

Article

# Environmental Risks and Uncertainty with Respect to the Utilization of Recycled Rolling Stocks

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**Abstract:** The railway industry is one of the most important sectors driving growth of regional economies worldwide. The industry has long dealt with both infrastructure and rolling stock. Many of these have reached the end of their lives. This paper highlights the rail policy for managing end-of-life rail vehicles. Initially when manufacturing rolling stock, different materials are considered in design and manufacture such as steel, aluminum, copper, polymers, glass. Based on the high economic and carbon costs of these materials, it is worthwhile to reuse or recycle them after their end-of-life cycle. In this study, three types of trains have been evaluated for comparison: freight, passenger and high speed. The material breakdowns from rail vehicles are evaluated for feasible applications in terms of reusing or recycling train components. We consider every material, taking into account the process of production, remaining life, advantages, disadvantages and potential threats derived from using such residual materials. The key aspects are risks and uncertainty associated with chemical and physical processes, corrosion and its varieties, oxidation, impact on the environment, release of toxicity, and pollution to the soil. These negative effects can indeed harm people, children, and assets in the vicinity. This paper therefore highlights the possibilities of recycling residual materials derived from rolling stock waste and any danger to the environment and the community, so that hazardous waste management can be put in place at the right time. Such insight will better shape sustainability policy for rolling stock procurement in the future.

**Keywords:** rolling stock; environment; recycling; train components; steel; aluminum; copper; polymers; glass; sustainability

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## 1. Introduction

The rail manufacturing industry is one of the sectors responsible for environmental harm in the world. This is evidenced by the fact that the transport sector is responsible for 23.1% of man-made carbon dioxide in 2012, of which 3.6% was caused by the rail sector [1]. Production and transport of materials are two significant contributors towards environmental impacts. Therefore, it is important to thoroughly consider and analyze feasibility to minimize both sources and their environmental impacts. As a response to these, some key approaches have been developed by International Union of Railways [2].

Each piece of rolling stock has its own life expectancy and durability characteristics. Its system is always susceptible to wear due to the dynamic contact condition between wheels and rails, exposure to diverse environments, and natural aging of the materials from which components of trains are made. Since the economic and carbon costs of materials used to manufacture rolling stock are significant, it is essential to avoid discards of worn materials from trains or unusable waste from their components at the end of their life cycle. In many cases, the recovered materials can then be recycled or reused as sub-products in various branches of manufacturing [3,4].

It is found that there are a number of steps to manage emerging risks and to save materials from disposal at the end of its operation. To recover end-of-life components, a complete range of technical skills and competence are required, involving different recovery methods such as shredding and re-melting, dismantling, mechanical separation and recycling processes. These processes are described in next section of this paper. In addition, considerable impact on the environment could be caused by the railway sector. If not recycled, rail car bodies that are no longer in operation need to be decommissioned and dismantled and prepared for further recycling. This necessity also requires relevant decommission methods and frameworks (e.g., hazard and environmental risk framework using International Standard Organisation (ISO) 31000, inspection specifications based on recycling plants, transportation capacity, logistics legislations of local road/rail authorities, occupational safety procedure at the recycling plant, and so on) and can generate additional costs to asset owners. Hence, the life cycle of rolling stock and the possibilities to recycle should be taken into consideration, especially during the initial stages of procurement, design and manufacture of the rolling stock [5,6]. At the end of a vehicle life, there must be a proper disposal, after reusing, recycling, and recovery (or "RRR"). Reusing means "any operation by which components of end-of-life rolling stock are used for the same purpose for which they were designed"; recycling is a method of "processing the waste materials for the original purpose or for other purposes, excluding processing as a means of generating energy"; and recovery applies to the concept of "processing the waste materials for the original purpose or for other purposes, including processing as a means of generating energy" [7].

According to a European directive with respect to the "Management of End of Life Vehicles", it is noteworthy that the "recycle, reuse and recovery" rate must be at least 95%; and the "reuse and recovery" rate should be a minimum of 85% for passenger vehicles and light duty trucks of the gross vehicle weight not exceeding 3.5 tons [8–10]. Recyclability and recoverability rates can be calculated according to the automobile industry guideline, which is partially adopted for ISO calculation standard [11]. However, the voluntary policy for rail industry (such as the Union des Industries Ferroviaires Européennes (UNIFE) method) on waste management of rolling stock has not been either enacted or adopted because of the strong presence of stakeholders (i.e., manufacturers, sales), which discourages adoption by the public. Based on this, this paper is very timely to present a critical evaluation of recycling applications of rolling stocks and highlights potential risks and uncertainty to enhance the policy for recycling rolling stocks.

## 2. Methods and Materials

### 2.1. Rolling Stock Types

Rolling stocks can be grouped into freight stock and rail cars (passenger stock and high-speed rail cars). Primarily manufactured locomotives and rail motor cars haul rolling stocks (wagons and carriages) for long distances. They could carry heavy freight burdens, for example, commodities and raw materials. Passenger rail cars usually support lighter loads. The recent development and improvement of rolling stock design enables freight rail cars to carry even more goods and to allow more and more passengers to be transported long distances in a faster manner. It is important to differentiate the type of wasted rolling stocks since they experienced different operational parameters and environments. Their life cycles vary significantly and their components might have also been exposed to various hazardous materials.

