University of Birmingham
Research at Birmingham

A through-life evaluation of end-of-life rolling stocks considering asset recycling, an energy recovering, and financial benefit

Kaewunruen, Sakdirat; Rungskunroch, Panrawee; Jennings, De'Von

DOI:
10.1016/j.jclepro.2018.11.271

License:
Creative Commons: Attribution-NonCommercial-NoDerivs (CC BY-NC-ND)

Document Version
Peer reviewed version

Citation for published version (Harvard):
Kaewunruen, S, Rungskunroch, P & Jennings, DV 2019, 'A through-life evaluation of end-of-life rolling stocks considering asset recycling, an energy recovering, and financial benefit', *Journal of Cleaner Production*, vol. 212, pp. 1008-1024. https://doi.org/10.1016/j.jclepro.2018.11.271

Link to publication on Research at Birmingham portal

Publisher Rights Statement:
Checked for eligibility 28/11/2018

General rights
Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

•Users may freely distribute the URL that is used to identify this publication.
•Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
•User may use extracts from the document in line with the concept of ‘fair dealing’ under the Copyright, Designs and Patents Act 1988 (?)
•Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy
While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Download date: 23. Apr. 2024

A through-life evaluation of end-of-life rolling stocks considering asset recycling, an energy recovering, and financial benefit

Sakdirat Kaewunruen[a,]*, Panrawee Rungskunroch[b] and De'Von Jennings[c]

[a,b]*School of Civil Engineering, University of Birmingham, Birmingham B15 2TT, UK*
[c]*School of Civil and Environmental Engineering, University of California Irvine, CA, USA*

Abstract

According to a large number of end-of-life rolling stocks were left over landfill, appropriate waste management should start by properly understanding the components of rolling stocks to determine their remaining potential. This paper evaluates efficient and feasible approaches to recovering and recycling wasted rolling stocks. The emphasis is placed on three broad train types, consisting of freight train, passenger train, and High-Speed Rail (HSR). In this article, all compositions of the three types of rolling stock are studied, with the results of the recyclability and recoverability rates being used to inform their productive treatment at the end-of-life.

The distinctive point of this research is an analysis of compositions, materials, and the percentage of value adopted from the end-of-life rolling stocks. With respect to find out the recyclability (R_{cyc}) and recoverability (R_{cov}) rates on end-of-life rolling stock, the equations are adopted from ISO 22628:2002 document to estimate the feasibility and suitability of each component on the rolling stock for taking advantage from unused parts. By comparing the R_{cyc} and R_{cov} rates among three types of rolling stock at the end-of-life stage, the highest value of R_{cyc} showed at 92.8% from freight train where the highest value of R_{cov} represented at 12.5% from HSR. It was found that those rates relate to the main components on rolling stock, which contained diversely characteristic to be reusable, recyclable or recoverable materials. Finally, the two key recommendations for further design on rolling stocks are provided regarding the proper selection of materials and the method to enhance efficiency of recycling and recovering process.

Keywords: railway; rolling stocks; waste management; recyclability; recoverability; End-of-life.

---

1. Project in Recyclability and Recoverability of Rolling Stock

1.1. Introduction

Global warming is the larger issue that needs to be corporate achieved by many countries around the world. Due to a restriction limiting the increase in the world's temperature to a maximum of 2°C (35.6 F), compared with the pre-industrial era (Damm *et al.*, 2016; UNFCCC, 2016), the significant economic countries like the US or the EU28 should become leaders in limiting CO_2 emissions (Meinshausen *et al.*, 2015). Based on industry data, the highest level of pollutants was emitted in European countries, especially in the United Kingdom, Germany and Poland. Pollution has mainly come from manufacturing, human activities, household and farming activities.

Manufacturing was reported as the largest producer of pollutant emission; for example, Great Britain has 16 of the 100 top polluting plants, showing a high damage cost from air pollution. The UK government spends £9.5 to £15.5 billion a year in health and environmental damages. Also, in the case of power plant emissions, the production processes cost £19.8 to £24.1 billion and manufacturing combustion costs £6.9 to £18.1 billion a year (EEA, 2012). For human activities, which mostly include transportation, there are 700 million vehicles that are currently in use around the world and this number is predicted to increase to two billion vehicles by 2050 (Del Pero et al., 2015). In fact, automobiles are responsible for 20% of greenhouse gas emissions, whereas railways are only responsible for less than 0.6% but carry 11% of goods among European countries (Merkisz *et al.*, 2014). A large number of researchers have stated that carbon emissions have dramatically increased and, the global temperature has been predicted to rise by approximately 4.8°C (40.6 F) in the next century (Andrade and D'Agosto, 2016). As mentioned, human activities on transportation produce carbon dioxide into the atmosphere. For example, the average number of miles each person travels in the UK is 6,500 miles per year. And, the amount of CO_2, emitted by passenger trains was found to be 140.3 kg (309.3 lb) of carbon per passenger, whereas HSR trains emitted only 35.5 kg (78.3 lb) of carbon over equal distances (Department of transport, 2015; European commission, 2015; Eurostat, 2016).

Moreover, an improper management at the end-of-life rolling stock causes a significant amount of wastes more than other vehicles. It has been claimed that the end-of-life of a single cargo railcar produces waste equal to 16-20 passenger vehicles, and passenger railcars generated waste equivalent to 48-57 passenger vehicles (Merkisz *et al.*, 2014) The leftover wastes have been seriously issued across European countries. Smink (2007) stated that only 75 percentages of the end-of-life vehicles were recyclable metals. It meant that the rest of the end-of-life vehicles turning to be wasted in a landfill. Therefore, numerous campaigns have been launched for encouraging companies to recycle and reuse automotive wastes rather than leave them until the end of their life. It included the achievement to reduce the amount of carbon emission during operation.

Recycling processes must be applied in advance to the waste due to the majority proportion of materials of rolling stocks can be recovered and recycled (Silva and Kaewunruen, 2017; Kaewunruen and Lee, 2017). Moreover, there are many benefits of recycling rail vehicles, such as reduced cost of resources and the lower cost of production of recycled materials.

1.2. Objectives

There are four primary objectives of this paper. The first is to break down and compare some raw materials that could be recycled, reused or should be properly managed such as disposal, landfill and incineration. The second is to investigate the application of the raw materials in transportation construction. The third is to identify a method of calculations for the net present value (NPV) of rolling stock materials. The final objective is to discuss the life cycle of the waste materials (metal, plastic, and glass). The novelty part of this research is the intensive analysis of all components of the three types of rolling stock. It encourages reader genuinely understand the composing raw materials and the way to manage them after the end-of-life stage.

1.3. Paper Organisations

This article is organised as follows: In section 2 the fundamentals of the recycling and recovering process are explained, with the principal components of rolling stocks described. The background of recycling different materials and equations for calculating recyclability rate (R_{cyc}) and recovery rates (R_{cov}) are included. Section 3 contains methodology and component analysis of the three types of rolling stocks (freight, passenger, and HSR) and how to find the Material Recover Facility (MRF) and the Energy Recover Facility (ERF) values. Section 4 includes the results and a discussion of recyclability and recoverability rate. Lastly, section 5 provides conclusions and suggestions for further improvement and future research.

1.4. Term used

The word ‘rolling stock’ referred to a railway vehicle, which moves along a rail network. Nevertheless, the word ‘rolling stock components’ referred to the removed parts from operation and, they were sent to marshalled or dismantled process. Regarding to this study mentioned on three types of rolling stocks, the ‘freight train’ referred to the set of rolling stocks that contained with one internal combustion locomotive and one platform-type of wagons. The ‘passenger train’ referred to the set of rolling stocks that composed of one internal combustion locomotive and one platform passenger-carrying cars. The ‘High-speed train’ or ‘HSR’ referred to the rolling stocks, which mostly composed of lightweight materials and operated over the speed 250 km/hr (155.34 miles/hr).

2. Recycling and recovering process on end-of-life rolling stock

With respect to the regulation the road vehicles-recyclability and recoverability calculation method document or ISO22628:2002 document, it provides the recyclability and recoverability rates to be an international standard. The document refers to the methods to manage the wastes from any road vehicles; thus, it supposes to apply with the end-of-life rolling stock. It aims at measures on the mass fraction of vehicles on reuse, recycle, and recovery processes.

As illustrated in Fig. 1, the recyclability rate (R_{cyc}) is a measure of the percentage of total mass that can be used for the same purposes from wastes. Also, it includes re-use and recycling stages on the materials to be usable parts; in other words, the recyclability rate measures the fraction of total waste recycled and total wastes. Network Rail (2017) mentioned that there are wide ranges of recycled rail parts and rail infrastructure such as panlock, fishplate, pad, screw, and insulators. For instance, in Sol-Sánchez, Moreno-Navarro, and Rubio-Gámez (2014), the study on the method to reduce environment impact from the used of wastes tires under sleeper pads (USPs), which used to stiffness absorbing noise and vibration and modifying track from rail track.

With respect to the reuse stage on rolling stock, some parts of end-of-life rolling stock can be reused rather than replaced; therefore, the reuse stage should be firstly concerned for reducing the end-of-life rolling stock wastes. In term of the recoverability rate (R_{cov}), it is a measure of vehicle mass that can be converted into heat and energy forms. The apparently benefit of thermal energy recovery relates to reduce the CO_2 and various greenhouse gas emissions (Zhang, Worrell and Crijns-Graus, 2015). In conclude, only the recycling and recovering processes are the main focus of this paper, as there is not a practical method for recycling or reusing rolling stocks.

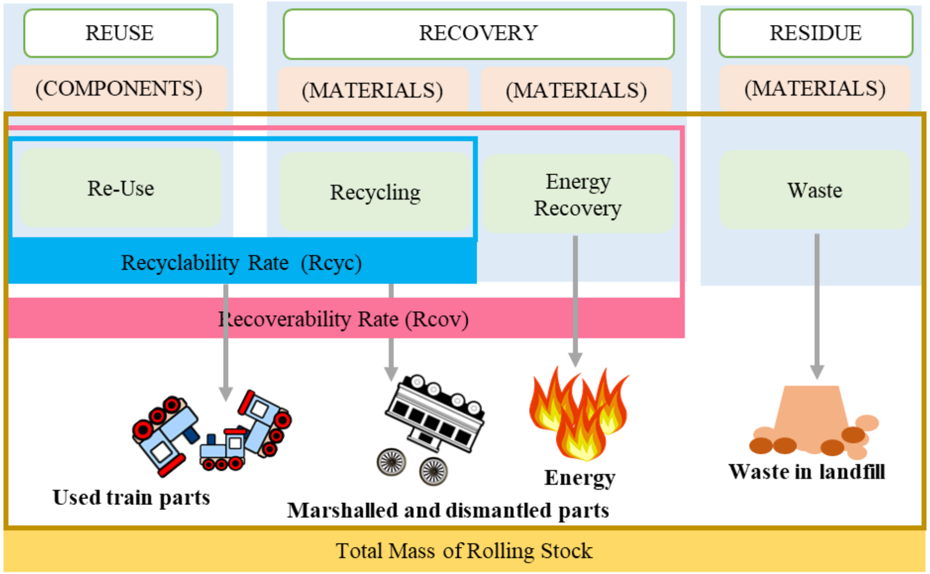

Fig. 1 An overview of recovery, recycle and reuse of end-of-life rolling stock

2.1. Recycling Process

Recycling is a process of treating or changing waste material into usable materials (Eurostats mullmagazine, 2008). By following the directive 2008/98/EC on waste document, the recycling process is one of the basic concepts and definition related to waste management, which consists of preparing for re-use, recycling, recovery, and disposal. The waste framework aims at generating positive impacts on human health and environment (European Commission, 2016)

The recycling process aims at increasing the quality and value of recycled products for decreasing the impact on the environment (Ravi, 2012). In the fact that, the process was applied to 241 million tons of waste per year in the UK and 2.5 billion tons of waste per year in the European Union, of which approximately 13.6 million tons of waste were generated from industrial work. Therefore, the vast amount of residues related to an idea of eco-design for new product development. The benefit of the new design was not only the cost but also the reduction on environment impacts (Giorgetti *et al.*, 2016).

Regarding to measure the benefits and costs of waste management, the life cycle assessment (LCA) methodology is properly applied for evaluation (Craighill and Powell, 1996). The LCA method quantified the environment impact of a product or material, which focused on energy, resources, and emissions of products from the cradle to the grave. A case study of HSR in the California, USA, for example, the main focus on the feasibility study to build HSR was using low energy and reduce GHG emission (Chester and Horvath, 2010). Another method called 4Rs, which is waste prevention techniques for manufacturing, strived to make their products environmentally friendly throughout the process of reducing, reusing, recycling, and remanufacturing (UNIFE, 2013). Both LCA methodology and 4Rs provides plentiful advantages across the business in term of recycling wastes in to new object.

The recyclability rate (R_{cyc}) is the main indicator to measure the performance of the recycling process. There was many sources mentioned on the recyclability rate (R_{cyc}) and recoverability rate (R_{cov}). For instances, document for railway application named 'ISO TC269/WG' indicates those rate for all components of rolling stocks that can be a guideline for industry to manage the end-of-life rolling stock (ISO/TC269, 2012).

2.2. Recovering Process

Recovering is a process that turns materials back into what they were originally intended to be and/or into new purposes. The process refers to the transformation of used equipment or materials into new energies such as thermal energy. Waste recovering process aims at the utilization of waste thermal energy (Haddad *et al.*, 2014). It can be found on widely manufacturing processes, i.e., agriculture (El Hanandeh, 2015; Lee *et al.*, 2016; Purdy *et al.*, 2018), cattle (Venier and Yabar, 2017), textile (Nunes and et al, 2018). The recovery concept has become a significant role in many countries due to it illustrated benefits profoundly and lead to sustainable development.

