathrm{R_{cov}}$). The highest RRR concerns MetroRomaC. This fact is explainable through

- the higher quota represented by metallic materials
- the lower quota represented by plastics and polymeric materials

with respect to the other vehicles. Indeed, as a metro-train is destined to an intensive mass transport that envisages also the presence of standing passengers, the quota represented by interior fittings, acoustic insulations, paneling and seats is lower, making metals more influential.

Compared to automotive vehicles, rolling stocks present a definitely higher recyclability rate, as a common value for the recyclability index of an automobile is 85%. Once again the reason lies in the material composition: against a metals content of about 85% for railway vehicles, cars present a lower metallic quota. More specifically plastics and polymers constitute a not negligible percentage of total car weight (Vermeleun et al. (2011) states that cars on average are made of about 15% by polymeric materials, including elastomers) and such a typology of materials is characterized by a definitely lower efficiency of recycling EoL processes in comparison to metals.

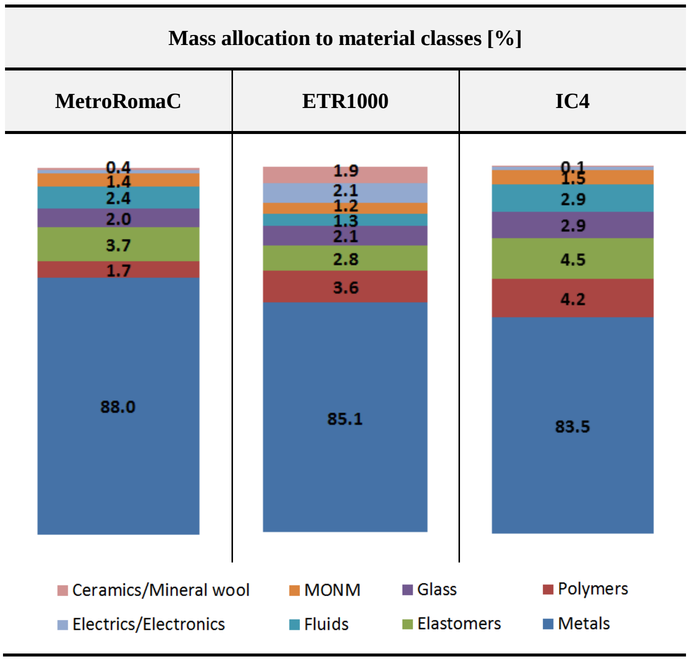


Figure 2. Mass allocation to material classes for MetroRomaC, ETR1000 and IC4

4.2. Influence of lightweighting on recyclability/recoverability

Figure 3 highlights the influence of lightweighting on recyclability/recoverability by reporting the percent variation of R_{cyc} and R_{cov}. For all the vehicles the change of car-body materials involves a reduction of both recyclability and recoverability rate. The higher decrease is for R_{cyc} (1.4., 1.9. and 2.1% respectively for MetroRomaC, ETR1000 and IC4) while for R_{cov} it does not exceed 0.2%. The higher influence on recyclability is due to the fact that lightweighting involves the introduction of materials whose dismantlability appears to be very critical, as they are integrated within the car-body structure without being easily accessible. Another element that contributes to lower R_{cyc} is the fact that material recovery factor of CFRP is definitely lower with respect to the one of metals. Otherwise, the recoverability is less affected by lightweighting, as post-shredding thermal recovery treatments are roughly independent with respect to dismantlability.

On the other hand the negative influence that lightweighting has on recyclability is counterbalanced by the energy saving during operation achievable through mass reduction. Indeed, basing on a simplified estimation of energy reduction by lightweighting from Castella et al. 2009 (10% mass reduction involves a 5.2% energy consumption reduction), the amount of energy saving offered by lightweight scenario is about 2%. As a train is long lasting (usually the life-time amounts to some decades) and it travels tens of millions kilometers before EoL, a 2% reduction in use stage consumption leads to saving a great amount of energy. Considering for instance that the ETR1000 has an expected LC mileage of 12.500.000 km and it consumes about 19 kWh/km (average estimation on different routes), a 2% consumption reduction leads to a total LC energy saving of approximately 4500 MWh.