### 2.1.1. Freight Trains

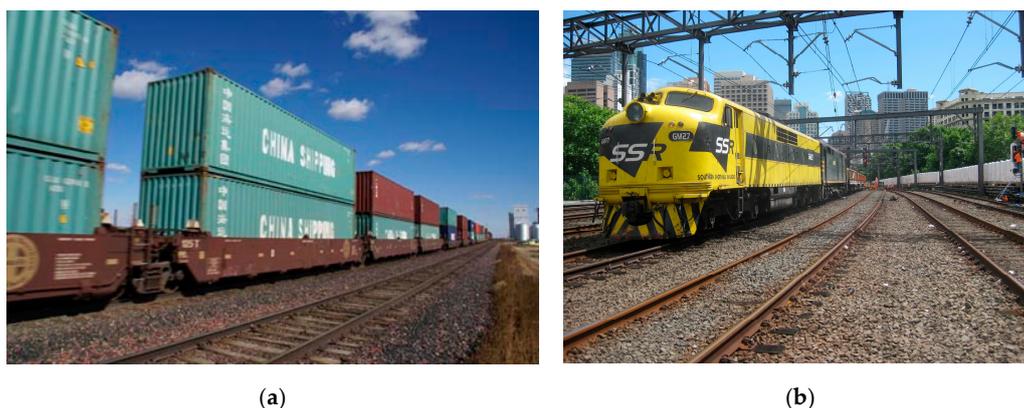
The freight logistics are a great engine for growing global and national economies around the world. Rail freight cars are the most common type of railway rolling stocks fabricated to transport heavy cargoes (e.g., goods and commodities). Locomotives are shunted onto long wagons in order to provide services for long distance and, typically, they have a constant speed performance.

#### Component Analysis of Freight Trains

Components of a freight trains are shown below in Table 1. This describes which materials are commonly used to manufacture every part of a freight train. The percentage by mass (%) of the materials as part of the train is also shown. Figure 1 shows an example of freight rolling stocks. Cargo railcars are the easiest to recycle, since around 60 to 80% of their mass is composed of cast iron and steel. Freight trains are, basically, divided into two parts: the locomotive and the cargo railcars. The component analysis and their respective percentages of recycling are recorded in the Table below:

**Table 1.** Component analysis of freight trains. Some component weights are available from the industry sources. All data has been taken from the parts manufacturers' documents available on Union des Industries Ferroviaires Européennes (UNIFE) and train companies' websites.

| Freight Train Components             |   |   |                        |
|--------------------------------------|---|---|------------------------|
| Components of Train [12–17]          | Type of Material  | Recovery Rate (%)   | Percentage (% by Mass) |
| Diesel Engine (large cylinder block) | Cast iron/aluminum alloys   | 80–90/80–95   | 4.22                   |
| Main Alternator                      | Steel   | 90–98   | 0.21                   |
| Auxiliary Alternator                 | Steel   | 90–98   | 0.14                   |
| Motor Blower                         | Cast iron/aluminum alloys/steel   | 80–90/80–95/90–98   | 0.18                   |
| Air Intakes                          | steel/aluminum  | 90–98/80–95   | 0.11                   |
| Rectifiers/Inverters                 | Heavy-gauge aluminum sheet metals with powder-coated or anodized and stainless fittings | 80–95   | 0.49                   |
| Battery                              | Polypropylene, polyethylene or plastic-coated steel                                     | 50–70   | 0.09                   |
| Traction Motor                       | Steel   | 90–98   | 0.70                   |
| Pinion/Gear                          | Steel   | 90–98   | 0.56                   |
| Fuel Tank                            | Steel/aluminum  | 90–98/80–95   | 0.35                   |
| Air Reservoirs                       | Steel/aluminum  | 90–98/80–95   | 0.09                   |
| Air Compressor                       | Aluminum  | 80–95   | 0.98                   |
| Drive Shaft                          | Aluminum alloys   | 80–95   | 0.60                   |
| Gearbox                              | Steel   | 90–98   | 2.32                   |
| Radiator and Radiator Fan            | Aluminum, brass or copper cores   | Aluminum (80–95), brass or copper cores (60–80)                     | 0.02                   |
| Turbo Charging                       | Cast aluminum   | 80–95   | 0.11                   |
| Truck Frame or Bogie Frame           | Steel plate/cast steel  | 90–98   | 18.98                  |
| Wheels                               | Steel R7 (carbon content % <0.52)   | 90–98   | 20.02                  |
| Roof                                 | Steel   | 90–98   | 2.11                   |
| Door                                 | Aluminum/Steel  | 80–95/90–98   | 0.53                   |
| Car body/tumblehome                  | Steel   | 90–98   | 45.67                  |
| Sand Box                             | Cast iron   | 80–90   | 0.53                   |
| Battery Box                          | CRCA (cold rolled close annealed) sheet and rolled sections of carbon steel             | CRCA sheet and rolled sections of carbon steel (90–98)              | 0.18                   |
| Brake Control Unit                   | Aluminum/cast iron/reinforced carbon-carbon   | 80–95/80–90   | 0.08                   |
| Brake Cylinder                       | Aluminum  | 80–95   | 0.34                   |
| Condenser                            | Copper, brass, aluminum, or stainless steel   | Copper (60–80), brass, aluminum (80–95), or stainless steel (80–90) | 0.42                   |



**Figure 1.** Freight train. (a) freight wagons; (b) locomotive.

### 2.1.2. Passenger Rail Cars

Passenger rail cars are defined as trains designed to carry mainly passengers. They travel either over long distances or within urban and suburban areas. Generally, they stop frequently at each intermediate station along its route. Passenger rail transport includes metro systems, fast suburban transport and subways. They can also transport baggage for railway post office, or many other purposes.