The regulations on the waste management were different among European countries. In the facts that, the wastes in the landfill were banned in some countries, i.e., Switzerland, Germany, Norway, Belgium, Sweden, and Denmark caused by the recovery rate was higher than other countries due to the wastes were directly sent to the recovery process. On the other hand, Cyprus and Malta didn't have recovery system caused by the recycling rate was lower than other countries. It could be confirmed by the results in 2012 that showed Norway represented the recoverability rate at 92-98%, while showed only 30-37% on the recyclability rate (Worrell and Reuter, 2013).

The waste dumping not only reduces gas emission to the environment but also produce renewable energy for other purposes (Wang *et al.*, 2012). In case of recovering on the end-of-life rolling stock, the wastes that mainly composed of elastomers and polymers (i.e. table, seat) will produce high recoverability rate, which will be mentioned on the material part.

In term of the end-of-life rolling stock, the shredded material cannot be reusable as the material in the recycling process. Normally, the shredded materials can be classified in two types by using the magnetic properties as shredder heavy fraction or SHF (steel, iron, copper) and shredder light fraction or SLF (plastic, fibre, glass) (Delogu *et al.*, 2017). The SHF may send to the recycling process but, the SLF should transfer to the recovering process. The study by (Krinke et al., 2006) defined that up to 66% of the total mass could be recovered.

2.3 Main Components

An intense analysis of the main components on the rolling stock has been focused on three materials; steel, plastic (polymers), and glass. It relates with the study of Del Pero *et al.* (2015) that shows the material compositions on the metro train. It composes of metals 87.5%, plastic (elastomers and polymers) 5.9%, and glass 2%. Besides, the collected data (*See table 5-7, Appendix A.*) represent a component of three type rolling stock and type of material, which mainly composed of steel, mixed aluminium and steel, aluminium, and glass. Hence, the recycling and recovering process of metals, plastics, and glass are analysed below.

2.3.1. Steel

The recycling process of a steel material is very efficient. The steel industries figured out an effective method to produce steel by using less energy and new materials more than 50 years ago. Steel is well known for having an up to 100% recyclable rate for making new steel products. If steel does not significantly lose its properties, it can be recycled over and over again (Kaewunruen, 2016).

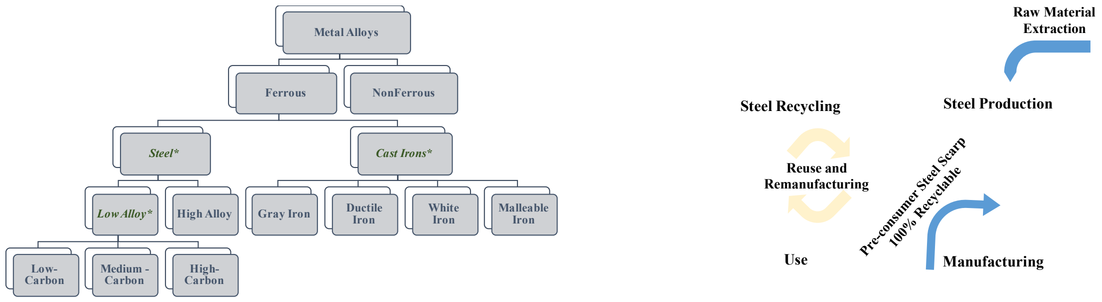

Fig. 2(a) The classification of metal alloys (The * symbol denotes the components on rolling stock) and Fig. 2(b) The life cycle of steel.

Based on studies of materials; however, the recovery rate of steel has been found to be up to 90-98% (Kaewunruen, 2016; UNIFE, 2013), whereas the realistic recovery on the industrial process is approximately 92% (Del Pero et al., 2015). Steel is an easily recoverable material, due to its magnetic characteristic, which makes it convenient to separate out from other particles (Kaewunruen, 2016). High speed and passenger rolling stocks are composed of around 20-25% steel, whereas a freight rolling stock is mainly made of steel. Moreover, other parts, such as bogies (wheels, bearings, axels, and motors), bridge, stations and power lines, are combined with steel (Kaewunruen, 2016).

With regarding the aluminium material, it normally used for application in transportation as shown in section 4.3. The aluminium shows as a component of a passenger train, HSR, and freight train up to 60.85%, 51.55%, and 24.97% respectively. In the study of Passarini and et al (2014) stated that up to 75% of recycled aluminium in Europe is applied in transportation sectors. The material provides the light-weighting characteristic that reduces the weight around 10%. Besides, the recyclability and recovery rate can be reached up to 95%.

However, the loss of metal elements occur during the recovery process under the conditions of economic and technical (Ohno et. al, 2014 and Ohno et. al, 2015). Regarding the recycling process of end-of-life vehicle, there are main three losses including material, quality and dilution (Amini and et. al, 2007). Some research identifies that the loss on quality and dilution comes from the contamination on the end of life vehicle i.e. the copper is mixed with steel (Nakamura and et. al. 2012).

2.3.2. Plastic (Polymers)

Plastic is known to be a non-biodegradable material, and it is not possible to reduce the waste at the end of its life. Most plastics take thousands of years to degrade and also release chemicals into the atmosphere. The burnt plastic released many toxic gases such as Furans, Dioxins, and Mercury that refers to lung damage and other diseases (Verma *et al.*, 2016). Some plastics can be degradation automatically, on the other hand, the rest type of plastic (i.e. low purity plastic, laminated) must be applied to chemically process (Worrell and Reuter, 2013).

As a crude oil's downstream product, every 1 tonne of recycled plastic saves 16.3 barrel of crude oil (Kaewunruen, 2016) and also saves 5,774 kilowatt-hours of electric energy in the production process (Del Pero et al., 2015). In 2012, there was 25.2 million tonnes of plastic wastes across European countries; nevertheless, it was only 60% of the wastes could be recovered or recycled. Regarding with the recovered and recycled wastes, the reports showed that an approximately 9.9 million tonnes of plastic wastes turned to be energy for manufacturing, household, and other purposes. And, the rest of plastic wastes or 6.6 million tonnes were sent to recycle process (Worrell and Reuter, 2013).

Some parts of rolling stocks such as tables, seats, and battery are composed of various types of plastic and polymeric materials. Hence, the recycling processes should apply after the end-of-life to save energy, reduce waste in landfills, and decrease toxic gases emissions. However, non-biodegradable parts are primarily used as rolling stock components, due to their properties that endure extreme temperatures and ability to support railway's structures (Kaewunruen, 2016). The thermosets, another type of plastic, also used in rolling stock but, the recycling process of thermoset plastic is complicated than other plastic types. The main issue is the thermoset plastic can't be remoulded due to it contains long fibres that refer to advanced recycling processes such as thermal processes or mechanical recycling. Regarding the manufacturing process, the recycling process of the thermoset may cost expensive. In the fact that, the vehicle contains a large variety of plastics caused by it requires a various process for recycling that leads to the formation of shredder residue. It conforms to the study of Gent et al., (2015) that focused on the automobile shredder residue of the end-of-life vehicle. In the UK, the shredded waste of plastic represented at 9.4% - 16.8% by mass of total shredded scraps (Ambrose et al., 2000; Cossu *et al.*, 2014; Miller *et al.*, 2014). Therefore, the proper method on the plastic recycling process of the end-of-life rolling stock becomes significant in a role.

Regarding the four stages of the plastic recycling process, the primary stage, which involves reprocessing plastic into a product with similar properties with a raw plastic material. The second stage consists in downgrading the plastic into a product that uses lower property that a product from the primary stage. The third stage is when the polymer is de-polymerised into its chemical components and used to make other similar products. Finally, the energy can be recovered from the plastic waste by applying heat.

2.3.2. Glass

Glass is a reusable material and, used glass can be broken down into cullet and mixed with sand, soda, and limestone before it is sent to the production process. The raw materials require less than 10% of the all the energy obtained in glass production process (Kaewunruen, 2016) and the amount of CO_2 saved from the process is higher than the carbon dioxide emissions from the transportation of it in the process. Also, one advantage of glass recycling processes is represented by the association of the European rail industry (UNIFE), which shows in the MRF rate is 66.7% and ERF rate is 33.3%, without any waste (UNIFE, 2013). In contrast, other sources have claimed that glass cannot be reused for any sources of energy; for example, many glass materials, such as windows, are made with fibre reinforced composites, which are difficult to make reusable (Sommerhuber, 2015; Guo *et al.*, 2018).

3. Methodology and Materials

3.1 Methodology

The end-of-life rolling stocks cause large volume of wastes in the landfill not only in European countries but also countries around the world. There are various methods used to calculate the lifecycle performance. As can be found in, Delogu et al, 2017, Lee and et al., (2016), Song and Lee, (2010), Jeong and Lee, (2009), they focused on the value of GHG emission on electric railway vehicle which analysed from reuse, recycling, and recovery process. However, the study designed to adopt the method from ISO 22628 document (ISO22628:2002) as mentioned in section 2. It used to calculate the recyclability rate (R_{cyc}), recovery rate (R_{cov}), and mass of material in pre-treatment, dismantling, and shredding, as the percentage by mass. Also, the Fig.3 shows an overview of the end-of-life process of rolling stock material, which represents the value of $m[P]_{Reuse}$, $m[P]_R$, $m[P]_{E,}$ $m[D]_{Reuse,}$ $m[D]_{R,}$ $m[D]_{E,}$ $m[S]_R$ and $m[S]_E$. All equations are derived as shown in equation 1 to 7 below:

$$m[S]_R = \frac{\sum m[S]_{iR} \times (100 - ShLF)}{100} \tag{1}$$

$$m[S]_E = \frac{\sum m[S]_{iE} \times (100 - ShLF)}{100} \tag{2}$$

$$R_{cyc\ (kg/kg)} = \frac{m[P]_{Reuse} + m[P]_{R\,i} + m[D]_{Reuse\,i} + m[D]_{R\,i} + m[S]_{R\,i}}{m_v} \tag{3}$$

$$R_{cov\ (kg/kg)} = R_{cyc\ (kg/kg)} + \frac{m[P]_{E\,i} + m[D]_{E\,i} + m[S]_{E\,i}}{m_v} \tag{4}$$

$$R_{cyc\ (\%)} = \frac{\sum (m[P]_{Reuse\,i} * MRF_{Reuse} + m[P]_{R\,i} * MRF_{[P]\,R\,i} + m[D]_{Reuse\,i} * MRF_{[D]\,Reuse\,i} + m[D]_{R\,i} * MRF_{[D]\,R\,i} + m[S]_{R\,i} * MRF_{[S]\,R\,i})}{m_v} \tag{5}$$

$$R_{cov\ (\%)} = R_{cyc\ (\%)} + \frac{\sum\left(m[P]_{E\,i} * ERF_{[P]\,E\,i} + m[D]_{E\,i} * ERF_{[D]\,E\,i} + m[S]_{E\,i} * ERF_{[S]\,E\,i} \right)}{m_v} \tag{6}$$

$$m_L = m_v - \frac{\sum\begin{pmatrix} (m[P]_{Reuse} * MRF_{Reuse}) + (m[P]_{R\,i} * MRF_{[P]\,R\,i}) + (m[P]_{E\,i} * ERF_{[P]\,E\,i}) + (m[D]_{Reuse} * MRF_{Reuse}) \\ + (m[D]_{R\,i} * MRF_{[D]\,R\,i}) + (m[D]_{E\,i} * ERF_{[D]\,E\,i}) + (m[S]_{R\,i} * MRF_{[S]\,R\,i}) + (m[S]_{E\,i} * ERF_{[S]\,E\,i}) \end{pmatrix}}{100} \tag{7}$$

where;

$R_{cyc\ (\%)}$ = vehicle recyclability by percentage [%];
$R_{cov\ (\%)}$ = vehicle recoverability by percentage [%];
$R_{cyc\ (kg/kg)}$ = vehicle recyclability by kilograms [kg];
$R_{cov\ (kg/kg)}$ = vehicle recoverability by kilograms [kg];
m_v = total mass of rolling stock [kg];
m_L = total mass of rolling stock remained to landfill [kg];
$m[P]_{Reuse}$ = total mass of materials which can be considered as reusable at pre-treatment step [kg];
$m[P]_R$ = mass of materials which can be considered as recyclable at pre-treatment step [kg];
$m[P]_E$ = mass of materials which can be considered as energy recoverable at pre-treatment step [kg];
$m[D]_{Reuse}$ = total mass of materials which can be considered as reusable at dismantling step [kg];
$m[D]_R$ = mass of materials which can be considered as recyclable at dismantling step [kg];
$m[D]_E$ = mass of materials which can be considered as energy recoverable at dismantling step [kg];

$m[S]_R$ = mass of materials which can be considered as recyclable at shredding step [kg];
$m[S]_E$ = mass of materials which can be considered as energy recoverable at shredding step [kg];
ShLF = Shredding loss factor [%]
MRF = Mass recovery factor [%];
ERF = Energy recovery factor [%];
i = material subscription;
Reuse, R, E, M, T_r = End-of-life treatments subscript.