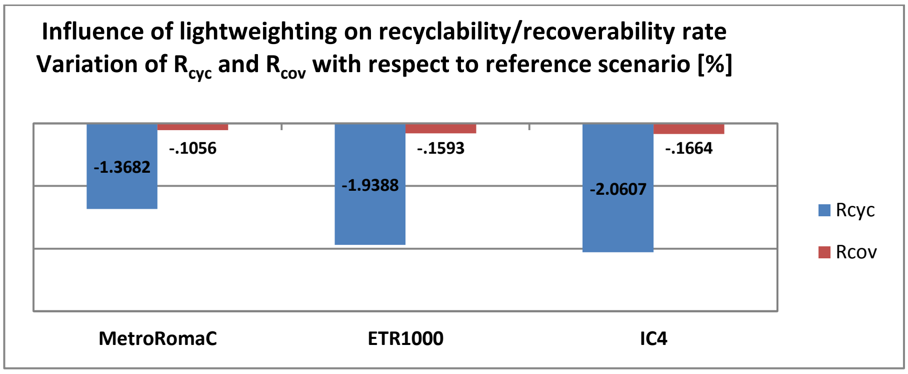


Figure 3. Influence of lightweighting on recyclability/recoverability rate - Variation of R_{cyc} and R_{cov} with respect to reference scenario for MetroRomaC, ETR1000 and IC4

4.3. Sensitivity analysis

Rolling stocks EoL processes are characterized by a high arbitrary which involves a not-negligible margin of inaccuracy in quantifying R_{cyc} and R_{cov}; this is primarily due to the fact that, contrary to the automotive context, in the railway sector

- specific EoL regulations
- a dedicated network of train dismantlers

do not exist. In the light of the previous considerations, this section analyzes the influence that the effectiveness of dismantling has on recyclability/recoverability rate. At this scope the calculation of R_{cyc} and R_{cov} is repeated for two additional dismantling scenarios, Deep and Light, where, for each material category, a respectively higher and lower value for the percent allocation to dismantling process is assumed with respect to the reference scenario.

Table 8 reports the allocation to EoL treatments of each material classes for MetroRomaC, ETR1000 and IC4.

	UNIFE material category	**Allocation to EoL treatments**		
		EoL treatment	**Deep dismantling [% in mass]**	**Light dismantling [% in mass]**
Metals	1. Fe metals	Dismantling (m_D)	0	20
		Metals separation (m_M)	100	80
	2. Non-Fe metals	Dismantling (m_D)	0	20
		Metals separation (m_M)	100	80
Polymers	3. Thermoplastics (unfilled)	Dismantling (m_D)	30	80
		Treatment of non-metallic residues (m_T)	70	20
	4. Thermoplastics (glass filled)	Dismantling (m_D)	30	80
		Treatment of non-metallic residues (m_T)	70	20
	5. Thermosets (unfilled)	Dismantling (m_D)	30	80
		Treatment of non-metallic residues (m_T)	70	20
	6. Thermosets (glass filled)	Dismantling (m_D)	30	80
		Treatment of non-metallic residues (m_T)	70	20
	7. Carbon or natural fiber reinforced polymers	Dismantling (m_D)	30	80
		Treatment of non-metallic residues (m_T)	70	20
Elastomers	8. Elastomers	Dismantling (m_D)	30	80
		Treatment of non-metallic residues (m_T)	70	20
Glass	9. Glass	Dismantling (m_D)	50	95
		Treatment of non-metallic residues (m_T)	50	5
	10. Safety glass	Dismantling (m_D)	50	95
		Treatment of non-metallic residues (m_T)	50	5
Fluids	11. Oil, grease	Pre-treatment (m_P)	50	100
		Treatment of non-metallic residues (m_T)	50	0
	12. Acids and cooling	Pre-treatment (m_P)	50	100
		Treatment of non-metallic residues (m_T)	50	0
MONM	13. MONM	Dismantling (m_D)	30	50
		Treatment of non-metallic residues (m_T)	70	50
Electrics / Electronics	14. Electrics/Electronics	Dismantling (m_D)	0	0
		Treatment of non-metallic residues (m_T)	100	100
Ceramics / Mineral wood	15. Ceramics	Dismantling (m_D)	0	30
		Treatment of non-metallic residues (m_T)	100	70
	16. Mineral wool	Dismantling (m_D)	60	85
		Treatment of non-metallic residues (m_T)	40	15