#### Component Analysis for Passenger Trains

Components of a passenger train are shown below in Table 2. It describes which materials are used to produce every part of a passenger train. The percentage by mass (%) of the materials as part of the train is also shown. Figure 2 shows an example of a passenger train.

**Table 2.** Component analysis of passenger trains. Some component weights are available from industry sources. All data has been taken from the parts manufacturers' documents available on Union des Industries Ferroviaires Européennes (UNIFE) and train companies' websites.

| Passenger Train Components  |   |   |                        |
|-----------------------------|---|---|------------------------|
| Components of Train [17–19] | Type of Material  | Recovery Rate (%)   | Percentage (% by mass) |
| Wheels                      | Steel R7 (carbon content % <0.52)                                   | 90–98   | 13.48                  |
| Window                      | Glass   | 50–100  | 0.37                   |
| Roof                        | Aluminum/steel  | 80–95/90–98   | 4.30                   |
| Table                       | Polypropylene, polyethylene   | 50–70   | 0.22                   |
| Seat                        | Polypropylene, polyethylene   | 50–70   | 1.87                   |
| Door                        | Aluminum/steel  | 80–95/90–98   | 1.80                   |
| Battery Box                 | CRCA sheet and rolled sections of carbon steel                      | CRCA sheet and rolled sections of carbon steel (90–98)                              | 0.09                   |
| Pantograph                  | High-strength tubular steel or alloy frame; alloy of carbon, copper | High-strength tubular steel or alloy frame (90–98); alloy of carbon, copper (60–80) | 0.04                   |
| Car body/frame/tumblehome   | Aluminum/steel  | 80–95/90–98   | 54.42                  |
| Brake Control Unit          | Aluminum/cast iron/reinforced carbon-carbon                         | 80–95/80–90   | 0.39                   |
| Condenser                   | Copper, brass, aluminum, or stainless steel                         | Copper (60–80), brass, aluminum (80–95), or stainless steel (80–90)                 | 0.11                   |
| Compressor                  | Aluminum  | 80–95   | 0.22                   |
| Coupler                     | Steel or composites   | 90–98   | 0.45                   |

Table 2. Cont.

| Passenger Train Components     |   |   |                        |
|--------------------------------|---|---|------------------------|
| Components of Train [17–19]    | Type of Material                                    | Recovery Rate (%)                         | Percentage (% by mass) |
| Gangway Bellows                | Silicone-coated fabric                              | 50–70                                     | 5.24                   |
| Electrical Auxiliary Equipment |   |   |                        |
| Battery                        | Polypropylene, polyethylene or plastic-coated steel | 50–70                                     | 0.15                   |
| Generator                      | Magnetic steel and copper                           | Magnetic steel (90–98) and copper (60–80) | 0.13                   |
| Alternator                     | Steel   | 90–98                                     | 0.03                   |
| Converter                      | Silicon carbide                                     | 50–70                                     | 0.08                   |
| Bogie Components               |   |   |                        |
| Bogie Frame                    | Steel plate/cast steel                              | 90–98                                     | 7.49                   |
| Bogie Transom                  | Steel plate/cast steel                              | 90–98                                     | 3.37                   |
| Brake Cylinder                 | Aluminum  | 80–95                                     | 0.75                   |
| Primary Suspension Coil        | Steel   | 90–98                                     | 0.30                   |
| Motor Suspension Tube          | Steel   | 90–98                                     | 0.28                   |
| Gearbox                        | Steel   | 90–98                                     | 1.68                   |
| Motor                          | Steel   | 90–98                                     | 2.62                   |
| Secondary Suspension Air Bag   | Textile-reinforced rubber                           | 50–70                                     | 0.09                   |



(a)



(b)

Figure 2. Passenger rail cars: (a) Virgin Trains, (b) London Midlands.

### 2.1.3. High-Speed Rail

Operating at significantly higher speed than traditional rail cars, high-speed rail cars use an integrated infrastructure running over specialized or dedicated tracks. The dedicated track improves the running stability of the vehicle. High-speed trains can reach operational velocity over 300 km/h. Countries such as the United Kingdom, Japan, Korea, China, France, Germany and Austria are locations where this type of rolling stock has been developed.

#### Component Analysis for High Speed Trains

Components of high-speed trains are shown below in Table 3. It portrays which materials are used to assemble every part of a high-speed train. The percentage by mass (%) of the materials as part of the train is also shown. Figure 3 shows an example of a high-speed passenger train.