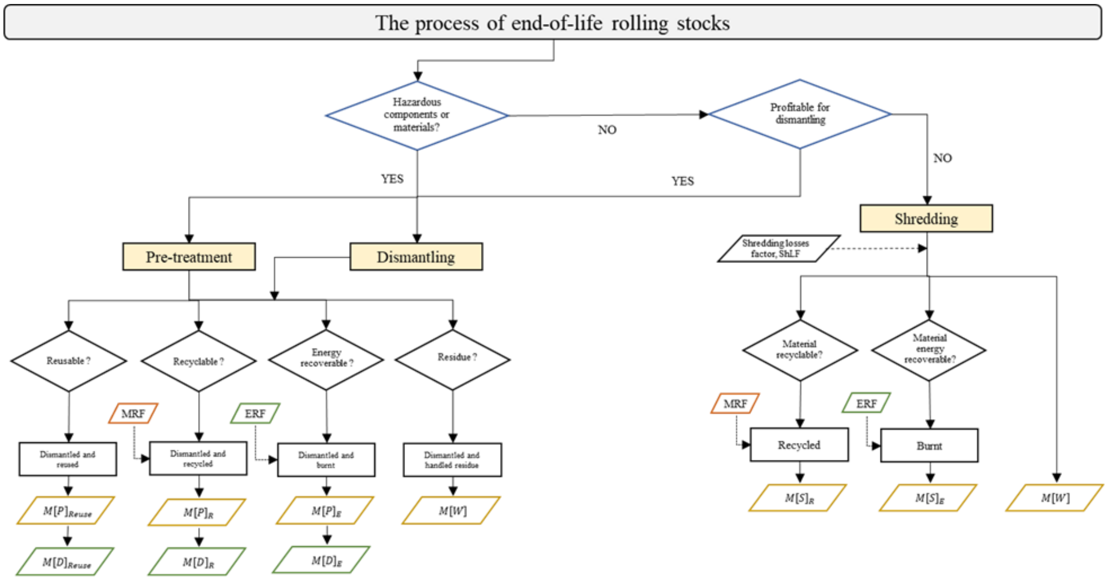

Fig. 3: Three steps of the end-of-life treatment for rolling stock-flow chart adopted from ISO/TC 269/SC 2/WG 4

3.2. Materials

With respect to the end of a vehicle's life, it needs to be correctly disposed of for the further recovery. The hazardous elements need to be separated out first before transferring to further stages. The materials extracted from the rail vehicles are put into seven categories:

- Metals;
- Polymers, excluding elastomers – reinforced polymers, polymer compounds, all other undefined polymers, foam, sorted fractions, and duromers;
- Elastomers (rubbers);
- Glass;
- Fluids – oils, lubricants, all chemical fluids;
- Modified organic natural materials (MONM), such as leather, wood, cardboard and cotton fleece;
- Other, including components and/or materials for which the material composition cannot be ascertained e.g. compounds, electronics and electrics.

These seven categories will be used to calculate the R_{cyc} and R_{cov} for the pre-treatment phase, dismantling phase and shedding phase. First, the specific information (e.g. materials and components of rolling stocks) needs to be listed. To comparing among the three types of rolling stocks, the masses of the rolling stock components can be found from either individually finding the masses of the components of the rolling stock or multiplying the percent mass of the component by the total mass of the rolling stock. After that, both of the material recover facility (MRF) and the energy recover facility (ERF) values of each component on the rolling stock can be carried out as shown in equation 8 and 9.

$$\% \text{ MRF}_i = \frac{m[R]_i}{m[AR]_i} \times 100 \tag{8}$$

$$\% \text{ ERF}_i = \frac{m[E]_i}{m[AE]_i} \times 100 \tag{9}$$

where;
m[R] = Total amount of output of material for recycling process [kg];
m[AR] = Total amount of material available for recyclable [kg];
m[E] = Total amount of output of material for recovering process [kg];
m[AE] = Total amount of material available for energy recoverable [kg];
i = The material set which it belongs to.

The generic values of MRF and ERF were collected from numerous industrial companies, commercial available data and professional organizations, and they were used to determine life cycle of the waste materials. The MRF and ERF values can precisely measure the efficiency of a recycling and recovery rates. As shown in table 1, the results of MRF (%) and ERF (%) of each material identify generic values between the recycling or recovery processes; for instance, metal has an MRF rate of 94%, which means it is proper to apply the R_{cyc} rather than R_{cov}. Nevertheless, there are slight differences between practical and theoretical results; for example, safety glass and glass show a 100% residue rate from based on a few sources, such as Lawrence (2003), ISO TC-267 (2015), and Silva and Kaewunruen (2016) stated that they could be recycled up to 100% (Silva and Kaewunruen, 2016). However, the results from industrial processes found an only 90% recoverable rate. The difference can be explained as window glass is made out of soda-silica and contains other non-reusable materials, which causes the industry rate to appear lower than the theoretical rate.

Table 1: The summarization of MRF and ERF values of material adapted from British Standards Policy and Strategy (Delogu et al., 2017; International Environmental Product Declaration (EPD) System, 2013; British Standards Policy and Strategy, 2002; ISO 22628, 2002)

Material categories	Mass Recovery Factors (%)	Energy Recovery Factors (%)
Pre-treatment Phase		
Acids, similar non-organic	85	0
Oil and greases	0	100
Electrics, electronics	79	19
Dismantling Phase		
Metal (Ferrous)	94 – 98	0
Metal (Non-ferrous)	94 – 98	0
Elastomers	80	20
Polymer (unfilled)	90-100	1
Polymer (Reinforced)	66.7	33.3
Glass	90 – 100	0
Safety glass	90 – 94	0
Ceramics	43	0
Mineral wool	97	0
MONM	95	5
Wood	95	5

Electric and electronics	79	19
Shredding Phase		
Mixed materials	14	19

In the practical side of rolling stock recycling, the three major phases consist of pre-treatment, dismantling and shedding phases. Firstly, the pre-treatment process aims to separate toxic, liquid and harmful gases from the materials, preventing an unexpected accident affecting humans during recycling and recovering process. Wasted rolling stocks are usually contaminated with various fluids, such as batteries, brake fluid, gear oil, antifreeze and other materials containing hazardous substances. Thus, these fluids must carefully be discharged before sending to the next stages. By following this stage, the values of $m[P]_{Reuse}$, $m[P]_R$ and $m[P]_E$ can be carried out. Secondly, the dismantling stage separates some useful materials such as windows, seats, floor, cables, and electronics parts to be reused. Moreover, some components can be removed for specific requirements such as economic feasibility, safety recycling process and suitability of technology. This stage can be figured out the $m[D]_{Reuse}$, $m[D]_R$ and $m[D]_E$ values. Finally, the remaining materials or parts are directly forwarded to the shredding process, which is separation and recovery stage of metal materials and small parts. The magnetic properties and eddy current separators are applied on this process for sorting (Silva and Kaewunruen, 2016). And, large materials are grinned and milled before being forwarded to further stages. The values of $m[S]_R$ and $m[S]_E$ are provided.

3.3. Types of Rolling Stocks

3.3.1. Freight Trains

Freight trains usually transport materials and goods and they are much more economically efficient when transporting goods in bulk over long distances compared to transporting freight on the road. By carrying the optimal volume of goods over long distances, the freight trains are competitive than other transportation. Growing in the rail network increased the role of the freight movement as shown in the freight's market share had been risen from 5% to 9% during 1995-2012 (European Commission, 2011; DfT, 2015; Woodburn, 2017)

A freight train set is split into two sections (locomotives and freight) and the treatment process of the freight section of the rolling stocks seems easier than passenger train and HSR. Moreover, 80% of the total mass is composed of steel and cast iron, which causing the freight railcar to have a high value of R_{cyc}. Calculating the R_{cyc} and R_{cov} of the rolling stocks, the equations 1 and 2 are applied respectively. Various important factors like $m[P]_R$, $m[P]_E$, $m[D]_R$, $m[S]_R$, and $m[S]_E$ should be used for the component breakdown of freight rolling stocks components, materials, and percentage values should be adopted from the recycling of rolling stock (Matsuoka, 2003; Silva and Kaewunruen, 2016), as shown in table 2. The results indicate that the majority of materials from freight trains can be recycled and recovered for energy.

3.3.2. Passenger Trains

The recycling process of passenger rolling stock is more complicated than for freight rolling stock because not only are the structures of commuter trains composed of various materials, but their structures are also separated into multiple units. Passenger trains contain self-powered railcars or locomotives and trailers or coaches (Kaewunruen, 2016; Lee *et al.*, 2010).

Moreover, the components of these rolling stocks are mostly different from freight trains, especially the composite materials. The rolling stocks's body is composed of carbon fibre reinforce plastic (CFRP) or glass fibre reinforced polymers, which are not economically efficient technologies to recycle. The composite material such as lightweight alloys applied on car body aiming to reduce the GHG emission (Rezaei et al, 2007). The report also found that the global CFRP market was expected to increase over 35% as its benefits on the environment.

In fact, the majority component of the rolling stock is made out of aluminium, but its dimension and shape at the end-of-life are incompatible with the recycling process. Both MRF and ERF rates are multiplied by the weight of each component. Therefore, the values of the pre-treatment ($m[P]_R$, $m[P]_E$), dismantling ($m[D]_R$, $m[D]_E$), and shredding ($m[S]_R$, $m[S]_E$) stages will be calculated throughout the equation 1 and 2 for finding the value of R_{cyc} and

$R_{cov.}$

3.3.3. High-Speed Rail (HSR)

HSR is designed to support high velocities above 250 km/h and, it is operated on specific tracks. Normally, HSR is the most efficient rolling stocks type for supporting customers' requirements regarding increasing conveniences, saving travel time, and enabling new areas when the distance for a trip is in the range of 300 to 1,000 km (Kojima and et al., 2017; MLIT, 2017). As they are supporting high velocities, mostly components of HSR are made with lighter materials such as silicon carbine and polypropylene for minimizing drag forces as can be seen in Fig. 6. For example, the HSR’s car body is made out of mixed aluminum and steel rather than pure steel as the freight train’s car body as can be seen in Table 7.

3.4 Future development on train compositions

As follow various aspects to enhance the railway system, to changing on material composition and adding innovations has been interested. Cost and energy saving, lightweight, high stress, and high modulus were essential key ideas to replace new materials.

Carbon fibre reinforced plastic (CFRP) has been suggested to replace on rolling stocks structures, e.g. door and rolling stocks body. Reducing body weight, high strength, corrosion resistance and vibration resistance are strong points making CFRP over steel and aluminium. CFRP is widely used in transportation industries (i.e. electric vehicle, aircraft) since 2012 and expected to cover 200,000 tons per year in 2020 (Dauguet and et al. 2015; Khalil, 2017). The reason is the feature of CFRP in broad containing high strength, durability, high stiffness, fatigue resistance, and able to conform to different shapes (Khalil, 2017). Moreover, the CFRP can also apply to other materials such as $AlMg_3$, which can be found in the existing rolling stocks model and leads to reducing total weight and using less energy. Also, the study on the replacement of CFRP in rail car body in Korean Tilting Train express (TTX), which found that the energy cost was reduced as a reduction in rail carriage weight (Castella et al., 2009).

In term of end-of-life CFRP, the complexity of CFRP structure makes complicated recycling process than other materials. Therefore, the pyrolysis method, which is one of a thermal treatment process, is highly suggested to apply to the CFRP recycling process for splitting carbon fibre out of the waste (Das, 2011; Khalil, 2017). The carbon fibre can be used as raw material for enhancing the hardness of new products.

4. Results and Discussions

4.1. Recyclability and Recoverability Rate of Rolling Stock

This research has analysed in depth the recyclability rate (R_{cyc}) and recoverability rates (R_{cov}) of three types of rolling stock (freight, passenger, HSR) based on calculations related to their components, via equations 1 and 2. Almost all the results for calculating recovery rates are within the range of recovery rates that are claimed by industries. For instance, the car bodies of freight trains are reported to be 90-98% recoverable (Silva and Keawunruen, 2017; UNEP and Reuter, 2013; Lee *et al.*, 2010; Lawrence, 2003), and the calculation result in this study shows at 93.7%, which is also value in range of the industries data. Nonetheless, various components of rolling stock (i.e., fuel tanks, air reservoirs, motors and batteries) fluctuate from industries’ data. The recovery rate of a fuel tank on a freight train, for example, was found to be only 33%, whereas industries claim to have data that shows that around 80%-98% of fuel tanks can be recovered (UNIFE, 2013). The reason for the difference is that components were combined with alloys, which are not comfortable to recover. Also, these need to be shred into small pieces before being transferred to the recovering process. Thus, it would not be worthwhile to waste time and cost on expanding the operation. In contrast, the calculation of the recovery rate of batteries was 98%, whereas the industry data claims that they are 50-70% recoverable (Silva and Kaewunruen, 2017). The reason is that batteries could be recharged and mostly reused if they are in excellent condition. To compare the results of R_{cyc} and R_{cov} between the three types of rolling stocks, table 2 provides a summary of results, with fundamental information as follows;

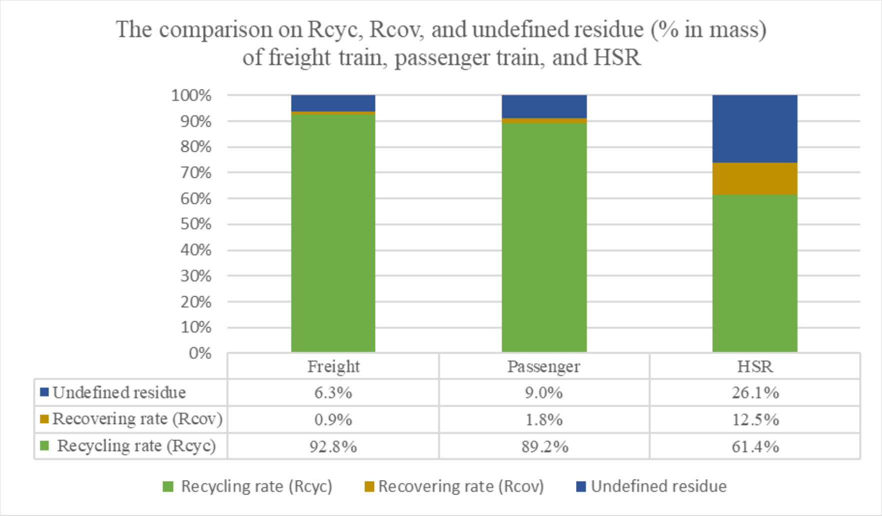

Fig. 4: The comparison on R_{cyc}, $R_{cov,}$ and undefined residue (% in mass) of freight train, passenger train and HSR

Table 2: Summary of total weight of rolling stocks (kg), recyclability rate (%) and recoverability rate (%) comparing with three types of rolling stocks

Type of rolling stocks	**Results**					
	Total weight (kg)	**Total waste (kg)**	**Fraction of total waste and total weight**	**Recyclability rate**	**Energy recovery rate**	**Recoverability rate**
Freight train	8,000,000	520,192	6.5%	92.8%	0.9%	93.7%
Passenger train	168,373.5	15,661.9	9.3%	89.2%	1.8%	91%
HSR	265,000	88,201.1	33.3%	61.4%	12.5%	73.9%

Firstly, freight rolling stock have a greater total weight at approximately 8,000,000 kg (17,636,981 lb), which is approximately 30 times heavier than HSR trains. Freight trains' structures have been designed to support their capacity to carry more goods and heavy loads; thus, the majority of components of a freight train are made out of metal like steel. Based on table 1, steel represents an MRF value at 94%, ERF value at 0% and a residue at 6%, which means the majority of components can be recycled and turned into their original forms. Also, another source shows that the MFR value is 98% with a 2% residue (UNIFE, 2013). As shown in the calculation results of this research, the energy recovery rate was only 0.9%; in other words, it is not being properly used as an energy source. Moreover, the fraction of total waste and weight was only 6.5%, which means that the remaining parts can be recycled.

