sustainability

Article

Influence of Material Selection and Product Design on Automotive Vehicle Recyclability

Xiaohui He [1,2,3], Dongmei Su [4], Wenchao Cai [1], Alexandra Pehlken [5,*], Guofang Zhang [1], Aimin Wang [2,*] and Jinsheng Xiao [1,*]

1 Hubei Key Laboratory of Advanced Technology for Automotive Components, Hubei Collaborative Innovation Center for Automotive Components Technology and Hubei Research Center for New Energy and Intelligent Connected Vehicle, School of Automotive Engineering, Wuhan University of Technology, Wuhan 430070, China; hexiaohui@whut.edu.cn or hexiaohui@dfmc.com.cn (X.H.); caiwenchao@whut.edu.cn (W.C.); zhanggf@whut.edu.cn (G.Z.)
2 School of Management, Wuhan University of Technology, Wuhan 430070, China
3 Dongfeng Motor Corporation Technology Center, Wuhan 430058, China
4 Dongfeng Peugeot Citroen Automobile Co. Ltd., Wuhan 430056, China; sudongmei@dpca.com.cn
5 OFFIS—Institut für Informatik Oldenburg, 26121 Oldenburg, Germany
* Correspondence: pehlken@offis.de (A.P.); wangam@whut.edu.cn (A.W.); Jinsheng.Xiao@whut.edu.cn (J.X.)

Abstract: From 2008 to 2020, Chinese automobile production and sales have ranked first in the world. The huge production, sales, and ownership of automobiles will inevitably lead to a rapid increase of end-of-life vehicles in the future and a corresponding issue of resource recycling. Based on the analysis of a practical dismantling study and statistics declared by the supplier of 19.5% of components and parts with a weight greater than 0.5 kg from two typical vehicle models from 2011 to 2013, this paper focuses on nonmetallic components and parts, the connection of components and parts materials, and the product life cycle of each stage, to find rational technical solutions, and therefore maximize recyclability and recoverability and achieve sustainable development. On one hand, recycling at each stage for vehicles is considered in the design and development of products. As a result, it is found that the main methods, which are conducive to recycling, are increasing the use ratio of materials that are easy to recycle. In addition, general principles of material selection are summarized. On the other hand, vehicles' dismantling is considered in the initial stage of product design and methods of structural design are summarized.

Keywords: end-of-life vehicle; recycling; material selection; product design; optimization; circular economy

Citation: He, X.; Su, D.; Cai, W.; Pehlken, A.; Zhang, G.; Wang, A.; Xiao, J. Influence of Material Selection and Product Design on Automotive Vehicle Recyclability. *Sustainability* **2021**, *13*, 3407. https://doi.org/10.3390/su13063407

Academic Editor: Valentina Rognoli

Received: 1 February 2021
Accepted: 16 March 2021
Published: 19 March 2021

1. Introduction

With more than 100 years of technological development, the world's major industrial countries are moving toward a mature automotive society. According to data from the Japan Automobile Recyclers Association, the total number of used automobiles in developed countries, such as the European Union, the United States, Japan, and South Korea, is about 25 to 27 million vehicles per year [1].

On one hand, the actual recyclability of automotive products sold in the market is required to reach 95% by the government. On the other hand, automobile manufacturers are required to continuously improve the information and openness of scrapped (end-of-life) vehicle management to facilitate the management and supervision by government departments. In addition, automobile manufacturers, recycling, dismantling and disposing companies, and consumers can all use network information to achieve a win-win situation for all parties. As for these developed countries, after more than 20 years of accumulated and continuous optimization, a relatively systematic working method has been formed and remarkable achievements have been made in the actual recycling of resources and the reduction of harmful substances [2].

Since 2008, China's automobile industry has been in a stage of rapid development, and its automobile production and sales have continuously ranked first in the world. According to the data from the Society of Automotive Engineers (SAE) of China, the production and sales volume of automobiles in 2017 reached 29.015 million and 28.879 million, respectively [3], accounting for about one-third of the global annual production of automobiles. Huge production, sales, and possession of automobiles will inevitably lead to a rapid increase of scrapped vehicles and a corresponding issue of resource recycling in the next few years. Therefore, to improve the level of the automobile manufacturing industry's resource recycling and promote the sustainable development of society and economy, many international scholars have done plenty of research on the recycling and reuse of scrapped vehicles.

Zhao et al. [4] introduced and compared the development status of scrapped vehicles in China and Japan, to find a strategy suitable for recycling end-of-life vehicles (ELVs) in China. Based on the analysis of the operating conditions of several dismantlers, Cheng et al. [5] introduced the development status of the scrapped vehicles recycling industry to study the relationship between the operating conditions of the dismantling factory and scrapped vehicles recycling. Taking Corolla taxis as an example, Li et al. [6] analyzed the life cycle of the entire vehicle from two aspects: environmental impact and resource recovery capability. They concluded that remanufacturing or reusing vehicles' parts must be regarded as the main direction in the future development of scrapped vehicles' recycling industry. Zhou et al. [7] elaborated on the theory and industrial background of China's scrapped vehicles' recycling management, using an interpretive structural modelling method to determine the factors affecting China's scrapped vehicles recycling from the perspective of the government, recycling organizations, and consumers.

Fernando Enzo et al. [8] elaborated on the disposal of automobile materials after vehicles are scrapped, and studied the environmental benefits of recycling scrapped vehicles from the aspects of energy-saving and carbon reduction, in order to promote the sustainable development of the environment. Vuk et al. [9] regarded scrapped vehicles as renewable energy, introduced the basic situation of scrapped vehicles recycling in developing countries, and made it clear that recycling scrapped vehicles is meant for sustainable development. Rovinaru et al. [10] compared and analyzed the dismantling and recycling of scrapped vehicles in Romania and the United States to determine the social, economic, and environmental impact of dismantling scrapped vehicles.

To improve the recycling level of secondary resources in the automobile manufacturing industry, the Ministry of Industry and Information Technology of China released Announcement No. 38 of 2015, Management Requirements of Automotive Hazardous Substances and Recyclability, which began on 1 January, 2016. The announcement specifies that the calculation method for the recyclability of new automotive products in all Chinese markets shall comply with the requirements of the national standard Road Vehicle Recyclability and Recoverability Calculation Method and shall be managed according to the Vehicle Production Enterprises and Product Announcement.

According to the data from the China Automotive Technology and Research Center, after two years of new automobile access declarations by original equipment manufacturers, at the end of 2019, there were 5033 new models, 12,552 revised models, and 2368 models in production had passed the end-of-life data compliance verification [11]. An analysis of relevant application data found that the theoretical recyclability and recoverability calculation results of the Chinese automotive industry generally were high, and the theoretical calculation values of recyclability and recoverability of a few products peaked at 99% and 93%, respectively. On the basis of the current number of scrapped vehicles in China and the associated recycling technology, the relevant results have a limited reference to actual recycling.

2. Materials and Methods

Research on the basic key technologies of automobile product recycling focuses on the development of a circular economy that can meet energy conservation and emission reduction targets as well as conform with automotive industry [12] While developing a product and establishing a scientific and reasonable recycling design control system, the level of resource recycling in the automobile manufacturing industry can be improved. In this study, with the technical support and equipment supply of an automobile company located in Wuhan, China, the materials and components and parts of about 200 different models of vehicles, which were dismantled by the company or calculated based on the data declared by the supplier, were counted and summarized from 2011 to 2013. To systematically study a large amount of the data, two vehicle models' data were selected to represent the average level of the data of about 200 models, which were called typical vehicle A and typical vehicle B. Therefore, based on the analysis of a practical dismantling study and statistics declared by the supplier of 19.5% of components and parts with a weight greater than 0.5 kg from two typical vehicle models from 2011 to 2013, this paper focuses on nonmetallic components and parts, the connection of components and parts materials, and each stage of the product life cycle. On one hand, based on design criteria for recyclability by material selection for the components and parts of vehicles, in order to improve the recoverability and recyclability of scrapped vehicles, the recycling at each stage in the design and development of products is considered. On the other hand, in order to maximize the recycling and reuse of components and parts materials after vehicles are scrapped, vehicles' dismantling in the initial stage of product design is considered. By material selection and product design, this paper's objective can be achieved, which is to find rational technical solutions by analyzing vehicles' material data and system design schemes, to maximize recyclability and recoverability in origin, minimize the reliance of scrapped vehicles on disassembling technology and recycling equipment, reduce waste landfill, and, therefore, achieve sustainable development in China.