**Table 3.** Component analysis of high-speed trains (calculated from industry sources). Some component weights are available from the industry sources. All data has been taken from the parts manufacturers' documents available on Union des Industries Ferroviaires Européennes (UNIFE) and train companies' websites. The furniture weights have been estimated from the drawing.

| High Speed Train Components                                   |   |   |                        |
|---|---|---|------------------------|
| Components of Train [17–21]                                   | Type of Material  | Recovery Rate (%)   | Percentage (% by mass) |
| Wheels  | Steel R7 (carbon content % <0.52)   | 90–98   | 16.63                  |
| Window  | Glass   | 50–100  | 1.85                   |
| Roof  | Aluminum/steel  | 80–95/90–98   | 5.31                   |
| Seat  | Polypropylene, polyethylene   | 50–70   | 3.00                   |
| Table   | Polypropylene, polyethylene   | 50–70   | 0.28                   |
| Door  | Aluminum/steel  | 80–95/90–98   | 2.77                   |
| Battery Box   | CRCA sheet and rolled sections of carbon steel  | CRCA sheet and rolled sections of carbon steel (90–98)                              | 0.12                   |
| “Grand Plongeur Unique” Pantograph                            | High-strength tubular steel or alloy frame; alloy of carbon, copper   | High-strength tubular steel or alloy frame (90–98); alloy of carbon, copper (60–80) | 0.92                   |
| Main Transformer  | Steel/aluminum  | 90–98/80–95   | 0.74                   |
| Thyristor controlled-rectifier bridge                         | Silicon steel   | 90–98   | 0.09                   |
| Traction Inverters  | Aluminum  | 80–95   | 0.60                   |
| Synchronous AC traction motor                                 | Steel   | 90–98   | 1.85                   |
| Mechanical Transmission                                       | Aluminum alloys/steel   | 80–95/90–98   | 0.92                   |
| Impact absorption block                                       | Aluminum  | 80–95   | 2.13                   |
| Car body/tumblehome   | Aluminum/steel  | 80–95/90–98   | 7.83                   |
| Brake Control Unit  | Aluminum/cast iron/reinforced carbon-carbon   | 80–95/80–90   | 36.96                  |
| Condenser   | Copper, brass, aluminum, or stainless steel   | Copper (60–80), brass, aluminum (80–95), or stainless steel (80–90)                 | 0.33                   |
| Compressor  | Aluminum  | 80–95   | 0.08                   |
| Signaling Antennas  | Aluminum  | 80–95   | 0.01                   |
| Coupler   | Steel   | 90–98   | 0.81                   |
| Gangway Bellows   | Silicone-coated fabric  | 50–70   | 3.23                   |
| Electrical Auxiliary Equipment                                |   |   |                        |
| Battery   | Polypropylene, polyethylene or plastic-coated steel   | 50–70   | 0.23                   |
| Braking Rheostat/Dynamic Brake                                | Aluminum/steel  | 80–95/90–98   | 0.43                   |
| Common Block/DC circuit breaker and the main filter capacitor | Insulation sheet, bimetallic strip, silver point, ceramic RFI/EMI suppression capacitors<br>[Note: EMI is Electromagnetic Interference), which is also called RFI (Radio Frequency Interference)] | 60–85   | 0.09                   |
| Generator   | Magnetic steel and copper   | Magnetic steel (90–98) and copper (60–80)   | 0.55                   |
| Alternator  | Steel   | 90–98   | 0.15                   |
| Converter   | Silicon carbide   | 50–70   | 0.25                   |

Table 3. Cont.

| High Speed Train Components  |                           |                   |                        |
|------------------------------|---------------------------|-------------------|------------------------|
| Components of Train [17–21]  | Type of Material          | Recovery Rate (%) | Percentage (% by mass) |
| Bogie Components             |                           |                   |                        |
| Bogie Frame                  | Steel plate/cast steel    | 90–98             | 8.32                   |
| Bogie Transom                | Steel plate/cast steel    | 90–98             | 3.70                   |
| Brake Cylinder               | Aluminum                  | 80–95             | 0.92                   |
| Primary Suspension Coil      | Steel                     | 90–98             | 0.37                   |
| Motor Suspension Tube        | Steel                     | 90–98             | 0.35                   |
| Gearbox                      | Steel                     | 90–98             | 2.08                   |
| Motor                        | Steel                     | 90–98             | 3.23                   |
| Secondary Suspension Air Bag | Textile-reinforced rubber | 50–70             | 0.12                   |



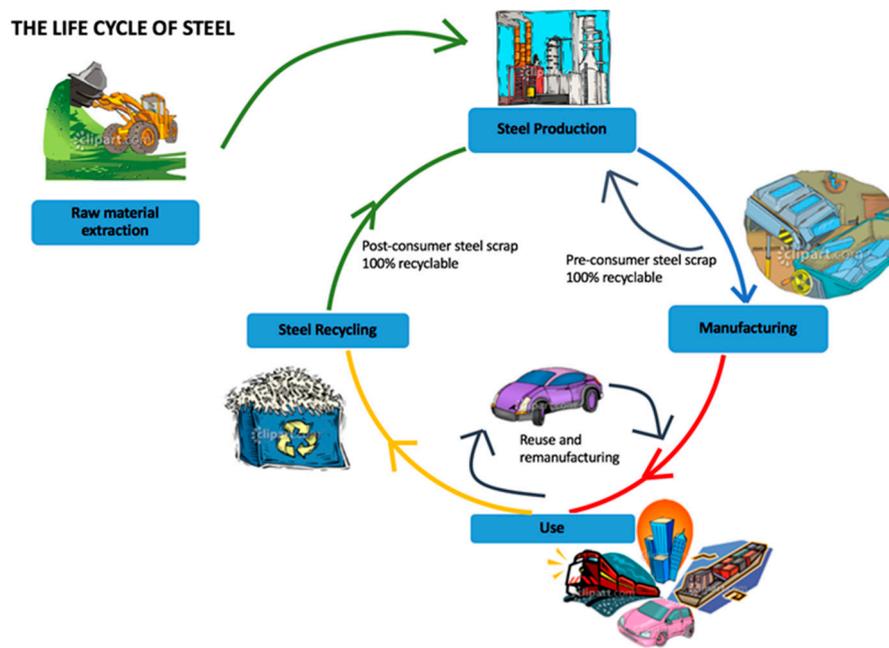
Figure 3. High-speed rail (Taiwan 700T).