Secondly, passenger trains represented a total waste of 15,661.9 kg (34,528.6 lb) or 9.3% of the total mass and their R_{cov} was 92%, as the majority of components, such as the car body, were made out of aluminium and steel. On the other hand, the energy recovery rate was found to be 1.8%, and the R_{cyc} was high at 89.2%. Owing to the passenger trains consisting of many items aimed at supporting passengers, such as seats, doors and panel components the recovery process is distinctly complicated than for freight trains.

Finally, HSR rolling stock showed the highest value of total waste at 33.3%, compared to the other rolling stocks. The recyclability rate was only 61.4% due to some parts of the HSR were made out of composite materials and other lightweight materials, which were not properly recycled as heavy scrap materials. On the other hand, those lightweight materials were suitable for energy recovery process regarding the manufacturing profitability. The HSR's end-of-life rolling stock showed the highest energy recovery rate among three type of the end-of-life rolling stock at 12.5%; in other words, some parts can be burned down and turned into energy. With regarding to some components compose with two or more materials, some parts are possible to loss their mass during the pre-treatment, recycling and recovering processes. Therefore, the MRF and ERF values of those components are lower than the passenger and freight train. As conform to the generic values of mixed materials, it contained an MRF value at 14% and ERF value at 19%. The R_{cov} of the HSR's end-of-life rolling stock was the lowest value out of other end-of-life rolling stocks, due to the majority of the HSR components being mixed with materials and polymers.

4.2. Net Present Value of Rolling Stock

The rolling stocks become crucial assets for railway organisation, which take the majority cost of investment. This study needs to evaluate the value of rolling stock along its lifetime during operation until the end-of-life time. The study can provide genuine information about cost of whole life rolling stocks that is directly benefit for railway companies and automotive manufacturers. The net present value (NPV), which is an essential factor widely used to identify the real value of a projected investment, is applied on this study to estimate the value of the end-of-life rolling stocks. The NPV result shows the present values (PV) of a project when it is operated over a period of time and the outcomes can be represented by positive and negative values. The positive values mean the project will be profitable; otherwise it is a non-profitable project (Martin, 1996; de Rus, 2009).

$$\text{NPV} = \sum_{t=0}^{N} \frac{C_t}{(1+k)^t} \tag{10}$$

Where;

C_t = net cash flow during the period;

k = discount rate;

t = year

N = number of time periods

The initial investment on rolling stock can be differed depending on the design requirements, number of ordered, suppliers, and type of rolling stocks (Railway Technical, 2016). The research found that the price of new locomotive was in range \$2 million (£1,480,847.2) and \$6 million (£4,442,671.4). Regarding with the calculation in this study, the average cost of single rolling stocks was taken from various suppliers such as Voith, Siemens, Hyundai, and Bombadier that sold their products along with worldwide railway projects. The initial cost of freight rolling stock is taken from the single rolling stock of diesel multiple unit (DMU) rolling stocks powered whereas, the passenger rolling stock is based on the single rolling stock of electrical multiple unit (EMU) rolling stocks powered. Regarding the design of HSR rolling stocks, the study from Maout and Kato (2016) showed the multiple model of rolling stock for HSR such as ICE1&2, Mini-shinkansen, future KTX, AGV2, Doule-decker wide ICE1&2, and Wide TGV, which were differ in number of seats, body width, body length, and wheelbase. Therefore, this study takes an average price from the 350 seats capacity HSR that has been estimated to cost \$17,849,000 (£13,181,524.4) (Levinson *et al.*, 1997; Kanafani, Wang and Griffin, 2012).

Regarding the passenger rolling stock, the annual cost could up to £2,580 per seat (Transport Watch UK, 2011) and, the average seat on one carriage is 75 seats so, the cash flow of single carriage of passenger train showed at £193,500 per year. And, the annual cost of the freight rolling stock had been estimated at £110,570 (European commission, 2015). In term of the HSR, the annual acquisition of the HSR could be up to £57,036.7 per seat (de Rus, 2009; Maout and Kato, 2016) and, the minimum seats for the second class of HSR showed around 60 seats per rolling stock (Maout and Kato, 2016) caused by the cash flow of single rolling stock of HSR represented at £3,422,160 per year.

The cash flow and relating to these rolling stocks will calculated at 30 years, which is the average life of rolling stock in services. Besides, a discount rate parameter is used to evaluate the costs and benefits over the period.

Various discount rate parameters were varied in the range of 0% to 10% (*i*=0%, 2.5%, 5%, 7.5%, 10%). The reasons for this were that a single discount is not appropriate within a fluctuating market (Tiwari, 1994), such as the one railway companies are in, and the different aspects through discount rate have been widely manifested. Moreover, the cost-effectiveness analysis suggests differential discount rates (O'Mahony *et al.*, 2011) that have found on the study of sensitivity analysis, Martin, 1996; Worrell, Ramesohl and Boyd, 2004; Pizer and Popp, 2008; Fleiter, Worrell and Eichhammer, 2011; Limon and Crozet, 2017. In other words, the different discount rate can reduce the error during estimation that refers to overestimation or underestimation results.

After doing calculations using equation 10, the results illustrate that HSR gains maximum NPV at all discount rates as can be seen in Table 8. Based on the initial investment in HSR trains, the results show a moderate level when compared with other rolling stocks; moreover, the higher prices for HSR ticket mean that every year its cash flow easily covers investments and operating costs, as shown in fig. 5. Regarding the freight and passenger trains, the sensitivity analysis on the end-of-life of single rolling stock indicates that the passenger train able to gain profit at all discount rate but, the freight train is predicted to lack profits at 10% discount rate as shown the NPV at -£ 11,666.07. This study aims at point out the sensitivity analysis along different discount rates, which is benefit for operators and investors concerning the values of wasted rolling stock. However, this study takes average costs of rolling stocks and incomes and, there are also factors relating to the NPV value (i.e., maintenance cost, ticket cost) excluding this study. Therefore, the NPV values of the end-of-life rolling stock can be differed depending on each railway operator's conditions.

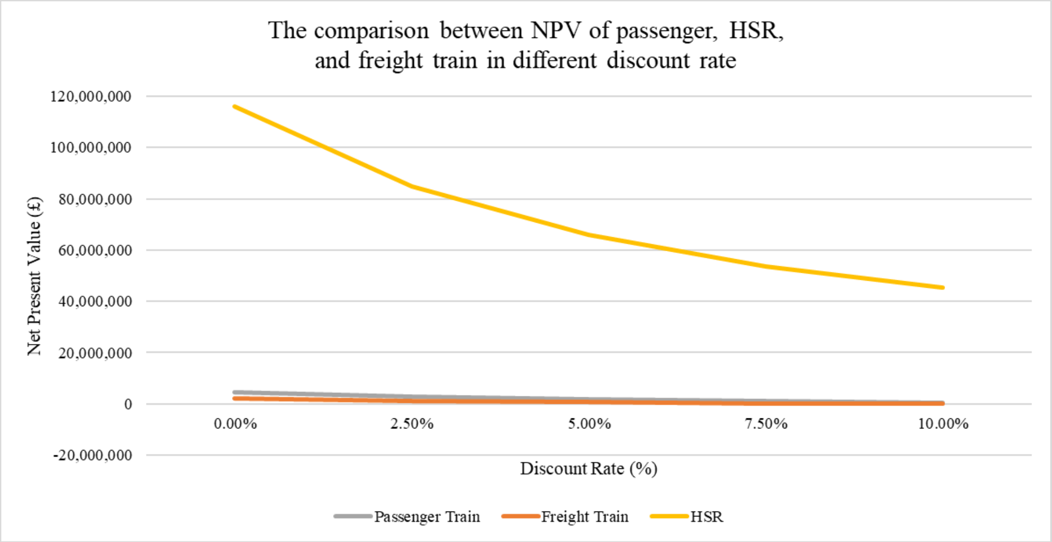

Fig. 5: The comparison between NPV of passenger trains, HSR and freight trains at different discount rates

Table 3: The summary of NPV of passenger trains, HSR and freight trains at different discount rates

Discount Rate	Freight Train	Passenger Train	HSR
10.00%	-11,666.10	574,108.00	45,441,934.00
7.50%	251,874.40	1,035,309.70	53,598,555.90
5.00%	645,731.90	1,724,569.30	65,788,511.40
2.50%	1,260,262.50	2,800,011.60	84,808,334.50
0.00%	2,263,100.00	4,555,000.00	115,846,324.00

4.3. An influential component of rolling stocks

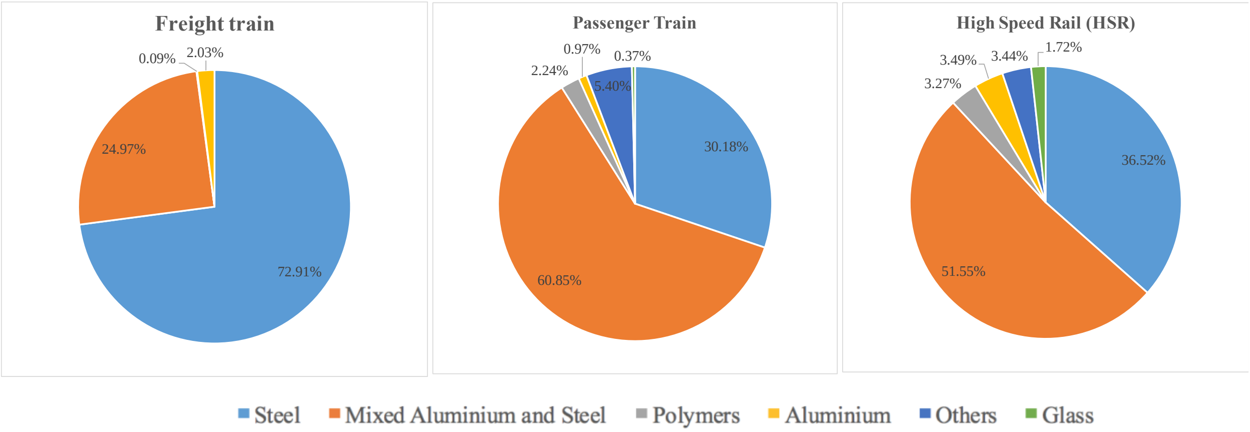

Fig. 6: The comparison between influential of passenger trains, HSR and freight trains

With respect to the differentiation on the R_{cyc} and R_{cov} values, this section aims to illustrate on the components of each end-of-life rolling stock that directly effects on both amounts.

The majority components of end-of-life rolling stock are steel, and mixed steel and aluminium as shows in Fig. 6. The freight train mainly composes of steel about 73% and 25% of combined aluminium with steel parts that represents the R_{cyc} and R_{cov} values at 92.8% and 93.7% respectively. The passenger train mainly contains steel around 91% that shows the R_{cyc} at 89.2% and R_{cov} at 91%. Likewise, the result of HSR shows the R_{cyc} and R_{cov} rates at 61.4% and 73.9% respectively conforming to the mainly components as steels, which shows the MRF values at 94%.

In conclude, the components of rolling stocks are directly related to the R_{cyc} and R_{cov} values. It can be explained that there are specific rate of MRF and ERF on each material. For example, the metal (ferrous and non-ferrous) has MRF rate at 94%; in other words, a high MRF value refers to a high value of R_{cyc}.

4.4. The sensitivity analysis of MRF and ERF rates

As mentioned in section 4.3, the MRF and ERF rates are fundamental factors that directly effect on the R_{cov} and R_{cyc} values. The study takes the generic values of MRF and ERF from the British standard policy and strategy document that leads to evaluation the R_{cyc} and R_{cov} throughout the equation 1 and 2.

Regarding the sensitivity analysis of MRF and ERF values, the changing in the MRF and ERF rates vary at ±10%. In the fact that, the MRF and ERF values can be differ depend on the potential of manufacture's recycle and recovery processes. The benefit of this section is to indicate the result of sensitivity analysis, which provides the possible range of R_{cyc} and R_{cov} on individual materials.

Firstly, changing in the MRF value directly effect on R_{cyc}; thus, the R_{cov}, which is calculated from the R_{cyc} and energy recovery, must be varied. As shown in Fig. 7, 8 and 9, the "MRF_R_{cyc}" (Blue line) and the "MRF_R_{cov}" (Orange line) represent the trend of R_{cyc} and R_{cov} after converting MRF value within the range ±10%. Those trends showed both lines increasingly harmonise because the changing on MRF value does not effect on R_{cov}.