Table 8. Allocation to EoL treatments for deep and light dismantling of MetroRomaC, ETR1000 and IC4 materials

Figure 4 reports R_{cyc} and R_{cov} of the three trains for light, reference and deep dismantling scenarios. As expected, the higher value refers to deep dismantling scenario followed by reference and light ones. However, the influence that the effectiveness of dismantling has on recyclability/recoverability rate is moderate; compared to the reference scenario, the variation of

- R_{cyc} does not exceed +0.7% and –3.4%
- R_{cov} does not exceed +1.2% and –3.2%

respectively for deep and light dismantling scenarios. The low variability of recyclability/recoverability rate can be explained by following points:

- contrary to road vehicles, rolling stocks are constituted by a major part of metals (about 85% on a mass basis);
- the efficiency of metals separation processes is close to 100%;
- post-shredding recycling processes of metals based on magnetic separation of ferrous and non-ferrous materials, followed by further selection such as shacking tables segregation, are available technologies, even if

further improvements are still possible (Joardo et al., 2016; Passarini 2012). Metal recovery factors for shredded and dismantled parts are equal (for both post-shredding and post-dismantling recycling processes MRF and ERF amount to 98%, see Table 1).

In conclusion, it can be stated that the implementation of advanced Design-for-Dismantling in the railway sector has a lower potential to enhance recyclability/recoverability with respect to the automotive context. On the other hand in case of introduction of innovative lightweight materials (such as carbon fiber reinforced composites, see previous section), the effectiveness of dismantling assumes more relevance, as recovery factors of CFRP are definitely lower with respect to the ones of metals.

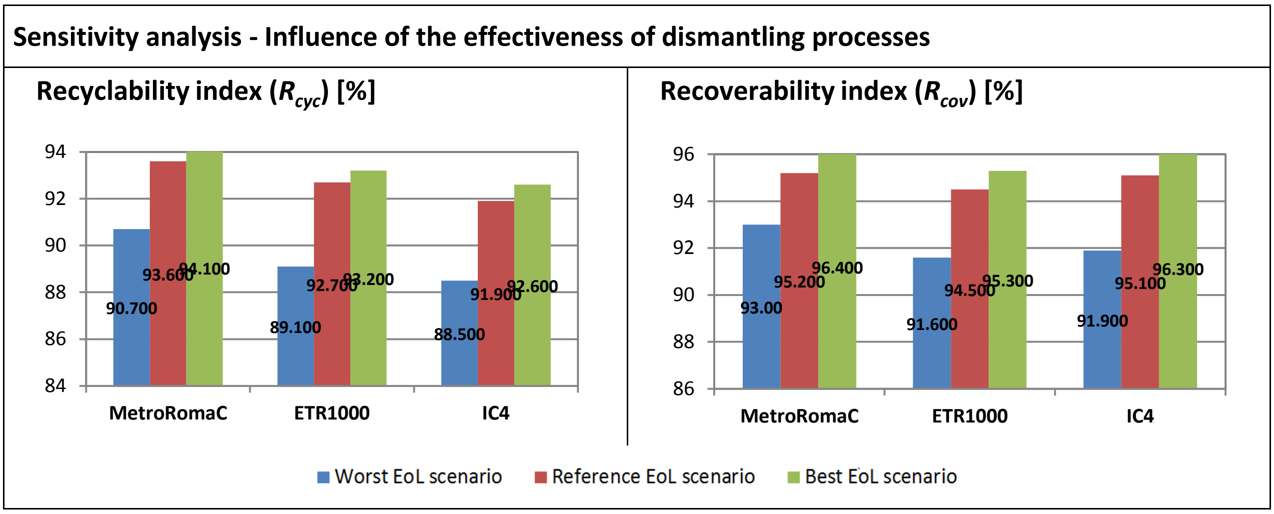


Figure 4. Sensitivity analysis – Influence of the effectiveness of dismantling processes

5. Conclusions

The present work performs an overview of EoL railway vehicles management issues and analyses the recoverability/recyclability rate for three typologies of railway vehicles (electric metro, diesel commuter train and electric high speed train electric train) taking into account different dismantlability and lightweighting scenarios (in case of adoption of innovative materials and manufacturing technologies for realization of car-body structure).