### 3. Materials Deterioration Mechanisms and Analysis

A detailed analysis on the final disposal management for extended recovery is required in order to maximize the use of train components at the end of their operation [22]. Firstly, the deterioration processes of rolling stock components during their lives should be considered as one of the most important aspects in managing the end-of-life rolling stocks. The possibilities for recovery or recycling depend largely on material characterization and properties. The main material groups derived from end-of-life rail vehicles are evaluated below.

#### 3.1. Steel

One of the most important and versatile alloys is steel. Generally, steel is essential for the development of industrial products and built environments. Steel is used for a significant number of components that compose the main frame and body of rail car bodies. Its life cycle and deterioration must be identified prior to recycling, as shown in Figure 4 [23]. The production of the steel involves a large number of preparation activities. At the beginning of this process, raw material requires extraction from earth. However, after material production processes, the metal material is often used for a great variety of activities and industries [24]. All the value chain activities during the life cycle can be briefly systematized into five important processes: the extractive industry; metallurgy—which is part of the steel industry; the production of durable intensive goods of steel; the use until the disposal of such goods and products; and the collection, trade and recycling of steel contained in products put into disuse.



**Figure 4.** Life cycle of steel.

There are a number of different branches of industry which are necessary in steel production processes. One of these is the mining industry. This provides iron ore and manganese, coal and limestone. Together with water and charcoal, these form the base of the primary inputs used in steel mills. A steel mill is a part of the metallurgy process, which is used to convert ferrous ores and non-ferrous into metallurgical products. In the next phase, different types of steel are produced from the metals and become among the most important materials in construction and manufacture of railway assets. After being used, the obsolete steel products can generally be recovered and reused or recycled. Some steel parts can feed back to this extensive production chain, avoiding the consumption of raw materials, which are important natural non-renewable resources. In contrast, some steel can deteriorate over time. Corrosion can be basically defined as the surface deterioration of a metal or an alloy. It is caused by the influence of harsh environments to which steel elements are exposed. The corrosion process involves oxidation and reduction reactions, which convert metal or metallic components into oxide, hydroxide or salt. The carbon steel usually contains more than 97% iron and up to 2% carbon with the other remaining elements from its fabrication process. Air corrosion occurs when the metal combines with the oxygen in the air, producing the oxides. By not considering the action of the vapor restrained in the air (from water, for instance), this corrosion process occurs at a slow pace for the iron in ambient temperatures.

As mentioned in [24,25], the action corrosion occurs where the metal is directly in contact with substances that can attack steel integrity. Another type of deterioration of steel is biological corrosion, which is caused by microorganisms. The most common deterioration is galvanic corrosion, which occurs with the participation of water, and it is almost always related to the galvanic process. In such a condition, the presence of water enables formation of galvanic cells as shown in Figure 5.



**Figure 5.** Clockwise from left: corroded internal door pillar; floor plate corrosion; corroded kick plate; cracked external door.

### 3.2. Aluminum

The production of aluminum is a process which needs time and is highly energy intensive. However, the aluminum can be recycled infinitely, without losing its properties. That is why this material is widely used in the railway industry, as shown in Figure 6 [26,27]. Its production process begins with the mining of the raw bauxite. Then, the aluminum oxide is obtained from the bauxite and is later used in the production of the primary aluminum. The aluminum can be widely used among other materials in the manufacture of rolling stock. Since reduction in the impact of production processes on the environment is essential, recycling has become a major part of the sustainable development of aluminum products. Any aluminum recycling process can help promote the preservation of resources and the minimization of waste [28].



**Figure 6.** New train with aluminum train compartment.

Unlike other metals, most aluminum alloys have good resistance to corrosion. This material is resistant to the harmful impact of both atmospheric factors and chemical substances. The aluminum is protected from corrosion by surface oxidation. In this process, a thin film of aluminum oxide ( $\text{Al}_2\text{O}_3$ ) is generated. It firmly adheres to the surface and prevents the continuation of corrosion.

### 3.3. Copper

The life cycle of copper is quite similar to the alloy materials described previously. The production process of copper starts from the extraction of minerals. The obtained raw minerals are further processed to become concentrated as copper plates by the metallurgical industry. The copper plates with more than 99% purity are obtained after passing through the refining process. Semi-finished products produced from the plates are used widely to fabricate other components and parts, such as train components [29,30].