On the other hand, secondly, varying in the ERF value precisely changes on R_{cov} only. As shown in the

“ERF_R_{cyc}” (Grey line) and “ERF_R_{cov}” (Yellow line), the trend of “ERF_R_{cyc}” line is constant due to the R_{cyc} does not include any R_{cov}. The distinctive point is the R_{cov} value slightly differ from R_{cyc} on the freight train and passenger train but, it obviously changes on HSR. The main reason is because the HSR contains with high recoverable rate materials that represent at R_{cov} 12.5%. Therefore, the sensitivity analysis of ERF value on HSR shows obviously different between R_{cyc} and R_{cov} lines.

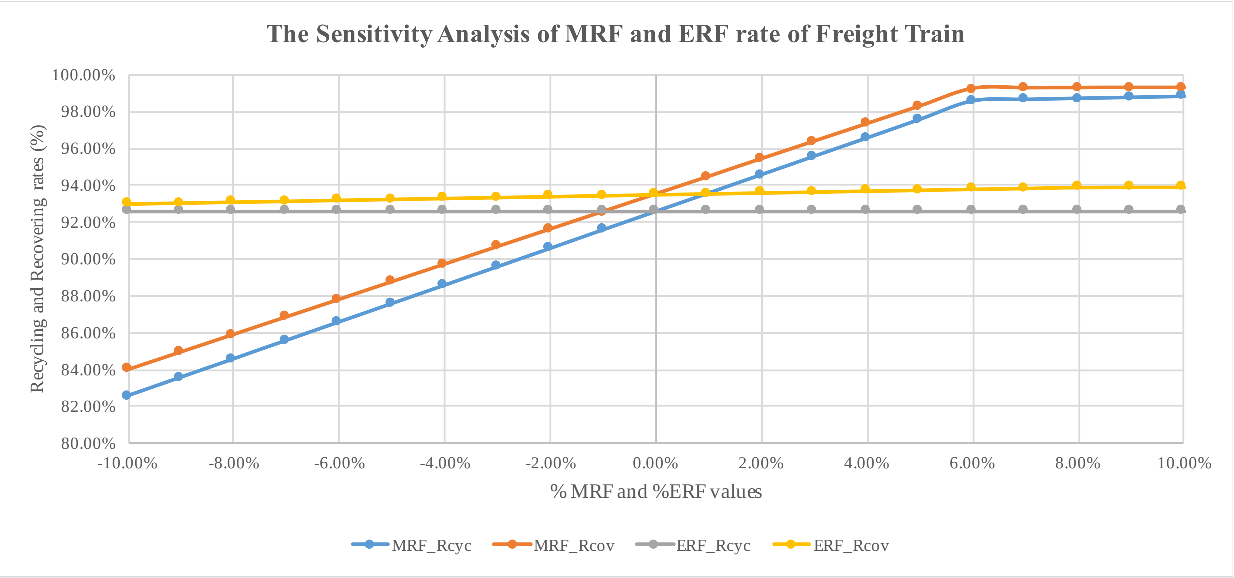

Fig. 7: The sensitivity analysis of MRF and ERF rates of freight train

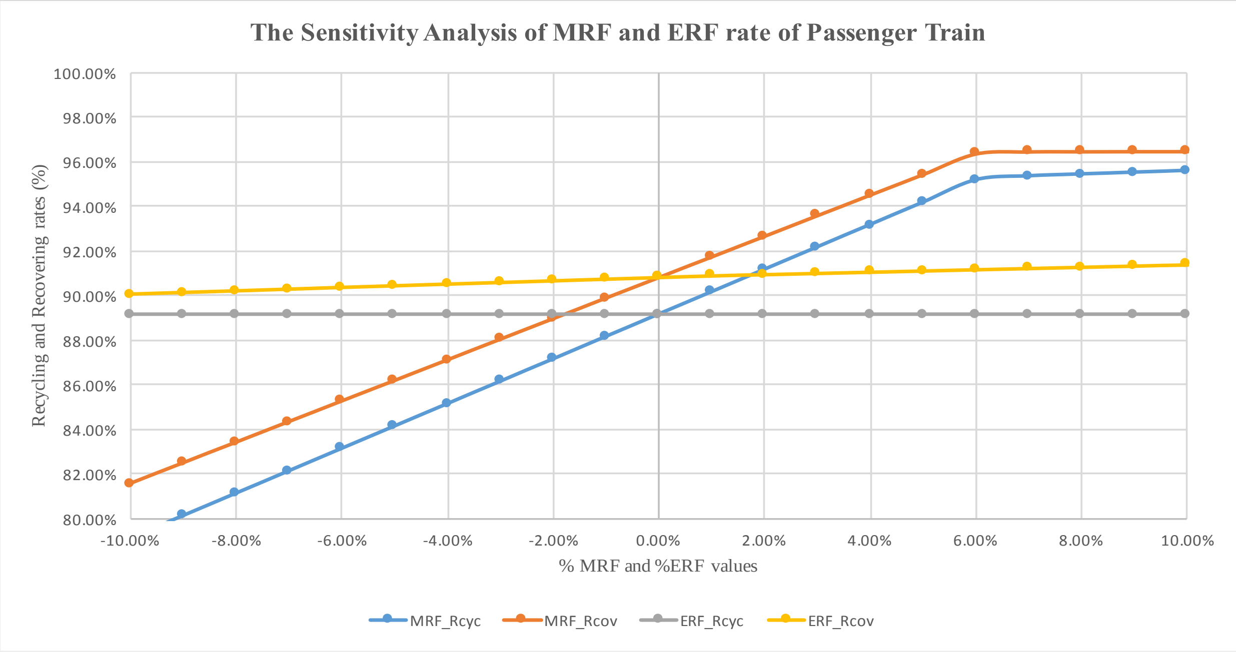

Fig. 8: The sensitivity analysis of MRF and ERF rates of passenger train

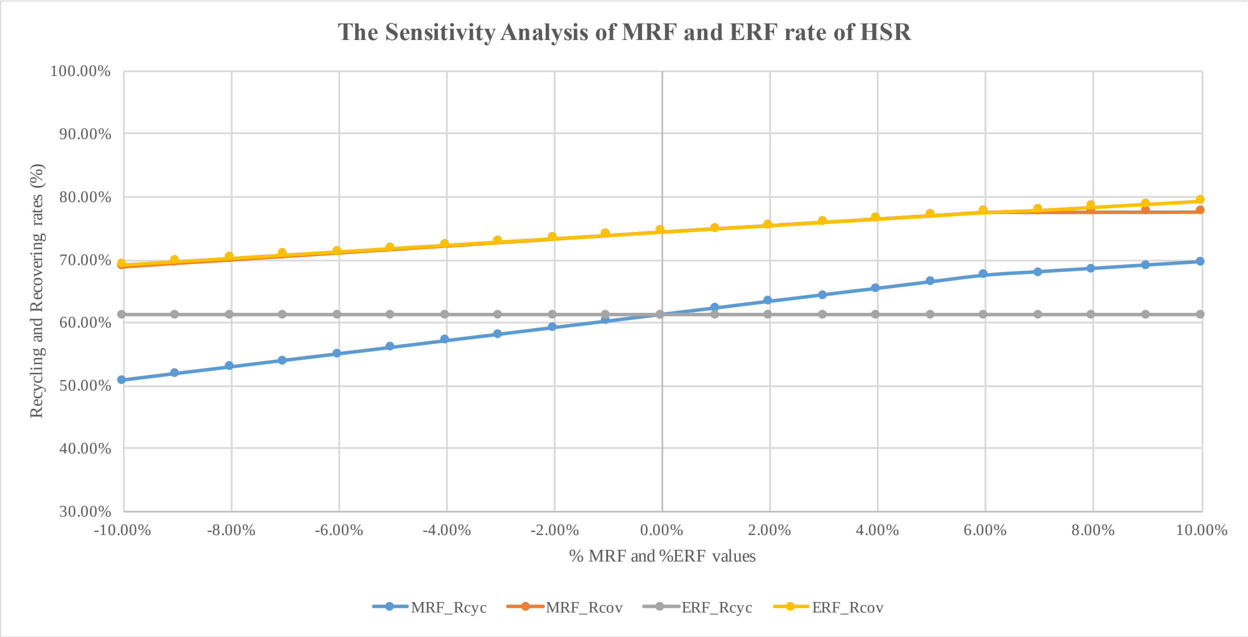

Fig. 9: The sensitivity analysis of MRF and ERF rates of HSR

5. Conclusion

In this day and age, railway has become essential transportation effecting on human life; however, the end-of-life rolling stock was turned into waste and left in landfill. As supported sustainable development, this research provides fundamental information about rolling stock and its main components and includes waste management processes like recycling and recovering. The methodology and component analysis illustrates that the properties of materials directly affect the R_{cyc} and R_{cov}. Therefore, waste management processes for rolling stock should strictly follow pre-treatment, dismantling, and shredding processes.

The outcomes are expected to reach high R_{cyc} and R_{cov}. After calculating on the end-of-life rolling stocks, the freight trains' yield shows at 92.8% on R_{cyc} and 93.7% on R_{cov}, which are the highest values out of other type of rolling stocks. The reason for this is that majority of components of freight rolling stock are kinds of recoverable materials, such as metals, which have high MRF rates. Passenger trains also has greater values for recoverability rates at 91.00%, whereas HSR has the lowest value only 73.9%. On the other hand, HSR has the highest energy recovery rate at 12.50%, due to its principal components being made out of polymers. These materials are applied on rolling stock to reduce drag force and support high velocity. Moreover, a clear characteristic of the polymer is that it is a flammable material, so it should be burnt down and transferred into energy form.

In line with other research aimed at making sustainable economics, this study focuses on the NPV of rolling stock after the end-of-life. The initial investment and the revenue per year represent in totally different values among three types of rolling stock. Regarding with uncertain cost of rolling stock and annual revenues, this study provides multiple discount rates to reduce overestimation (underestimation) value. The results show that HSR has a maximum NPV of around £45,441,934 at a 10.00% discount rate with calculations based on 30 years of rolling stock life in services. However, the NPV value can be differ depending on the conditions of the railway operators.

This study found that the majority of components on rolling stock can be reused and recycled. This not only saves energy but the amount of waste in landfill is also reduced. Therefore, having mandated uniform processes for manufacturers to reuse rolling stock would be an efficient method in European countries, instead of leaving waste in the landfills.

6. Appendix A: Component Analysis of Components, Materials, and Percentage Value Adopted from Recycling of Rolling Stocks

Table 5: Component Analysis of Freight Train Components, Materials, and Percentage Values.

Component of rolling stock	**Type of material** [a]	**Weight (kg)** [b]	$m[P]_{Reuse}$ **(kg)** [c]	$m[P]_R$ **(kg)**	$m[P]_E$ **(kg)**	$m[D]_R$ **(kg)**	$m[D]_E$ **(kg)**	$m[S]_R$ **(kg)**	$m[S]_E$ **(kg)**	R_{cyc} **(%)**	R_{cov} **(%)**	**Waste (kg)**	**Percentage %** [d]
Freight train		8,000,000											
Diesel Engine	Cast Iron/ Aluminium Alloys	337,600		246,448	64,144					73	92	27,008	4.2
Main Alternator	Steel	16,800		15,624						93	93	1,176	0.2
Auxiliary/Alternator	Steel	11,200		10,528						94	94	672	0.1
Motor Blower	Cast Iron/ Aluminium Alloys/ Steel	14,400		2,016	2,736					14	33	9,504	0.2
Air Intakes	Steel/ Aluminium	8,800		8,272						94	94	528	0.1
Rectifier/ Inverters	Steel	39,200		36,848						94	94	2,352	0.5
Battery	PPE/PET or plastic coated steel	7.200		5,688	1,368					79	98	144	0.1
Traction Motor	Steel	56,000	52,640							94	94	3,360	0.7
Pinion/Gear	Steel	44,800		42,112						94	94	2,688	0.6
Fuel Tank	Steel/ Aluminium	28,000	3,920				5,320			14	33	18,480	0.4
Air Reservoirs	Steel/ Aluminium	7,200						1,008	1,296	14	32	4,896	0.1
Air Compressor	Aluminium	78,400				72,912				93	93	5,488	1
Drive Sharp	Aluminium Alloys	48,000		44,160						92	92	3,840	0.6
Gearbox	Steel	185,600	174,464							94	94	11,136	2.3
Radiator and Radiator Fan	Aluminium, Brass or Copper cores	1,600				1,504				94	94	96	0.02

[a,b,c] *The data is taken from these research and manufacturing sources (Silva and Kaewunruen, 2017; Steel Recycling Institute, 2017; United Nation Environmental Programme, 2013; The Aluminum Association, 2018; Novelis Recycling UK, 2018; Popular Mechanics, 2010)*

[d] *The word 'percentage' in the above table refers to the component of rolling stock parts (kg) compared with total weight of the freight train (kg).*

Table 5: Component Analysis of Freight Train Components, Materials, and Percentage Values (Cont.)

Component of rolling stock	**Type of material** [a]	**Weight (kg)** [b]	$m[P]_{Reuse}$ **(kg)** [c]	$m[P]_R$ **(kg)**	$m[P]_E$ **(kg)**	$m[D]_R$ **(kg)**	$m[D]_E$ **(kg)**	$m[S]_R$ **(kg)**	$m[S]_E$ **(kg)**	R_{cyc} **(%)**	R_{cov} **(%)**	**Waste (kg)**	**Percentage %** [d]
Turbo Changing	Cast Aluminium	8,800				28,272				94	94	528	0.1
Truck Frame	Steel plate/ Cast Steel	1,518,400						1,427,296		94	94	91,104	19
Wheel	Steel R7	1,601,600						1,505,504		94	94	96,096	20.0
Roof	Steel	168,800						158,672		94	94	10,128	2.1
Vacuum													0
Door	Aluminium/ Steel	42,400		39,856						94	94	2,544	0.5
Carboy	Steel	3,653,600						3,434,384		94	94	219,216	45.7
Sandbox	Cast Iron	42,400		39,432						93	93	2,968	0.5
Battery Box	CRCA sheet and rolled sections of carbon steel	14,400	13,536							94	94	864	0.2
Brake Control Unit	Aluminium/ Cast Iron/ Reinforced carbon	6,400	6,016							94	94	384	0.1
Brake Cylinder	Aluminium	27,200	12,784					12,784		94	94	1,632	0.3
Condenser	Copper brass, Aluminium or Stainless Steel	33,600				30,240				90	90	3,360	0.4
Total Waste (kg)			520,192										
Recyclability Rate of Train			$\frac{7,426,920}{8,000,000} \times 100\% = 92.8\%$ **(1)**										
Recoverability Rate of Train			$\frac{74,864}{8,000,000} \times 100\% = 0.94\% + 92.8\% = 93.7\%$ **(2)**										

Table 6: Component Analysis of Passenger Train Components, Materials, and Percentage Values.