It is well known [13] that serious environmental impact of a product or service is determined in the design phase in order for the product design to have a great responsibility on sustainability and circularity. The objective of this study is to improve scrapped vehicles' recyclability and recoverability through material selection and product design, and further to guide the transition toward a more sustainable and circular economy in the field of automotive engineering.

To find rational technical solutions that can maximize recyclability and recoverability, reduce the dependence on disassembly technology and recycling equipment in the later stage of vehicle scrapping, solve problems from the source, propose a management plan for huge material data information, and, ultimately, achieve the goal of minimizing waste landfill and maximizing secondary resource recycling with a minimal economic cost on the basis of relatively mature recycling technologies in China as well as in developed economies, such as Europe, the United States, Japan, and South Korea, by the optimization of vehicles' material selection and structure design. This study focuses on maximizing scrapped vehicles' recyclability and recoverability on the premise of meeting the requirements of relevant laws and regulations in China and other countries. In addition, the supervision of government management departments is also needed to ensure that manufacturers use suitable materials. The roadmap of this study is shown in Figure 1.

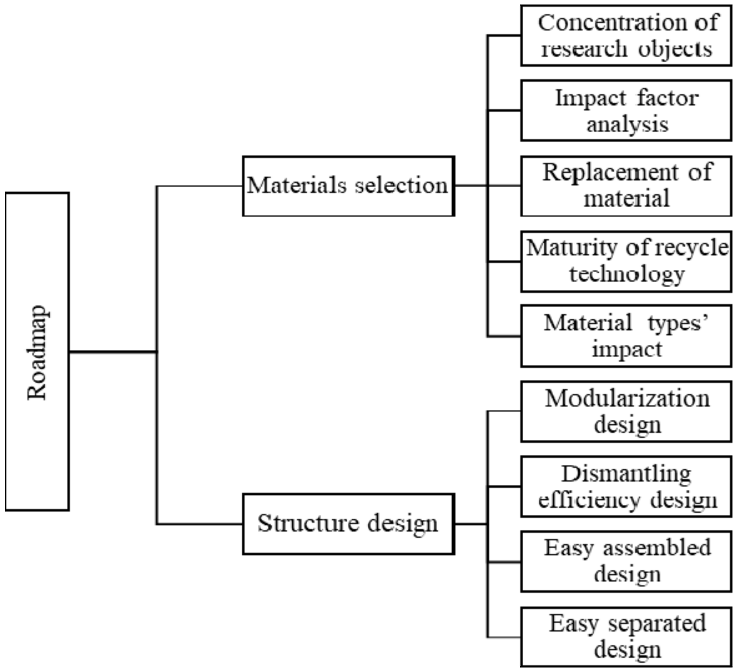

Figure 1. Diagraph of the research roadmap.

International Organization for Standardization (ISO) 22628:2002 Road Vehicles—Recyclability and Recoverability—Calculation Method [14] states that the recyclability (R_{cyc}) and recoverability (R_{cov}) of scrapped vehicles are based on the corresponding recovery techniques, and the percentage is calculated according to the following equations.

$$R_{cyc} = \frac{m_P + m_D + m_M + m_{Tr}}{m_V} \times 100(\%) \quad (1)$$

$$R_{cov} = \frac{m_P + m_D + m_M + m_{Tr} + m_{Te}}{m_V} \times 100(\%) \quad (2)$$

where m_P is mass of materials taken into account at the pre-treatment step, m_D is the mass of materials taken into account at the dismantling step, m_M is the mass of materials taken into account at the metal separation step, m_{Tr} is the mass of materials taken into account at the non-metallic residual treatment step and can be considered recyclable, m_{Te} is the mass of materials taken into account at the non-metallic residue treatment step and can be considered for energy recovery, and m_V is the vehicle mass. To improve scrapped vehicles' recyclability (R_{cyc}) and recoverability (R_{cov}), it is necessary to increase the number of m_P, m_D, m_M, m_{Tr}, and m_{Te} in the numerator. The calculation formula of recyclability (R_{cyc}) and recoverability (R_{cov}) is simple, but the composition of automobile components and parts is complex. Lower-level vehicles are composed of more than 10,000 components and parts, and high-level vehicles are composed of more than 20,000 components and parts [15] Therefore, identifying key impact factors and analyzing these components and parts or materials is the simplest and the most effective method for conducting this research. Scientific and reasonable technical solutions must be based on actual working objects. The data from SAE-China [3] have shown that the past 10 years have been an important stage in the rapid development of China's automobile industry, and automobile production and sales volume have reached 30% of the global total trade. In the next five years, the number of China's scrapped vehicles will reach a new height in history, topping 10 million vehicles per year. According to the data from China Automotive Research Center [11], since the implementation of the Management Requirements of Automotive Hazardous Substances and Recyclability in 2016, the Chinese government has completed the review and approval of the ELV parameters for approximately 3000 vehicles.

3. Results

The design of recyclability of a vehicle usually begins with the design and selection of materials. After a vehicle is scrapped, whether or not the components as well as parts and materials can be recycled depends largely on the retention of the original properties of the material and the performance of the material itself. In addition to considering the basic properties of materials (e.g., strength, stiffness, and safety), material recyclability is one of the most important indicators, based on the actual recycling technology in China, Europe, the United States, Japan, and South Korea as well as other industrial economies. Given the value of the material itself, metallic materials have high economic value and the recycling technology is mature. As shown in Figure 2, this paper narrows the scope to focus on nonmetallic components and parts of typical vehicles A and B, which are composed of polymers, rubber, glass, organic natural materials, and other materials. Figure 2a,b are material weight distribution and material proportions of typical vehicles A and B, respectively. The different materials are given in proportion from large to small and carried out according to the order of the proportion of the entire vehicle.