Similarly to iron, corrosion has a significant impact on the deterioration of copper. In this case, the material will change its color to a greenish one. It is found that the copper and its alloys are oxidized, creating a layer called “verdigris”, which is responsible for this green appearance [30]. This insight can help rolling stock engineers identify the prioritized area for maintenance, repair and refurbishment.

### 3.4. Polymer and Plastic

Polymer production also begins at the extraction of natural resources such as oil, vegetables, and vegetable oils. Then, the process continues with the refining, cracking and even distillation (in specific cases, if the oil is the raw material). Considering this, the raw material is transformed into monomers. Therefore, chemical processes create resins, which will later be transformed into the final products. Then polymers can be used in various forms, for example as components in trains (chairs, tables, panels, internal coating, etc.). Worn polymeric elements can be sent for disposal, or separated for recycling. Polymers could potentially be damaged by physical and/or chemical agents, which can react with the surface of the material. Various physical and chemical action processes can cause the degradation of polymers. One of these is the rise in temperature, which can cause oxidation and

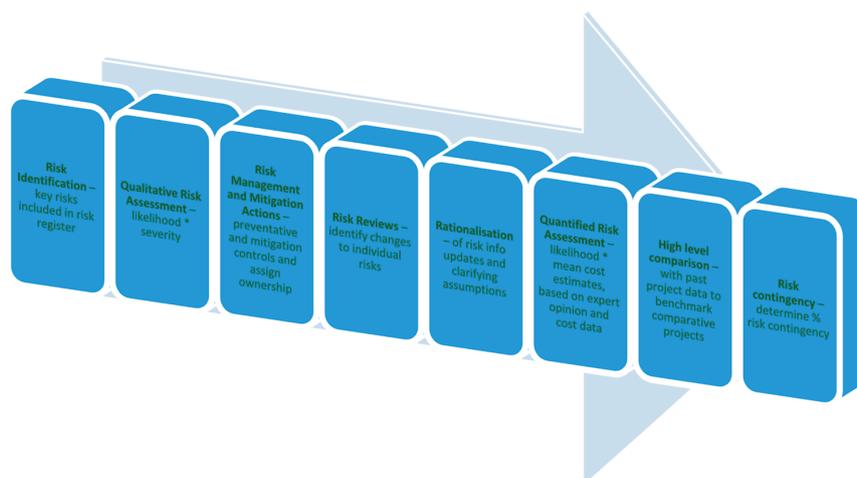
warping. Polymer elements are vulnerable in applications containing any physical force which can cause mechanical damage or breakage of the material. Chemical structures of polymers can be attacked by chemical agents or certain gases. This can cause oxidation, brittleness and fraying. The biological structure of polymers can also be attacked by microorganisms.

### 3.5. Glass

Glass is a material which can be used and reused several times. Its recovery rate ranges from 50% to 100%. Broken glass might be taken back to the recycling process and separated by color to avoid alterations in the visual standard of the final product. Raw glass is usually stored in gallons and it is submitted to electromagnets in order to eliminate contaminants. The material is taken to a water tank, because after the process it needs to be treated and recovered to avoid waste and minimize the contamination of the watercourse. After that, the glass passes through a special table, where impurities such as scrap metals, stones, plastics, and undesired glasses that were not retained are cleaned. Then, the glass is pressed and broken into uniform sizes and taken to vibrating sieves. In the last stage of production, the material is taken to a second electromagnet that separates metals, which could still be in shards. The glass is not biodegradable because it is composed of sand, sodium, lime and many admixtures. This material is able to survive up to 4000 years without being disintegrated by erosion or chemical agents. As a result, it is vital that careful treatment during all stages of rolling stock disassembling is arranged in order maximize the reuse and recycling ability.

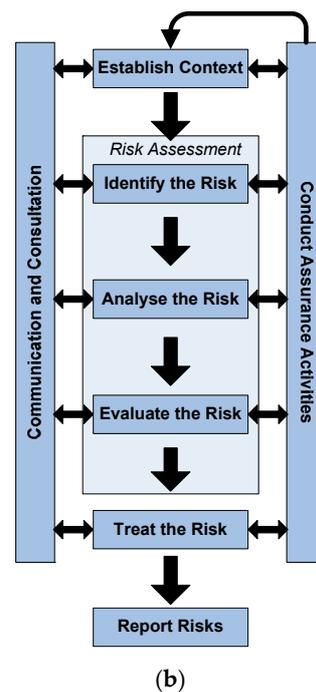
## 4. Risk Analysis Results

In general, railway organizations take risk management to be fundamental to its management practice and an essential part of organizational governance [31–34]. A consistent and structured approach using Enterprise Risk Management (ERM) framework has been established to effectively and efficiently manage risks, and to enable the organization to make better decisions, as per ISO 31000:2009 [35,36]. It also enables an integrated and holistic approach to be taken, which examines all aspects of risk, and enables railway sector to select and priorities those management actions, which will provide the greatest potential benefit to the public. A typical enterprise level and escalation of risk management can be illustrated in Figure 7. In this paper, the key focus is to identify environmental risks and to qualitatively assess them so that preventative measures can be put in place prior to the utilization of recycled materials derived from wasted rolling stocks. The insight from this study will form environmental management guidance for risk mitigation assurance in the railway sector.