Component of rolling stock	**Type of material [a]**	**Weight (kg) [b]**	m[P]$_{Reuse}$ (kg) [c]	**m[P]$_{R}$ (kg)**	**m[P]$_{E}$ (kg)**	**m[D]$_{R}$ (kg)**	**m[D]$_{E}$ (kg)**	**m[S]$_{R}$ (kg)**	**m[S]$_{E}$ (kg)**	**R$_{cyc}$ (%)**	**R$_{cov}$ (%)**	**Waste (kg)**	**Percentage % [d]**
Passenger Train (Electric Diesel)		168,373.5											
Wheels	Steel R7	22,696.7				21,334.9				94	94	1,361.8	13.5
Window	Glass	623				560.7				90	90	62.3	0.4
Roof	Aluminium/ Steel	7,122.2						6,694.9		94	94	427.3	4.2
Table	Polypropylene/ Polyethylene	370.4	88	88			144.8		18.5	47.5	52.5	175.9	0.2
Seat	Polypropylene/ Polyethylene	3,148.6	2,100				1,048.5			66.7	99	31.5	1.9
Door	Aluminium/ Steel	3,030.7				2,848.9				94	94	181.8	1.8
Battery Box	CRCA sheet and rolled sections of carbon steel	151.5				142.4				96	96	9.1	0.1
Pantograph	High-strength tubular steel or alloy frame; Alloy of carbon copper	67.3						63.3		94	94	4.1	0.1
Vacuum	-												0
Carboy/ tumblehome	Aluminium/ Steel	91,628.9						86,131.1		94	94	5,497.7	54.4
Brake Control Unit	Aluminium/ Steel	656.7						604		92	92	52.5	0.39
Condenser	Copper, brass, Aluminium or stainless steel	185.2						174.1		94	94	11.1	0.11
Compressor	Aluminium	370.4						344.5		93	93	25.9	0.22
Coupler	Steel or Composites	757.7						704.6		93	93	53	0.45
Gangway Bellows	Silicone-coated fabric	8,822.8						1,235.2	1,676.3	14	33	5,823	5.24

[a,b,c] *The data is taken from these research and manufacturing sources (Silva and Kaewunruen, 2017; Steel Recycling Institute, 2017; United Nation Environmental Programme, 2013; The Aluminum Association, 2018; Novelis Recycling UK, 2018; Popular Mechanics, 2010).*

[d] *The word 'percentage' in the above table refers to the component of rolling stock parts (kg) compared with total weight of the passenger train (kg).*

Table 6: Component Analysis of HSR Train Components, Materials, and Percentage Values. (Cont.)

Component of rolling stock	**Type of material** [a]	**Weight (kg)** [b]	$m[P]_{Reuse}$ **(kg)** [c]	**$m[P]_R$ (kg)**	**$m[P]_E$ (kg)**	**$m[D]_R$ (kg)**	**$m[D]_E$ (kg)**	**$m[S]_R$ (kg)**	**$m[S]_E$ (kg)**	**R_{cyc} (%)**	**R_{cov} (%)**	**Waste (kg)**	**Percentage %** [d]
Battery	Polypropylene/ Polyethylene	252.6		199.5	48					79	98	5.1	0.2
Generator	Magnetic steel and copper	218.9		205.8						94	94	13.1	0.1
Alternator	Steel	505.1		474.8						94	94	30.3	0.03
Converter	Silicon Carbide	134.7		121.2	1.4					90	91	12.1	0.1
Bogie Frame	Steel plate/ Cast Steel	12,611.2						11,728.4		93	93	882.8	7.5
Bogie Transom	Steel plate/ Cast Steel	5,674.2						5,333.7		94	94	340.5	3.4
Brake Cylinder	Aluminium	1,262.8		1,187.						94	94	75.8	0.8
Primary Suspension Coil	Steel	505.1		469.7						93	93	35.4	0.3
Motor Suspension Tube	Steel	471.4		443.2						94	94	28.3	0.3
Gear box	Steel	2,828.7		2,659						94	94	169.7	1.7
Motor	Steel	4,411.4		4,146.7						94	94	248.8	2.6
Secondary Suspension Air Bag	Textile-reinforced rubber	151.5		21.2	27.3					14	32	103	0.1
Total Waste (kg)	15,661.90												
Recyclability Rate of Train	$\frac{150{,}104.8}{168{,}373} \times 100\% = 89.2\%$ **(1)**												
Recoverability Rate of Train	$\frac{2{,}964.8}{168{,}373} \times 100\% = 1.8\% + 89.2\% = 91\%$ **(2)**												

Table 7: Component Analysis of HSR Train Components, Materials, and Percentage Values. (Kaewunruen, 2016)

Component of rolling stock	**Type of material** ^{a}	**Weight (kg)** ^{b}	m[P]$_{Reuse}$ **(kg)** ^{c}	**m[P]$_{R}$ (kg)**	**m[P]$_{E}$ (kg)**	**m[D]$_{R}$ (kg)**	**m[D]$_{E}$ (kg)**	**m[S]$_{R}$ (kg)**	**m[S]$_{E}$ (kg)**	**R$_{cyc}$ (%)**	**R$_{cov}$ (%)**	**Waste (kg)**	**Percentage %** ^{d}
High Speed Rail		265,000											
Wheels	Steel R7	44,069.5				41,425.3				94	94	2,644.2	16.7
Window	Glass	4,902.5	4,412.3							90	94	490.3	1.9
Roof	Aluminium/ Steel	14,071.5						1,970	2,673.5	14	33	9,287.2	5.3
Table	Polypropylene/ Polyethylene / Composites	742	704.9		37.1					67	98	0	0.3
Vacuum	-												0
Seat	Polypropylene/ Polyethylene	7,950	5,302.7		2,623.5					67	98	79.5	3
Door	Aluminium/ Steel	7,340.5				6,900				94	94	440	2.7
Battery Box	CRCA sheet and rolled sections of carbon steel / Composites	318	149.5			149.5				94	94	19.1	0.1
Pantograph	High Strength tubular steel or alloy frame	2,438	2,291.7							94	94	137.5	0.9
	Alloy of carbon copper												
Main Transformer	Steel/ Aluminium	1,961		274.5	372.6					11	31	1,294.3	0.7
Thyristor Controlled Rectifier	Silicon Steel	238.5		33.4	45.3					13	32	157.4	0.1
Traction Inverters	Aluminium	1,590	1,431							90	90	159	0.6
Synchronous AC Traction Motor	Steel	4,902.5	4,607.9							94	94	294.1	1.9
Mechanical Transmission	Aluminium Alloys/ Steel	2,438		341.3	463.2					14	33	1,609.1	0.9
Impact Absorption Block	Aluminium	5,644.5				5,080.1				90	90	564.5	2.1

[a,b,c] *The data is taken from these research and manufacturing sources (Silva and Kaewunruen, 2017; Steel Recycling Institute, 2017; United Nation Environmental Programme, 2013; The Aluminum Association, 2018; Novelis Recycling UK, 2018; Popular Mechanics, 2010)*

[d] *The word 'percentage' in the above table refers to the component of rolling stock parts (kg) compared with total weight of the HSR.*

Table 7: Component Analysis of HSR Train Component, Material, and Percentage Values (Cont.)

Component of rolling stock	Type of material ^{a}	Weight (kg) ^{b}	m[P]$_{Reuse}$ (kg) ^{c}	m[P]$_{R}$ (kg)	m[P]$_{E}$ (kg)	m[D]$_{R}$ (kg)	m[D]$_{E}$ (kg)	m[S]$_{R}$ (kg)	m[S]$_{E}$ (kg)	R$_{cyc}$ (%)	R$_{cov}$ (%)	Waste (kg)	Percentage % ^{d}
Carboy/ Tumblehome	Aluminium/ Steel / Composites	20,749.5						19,504.5		94	94	12,45	7.8
Brake Control Unit	Aluminium/ Steel / Composites	97,944						14,691.6	18,609.4	15	36	64,643	37
Condenser	Copper, Brass, Aluminium or Stainless Steel	874.5						839.5		96	96	35	0.3
Compressor	Aluminium	212				167.5	40.3			79	98	4.3	0.1
Signalling Antennas	Aluminium	26.5	24.9							94	94	1.6	0.01
Coupler	Steel or Composites	2,146.5				1,996.2				93	93	139.7	0.8
Gangway Bellows	Silicon-coated fabric	8,559.5							7,703.6	0	90	856	3.2
Battery	Polypropylene, polyethylene or plastic-coated steel	609.5		481.5	115.8					79	98	12.2	0.2
Braking Rheostat/ Dynamic Brake	Aluminium/ Steel	1,139.5				159.5	114			14	24	866	0.4
Common Block/ DC circuit braker and the main filter capacitor	Insulation sheet, bimetallic, strip, silver point, ceramic RFI/ EMI suppression capacitors/ Composites	238.5	102.6							43	43	136	0.1
Generator	Magnetic steel and copper	1,457	1,151	175.7						79	91	29	0.6
Alternator	Steel/ Composites	397.5		314	75.5					79	98	8	0.2
Converter	Silicon Carbide	662.5		523.4	125.9					79	98	13.3	0.3
Bogie Frame	Steel plate/ Cast steel/ Composites	22,048						20,725.1		94	94	1,322.9	8.3
Bogie Transom	Steel plate/ Cast steel/ Composites	9,805						9,216.7		94	94	588.3	3.7

Table 7: Component Analysis of HSR Train Component, Material, and Percentage Values. (Cont.)

Component of rolling stock	**Type of material** [a]	**Weight (kg)** [b]	m[P]$_{Reuse}$ **(kg)** [c]	**m[P]$_{R}$ (kg)**	**m[P]$_{E}$ (kg)**	**m[D]$_{R}$ (kg)**	**m[D]$_{E}$ (kg)**	**m[S]$_{R}$ (kg)**	**m[S]$_{E}$ (kg)**	**R$_{cyc}$ (%)**	**R$_{cov}$ (%)**	**Waste (kg)**	**Percentage %** [d]
Brake Cylinder	Aluminium	2,438						2,291.7		94	94	146.3	1
Primary Suspension Coil	Steel	980.5						921.7		94	94	58.8	0.4
Motor Suspension Coil	Steel	927.5						871.9		94	94	55.7	0.4
Gearbox	Steel	5,512				5,181.3				94	94	330.7	2.1
Motor Suspension Coil	Steel	8,559.5				8,045.9				94	94	513.6	3.2
Secondary Suspension Air Bag	Textile reinforced Rubber	318				298.9				94	94	19.1	0.1
Total Waste (kg)	88,201.1												
Recyclability Rate of Train	$\frac{162,759}{265,000} \times 100\% = 61.4\%$ **(1)**												
Recoverability Rate of Train	$\frac{32,999.67}{265,000} \times 100\% = 12.5\% + 61.4\% = 73.9\%$ **(2)**												

Table 8: The summarisation of net present value (NPV) of freight train, passenger train and HSR during 30 years of operation