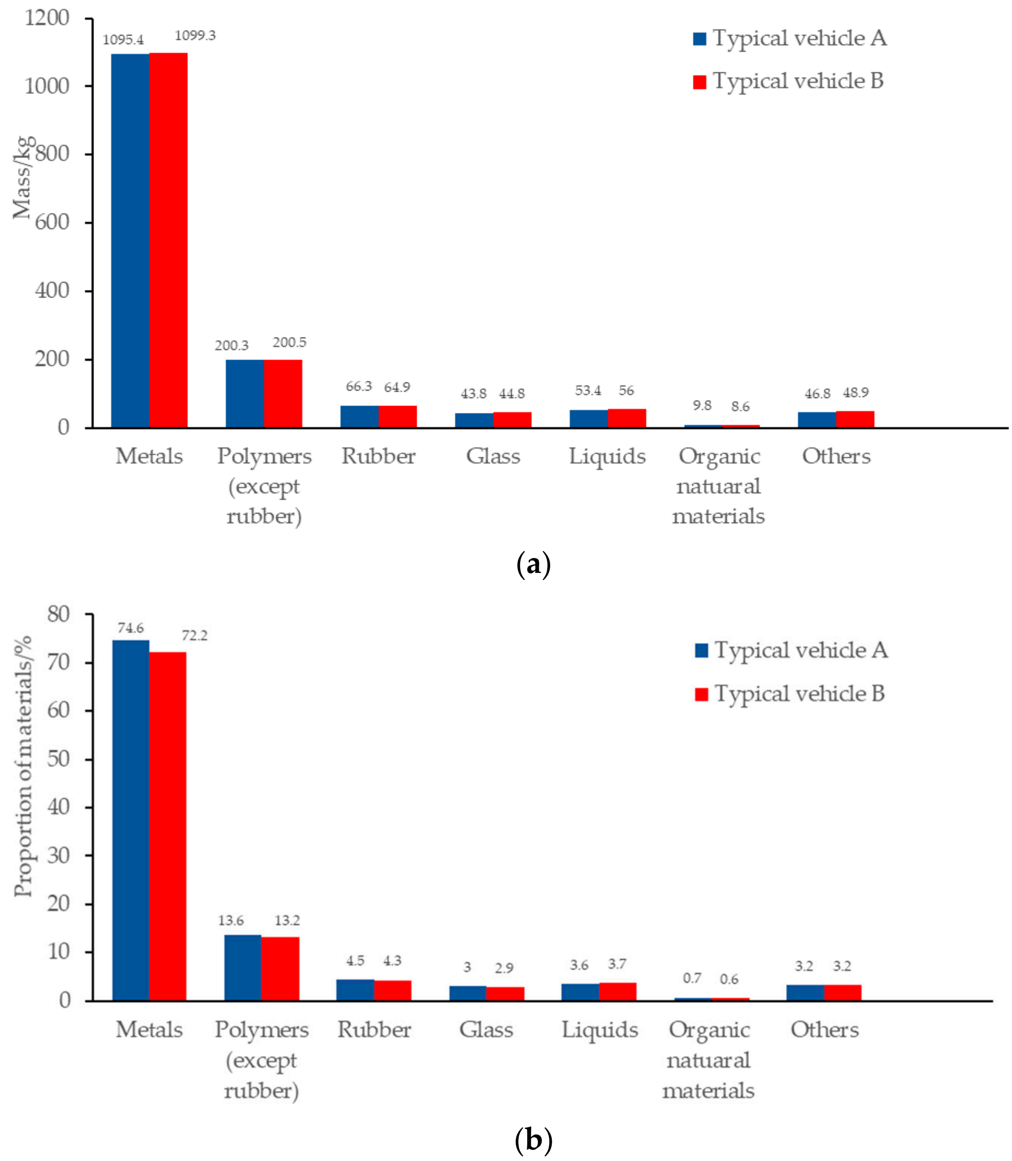

Figure 2. Material weight distribution (**a**) and material proportions (**b**) of typical vehicles A and B.

The connection between components and parts directly affects the recyclability of vehicles after they are scrapped. Some materials that can be recycled or easily recycled will become difficult to recycle or will become non-recyclable because the connection with other materials was bonding and welding, which are difficult to separate or dismantle. Therefore, researching the connection of components and parts is the second most important aspect of this paper.

The recycling of resources runs through every step of a product's life cycle, including mining, transportation, manufacturing, assembly, use of the vehicles, and end-of-life recycling. Every step of this process has an impact on the results. An empirical approach toward considering recycling issues from every stage of the product life cycle is the third most important consideration in this paper.

Vehicles' components, parts, and their material compositions are complex, and the related information and data volume are more than 10 million units. When considering the differences in materials and the standards in different countries that have been brought about by the globalization of production and procurement as well as massive work process records, confidentiality of technical data and other factors, the use of a scientific, reasonable, simple, and effective information management and statistical analysis framework is an indispensable means to achieve the objectives of this study. This framework is the last important aspect of this paper.

A vehicle is composed of many part assemblies. Each part assembly is composed of subcomponents or materials, and the material is composed of substances. This relationship is shown in Figure 3 as a tree structure. For example, part A is tire, then material A1 is chemical synthetic rubber, material A2 is natural rubber, substance A1.1 is petroleum, and substance A2.1 is rubber tree. Based on the analysis of materials of automotive components and parts, this paper focuses on improving scrapped vehicles' recyclability and recoverability.

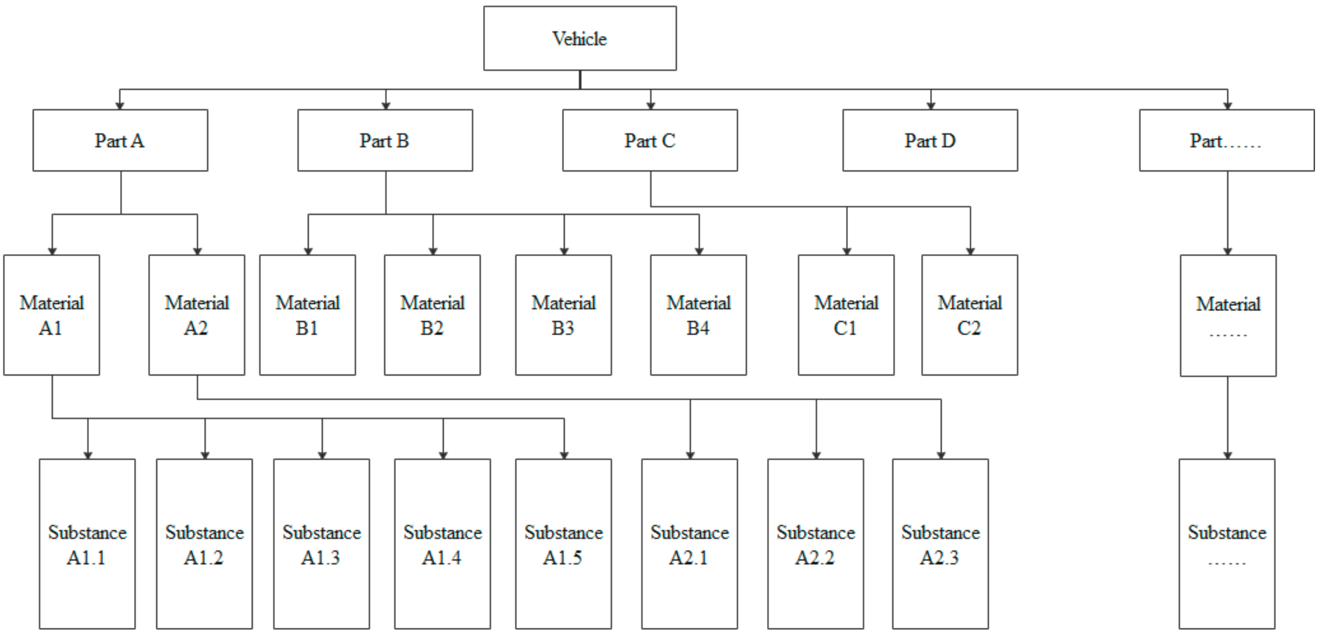

Figure 3. Diagram of a material composition relationship of various parts of the vehicles.

According to the tree structure of vehicle-part-material-substance, the equation of the total mass of a vehicle is as follows:

$$M = m_1 + m_2 + m_3 + \ldots + m_n = \sum_{i=1}^{i=n} m_i \quad (3)$$

where M is the total mass of a vehicle by design, kg, or g, m_1, m_2, m_3, m_n, and m_i are the declared mass of each part in a vehicle composition, kg, or g.

The total mass of part assemblies or components of different levels also follows this formula. In this study, though statistics of the number and mass of components and parts of typical vehicle A, the weight composition of components and parts of a typical vehicle A are given in Table 1. As is shown in the table, 88.6% of parts account for 12.2% of the total weight of one vehicle, 5.1% of the parts occupy 20.1% of the total weight of a second vehicle, and 1.6% of the parts account for 66% of the total weight of a third vehicle. This paper focused on the latter two types of components and parts. Specifically, vehicles have a weight of 0.5 kg or more, and have 19.5% of the larger parts occupy about 95.2% of the vehicle weight.

Table 1. Weight distribution of components and parts of typical vehicle A.

Part Weight (kg)	Actual Number of Parts	Total Weight (kg)	Proportion of the Number of Parts	Proportion of Parts	Proportion of Total Weight	Proportion of Weight
<0.01	856.5	3.04	45.6%	88.6%	0.2%	12.2%
0.01–0.1	431	17.55	22.9%		1.2%	
0.1–0.5	226	49.94	12.0%		3.4%	
0.5–1	152	109.68	8.1%		7.4%	
1–2	43	60.376	2.3%	5.1%	4.1%	20.1%
2–3	11	26.8	0.6%		1.8%	
3–5	23	85.807	1.2%		5.8%	
5–10	18	125.07	1.0%		8.4%	
10–20	11	181.76	0.6%	1.6%	12.2%	66%
20–30	11	226.15	0.6%		15.2%	
30–40	1	35.25	0.1%		2.4%	
80–90	1	88.3	0.1%		5.9%	
100–200	1	122.3	0.1%		8.2%	
>300	1	328.47	0.1%		22.1%	

Even when the standard composition of a vehicle is given, selected standard components as lead batteries show high variations. In order to analyze the distribution of Pb in the powertrain with different configurations, three configurations of a vehicle model are selected from 200 models, in which the engine is naturally aspirated or turbocharged and the gearbox is automatic or manual. As shown in Table 2, these three configurations are: A: Naturally aspirated and automatic, B: turbocharged and automatic, and C: turbocharging and manual.

Table 2. Lead contents of three different configurations of a model.