(a)

Figure 7. Cont.



**Figure 7.** Risk management framework commonly adopted within the railway industry: (a) risk management process; (b) risk assurance policy development. The processes are in accordance with ISO31000. Ongoing risk management within a business unit is carried out through risk assessment and maintenance of operational, project, and safety risk registers. The direct and indirect risk systematic tools and templates are developed and structured in order to comprehensively identify, assess, mitigate, assure, monitor and review, and report risks, consequences and its potential. Risk communication and consultation are facilitated through competency-based authority, and all processes are recorded in auditable risk registers and risk ranking tables.

In recent years, it has been recognized that using recycled materials is very important and has to be prioritized. Engineers should consider the future possibility of recycling in the designing and planning processes of rolling stock manufacture. Appropriate planning and design can guarantee durability during the rolling stock's life cycle and also allow its recycling processes to take place. It should be possible to recycle and reuse train components using any suitable "end-of-life treatment". However, according to Figure 7, the environmental risk evaluation with respect to various utilizations and applications of recycled or reused rolling stock is also essential to create a non-hazardous and harmonized environment [4]. The emerging risks due to the utilization of wasted rolling stocks to the environment have been identified from the perspective of material risk analyses.

Recovery rates of some ferrous metals, such as steel and cast iron, are considerably high (as shown in data in Tables 1–3). Therefore, usual or adaptive reuses after the suitable treatment of these materials are possible [37]. In this case, the steel or the cast iron would have already passed through the processes of recovery, including shredding and re-melting. Then, the separated steel and cast iron can be recycled in the production of other products, for example, containers, benches, tables, gliders or lamps. In reusing such materials as steel and cast iron, it should be remembered that their main deterioration process is the corrosion caused by the reactions between the materials and the atmosphere, as already discussed (and exemplified in Figure 8). At the end of rolling stock's operation, this corrosion process might be increased during the time of exposure [38,39]. Subsequently, if reused as sub-products such as in a pipe network or in bridges, this material can contaminate water and soil that it contacts. The corrosion can also compromise the integrity of the structure and contaminate neighboring elements. In addition, the steel and iron re-melting process can release pollution from

coke ovens—such as coke oven gas, naphthalene, ammonium compounds, crude light oil and sulfur. Moreover, water, which is used to cool the coke at the end of the re-melting process, can be at risk of contamination.



**Figure 8.** Corrosion of steel. (a) Extreme corrosion in a bridge. (b) Railway rolling stock being renovated.

Some of the train components are also composed by other metals such as copper and brass. These materials, if not correctly treated at the end of rolling stock's operational life, can cause significant environmental hazards. Some applications of the recycled copper from the train components can be as follows:

- electrical equipment;
- construction (such as roofing and plumbing), and;
- industrial machinery (such as heat exchangers).

The emerging risks with respect to the reuse of aged copper includes the toxicity of the worn material, which can contaminate water and underground water that passes through the pipes to rivers [40,41]. Another hazard would be a case in which the deteriorated copper dust enters into the air, through any process that can release this material, and the remaining dust in the air can cause acid/polluted rain, and then will penetrate into the soil and ground water systems.

The other examples for industrial applications of recycled rolling stock materials are as granular aggregates in construction. The recycled aggregates are commonly used in the rail infrastructure buildings (non-critical types such as pedestrian walkway, platform walkway, noise barrier walls) and in the construction sector, especially in concrete, asphalt, paving material and bridges. The recycled aggregated can be comparatively safely reused with low risk of damage to the environment as the main part, the concrete or composite, locks the aggregates in its matrix.

Another material often used in the production sector is aluminum. Presently, many train manufacturers use this material to fabricate train components, such as, for instance, the car body and impact cushion beam/frame. Compared with steel, aluminum is a much lighter material, despite being much more recoverable, with a high recovery rate from 80% to 95%. There are various reuse applications of aluminum after its end-of-life, such as in door knobs, window frames, kitchen utensils or indoor and outdoor furniture. It should be noted that this material has to be rightly availed otherwise it could turn to be a toxic agent if presented in high concentrations. Accordingly, aquatic and terrestrial ecosystems can potentially be affected, taking into consideration acidic precipitation and contamination of soil and freshwater.

In addition, if used as kitchen utensils, there are also some safety risks in the light of human health. Aluminum is known as a complex compound and can release significant amounts of toxicity directly into the food and drinkable or running water. These parts of trains, which are made from

aluminum, are the train transformers. They contain various hazardous materials, which are present in the composition of their electrical and electronic equipment. At the end of their operational ability, they are useless for the asset owner and can no longer be useful to the rail vehicles. However, this component can still have useful parts that can be well utilized in other branches of industry. In such cases, it is reasonable to retain the aluminum elements so that this material is not irrevocably lost.