Results show that recyclability/recoverability rates of the three vehicles are abundantly over the quota of 90%; the analysis of material composition reveals that the high recyclability is due to the fact that trains are made in major part of metals, these latter being characterized by very efficient recycling/recovery processes. The introduction of innovative materials and manufacturing technologies for realizing car-body structure involves a scarce reduction of recyclability and recoverability rate (about 2% and 0.2% respectively). The higher reduction of R_{cov} is explainable by the introduction of materials whose dismantlability appears to be very critical since they are integrated within the car-body structure; additionally CFRP is characterized by a lower material recovery factor definitely lower with respect to metals. On the other hand, the recoverability is less affected by lightweighting, as post-shredding thermal recovery treatments are roughly independent with respect to dismantlability.

Sensitivity analysis based on different dismantling scenarios reveals that the effectiveness of dismantling has a moderate influence on recyclability/recoverability rate (the variation does not exceed 3%). The low variability of recyclability/recoverability rate can be explained by the metal predominant composition of trains, related high efficiency of separation and post-shredding recycling processes, characterized by recovery factors equal to the ones of post-dismantling recycling processes.

ACKNOWLEDGEMENTS

The authors would like to thank AnsaldoBreda – today Hitachi Rail Italy - for the cooperation and for the fruitful contributions provided to the study.

Bibliography

Alves, C., Ferrao, P.M.C., Silva, A.J., Reis, L.G., Freitas, M., Rodrigues, L.B., Alves, D.E., 2010. Ecodesign of automotive components making use of natural jute fibre composites. J Clean. Prod. 18.

AnsaldoBreda, 2010. MetroBrescia Environmental Product Declaration (EPD).

AnsaldoBreda, 2011. MetroRomaC Environmental Product Declaration (EPD).

AnsaldoBreda, 2013 ETR 1000 Environmental Product Declaration (EPD)

Barwood, M., Li, J., Pringle, T., Rahimifard, S., 2015. Utilisation of Reconfigurable Recycling Systems for Improved Material Recovery from E-Waste. Procedia CIRP, The 22nd CIRP Conference on Life Cycle Engineering 29, 746-751. doi:10.1016/j.procir.2015.02.071

Berzi, L., Delogu, M., Giorgetti, A., Pierini, M., 2013. On field investigation and process modelling of end-of-life vehicles treatment in the context of Italian craft-type authorized treatment facilities. Waste Manag. 33 (4), 892-906.

Berzi, L., Delogu, M., Pierini, M., Romoli, F., 2016. Evaluation of the end-of-life performance of a hybrid scooter with the application of recyclability and recoverability assessment methods. Resources, Conservation and Recycling, 108, pp. 140-155. DOI: 10.1016/j.resconrec.2016.01.013.

Bombardier, 2010a. Innovia Art 200 Environmental Product Declaration (EPD).

Bombardier, 2010b. SPACIUM Environmental Product Declaration (EPD).

Bombardier, 2010c. Talent 2 Environmental Product Declaration (EPD).

Bombardier, 2012a. REGINA Intercity X55 Environmental Product Declaration (EPD).

Bombardier, 2012b. FLEXITY Outlook Environmental Product Declaration (EPD).

CAF Construcciones y auxiliar de Ferrocarriles S.A., 2011a. CIVITY - EMU for Friuli Venecia Giulia Region Environmental Product Declaration (EPD).

CAF Construcciones y auxiliar de Ferrocarriles S.A., 2011b. ZARAGOZA TRAM Environmental Product Declaration (EPD).

Camanes, V., Elduque, D., Javierre, C., Fernandez, A., 2014. The influence of difefrent recycling sceanrios on the mechanical design of an led weatherproof light fitting. Materials, 7, 5769-5788, http://doi.org/103390/ma7085769.

Cappelli, F., Delogu, M., Pierini, M., Schiavone, F., 2007. Design for disassembly: a methodology for identifying the optimal disassembly sequence. J. Industrial Eng. Des. 18 (6), 563-575.