Configurations	A	B	C
Total Pb weight/g	12,730.01	12,744.17	12,713.41
Battery Pb weight/g	12,611.40	12,611.40	12,611.40

It can be found that about 99% of the banned substance Pb in the vehicles comes from lead in the battery. At the same time, the batteries assembled in the three configurations are of the same type, but there are differences in the total lead content, indicating that the difference of the remaining 1% of the Pb content in the vehicle mainly comes from other non-battery components. According to the comparison of these three configurations, the lead content of a turbocharged engine and automatic gear is the highest. This is followed by a turbocharged engine and manual lead content, and natural inspiration and automatic lead content is the lowest.

The contribution of 1% lead content in vehicles comes from other components and parts except for storage batteries. The weight of all lead-containing nodes is aggregated by the summation method by using optimized calculation rules. The parts of the top 15 with lead content after aggregation of the three kinds of vehicle configurations are shown in Table 3.

Table 3. Parts of the top 15 with lead content of the three configurations of a model.

No.	Configuration A		Configuration B		Configuration C	
	Components	**Pb Content/g**	**Components**	**Pb Content/g**	**Components**	**Pb Content/g**
1	Transmission	45.01	Transmission	45.11	Steering	29.50
2	Steering	29.50	Engine	32.21	Engine	24.50
3	Engine	10.85	Steering	29.50	Transmission	10.47
4	Oil sump	6.30	Retractable machine	4.90	Engine bracket	3.98
5	Brake caliper	2.97	Engine bracket	3.98	Knock sensor	3.51
6	Compressor	2.26	Knock sensor	3.51	Brake caliper	2.97
7	Generator	1.85	Brake caliper	2.97	Compressor	2.26
8	Oil pump	1.64	Compressor	2.26	Oil pump	2.13
9	Rear wiper	1.56	Oil pump	2.13	Differential	2.07
10	Air conditioning control	1.41	Generator	1.85	Generator	1.85
11	Brake shifter	1.11	Rear wiper	1.56	Rear wiper	1.56
12	Front oil seal seat	0.97	Sensor	1.14	Sensor	1.14
13	Outlet room	0.74	Brake shifter	1.11	Brake shifter	1.11
14	Torsion bar	0.71	Oil and gas separator assembly	1.09	Oil and gas separator assembly	1.09
15	Throttle body	0.70	Electronic control unit	1.05	Electronic control unit	1.05

According to the previously mentioned list of parts, it can be found that the common parts with high lead content in the vehicles' model are gearbox, engine, steering assembly, brake caliper, compressor, oil pump, generator, rear wiper, and hand brake lever assembly, among which the engine, gearbox, and steering system have the highest lead content and are the top three contributions of Pb. Except for the parts in Table 3, the remaining major lead-containing parts are electronic and electrical components.

4. Discussion

To improve the recoverability and recyclability of vehicles, it is necessary to abundantly consider the recycling of each stage of scrapped vehicles in the design and development of new products, and it is important to follow rational design criteria to guide product design. Generally speaking, the recyclability of components and parts mainly includes the following three levels.

- Reusability: the ability of components and parts to be dismantled from vehicles for reuse.
- Recoverability: the ability of components and parts or materials to be dismantled and reused from scrapped vehicles.
- Recyclability: the ability of components and parts or materials to be dismantled from scrapped vehicles for recycling.

The design of recyclability integrates the above three levels of content, combining the reusability, recoverability, and recyclability of components and parts into the design elements and transforming the recyclability requirements of vehicles into general product criteria when specific products are designed [16]. Compared with the material properties of metals that are easy to recycle, chemical materials and polymer materials have significant differences in material recycling characteristics because of differences in material chemical properties. Therefore, the control of recovery characteristics of chemical materials and polymer materials is an important link affecting the recycling characteristics of vehicles and their components and parts. To improve the values of R_{cyc} and R_{cov}, it is necessary to improve the ratio of recyclable and recoverable parts or materials, that is, to increase the ratio of materials that are easy to recycle.

4.1. Reduce the Use of Thermosetting Materials and Replace Them with Thermoplastic Materials That Are Easy to Recycle

Based on the statistical data of this study, it is found that polymer materials occupy a larger portion of weight in automotive products, responding to 13%. Thermoplastic materials could be used widely in vehicles with a low environmental effect due to their mature recycling technology and low-cost recovery. In contrast, the thermosetting materials should not be used or should be used as little as possible due to the fact that they are difficult to recycle. The thermosetting materials commonly used for vehicles' components and parts include various rubber, polyurethane, sheet molding compound (SMC), bulk molding compound (BMC), phenolic resin, and epoxy resin, and their main application fields and dosages are shown in Table 4.

Table 4. Alternative cases and profit analysis of thermosetting materials that are difficult to recycle.

Material Type	Main Application Area	Usage in Vehicles (kg)	Recoverability Improvement
Rubber	Door and window sealing strips, various soft pipelines, transmission belts, shock absorbers, seals, stopper blocks, and protective covers	30	2.1%
Polyurethane	Seat cushion, backrest, headrest, noise dampening mat, and cushion	25–30	2.1%
SMC/BMC	Back door, spare tire seat, headlight reflector, and spoiler	5–10	0.7%
Phenolic resin	Cotton-based sound-absorbing mat, ashtray body	0.5–1	0.08%
Epoxy resin	Adhesive	0.5–1	0.08%

To achieve an effective replacement of thermosetting materials, a technical feasibility analysis is conducted by following three aspects.

- Finding and developing thermoplastic materials that can replace thermosetting materials with key technical properties and other green materials with better recycling characteristics.
- Reducing the material performance requirements of components and parts by optimizing product structure and performance.
- Improving the performance of existing thermosetting materials to minimize this kind of material usage while meeting product performance.

Rubber materials and polyurethane materials are the two kinds of thermosetting materials with the largest usage on vehicles. Therefore, optimizing and reducing these two kinds of materials are worth studying.

An Ethylene-Propylene-Diene Monomer (EPDM) can be used as traditional materials for various door and window sealing strips, hoods, and luggage compartment sealing strips because of their excellent permanent compression deformation properties and durability. With the development of thermoplastic elastomer materials technology, Thermoplastic Vulcanizate (TPV) and Thermoplastic Styrene (TPS) with excellent comprehensive performance can fully meet the technical performance requirements of sealing strips. TPV is widely used for stopper block, steering column dust cover, hand brake shield, and other products. TPV in these products should be replaced with thermoplastic elastomer materials that have good recovery characteristics.

The most popular usage of polyurethane (PU) foam in vehicles are seat cushions and backrests. When it is not possible to find alternative materials with better recycling characteristics, the method of reducing foam density by improving mechanical properties of the foam, such as rebound and durability, which can significantly reduce the number of materials used.

Another field of significant use of polyurethane foams is noise-dampening components, such as front-bezel-deadening mats and channel-deadening mats. Due to the special installation and use conditions of these components, these materials are required to have good sound absorption-deadening properties as well as mechanical properties. Therefore, polyurethane foam with excellent comprehensive properties has always been the material of choice for such components. When new products are designed, the vehicle noise reduction system is optimized and integrated. The sound-absorption and sound-deadening requirements of the sound-deadening mat are appropriately adjusted without compromising the noise-reduction properties of the system. In addition, cotton felt material consisting of polyethylene terephthalate (PET)and polypropylene (PP) with a better sound absorption effect are developed by improving the felting process of cotton felt to realize the goal of replacing polyurethane in a sound-deadening mat product with thermoplastic material like PET/PP, so as to improve the recycling characteristics of this type of material.

Phenolic resin material is mainly used as a binder in various cotton felt-type noise-reducing parts in vehicles. As shown in Table 5, it lists practical cases of component materials based on improving a product's recycling characteristics.

Table 5. Typical examples of material selection optimization to improve product recovery characteristics.

Part Name	Original Design	Improved Design	Current Material Used	Thermosetting Material Reduced (kg)
Door and window sealing strips	EPDM	Use thermoplastic elastomers	TPV, SEBS	4~5
Seat foam	PU (ρ = 55~65 g·cm^{-3})	Reduce the density of the foam to improve its performance	PU (ρ = 45~55 g·cm^{-3})	3~5
Sound deadening mat	PU and EPDM	Optimize product features and use thermoplastic cotton felt	PET/PP	7~8
Back door	SMC	Improve product structure design and use thermoplastic material	PP	25~30

Note: EPDM = Ethylene Propylene diene monomer, TPV = Thermoplastic Vulcanizate, SEBS = Styrene-ethylene-butylene-styrene, PU = Polyurethane, PET = Polyethylene terephthalate, PP = Polypropylene, SMC = sheet molding compound.