	Freight Train (£)					**Passenger Train (£)**					**HSR (£)**				
Year/ Discount rate	**0.0%**	**2.5%**	**5.0%**	**7.5%**	**10.0%**	**0.0%**	**2.5%**	**5.0%**	**7.5%**	**10.0%**	**0.0%**	**2.5%**	**5.0%**	**7.5%**	**10.0%**
0	-1,054,000.0	-1,054,000.0	-1,054,000.0	-1,054,000.0	-1,054,000.0	-1,250,000.0	-1,250,000.0	-1,250,000.0	-1,250,000.0	-1,250,000.0	13,181,524.4	13,181,524.4	13,181,524.4	13,181,524.4	13,181,524.4
1	110,570.0	107,873.2	105,304.8	102,855.8	100,518.2	193,500.0	188,780.5	184,285.7	180,000.0	175,909.1	3,422,160.0	3,338,692.7	3,259,200.0	3,183,404.7	3,111,054.5
2	110,570.0	105,242.1	100,290.2	95,679.8	91,380.2	193,500.0	184,176.1	175,510.2	167,441.9	159,917.4	3,422,160.0	3,257,261.2	3,104,000.0	2,961,306.7	2,828,231.4
3	110,570.0	102,675.2	95,514.5	89,004.5	83,072.9	193,500.0	179,684.0	167,152.6	155,759.9	145,379.4	3,422,160.0	3,177,815.8	2,956,190.5	2,754,703.9	2,571,119.5
4	110,570.0	100,171.0	90,966.2	82,794.9	75,520.8	193,500.0	175,301.4	159,192.9	144,892.9	132,163.1	3,422,160.0	3,100,308.1	2,815,419.5	2,562,515.2	2,337,381.3
5	110,570.0	97,727.8	86,634.5	77,018.5	68,655.3	193,500.0	171,025.8	151,612.3	134,784.1	120,148.3	3,422,160.0	3,024,690.8	2,681,351.9	2,383,735.1	2,124,892.1
6	110,570.0	95,344.2	82,509.0	71,645.1	62,413.9	193,500.0	166,854.4	144,392.7	125,380.6	109,225.7	3,422,160.0	2,950,917.8	2,553,668.5	2,217,428.0	1,931,720.1
7	110,570.0	93,018.7	78,580.0	66,646.6	56,739.9	193,500.0	162,784.8	137,516.8	116,633.1	99,296.1	3,422,160.0	2,878,944.2	2,432,065.2	2,062,723.7	1,756,109.2
8	110,570.0	90,749.9	74,838.1	61,996.8	51,581.7	193,500.0	158,814.5	130,968.4	108,495.9	90,269.2	3,422,160.0	2,808,726.1	2,316,252.6	1,918,812.8	1,596,462.9
9	110,570.0	88,536.5	71,274.4	57,671.5	46,892.5	193,500.0	154,940.9	124,731.8	100,926.4	82,062.9	3,422,160.0	2,740,220.6	2,205,954.8	1,784,942.1	1,451,329.9
10	110,570.0	86,377.1	67,880.4	53,647.9	42,629.5	193,500.0	151,161.9	118,792.2	93,885.0	74,602.6	3,422,160.0	2,673,385.9	2,100,909.4	1,660,411.3	1,319,390.8
11	110,570.0	84,270.3	64,648.0	49,905.0	38,754.1	193,500.0	147,475.0	113,135.4	87,334.9	67,820.6	3,422,160.0	2,608,181.4	2,000,866.1	1,544,568.6	1,199,446.2
12	110,570.0	82,215.0	61,569.5	46,423.3	35,231.0	193,500.0	143,878.1	107,748.0	81,241.8	61,655.1	3,422,160.0	2,544,567.2	1,905,586.7	1,436,808.0	1,090,405.6
13	110,570.0	80,209.7	58,637.6	43,184.4	32,028.2	193,500.0	140,368.8	102,617.2	75,573.7	56,050.1	3,422,160.0	2,482,504.6	1,814,844.5	1,336,565.6	991,277.9
14	110,570.0	78,253.4	55,845.4	40,171.6	29,116.5	193,500.0	136,945.2	97,730.6	70,301.2	50,954.6	3,422,160.0	2,421,955.7	1,728,423.3	1,243,316.8	901,161.7
15	110,570.0	76,344.8	53,186.1	37,368.9	26,469.6	193,500.0	133,605.1	93,076.8	65,396.4	46,322.4	3,422,160.0	2,362,883.6	1,646,117.5	1,156,573.8	819,237.9
16	110,570.0	74,482.7	50,653.4	34,761.8	24,063.3	193,500.0	130,346.4	88,644.6	60,833.9	42,111.2	3,422,160.0	2,305,252.3	1,567,730.9	1,075,882.6	744,761.7
17	110,570.0	72,666.1	48,241.3	32,336.5	21,875.7	193,500.0	127,167.2	84,423.4	56,589.7	38,282.9	3,422,160.0	2,249,026.6	1,493,077.1	1,000,821.0	677,056.1
18	110,570.0	70,893.7	45,944.1	30,080.5	19,887.0	193,500.0	124,065.6	80,403.2	52,641.5	34,802.7	3,422,160.0	2,194,172.3	1,421,978.2	930,996.3	615,505.6
19	110,570.0	69,164.6	43,756.3	27,981.9	18,079.1	193,500.0	121,039.6	76,574.5	48,968.9	31,638.8	3,422,160.0	2,140,655.9	1,354,264.9	866,043.1	559,550.5
20	110,570.0	67,477.7	41,672.7	26,029.6	16,435.5	193,500.0	118,087.4	72,928.1	45,552.4	28,762.5	3,422,160.0	2,088,444.8	1,289,776.1	805,621.5	508,682.3
21	110,570.0	65,831.9	39,688.3	24,213.6	14,941.4	193,500.0	115,207.2	69,455.3	42,374.4	26,147.8	3,422,160.0	2,037,507.1	1,228,358.2	749,415.3	462,438.4
22	110,570.0	64,226.2	37,798.3	22,524.3	13,583.1	193,500.0	112,397.3	66,148.0	39,418.0	23,770.7	3,422,160.0	1,987,811.8	1,169,865.0	697,130.5	420,398.6
23	110,570.0	62,659.7	35,998.4	20,952.8	12,348.3	193,500.0	109,655.9	62,998.0	36,667.9	21,609.7	3,422,160.0	1,939,328.6	1,114,157.1	648,493.5	382,180.5
24	110,570.0	61,131.4	34,284.2	19,491.0	11,225.7	193,500.0	106,981.4	59,998.1	34,109.7	19,645.2	3,422,160.0	1,892,027.9	1,061,102.0	603,249.8	347,436.8
25	110,570.0	59,640.4	32,651.6	18,131.2	10,205.2	193,500.0	104,372.1	57,141.1	31,729.9	17,859.3	3,422,160.0	1,845,880.9	1,010,573.3	561,162.6	315,851.7
26	110,570.0	58,185.8	31,096.8	16,866.2	9,277.4	193,500.0	101,826.4	54,420.1	29,516.2	16,235.7	3,422,160.0	1,800,859.4	962,450.8	522,011.7	287,137.9
27	110,570.0	56,766.6	29,616.0	15,689.5	8,434.0	193,500.0	99,342.8	51,828.6	27,457.0	14,759.7	3,422,160.0	1,756,936.0	916,619.8	485,592.3	261,034.4
28	110,570.0	55,382.1	28,205.7	14,594.9	7,667.3	193,500.0	96,919.9	49,360.6	25,541.4	13,417.9	3,422,160.0	1,714,083.9	872,971.2	451,713.8	237,304.0
29	110,570.0	54,031.3	26,862.6	13,576.6	6,970.3	193,500.0	94,556.0	47,010.1	23,759.4	12,198.1	3,422,160.0	1,672,277.0	831,401.2	420,198.8	215,730.9
30	110,570.0	52,713.4	25,583.4	12,629.4	6,336.6	193,500.0	92,249.7	44,771.5	22,101.8	11,089.2	3,422,160.0	1,631,489.7	791,810.6	390,882.6	196,119.0
NPV	2,263,100.0	1,260,262.5	645,731.9	251,874.4	-11,666.1	4,555,000.0	2,800,011.6	1,724,569.3	1,035,309.7	574,107.9	115,846,324.4	84,808,334.5	65,788,511.4	53,598,555.9	45,441,934.0

Acknowledgement

The first author is grateful to Australian Academy of Science (AAS) and Japan Society for the Promotion of Sciences (JSPS) for his JSPS Invitation Fellowship for Research (Long-term), Grant No. JSPS-L15701, at Railway Technical Research Institute (RTRI) and the University of Tokyo, Japan. The second author gratefully appreciates the Royal Thai Government for her PhD scholarship. The authors are sincerely grateful to European Commission for the financial sponsorship of the H2020-MSCA-RISE Project No. 691135 "RISEN: Rail Infrastructure Systems Engineering Network," which enables a global research network that tackles the grand challenge in railway infrastructure resilience and advanced sensing.

References

Ambrose, C.A., Singh, M.M., Harder, M.K. The material composition of shredder waste in the UK. Institute of Waste Management Scientific & Technical Inst. Waste Manage. Sci. Tech. Rev. (2000), pp. 27-35

Andrade C.E.S. and D'Agosto A.M. (2016). The Role of Rail Transit Systems in Reducing Energy and Carbon Dioxide Emissions: The Case of The City of Rio de Janero. Sustainability 2016,8, 150

Association of Train Operation Companies (ATOC) 'Baseline energy statement – energy consumption and carbon dioxide emission on the railway'; 2007.

Bowyer, J., Bratkovich, S. F., Kathryn F, Frank, M., Groot, H., Howwe, J., Pepke, E., Understanding Steel Recovery and Recycling Rates and Limitations to Recycling. 2015, 1, 1-10. [cited 2017 Aug 6] Available from: URL: http://www.dovetailinc.org/report_pdfs/2015/dovetailsteelrecycling0315.pdf.

Buekens, A. and Zhou, X. (2014) 'Recycling plastics from automotive shredder residues: A review', *Journal of Material Cycles and Waste Management*, pp. 398–414. doi: 10.1007/s10163-014-0244-z.

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 environmental 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

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

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 Management*, 34(10), pp. 1752–1762. doi: 10.1016/j.wasman.2013.11.014.

Craighill, A. L. and Powell, J. C. (1996) 'Lifecycle assessment and economic evaluation of recycling: A case study', *Resources, Conservation and Recycling*, 17(2), pp. 75–96. doi: 10.1016/0921-3449(96)01105-6.

Damm, A., Koberl, J., Prettenthaler, F., Rogler, N., Toglhofer, C., (2016) 'Impacts of +2°C global warming on electricity demand in Europe', *Climate Services*. doi: 10.1016/j.cliser.2016.07.001.

Das, S. (2011) 'Life cycle assessment of carbon fiber-reinforced polymer composites', *International Journal of Life Cycle Assessment*, 16(3), pp. 268–282. doi: 10.1007/s11367-011-0264-z.

Dauguet, M., Mantaux, O., Perry, N., Zhao, Y.F., (2015) 'Recycling of CFRP for high value applications: Effect of sizing removal and environmental analysis of the Super Critical Fluid Solvolysis', in *Procedia CIRP*, pp. 734–739. doi: 10.1016/j.procir.2015.02.064.

Delogu, M., Del Pero, F., Berzi, L., Pierini, M., Bonaffini, D., 2017. "End-of-Life in the railway sector: Analysis of recyclability and recoverability for different vehicle case studies", Waste Management, Volume 60, 2017, Pages 439-450, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2016.09.034

Department for Transport. Transport Statistics Great Britain 2015 [serial online] 2015 [cited 2018 Jul 23]. Available from URL: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/489894/tsgb-2015.pdf

European Environment Agency (EEA). Annual report 2011 and Environment statement 2012. ISSN 1561-2120. EEA. ISBN 978-92-9213-322-1. Copenhagen, 2012.

European commission. Guidance on the interpretation of key provision of Directive 2008/98/EC on waste. [Serial online] 2008 [cited 2018 Jul 23] Available from URL: http://ec.europa.eu/environment/waste/framework/pdf/guidance_doc.pdf

European Commission. Statistical pocketbook 2015 - Transport [serial online] 2015 [cited 2018 Oct 25] Available from: URL: http://ec.europa.eu/transport/facts-fundings/statistics/pocketbook-2015_en.htm

Eurostat. Transport Database - Eurostat [serial online] 2016 [cited 2018 Oct 25] Available from: URL: http://ec.europa.eu/eurostat/web/transport/data/database

Fleiter, T., Worrell, E. and Eichhammer, W. (2011) ‘Barriers to energy efficiency in industrial bottom-up energy demand models - A review’, *Renewable and Sustainable Energy Reviews*, pp. 3099–3111. doi: 10.1016/j.rser.2011.03.025.

Gent, M. R., Menendez, H., Muriiz, H., Tomo, S., (2015) ‘Recycling of a fine, heavy fluff automobile shredder residue by density and differential fragmentation’, *Waste Management*, 43, pp. 421–433. doi: 10.1016/j.wasman.2015.06.010.

Giorgetti, A., Girgenti, A., Citti, P., Delogu, M., (2016) ‘A novel approach for axiomatic-based design for the environment’, in *Axiomatic Design in Large Systems: Complex Products, Buildings and Manufacturing Systems*, pp. 131–148. doi: 10.1007/978-3-319-32388-6_5.

Guo, M. Z., Tu, Z., Poon, C. S., Shi, C., (2018) ‘Improvement of properties of architectural mortars prepared with 100% recycled glass by CO2curing’, *Construction and Building Materials*, 179, pp. 138–150. doi: 10.1016/j.conbuildmat.2018.05.188.

Haddad, C., Perilhon, C., Danlos, A., Francois, M. X., Descombes, G. (2014) ‘Some efficient solutions to recover low and medium waste heat: Competitiveness of the thermoacoustic technology’, in *Energy Procedia*, pp. 1056–1069. doi: 10.1016/j.egypro.2014.06.125.

El Hanandeh, A. (2015) ‘Energy recovery alternatives for the sustainable management of olive oil industry waste in Australia: Life cycle assessment’, *Journal of Cleaner Production*, 91, pp. 78–88. doi: 10.1016/j.jclepro.2014.12.005.

Hwang, I. H., Yokono, S. and Matsuto, T. (2008) ‘Pretreatment of automobile shredder residue (ASR) for fuel utilization’, *Chemosphere*, 71(5), pp. 879–885. doi: 10.1016/j.chemosphere.2007.11.035.

International Environmental Product Declaration (EPD) System, 2013. Product Category Rules (PCR) for Preparing an EPD for Rail Vehicles Version 2.0

ISO/TC267. Facility management. Switzerland: International Organisation for Standardization; 2015.

ISO/TC269/SC2. Standard Catalogue (Rolling Stock). Switzerland: International Organisation for Standardization; 2015.

ISO/TC269/SC2/WG4. Recyclability and recoverability of rolling stock. Birmingham: International Organisation for Standardization; 2018.

ISO22628:2002. Road Vehicles-Recyclability and Recoverability-Calculation Method. Switzerland: International Organisation for Standardization; 2003.

Jeong, I.-T. and Lee, K.-M. (2009) ‘Assessment of the ecodesign improvement options using the global warming and economic performance indicators’, *Journal of Cleaner Production*, 17(13), pp. 1206–1213. doi: 10.1016/j.jclepro.2009.03.017.

Kaewunruen S and Lee CK (2017) Sustainability Challenges in Managing End-of-Life Rolling Stocks. *Front. Built Environ.* 3:10. doi: 10.3389/fbuil.2017.00010

Kanafani, A., Wang, R. and Griffin, A. (2012) ‘The Economics of Speed – Assessing the performance of High Speed Rail in Intermodal Transportation’, *Procedia - Social and Behavioral Sciences*, 43, pp. 692–708. doi: 10.1016/j.sbspro.2012.04.143.