Castella, P.S., Blanc, I., Ferrer, M.G., Ecabert, B., Wakeman, M., Manson, J.A., Emery, D., Han, S.H., Hong, J., Jolliet, O., 2009. Integrating life cycle costs and environemental impacts of composite rail car-bodies for a Korean train. Int J Life Cycle Assessment (2009) 14:429-442. DOI 10.1007/s11367-009-0096-2.

Chanaron, J.-J., 2007. Life cycle assessment practices: benchmarking selected European automobile manufacturers. Int. J. Prod. Lifecycle Manag. 2 (3), 290-311.

Chester, M.V., Horvath, A., Madanat, S., 2009. Comparison of life-cycle energy and emissions footprints of passenger transportation in metropolitan regions. Atmos. Environ. 44, 1071-1079.

Chester, M.V., Pincetl, S., Elizabeth, Z., Eisenstein, W., Matute, J., 2013. Infrastructures and automobile shifts: positioning transit to reduce life-cycle environmental impacts for urban sustainability goals. Environ. Res. Lett. 8.

Chester, M.V., Horvath, A., 2009. Environmental assessment of passenger transportation should include infrastructure and supply chains. Environ. Res. Lett. 4,024008.

Chester, M.V., Horvath, A., 2010. Life-cycle assessment of high-speed rail: the case of California. Environ. Res. Lett. 5, 014003.

Chester, M.V., Horvath, A., 2012. High-speed rail with emerging automobiles and aircraft can reduce environmental impacts in California's future. Environ. Res. Lett. 7.

Ciacci, L., Chen, W., Passarini, F., Eckelman, M., Vassura, I., Morselli, L., 2013. Historical evolution of anthropogenic aluminum stocks and flows in Italy. Resour. Conserv. Recycl. 72, 1-8. doi:10.1016/j.resconrec.2012.12.004.

Cossu, R., Fiore, S., Lai, T., Luciano, A., Mancini, G., Ruffino, B., Viotti, P., Zanetti, M.C., 2014. Review of Italian experience on automotive shredder residue characterization and management. Waste Manag., Industrial Waste 34, 1752-1762. doi:10.1016/j.wasman.2013.11.014.

Cucchiella, F., D'Adamo, I., Rosa, P., Terzi, S., 2016. Automotive printed circuit boards recycling: an economic analysis. J. Clean. Prod. 121, 130-141. doi:10.1016/j.jclepro.2015.09.122.

Delogu, M., Del Pero, F., Romoli, F., Pierini, M., 2015. Life cycle assessment of a plastic air intake manifold International Journal of Life Cycle Assessment, 20 (10), pp. 1429-1443. DOI: 10.1007/s11367-015-0946-z

Directive 2000/53/EC of the European Parliament and the Council of 18 September 2000 on end-of-life vehicles, Official Journal of the European Communities, no 269, 2000.

Du, J.D., Han, W.J., Peng, Y.H., Gu, C.C., 2010. Potential for reducing GHG emissions and energy consumption from implementing the aluminium intensive vehicle fleet in China. Energy 35 (12), 4671-4678.

Duflou, J.R., De Moor, J., Verpoest, I., Dewulf, W., 2009. Environmental impact analysis of composite use in car manufacturing. CIRP Ann. Manuf. Technol. 58, 9-12.

European Commission, 2015. Statistical pocketbook 2015 - Transport [WWW Document]. URL http://ec.europa.eu/transport/facts-fundings/statistics/pocketbook-2015_en.htm (accessed 2.1.16).

Eurostat, 2016. Transport Database - Eurostat [WWW Document]. URL http://ec.europa.eu/eurostat/web/transport/data/database (accessed 5.3.16).

Finkbeiner, M., Hoffmann, R., Ruhland, K., Liebhart, D., Stark, B., 2006. Application of life cycle assessment for the environmental certificate of the Mercedes-Benz S-class. Int. J. Life Cycle Assess. 11 (4), 240-246.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinee, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. J. Environ. Manag. 91, 1-21.

Froelich, D.; Haoues, N.; Leroy, Y. & Renard, H., 2007. Development of a new methodology to integrate ELV treatment limits into requirements for metal automotive part design Minerals Engineering, Selected papers from Material, Minerals & Metal Ecology '06, Cape Town, South Africa, November 2006, 20, 891-901.