4.2. Use Materials That Are Easy to Recycle or Have Mature Recycling Technology

In theory, all thermoplastic polymer materials can be recycled and reused. However, because of the different material properties, there are clear differences in the implementation process of recycling and reusing of different materials and, therefore, the value after recycling is not the same [17], which was described in detail by the PARC (USA) Corporation on the "Development direction of high-value utilization technology of automobile renewable plastics industry" at the 2017 International Forum on China Automobile Material. The selection of materials that are easy to recycle or that have mature recycling technology in product design will directly reduce difficulties associated with the recycling and reuse of vehicles, increase the recycling value of scrapped vehicles, and improve automobile components and parts' recyclability or recoverability.

For example, the recycling process of polyvinyl chloride (PVC) material, which is usually used as the skin of automobile components and parts because it contains volatile organic substances and chlorine, is more complicated than that of PP, polyamide (PA), acrylonitrile butadiene styrene (ABS), and thermoplastic polyurethane (TPU) and other materials. Therefore, considering environmental protection and material properties, non-toxic, environmentally-friendly, and more easily recycled materials, such as thermoplastic olefin (TPO) and TPU, have been gradually sought to replace PVC in the development of new products and future materials. The use of high-performance homogeneous modified composite thermoplastic resin is another effective measure to improve the recycling characteristics of components and parts. For example, a typical successful application of under-engine trim is the replacement of glass mat thermoplastic (GMT) material with long fiber, thermoplastic (LFT) material.

4.3. Minimize the Number of Types of Materials

Generally speaking, the fewer types of materials used in automotive components and parts, the easier the dismantling and sorting of scrapped vehicles will be. No matter whether it is a special component product or an auxiliary product used on the product assembly line, the same types of materials should be used as much as possible to facilitate sort and, therefore, create the greatest possibility for reuse, remanufacturing, recovery, and energy recovery of components and parts and their materials [18].

Whenever possible, similar automotive components and parts on the same product platform should use the same material type. For the same component and part or assembly, the same type of materials should be used as much as possible. The number of composite materials should be reduced, and the use of multiple material components and inseparable components composed of different materials should be avoided. Otherwise, there will be some disadvantages to the economy and dismantling for recycling scrapped vehicles. For example, in the instrument panel of a certain product, the same kind of polyurethane (PU) skin as soft-foamed PU is used instead of plastic PVC skin, and a long-glass-fiber-reinforced PP material similar to the PP is used in the hard part of the product to replace steel to manufacture the skeleton beam, thereby effectively reducing the frame beam. As a result, the workload of material sorting in the recycling process of the component is effectively reduced, and the weight of components is reduced.

When the type of materials on the assembly is limited, the type and quantity of the assembly materials are considered to be the least and the cost of separation and recycling at the time of scrapping is considered to be the lowest. The following principles should be observed for the design of related polymer parts.

- Assembly such as door trim panels should be designed with same material system.
- The materials used on the assembly should be compatible with each other during the recycling process.
- The parts in a component should be easy to separate.
- The combination of materials used in vehicles should be easy to separate.

With the development of automotive lightweight materials, rapid advancements in recycling control technology and cost control for vehicles are needed and the application ratio of plastic materials in vehicles has been increasing yearly. More than 500 components and parts are now designed by using plastic materials, whose weight accounts for 10% of the total weight of components and parts. In this study, the weight of the main components and parts using thermoplastic materials is more than 1 kg. For example, a specific car uses nearly 50 components and parts made of ABS plastic material with a cumulative weight of 6.19 kg in each car. It is found that the use of ABS material is reduced to a weight of 4.37 kg and the ABS material accounts for 0.3% of the total material.

By improving product structure design, developing high-performance PP materials, especially long-glass or carbon-fiber-reinforced PP materials, and expanding PP materials dosage and application ratio, traditional reinforcement engineering plastics can be replaced, such as PA and polybutylene terephthalate (PBT) applied in structural components, which is an important measure to reduce the types of plastic materials in vehicles. At present, in the design of new products, PP-LFT has been used to manufacture body door panel modules, instrument panel skeletons, cooling fans and frames, battery brackets, pedals, etc. Therefore, not only is the weight of the vehicle body reduced, but also the number of engineering materials, such as steel plate and PA, are effectively reduced.

The reduction of inseparable polymer composites is achieved mainly through the change of a connection structure, reducing the use of adhesives, welding, and other processes. Instead of using riveting, snapping, and other connection methods, this optimization can not only improve recyclability and recoverability but also can reduce volatile organic compounds (VOC) and odor as well as contribute to lightweight material. The components and parts involved include sound-deadening mats, door guards, sealing strips, and some adhesive parts used in electrical components.

4.4. Use Materials with Good Compatibility

Good compatibility means that materials can be recycled together, which can greatly reduce the workload of dismantling and sorting and can directly affect the future reuse and recovery of components and parts.

A large number of composite materials used in automotive interior and exterior trim are composed of a variety of materials, so it is necessary to consider the compatibility among these various materials in the design. Using the same material or compatible materials can reduce the number of disassembly and increase the recovery rate.

As shown in Table 6, the compatibility of automotive engineering plastic materials is summarized. For example, polymathic methacrylate (PMMA) is used for automotive taillights and an inseparable material gasket, and ABS is used for the shell. It is easy to find that the mixture of these two materials is compatible, so it is very suitable from the perspective of recycling economy and easy dismantling. Another typical example is the product with a soft sealing edge, such as a front air intake grille or a front windshield pillar exterior trim, which adopts a material-technical scheme in which the mainframe is reinforced PP and the soft edge material is TPV. These two materials are very compatible.

Table 6. Compatibility of common engineering plastic materials [19].

Compatibility	ABS	PA	PBT	PC	PE	PET	PMMA	POM	PP	PPE	PVC
ABS	+	○	+	+	○	○	+	○	○	○	+
PA	○	+	○	-	○	○	○	○	○	-	-
PBT	+	○	+	+	○	○	○	○	○	○	-
PC	+	-	+	+	○	+	+	-	○	○	-
PE	-	○	-	-	+	-	-	-	+	-	○
PET	+	○	+	+	○	+	○	○	○	○	-
PMMA	+	○	○	+	○	○	+	-	○	○	○
POM	○	○	○	-	○	○	-	+	○	○	○
PP	-	○	-	-	○	-	-	-	+	-	○
PPE	○	○	○	○	○	○	○	○	○	+	-
PVC	+	-	-	-	○	-	+	+	○	-	+

Note: + = good compatibility, - = incompatibility, ○ = conditional compatibility; ABS = Acrylonitrile butadiene styrene, PA = Polyamide, PBT = Polybutylene terephthalate, PC = Polycarbonate, PE = Polyethylene, PET = Polyethylene terephthalate, PMMA = Poly(methyl methacrylate), POM = Polyoxymethylene, PP = Polypropylene, PPE = Polyphenylene Ether, PVC = Polyvinyl chloride.

4.5. Avoid or Minimize Toxic and Harmful Materials with a Focus on Lead

The use of hazardous heavy metals (such as Pb, Cr^{6+}, Cd, and Hg) and brominated flame retardants such as Polybrominated biphenyls (PBBs) and Polybrominated diphenyl ethers (PBDEs) are restricted according to the requirements of the Automobile Recycling Technology Policy [19]. Therefore, in the process of product design, the use of banned and restricted substances should be controlled strictly, so that the negative impact on the environment caused by the disposal of components and parts after the vehicle is scrapped is minimized, and the cost of recycling is also lower. If such substances have to be used to ensure the performance requirements of the product itself, their use should be controlled within the limits allowed by regulations. It is also necessary to actively research alternative technologies for banned substances, as flame retardants used in all polymer material formulations have been controlled and Chinese companies have achieved the goal of not using brominated flame retardants. For example, the balance block is an unnoticeable component on the wheel assembly and it is normally not accessible to the user. The traditional material used in the balance block is lead and it can be replaced by a steel block. In our study, it is found that the lead content of the typical vehicle that is researched is 70% less than the average level of the industry.