Khalil, Y. F. (2018) ‘Comparative environmental and human health evaluations of thermolysis and solvolysis recycling technologies of carbon fiber reinforced polymer waste’, *Waste Management*, 76, pp. 767–778. doi: 10.1016/j.wasman.2018.03.026.

Kojima, Y., Matsunaga, T. and Yamaguchi, S. (2017) ‘The impact of new Shinkansen lines (Tohoku Shinkansen (Hachinohe - Shin-Aomori) and Kyusyu Shinkansen (Hakata - Shin-Yatsushiro))’, in *Transportation Research Procedia*, pp. 344–357. doi: 10.1016/j.trpro.2017.05.412.

Krinke, S., Boßdorf-Zimmer, B., Goldmann, D. The Volkswagen-Si Con Process: Eco-efficient solution for future end-of-life vehicle treatment. In: Proceedings LCE2006. Wolfsburg, Volkswagen AG, pp. 359–364; 2006.

Lawrence, T. (2003) ‘Recycling of rolling stock’, *Public Transport International*, 52(5), pp. 46–47. doi: 10.3390/environments4020039.

Lee, C. K., Kim, Y. K., Prutichaiwiboon, 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’, *Transportation Research Part D: Transport and Environment*, 15(4), pp. 197–203. doi: 10.1016/j.trd.2010.02.001.

Lee, C. K., Lee, J. Y., Choi, Y. H., Lee, K. M., (2016) ‘Application of the integrated ecodesign method using the GHG emission as a single indicator and its GHG recyclability’, *Journal of Cleaner Production*, 112, pp. 1692–1699. doi: 10.1016/j.jclepro.2014.10.081.

Lee, C.K., Kim, Y.K., Lee, J.Y., Choi, Y.H., Kim, C.Y (2014). Study on Improving the Environmental Performance of a Railway Vehicle through a Life Cycle Assessment of the Tilting Train. Journal of the Korean society for railway Vol.17. Issue 1. pp.1-6. doi: 10.7782/JKSR.2014.17.1.1

Levinson, D., Mathieu, J. M., Gillen, D., Kanafani, A., (1997) ‘The full cost of high-speed rail: an engineering approach’, *The Annals of Regional Science*, 31(2), pp. 189–215. doi: 10.1007/s001680050045.

Maout, L. E., and Kato, H. (2016). ‘Life Cycle Cost-Estimation Model for Building, Operating, and Maintaining High-Speed Rail Systems’ Asian Transport Studies, Volume 4, Issue 1, pp. 245–260. doi: https://doi.org/10.11175/eastsats.4.245

Martin, F., (1997) ‘Justifying a high-speed rail project: social value vs. regional growth’. The annals of regional science. Vol 31. Issue 2. pp 155-174

Matsuoka, S. (2003) ‘Recyclability of stainless steel railway vehicles’, in *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, pp. 279–284. doi: 10.1243/095440903322712883.

Meinshausen, M., Jeffery, *L.*, Guetschow., J., du Pont, Y. R., Rogelj, J., Schaeffer, M., Hohne, N., Oberthur, S., Meinshausen, N., (2015) ‘National post-2020 greenhouse gas targets and diversity-aware leadership’, *Nature Climate Change*, 5(12), pp. 1098–1106. doi: 10.1038/nclimate2826.

Merkisz, J., Jacyna, M., Merkisz-Guranowska, A., Pielecha, J., (2014) ‘Exhaust emissions from modes of transport under actual traffic conditions’, *WIT Transactions on Ecology and the Environment*, 190 VOLUME, pp. 1139–1150. doi: 10.2495/EQ141062.

Miller, L., Soulliere, K., Sawyer-Beaulieu, S., Tseng, S., Tam, E., (2014) ‘Challenges and alternatives to plastics recycling in the automotive sector’, *Materials*, pp. 5883–5902. doi: 10.3390/ma7085883.

Nakamura, S., Y. Kondo, K. Matsubae, K. Nakajima, T. Tasaki, and T. Nagasaka. 2012. *'Quality- and dilution losses in the recycling of ferrous materials from end-of-life passenger cars: Input-output analysis under explicit consideration of scrap quality'*. Environmental Science & Technology 46(17): 9266–9273.

Network Rail. Recycled materials directs from the UK’s railways. [serial online] 2016 [cited 2018 Jul 23] Available from: URL: https://www.railwayrecycling.co.uk/railway-parts-components.html

Novelis Recycling UK. ‘No Other Material Offers the Versatility and Environmental Benefits of Aluminum’. [serial online] 2018 [cited 2018 Jul 23] Available from: URL: http://www.novelisrecycling.co.uk/novelis-recycling/why-recycle-Aluminum/

Nunes, L. J. R., Godina, R., Matias, J. C.O., Catalao, J.P.S., (2018) ‘Economic and environmental benefits of using textile waste for the production of thermal energy’, *Journal of Cleaner Production*, 171, pp. 1353–1360. doi: 10.1016/j.jclepro.2017.10.154.

Ohno, H., Matsubae, K., Nakajima, K., Kondo, Y., Nakamura, S., Nagasaka, T., 2015. *'Toward the efficient recycling of alloying elements from end of life vehicle steel scrap'*. Resources, Conservation and Recycling 100, 11-20. https://doi.org/10.1016/j.resconrec.2015.04.001

Ohno, H., Matsubae, K., Nakajima, K., Nakamura, S., Nagasaka, T., 2014. *'Unintentional Flow of Alloying Elements in Steel during Recycling of End-of-Life Vehicles'*. Journal of Industrial Ecology n/a-n/a. https://doi.org/10.1111/jiec.12095

O'Mahony, J. F., de Kok IM, van Rosmalen, J., Habbema, J.D., Brouwer, W., van Ballegooijen, M., (2011) 'Practical implications of differential discounting in cost-effectiveness analyses with varying numbers of cohorts', *Value in Health*, 14(4), pp. 438–442. doi: 10.1016/j.jval.2010.09.009.

Passarini, F., Ciacci, L., Santini, A., Vassura, I., Morselli, L., (2014) 'Aluminium flows in vehicles: Enhancing the recovery at end-of-life', *Journal of Material Cycles and Waste Management*, 16(1), pp. 39–45. doi: 10.1007/s10163-013-0175-0.

Del Pero, F., Delogu, M., Pierini, M., Bonaffini, D., 2015. '*Life Cycle Assessment of a heavy metro train*'. J. Clean. Prod. 87, 787-799.

Pizer, W. A. and Popp, D. (2008) 'Endogenizing technological change: Matching empirical evidence to modeling needs', *Energy Economics*, 30(6), pp. 2754–2770. doi: 10.1016/j.eneco.2008.02.006.

Purdy, A., Pathare, P. B., Wang, Y., lRoskilly, A. P., Huang, Y. (2018) 'Towards sustainable farming: Feasibility study into energy recovery from bio-waste on a small-scale dairy farm', *Journal of Cleaner Production*, 174, pp. 899–904. doi: 10.1016/j.jclepro.2017.11.018.

Ravi, V. (2012) 'Selection of third-party reverse logistics providers for End-of-Life computers using TOPSIS-AHP based approach', *International Journal of Logistics Systems and Management*, 11(1), p. 24. doi: 10.1504/IJLSM.2012.044048.

Rezaei, F., Yunus, R. and Ibrahim, N. A. (2009) 'Effect of fiber length on thermomechanical properties of short carbon fiber reinforced polypropylene composites', *Materials and Design*, 30(2), pp. 260–263. doi: 10.1016/j.matdes.2008.05.005.

Roh, S. A., Kim, W. H., Yun, J. H., Min, T. J., Kwak, Y. H., Seo, Y. C., (2013) 'Pyrolysis and gasification-melting of automobile shredder residue', *Journal of the Air and Waste Management Association*, 63(10), pp. 1137–1147. doi: 10.1080/10962247.2013.801373.

Ruffino, B., Fiore, S. and Zanetti, M. C. (2014) 'Strategies for the enhancement of automobile shredder residues (ASRs) recycling: Results and cost assessment', *Waste Management*, 34(1), pp. 148–155. doi: 10.1016/j.wasman.2013.09.025.

de Rus, G. (2009) 'The Economic Effects of High Speed Rail Investment', in *Competitive Interaction Between Airports, Airlines and High-Speed Rail*, pp. 165–200.

Serrano, L., Lewandrowski, T., Liu, P., Kaewunruen, S., (2017) 'Environmental Risks and Uncertainty with Respect to the Utilization of Recycled Rolling Stocks', *Environments*, 4(3), p. 62. doi: 10.3390/environments4030062.

Smink, C. K. (2007) 'Vehicle recycling regulations: lessons from Denmark', *Journal of Cleaner Production*, 15(11–12), pp. 1135–1146. doi: 10.1016/j.jclepro.2006.05.028.

Sol-Sánchez, M., Moreno-Navarro, F. and Rubio-Gámez, M. C. (2014) 'Viability of using end-of-life tire pads as under sleeper pads in railway', *Construction and Building Materials*, 64, pp. 150–156. doi: 10.1016/j.conbuildmat.2014.04.013.

Sommerhuber, P. F., Wenker, J. L., Ruter, S., Krause, A., (2017) 'Life cycle assessment of wood-plastic composites: Analysing alternative materials and identifying an environmental sound end-of-life option', *Resources, Conservation and Recycling*, 117, pp. 235–248. doi: 10.1016/j.resconrec.2016.10.012.

Song, J.-S. and Lee, K.-M. (2010) 'Development of a low-carbon product design system based on embedded GHG emissions', *Resources, Conservation and Recycling*, 54(9), pp. 547–556. doi: 10.1016/j.resconrec.2009.10.012.

The Railway Technical Website. Railway Finance. Complete Rail Project [serial online] 2018 [cited 2018 Jul 23] Available from: URL: http://www.railway-technical.com/operations/railway-finance.html

The Railway Technical Website. Rolling Stock Manufacturing. Rolling stock index [serial online] 2018 [cited 2018 Jul 23] Available from: URL: http://www.railway-technical.com/trains/rolling-stock-index-l/

Tiwari, K.N. (1994). Single Versus Multiple Discount Rates in Investment Theory. Journal of Financial and Strategic Decision. Vol.7. Number 2.

Transport Watch UK. ‘Facts Sheet 9: Rail versus road: Passenger Rolling Stock costs’. [serial online] 2011 [cited 2018 Jul 23] Available from: URL: http://www.transport-watch.co.uk/facts-sheet-9-rail-versus-road-passenger-rolling-stock-costs.

UNEP and Reuter, M. (2013) *Metal Recycling: Opportunities, Limits, Infrastructure, United Nations Environmental Programme*. doi: 978-92-807-3267-2.

UNFCCC. Adoption of the Paris Agreement. Decision 1/CP.21. [serial online] 2016 [cited 2018 Jul 23] Available from: URL: https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf

UNIFE Sustainable Transport Committee Topical Group: Life Cycle Assessment, Recyclability and Recoverability Calculation Method Railway Rolling Stock, 2013

United Nation Environmental Programme. Metal Recycling: Opportunities, Limits, Infrastructure; A Report of the Working Group on the Global Metal Flows to the Inter-national Resource Panel; UNEP: Nairobi, Kenya, 2013.

UK Department of Transport. Retrieved from Guidance on Measuring and Reporting Greenhouse Gas (GHG) Emissions from Freight Transport Operations: [serial online] 2014 [cited 2018 Jul 23] Available from: URL: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/218574/ghg-freight-guide.pdf

Venier, F. and Yabar, H. (2017) ‘Renewable energy recovery potential towards sustainable cattle manure management in Buenos Aires Province: Site selection based on GIS spatial analysis and statistics’, *Journal of Cleaner Production*, 162, pp. 1317–1333. doi: 10.1016/j.jclepro.2017.06.098.

Verma, R., Vinoda, K.S., Papireddy, M., Gowda, A.N.S., (2016) ‘Toxic Pollutants from Plastic Waste- A Review’, *Procedia Environmental Sciences*, 35, pp. 701–708. doi: 10.1016/j.proenv.2016.07.069.

Wang, Y., He, Yu, Yan, B., Ma, W., Han, M., (2012) ‘Collaborative Emission Reduction of Greenhouse Gas Emissions and Municipal Solid Waste (msw) Management-Case Study of Tianjin’, *Procedia Environmental Sciences*, 16, pp. 75–84. doi: 10.1016/j.proenv.2012.10.011.

World Steel Association. Life Cycle of Steel. Retrieved from World Steel Association: [serial online] 2016 [cited 2018 Jul 23] Available from: URL: https://www.worldsteel.org/steel-by-topic/life-cycle-assessment.html

Woodburn, A. (2017) ‘The impacts on freight train operational performance of new rail infrastructure to segregate passenger and freight traffic’, *Journal of Transport Geography*, 58, pp. 176–185. doi: 10.1016/j.jtrangeo.2016.12.006.

Worrell, E., Ramesohl, S. and Boyd, G. (2004) ‘ADVANCES IN ENERGY FORECASTING MODELS BASED ON ENGINEERING ECONOMICS’, *Annual Review of Environment and Resources*, 29(1), pp. 345–381. doi: 10.1146/annurev.energy.29.062403.102042.

Worrell, E. and Reuter, M. A. (2013) *Handbook of Recycling*, *Journal of Chemical Information and Modeling*. doi: 10.1017/CBO9781107415324.004.

Yeh, S., Mishra, G.S., Fulton, L., Kyle, P., McCollum, D. L., Miller, J., Cazzola, P., Teter, J., (2017) ‘Detailed assessment of global transport-energy models’ structures and projections’, *Transportation Research Part D: Transport and Environment*, 55, pp. 294–309. doi: 10.1016/j.trd.2016.11.001.

Zhang, S., Worrell, E. and Crijns-Graus, W. (2015) ‘Cutting air pollution by improving energy efficiency of China’s cement industry’, in *Energy Procedia*, pp. 10–20. doi: 10.1016/j.egypro.2015.12.191.