Garcia, J., Millet, D., Tonnelier, P., 2015. A tool to evaluate the impacts of an innovation on a product's recyclability rate by adopting a modular approach: automotive sector application. Int. J. Veh. Des. 2015, 1-18.

Hawkins, T.R., Singh, B., Majeau-Bettez, G., Stromman, A.H., 2012. Comparative environmental life cycle assessment of conventional and electric vehicles. J. Industrial Ecol. 17 (1), 53-64.

International Environmental Product Declaration (EPD) System, 2009. Product Category Rules (PCR) for Preparing an EPD for Rail Vehicles Version 1.0. Available at: http://www.unife.org/uploads/PRC_Document.pdf.

International Environmental Product Declaration (EPD) System, 2013a. Website:http://www.environdec.com (accessed October 2013).

International Environmental Product Declaration (EPD) System, 2013b. Product Category Rules (PCR) for Preparing an EPD for Rail Vehicles Version 2.0. Available at: http://www.unife.org/uploads/Product_Category_Rules_Document_Rolling_stock_2_0_2012.pdf.

ISO 14025, 2010. Environmental Labels and Declarations e Type III Environmental Declarations e Principles and Procedures. Geneva, Switzerland.

ISO 14040/14044, 2006. Environmental Management - Life Cycle Assessment - Principals and Framework/Requirements and Guidelines. Geneva, Switzerland.

ISO 22628, 2002. Road Vehicles e Recyclability and Recoverability e Calculation Method. Geneva, Switzerland.

Ito, M., Nagai, K., 2008. Degradation issues of polymer materials used in railway field. Polym. Degrad. Stab. 93, 1723-1735. doi:10.1016/j.polymdegradstab.2008.07.011.

Ito, M., Nagai, K., 2007. Degradation behavior and application of recycled PVC sheet made of floor sheet for railway vehicle. Polym. Degrad. Stab. 92, 1692-1699. doi:10.1016/j.polymdegradstab.2007.06.005.

Jordão, H., Sousa, A.J., Carvalho, M.T., 2016. Optimization of wet shaking table process using response surface methodology applied to the separation of copper and aluminum from the fine fraction of shredder ELVs. Waste Management 48, 366–373. doi:10.1016/j.wasman.2015.10.006.

Lee, C.-K., Kim, Y.-K., Pruitichaiwiboon, P., Kim, J.-S., Lee, K.-M., Ju, C.-S., 2010. Assessing environmentally friendly recycling methods for composite bodies of railway rolling stock using life-cycle analysis. Transp. Res. Part Transp. Environ. 15, 197-203. doi:10.1016/j.trd.2010.02.001.

Luz, S., Caldeira-Pires, A., Ferrao, P.M.C., 2010. Environmental benefits of substituting talc by sugarcane bagasse fibers as reinforcement in polypropylene composites: ecodesign and LCA as strategy for automotive components. Resour. Conserv. Recycl. 54, 1135-1144.

Matsuoka, S., 2003. Recyclability of stainless steel railway vehicles. Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit 217, 279-284. doi:10.1243/095440903322712883.

Mayyas, A., Qattawi, A., Mayyas, A.R., Omar, M.A., 2011. Life cycle assessment-based selection for a sustainable lightweight body-in-white design. Energy 39, 412-425.

Mayyas, A., Qattawi, A., Omar, M., Shan, D., 2012. Design for sustainability in automotive industry: a comprehensive review. Renew. Sustain. Energy Rev. 16, 1845-1862.

Melo, M.T., 1999. Statistical analysis of metal scrap generation: the case of aluminium in Germany. Resour. Conserv. Recycl. 26, 91-113. doi:10.1016/S0921-3449(98)00077-9.

Merkisz-Guranowska, A., Merkisz, J., Jacyna, M., Stawecka, H., Wasiak, M., 2014. Recycling Guidelines of the Rolling Stock. Second International Conference on Railway Technology: Research, Development and Maintenance.

Millet, D., Yvars, P.-A., Tonnelier, P., 2012. A method for identifying the worst recycling case: Application on a range of vehicles in the automotive sector. Resour. Conserv. Recycl. 68, 1-13. doi:10.1016/j.resconrec.2012.07.002.