As shown in Figure 4, by analyzing configuration B as an example, the total lead content is 12,744.17 g, the lead content of the battery is 12,611.4 g, and the remaining Pb is mainly concentrated in aluminum, copper alloy, and solder, at about 116.3 g. 87.6% of the lead content comes from the battery. It is noticeable that the mass fraction of Pb, which is less than 0.1% devotes about 13.6 g. Aluminum and copper alloys used in mechanical processing are the main reasons for lead in engine shells. Lead can achieve a better demolding effect and ensure the relevant functionality of parts. Solder is an indispensable material in the welding process. By comparing and analyzing the requirements of banned substances for Chinese automobiles in GB/T30512 and the EU ELV Directive (2000/53/EC), it is found that lead is irreplaceably used in the materials, components, and parts covered by the exemptions of Article 2 (c), 3, and 5, and its substitutes are not expected to appear in the near future. Therefore, this paper focuses on the research of solders in electronic and electrical appliances, which is the main source of lead.

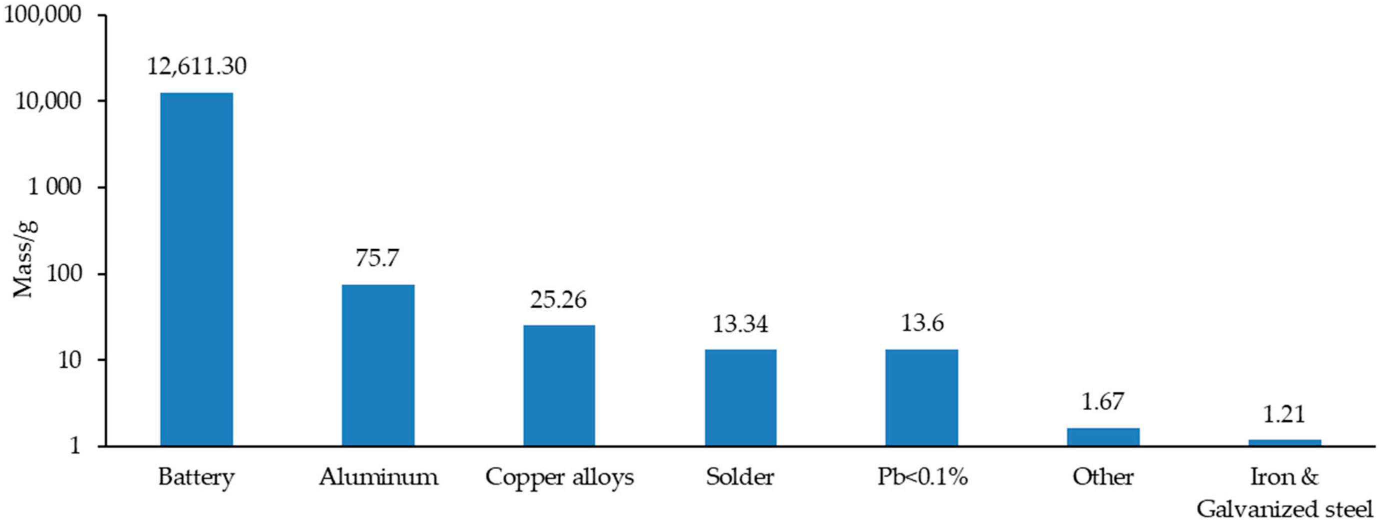

Figure 4. Distribution of lead in different components.

As a traditional welding material, a lead-tin alloy is widely used in the modern electronic assembly industry. As a connecting material of the electronic industry, solder provides electrical, heat conduction and mechanical connection. Sn-Pb alloy solder meets this requirement with its excellent performance. With the increasingly prominent problems of health and environmental protection, developed countries such as European countries, the United States of America, and Japan have put forward the requirements of lead-free. The Electronics and Electrical Equipment Waste Organization (WEEE), under the leadership of the European Union, calls for the discontinuation of the use of lead-containing materials in the electronics assembly industry by 2006 [20]. The National Electronics Manufacturing Initiative (NEMI) has implemented a lead-free soldering program called NEMI to systematically study the use of lead-free assembly in the electronic industry. As the largest electronic assembly industry country in the world, Japan's major consumer electronics enterprises have also promised to complete lead-free electronic assembly as soon as possible, which makes the research and application of lead-free solder imminent. According to the Chemical Composition and Morphology of Lead-free Solder (SJ/T 11392-2009), the content of lead in alloy material is less than 0.1%. For the lead-free work of automotive electronic and electrical circuit boards, there exist some difficulties to be conquered.

Cost is the biggest obstacle to the lead-free printed circuit board (PCB). For the same PCB, the cost of the lead-free process is usually more than twice that of a traditional process. Through cost analysis, it is found that the high cost of the lead-free process mainly comes from technology centralization, equipment investment in new production lines, and small demand for lead-free circuit boards in the automotive industry, resulting in high apportionment fees for individual parts. In this study, lead-free circuit boards with mature European technology were used to solve the problem of cost-sharing and equipment investment.

Developing new alternative materials, such as Sn63Pb37, is one of the main Sn-Pb solder materials, while Sn is the main component of lead-free solder. Binary or ternary alloys are formed by adding Ag, Cu, Bi, Zn, Al, and other elements. At present, Ag is a more qualified substitute for Pb. Ag is abundant and non-toxic on the earth, so its price is not high. Sn-Ag solder is a suitable lead-free solder. At present, Sn3.5Ag is widely used in the electronic and electrical industry. The content of Ag in Sn3.5Ag is adjusted in a certain proportion within the scope of process implementation. The comparison of the performance of Sn3.5Ag and Sn63Pb37 is shown in Table 7.

Table 7. Comparison of performances of Sn3.5Ag and Sn63Pb37 [21,22].

Performance Parameter	Sn3.5Ag	Sn63Pb37
Melting point T/°C	221	183
Surface Tension F/($\times 10^{-5}$ N)	460 (260 °C, Air) 431 (271 °C, Air) 493 (271 °C, N_2)	380 (260 °C, Air) 471 (233 °C, Air) 464 (233 °C, N_2)
Density ρ/(g·cm^{-3})	7.5	8.4
Resistivity ρ/(μΩ·cm)	10.8	15
Thermal conductivity λ/(W·cm^{-1}·°C^{-1})	0.33 (85 °C)	0.5 (30 °C~85 °C)
Coefficient of thermal expansion (CTE) ($\times 10^{-6}$·K^{-1})	30	25

PCB substrate, solder, wire, components, and copper through the hole wall expansion coefficient are inconsistent, resulting in welding cooling cracks on the surface of solder joints. By different experiments, four kinds of ways are found to solve the problem.

- Control appropriate welding temperature and tin dipping time to reduce deformation;
- Control the deformation of the solder joint before cooling and solidification, such as increasing preheating temperature;
- Control the appropriate cooling rate: generally, the cooling rate is controlled at 6 °C/s~10 °C/s. The cooling rate has a great influence on the grain size, morphology, and crystallization rate, and avoids the formation of dendrites with a clear orientation affecting the performance of the solder matrix.
- Regarding control material technicality, adopting PCB with a high glass transition temperature and low coefficient of thermal expansion in the z-axis direction can prevent plate-level stress from massive deformation by choosing eutectic filler metal or filler metal containing elements (adding Ni), which have a significant influence on crack shrinkage of a lead-free alloy.

The first stage is an attempt at small-scale switching. At present, two technical schemes are Sn-Ag and Sn-Pb. Sn-Ag solder is used in most PCBs and Sn-Pb solder is used in the parts with higher requirements. The scheme has been implemented in the combined instrument. Sn96Ag3.7 is used as lead-free solder. The content of lead in solder is between 0% and 0.1%, which accords with the national definition of lead-free solder.

The second stage is comprehensive promotion. In order to push out the comprehensive promotion of lead-free PCB, more work should be provided by the government and the PCB industry at this stage. For the government, the main task is to promote the technological upgrading of the industry by implementing laws and regulations to encourage the use of lead-free PCB parts by the mainframe factories through subsidies. For the PCB industry, the main task is to achieve industrial integration and standardization as soon as possible and to reduce costs by means of scale and standardization. In this study, lead-free technology is realized simultaneously with Europe by reducing costs on a large scale. For other parts, this study cooperates with major suppliers of electronics and electrical appliances, pays close attention to technological changes and cost changes in the industry, and implements a lead-free process within acceptable cost.

With the implementation of the RoHs directive, the electronic and electrical industry has begun to realize lead-free gradually. It is believed that, in the near future, with the progress of technology and the reduction of cost, lead-free electronics and electrical appliances in the automotive industry will be realized.