Last but not least, components that are plastics [42,43]. One example is PVC (Polyvinyl chloride), which is used for train floor sheets, cable pipes, insulation layers, and as the interior material of rolling stocks. According to recent research [44], appropriate treatment of train floor sheets and insulation materials should be carried out before recycling in order to enable safe and long-term outdoor reuses. Another plastic commonly used in a passenger rolling stock is PCB (polychlorinated biphenyls). It is often used in condenser transformers, heat transfer devices, hydraulic equipment and shredders. PCB can sometimes be reused after its lifetime of operation as well. The recycling of the scraps of metal composites, which are waste from trains, is one of many PCB sources. However, about 60% of the PCB sources are in contact with closed fluids and heat transfer fluids [45]. PCBs have been indicated to cause cancer and non-cancer health effects in animals and possibly humans. As a result, PCB must be carefully treated prior to reuse or recycling applications [46].

## 5. Discussions

Recycling should be firmly considered in the planning, procurement, design and over the life cycle of the rolling stocks. It is important that asset owners embrace all possibilities to reuse and recycle all ageing train components that are recoverable. However, since there are significant risks and impacts on the environment, recycling processes should be properly conducted in an appropriate and careful manner. Waste management should be thoughtfully planned. It is important to ensure that suitable recycling applications take into account all the environmental impacts or risks that could be caused by recycled materials. Considering all these factors, a set of initiatives for evaluation and analysis could be put into practice to develop and improve recycling processes. The policy should not only be focused on waste management—including recycling and reuse, but also on the main risks that the possible applications could cause to the planet. This aspect should be considered in three main areas: environmental, economic and societal risks [47–51]. It is imperative that the processes of planning, procurement, design and manufacture of rolling stocks consider life cycle and waste managements. The stakeholders and their impacts can be seen in Table 4. The main possible risks of reusing the described materials are presented below in Table 5.

**Table 4.** Stakeholders and impact of recycling and reusing aging materials.

| Key Stakeholders  | Scale  | Impact  |
|---|--------|---|
| Train manufacturers, Train repair/refurbish, modification                                     | Medium | The method does not impose penalty to manufacturers. It encourages the uses of recyclable materials and more accurate data records.   |
| Train designers, Rolling Stock designers, Procurement officers, Train Operators, Asset Owners | High   | The public awareness of rolling stock recycling encourages them to use more recyclable materials. However, there is no environmental legislation to impose any limit or minimal level to railway sector at this stage. It is noted that European Directive (2005) currently imposes in Article 7(3) [52] for automobile recycling targets: min. 95% reuse and recovery and min. 85% reuse and recycling by 2015. This directive could apply to rail sector later in the future. |
| Infrastructure Managers   | High   | Infrastructure managers need to provide some effort to help increase recycling potentials. They need to identify risks of the utilization and manage them to assure that there is no harm to staff, neighborhoods in rail corridor and the environment.   |
| Rail regulators, Governments  | Medium | New contracts, incentives and assurance process for rolling stock recycling should be developed. At the same time, environmental risk assurance must be included in the sustainability-based contractual process.   |
| Rail passengers   | Low    | New trains and infrastructure will be more environmental friendly. They will be more motivated to use public transports and play a key role in the contribution towards the reduction of carbon emission.   |

**Table 5.** Emerging risks of recycling and reusing aging materials.

| Material   | Risk                 | Description   |
|------------|----------------------|---|
| Steel      | Corrosion            | If corroded steel is used as a sub-product such as in a pipe networks or in bridges, it can contaminate the water it contacts.  |
|            | Re-melting process   | Many pollutions can be released from coke ovens such as coke oven gas, naphthalene, ammonium compounds, crude light oil and sulfur.<br>Water, which is used to cool the coke at the end of the re-melting process can be contaminated.  |
| Copper     | Toxicity             | Worn material can contaminate water that passes through the pipes and flows into rivers.  |
|            | Acid rain            | The copper enters the air, through any process that can release it, remaining in the air until it starts to rain and, then, will penetrate the soil and ground water.   |
| Aggregates | -                    | It can be comparatively safely reused with low risk to the environment.   |
| Aluminum   | Acidic precipitation | Aquatic and terrestrial ecosystems are affected, taking into consideration acidic precipitation and contamination of the soil and freshwater.   |
|            | Toxicity             | In addition, if used as kitchen utensils, there are also some risks to human health. Aluminum is known as a complex compound and can release significant amounts of toxicity directly into the food and the drinkable or running water. |
| Glass      | -                    | -   |
| Plastics   | Toxicity             | About 60% of polychlorinated biphenyls (PCB) sources are related to closed fluids and heat transfer fluids [26]. PCBs have been indicated to bring about cancer and non-cancer health effects.  |

## 6. Conclusions

The emphasis of this study is on the management policy of end-of-life rolling stocks and their possibilities for recovering worn materials for recycling processes. In this paper, various types of rolling stocks and their components are evaluated. Freight rail cars, passenger trains and high-speed trains are the main considerations of the rolling stock aspect. Each component of trains and each type of material from which they are made are quantified. The recovery rate for each element is presented. Each material is then critically reviewed and analyzed in great detail. The group of key materials includes steel, aluminum, copper, polymers and glass. The production process of these materials and their properties are discussed in order to identify carbon costs and energy embedment. In addition, physical threats of using these deteriorated materials on water recourses, air quality, the environment, human and animal health are evaluated. The advantages and disadvantages of reusing and recycling each type of material are underlined. The fact that recycling processes should be properly planned and executed is strongly highlighted. It is found that all factors, not only the benefits from recycling, but also all potential hazards, must be taken into account in planning, procurement, design and manufacture of rolling stock.

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