Mizuno, T., Kunii, E., Fukushige, S., Umeda, Y., 2012. Recyclability Evaluation of LCD TVs Based on End-of-Life Scenarios, in: Dornfeld, D.A., Linke, B.S. (Eds.), Leveraging Technology for a Sustainable World. Springer Berlin Heidelberg, pp. 179-183.

Passarini, F., Ciacci, L., Santini, A., Vassura, I., Morselli, L., 2013. Aluminium flows in vehicles: enhancing the recovery at end-of-life. J Mater Cycles Waste Manag 16, 39–45. doi:10.1007/s10163-013-0175-0.

Rozycki, C.V., Koeser, H., Schwarz, H., 2003. Ecology profile of the German high-speed rail passenger transport system, ICE. Int. J. Life Cycle Assess. 8 (2), 83-91.

Ruhrberg, M., 2006. Assessing the recycling efficiency of copper from end-of-life products in Western Europe. Resour. Conserv. Recycl. 48, 141-165. doi:10.1016/j.resconrec.2006.01.003.

Schmidt, W.P., Dahlqvist, E., Finkbeiner, M., Krinke, S., Lazzari, S., Oschmann, D., Pichon, S., Thiel, C., 2004. Life cycle assessment of lightweight and end-of-life scenarios for generic compact class passenger vehicles. Int. J. Life Cycle Assess. 9 (6), 405-416.

SIEMENS, 2005. Metro Oslo Environmental Product Declaration (EPD).

Simic, V., 2016. Interval-parameter chance-constraint programming model for end-of-life vehicles management under rigorous environmental regulations. Waste Manag. doi:10.1016/j.wasman.2016.03.044.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L., 2007. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge (UK).

Spielmann, M., Althaus, H.J., 2006. Can a prolonged use of a passenger car reduce environmental burdens? Life Cycle analysis of Swiss passenger cars. J Clean. Prod. 15 (11e12), 1122-1134.

Stodolsky, F., Gaines, L., Cuenca, R., Eberhardt, J.J., 1998. Lifecycle Analysis for Freight Transport. SAE Technical paper series.

Struckl, W., Wimmer, W., 2007. Green Line e Strategies for Environmentally Improved Railway Vehicles. In: Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses, pp. 77e82.

Union Des Industries Ferroviaires Eurpeennes (UNIFE), 2013. UNI LCA 001-Recyclability and Recoverability Calculation Method Railway Rolling Stock.

Union Des Industries Ferroviaires Eurpeennes (UNIFE), 2014. Website: http://www.unife.org/(accessed June 2014).

Vandermeulen, B., Dewulf, W., Duflou, J., Ander, Å., Zimmermann, T., 2003. The use of performance indicators for environmental assessment within the railway business: the RAVEL workbench prototype, a web-based tool. J. Clean. Prod. 11, 779-785. doi:10.1016/S0959-6526(02)00149-X.

Vermeulen, I., Van Caneghem, J., Block, C., Baeyens, J., Vandecasteele, C., 2011. Automotive shredder residue (ASR): Reviewing its production from end-of-life vehicles (ELVs) and its recycling, energy or chemicals' valorisation. Journal of Hazardous Materials 190, 8–27. doi:10.1016/j.jhazmat.2011.02.088.

Vinodh, S., Jayakrishna, K., 2011. Environmental impact minimisation in an automotive component using alternative materials and manufacturing processes. Mater. Des. 32 (10), 5082-5090.

Witik, R.A., Payet, J., Michaud, V., Ludwig, C., Manson, J.-A.E., 2011. Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. Composites 42 (11), 1694-1709.

World Business Council for Sustainable Development (WBCSD), 2004. Mobility 2030: Meeting the Challenges to Sustainability e the Sustainable Mobility Project.

Zanchi, L., Delogu, M., Ierides, M., Vasiliadis, H., 2016. Life Cycle Assessment and Life Cycle Costing as Supporting Tools for EVs Lightweight Design. Sustainable Design and Manufacturing, Vol. 52 of the series Smart Innovation, Systems and Technologies pp 335-348.