4.6. Choose Renewable or Natural Materials

Components and parts should be produced from renewable or natural materials to minimize the dependence on fossil materials. Article 12 of the Technical Policy on

Recycling and Utilization of Automobile Products clearly points out that small or lightweight, renewable parts or materials should be used in product design as far as possible. Recyclable materials should be selected to the greatest extent in the selection of production materials, and the types of materials should be continuously reduced in order to facilitate the recycling. Based on the composition and structure of vehicle materials, steel accounts for more than 60%, aluminum and alloy accounts for more than 10%, and polymer accounts for more than 14%. The above three kinds of materials belong to the category of materials that consume a lot of resources.

China is the largest automobile producer and seller in the world, and also a major producer and consumer of iron and steel resources. World crude steel consumption (2015): 1617 million tons, China (700) > the United States (108) > India (89) > Japan (68), Asia's steel use accounts for more than 60%, and the use of metal recycling materials will greatly reduce the consumption of fossil energy resources. In this study, the typical material manufacturers at home and abroad were investigated and applied to the research of vehicle models. Detailed data are shown in Table 8.

Table 8. Proportions of different materials in a vehicle.

Material	Vehicle Material Ratio	Recycled Materials Ratio	Green Material Ratio
Steel plate	29.80%	20%	6.00%
Bar	11.20%	90%	10.08%
Other steel	5.20%	20%	1.04%
Sintered steel	4.0%	0%	0.00%
Stainless steel	1.50%	50%	0.75%
Cast iron	4.0%	90%	3.60%
Aluminum plate	1.0%	50%	0.50%
Primary aluminum	2.3%	0%	0.00%
Secondary aluminum	3.0%	100%	3.00%
Aluminum profile	2.1%	10%	0.20%

More commonly used materials are carpets or sound-deadening mats. These sound-deadening mats are usually made of a variety of recycled fibers, with low cost and good effect. In addition, the development and use of natural materials or composite materials with natural materials is an important direction to enhance the environmentally-friendly properties of materials. For example, the material scheme of PP wood board has been adopted on the back separator of all products. In addition, considering the demand for weight reduction (lightweight), the PU board with honeycomb paperboard as the sandwich layer is a better solution to manufacture the material of a rear partition and trunk floor.

Technical stability and cost control are critical for enabling the use of recycled materials in a large number of automotive components and parts. At present, no perfect industrial chain exists for recycling, processing, and quality control of recycled materials in China, and effective industrial and policy support is lacking in the application of recycled materials. Recycled PA66 materials are currently available only for some small products, such as buckles and clips. In addition, recycled PP materials are used to manufacture components and parts with lower functional requirements, such as fenders, bumper bracket, fender bracket, and a diversion plate.

This study involved the use of 15 kg of natural or recycled materials per vehicle, which saved 6300 tons of fossil resources annually and improved vehicle recyclability by about 1.2%.

On the basis of material selection for improved product recyclability, the following basic principles should be followed to the extent possible.

- Reduce the use of thermosetting materials, replacing them with thermoplastic materials that are easy to recycle.
- Use materials that are easy to recycle or have mature recycling technology.
- Minimize the number of types of materials.

- Use materials with good compatibility.
- Avoid or minimize toxic and harmful materials with a focus on lead.
- Choose renewable or natural materials.

As shown in Table 9, material optimization options on the basis of these principles are carried out: increasing the use of thermoplastic materials, thermoplastic elastomer materials, minerals, and organic natural materials, and decreasing the use of thermosetting plastics, paint adhesive materials, and inseparable polymer composites. Among these materials, the use of copper, aluminum, and their alloys is slightly reduced in automobiles.

Table 9. Material compositions of the vehicle before and after optimizing materials.

Type of Material	Material Composition (%)	Optional Material Composition (%)	Difference (%)
Iron steel	54.19	54.30	−0.11
Iron cast	5.50	5.50	0
Aluminum	8.91	5.10	3.81
Copper alloys	1.21	1.10	0.11
Lead	0.64	0.49	0.15
Other metals	0.02	0.50	−0.48
Thermoplastic materials	8.13	12.6	−4.47
Thermosetting materials	1.58	0.40	1.18
Elastomers	2.40	5.80	−3.4
Foam	1.57	1.70	−0.13
Inseparable polymer composites	4.96	2.63	2.33
Synthetic fabric	1.33	0.80	0.53
Paint and adhesive	0.80	0.37	0.43
Mineral materials	2.63	4.40	−1.77
Organic natural materials	2.77	1.30	1.47
Liquids	4.63	4.60	0.03
Electronic components	0.31	0.30	0.01

5. Recommendation on Product Design

Generally, the design of a car is influencing the recyclability. Directives on car recycling quotas need to be fulfilled by the automotive industry. Therefore, the pressure on car recycling technologies will increase in the future. The purpose of vehicle dismantling and recycling is to maximize the recycling and reuse of components, parts, and materials so that the number of waste generated will be reduced to save resources, protect the environment, and maximize profits. Therefore, the basis for effective recycling or reusing of automotive products pertains to whether dismantlement and separation can be easily achieved between part assemblies and vehicle body, between part assemblies, and between subcomponents, and whether they can be conveniently separated into homogeneous constituents to realize effective recycling of automobile products. A vehicle with good detachability will greatly reduce the difficulty associated with subsequent product disassembly and material sort and will reduce the control risk of material reuse, thus, improving the efficiency and effectiveness of the entire recycling chain. Unfortunately, in the early stage of product and vehicle body structural design, many considerations in China are about the reliability, stability, and durability of product fixing and connection, while the ability of vehicles and components and parts to be dismantled and easy to dismantle during recycling are often neglected. Usually, the design phase is more about how to assemble. Assembly and disassembly are mutually reverse processes. Easy assembly does not mean easy disassembly and vice versa [23], so assembly design and disassembly design must be comprehensively analyzed in the automobile design stage. Post-scrapping disassembly should be taken into account in the initial stage of product design, which can be beneficial for the recycling of products. The detachable design has become a primary element of green product design advocated by vehicle designers, which requires detachability as an important indicator of structural design in the initial stage of product design [24]. In fact, the disassembly of a vehicle can provide a clear understanding of the reverse process of the assembly, which can provide a better experience for design recyclability. Dismantling is an important strategy to realize effective recycling. In addition, actual technical support can be established for detachability design standards and it can convert this information to detachability design standards. The following subchapters give some recommendation to increase design for recycling.

5.1. Modular Design

Modularization is an effective way to realize universal interchange, quick replacement, and disassembly of components and parts [25]. Modular design can be divided into several modules that can perform certain functions according to functional productization [26] and can unify the connection structure and size between the modules, which not only makes manufacturing easy but is also advantageous for disassembly and recovery. Common modules include instrument panels, doors, etc.

The principle of modular design is to make as many products as possible with a few modules. On the basis of meeting the requirements, the products are made with high precision, stable performance, simple structure, and low cost, and the module structure should be as simple and as standardized as possible, while the connection between modules is as simple as possible. Therefore, how to divide modules scientifically and in a controlled manner is a very important task in modular design. In general, the system must be analyzed carefully, systematically, and structured before partitioning, and the following points should be noticed:

- The role of the module in the entire system and the possibility and necessity of replacement.
- Maintain a certain degree of independence and integrity of the module in terms of function and structure.
- The joining elements between modules should be easy to connect and separate.
- The division of modules cannot affect the main functions of the system.

5.2. Disassembly Work-Minimization

Minimizing the disassembly workload can be defined in two ways. On the one hand, under the premise of meeting the functions and user requirements, the product should be designed to be of the simplest structure and shape, and the types of materials that make up the product's components and parts should be limited as much as possible. For example, the principle of material design of a complex assembly product, such as an instrument panel, door guard, and bumper is as follows: electroplating decorative components and parts (such as a logo) are uniformly made of ABS materials, and others are made of PP materials according to different functional requirements, thereby minimizing the workload in the process of dismantling and recycling without a large number of materials. On the other hand, the meaning of minimizing the disassembly workload is that the work of maintenance, dismantling, and recycling is simplified, and the technical requirements for this work are reduced, making the toxic and hazardous materials in the product easy to classify and dispose.

5.3. Easy Operation of Components and Parts

In the traditional automotive product design, much attention is paid to the comfort, safety, and environmental protection (e.g., fuel consumption, exhaust emissions) of vehicles as usual, but the recycling of vehicles and the environmental impact of vehicles after they are scrapped are rarely considered. Because of the limitation of scrapped vehicles' resources and the relatively low labor cost, most of the scrapped vehicles in China currently are manually dismantled or semi-mechanically dismantled. In order to make the disassembly more convenient, the product design should try to meet the requirements of easy operation as follows:

- Use components and parts made of simple materials to the greatest extent possible, that is, avoid the mutual embedding of metal materials and plastic parts, which will make the subsequent disassembly and separation work more difficultly.
- Design a reasonable location for waste oil discharging. In product design, it is necessary to leave a drain that facilitates access to various waste oil (such as engine oil, various lubricating oil, etc.) so that the waste oil can be discharged easily and completely. In this study, an easy-to-pierce structure is reserved at the bottom of the fuel tank, which is the easiest way to discharge residual oil when vehicles are scrapped, and the waste oil can be completely drained by piercing with the simplest tool.
- Regarding rigid parts, a non-rigid design will cause inconvenient disassembly, so try not to use it.
- For easy-to-grab components and parts, it is necessary to design the parts on the surface of the parts for easy grasping so that the target parts can be taken out accurately and quickly.

5.4. Easy Separation of Parts, Components, and Materials

In product design, the assembly property of the product's components and parts is usually taken into consideration more. However, the disassembly property of these is often considered less, which will result in much contradiction in the real situation.

Whether a component or part can be reused or recovered depends largely on its ease of disassembly. Therefore, it is essential that the connection structure of components and parts is designed to be reasonable. Under the premise of meeting the performance and functional requirements of the components and parts, the design of the connection structure of these components and parts should be as simple as possible. When the product structure is designed, the designer must change traditional connection methods that are not easy to disassemble and replace them with easy-to-disassemble connection methods. In addition, designers should minimize the number of fasteners, unify the type of fasteners, and ensure that the disassembly process is accessible and features a simple disassembly action. Designers should also try to ensure that the standardized disassembly equipment and tools can be selected at the disassembly stage, which is another important factor that can facilitate quick disassembly of components and parts.

In the design of components and parts, the principle of recycling value must be followed. Specifically, when the part recycling value and the cost of the part not being recycled for other processing is greater than the disassembly cost, recycle the part. When the part recycling value is less than the disassembly cost, and the difference between the two is less than the processing cost of the part, recycle the part. Otherwise, if the difference between the two is greater than the processing cost of the part, it is not recycled. The following eight-structure designs facilitate the disassembly of components and parts and can significantly improve the product's recyclability and recoverability.

- Standardization and simplification of the connecting and fixing method between components and parts. Try to use the mechanical connection to reduce the difficulty of disassembly and improve disassembly efficiency.
- Adopt serialized and modular product design. Use the same or standard components and parts to the greatest extent possible in different series of products to facilitate the sort.
- Select as many reusable components and parts as possible or select those that have the same function and service life as similar new components and parts.
- Consider the possibility of reusing components and parts. Find ways to reuse components and parts in other aspects of consumer society and make full use of recycled components and parts.
- Minimize the number of materials used. Following the principle of "the minimum is the best," the design should be completed with the least use of materials to meet the required function.

- Minimize the number of different types of materials. Design components and parts to minimize the variety of materials used to improve sort efficiency and recovery rate and to reduce the purchase price of materials.
- Choose environmentally-friendly materials. Recycling materials, biological materials, and recycled materials should be used as much as possible as long as the function is not affected, to form a virtuous circle of effective use of resources.
- Use materials with good compatibility. Even if these materials cannot be disassembled after they are formed into components and parts, compatible materials can be recycled together.

5.5. Auto Part-Packaging Design

To minimize energy consumption and reduce resource consumption, the automobile manufacturing industry is based on the principle of "compliance with regulations, the establishment of a sound environmental management system, systematic environmental load management for products and processes, minimization of resources and energy, and minimum carbon emission principles." The Japan Auto Parts Industry Association requires its vehicle and component and part manufacturers to jointly build a green supply chain system [26] and to issue a green procurement guide to suppliers, which requires reduced packaging requirements. Recyclable packaging materials should be selected, including reusable packaging of components, parts, and materials. China's automotive product recycling technology policy requires that automobile manufacturers or imported automobile general agents be responsible for recycling and processing their sold automobile products and their packaging items [20]. The design principle of packaging container standardization has generally been adopted in China, and a unified serialized and standardized packaging container technical standard and management system has been formed according to the storage and transportation requirements of different products. This effort has ensured that more than 90% of components and parts are packed in recyclable packaging, fully eliminating the investment and waste of disposable packaging from the component and part manufacturers to the assembly line, which has not only reduced production costs but also reduced the workload of environmental pollution and recycling of packaging materials.

6. Conclusions

The components, parts, and material compositions of a vehicle are complex and become even more complex in the future. The information required to disclose for a typical vehicle results in more than 10 million units. In addition, raw material procurement and production globalization introduce different materials and standards in different countries. In addition, some materials are becoming more critical and the supply chain is becoming more vulnerable. A significant work process that meets records and technology data confidentiality requirements and the construction of a scientific, reasonable, simple, and effective information management and statistical analysis framework would be an indispensable means to achieve the goal of recycling and recovery.

Considering comprehensively the prospects of this study and the actual problems faced by users, the following six principles and requirements should be considered to ensure the practicality, advancement, and sustainability of this study.

- Advancement: adopt advanced sustainable development technology methods and combine advanced management ideas and concepts with actual management.
- Maturity: the adopted solution is mature and feasible, and has a wide range of commercial application examples to ensure the robustness of the system.
- Practicality: after this study is completed, it can meet the unified collaborative development management system requirements of software development enterprises.
- Usability: the system can be user-oriented in the interface display and front-end operation, and complete business conveniently and quickly.

- Scalability: for the products used, the fact that, with the gradual improvement of applications and the gradual increase of networked enterprises, the system can also be expanded and should be taken into account.
- Confidentiality: key contents such as bill of materials of the vehicle parts department, composition of core parts, and results of the vehicle calculation are kept confidential.

Implementing product design for recycling is the most important measure to achieve recoverability, recyclability, and banned or restricted substance management of automotive products. The related work includes not only the recyclability and detachability design of material selection and structural design but also a series of content such as banned or restricted substance control, supply chain information collection, disassembly analysis, recycling strategy, recoverability and recyclability calculation, and other aspects of the product life cycle. In the initial stage of product design, the most direct way to meet the regulations is by real-time intervention from the source and through scientific and rational material selection. This study was based on an analysis of 19.5% of components or parts with a weight greater than 0.5 kg from two typical vehicle models.

In conclusion, it can be identified that, through material selection for the components and parts of vehicles, the use ratio of thermoplastic materials, thermoplastic elastomer materials, minerals, and organic natural materials is increased, which were easy to recycle. In contrast, the use of difficult-to-recycle or non-recyclable materials, such as thermosetting plastics, paint adhesive materials, and inseparable polymer composites, is decreased. The basic requirements of the regulations were met through material design.

The core of automotive product design is environmentally-friendly, and adaptive to global development. Europe, the United States, Japan, and South Korea have accumulated rich experience in the field of scrapped automobiles with more than 20 years of development, but there still exist shortcomings. For example, specific requirements for green materials have not fully been established. Plastic and glass are recycled at a lower grade. Persistent organic pollutants may limit the recovery of broken residues.

Furthermore, new ways to disassemble electric vehicles (various types, valuable components in batteries, motors, and power electronic components) need to be developed. These shortcomings reduce the recycling value of end-of-life vehicles (ELVs). In the context of the rapid development of a global economy, the deterioration of the living environment, and a severe shortage of resources and energy, only an all-round upgraded circular economy strategy, such as raw material recycling, resource reconstruction, an extending product life, product service, and transformation from ownership to sharing can maximize the value of products and materials in all economic activities. This core competitive advantage is the future development direction in the field.

Author Contributions: Conceptualization, X.H., D.S., and A.P. Methodology, X.H., D.S., and G.Z. Validation, D.S., G.Z., and A.W. Formal analysis, X.H. and D.S. Investigation, D.S. and J.X. Resources, A.W. and J.X. Data curation, D.S. and A.P. Writing—original draft preparation, X.H., D.S., and A.P. Writing—review and editing, W.C., D.S., and J.X. Visualization, W.C. and J.X. Supervision, A.P., G.Z., and A.W. Project administration, X.H. and D.S. Funding acquisition, J.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by the National Natural Science Foundation of China (No. 51476120).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Acknowledgments: Thanks are given to Yaze Li for his help in preparing graphs and to Suying Zeng for her language proof reading.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Minoru, G. Construction of Japanese ELV Resource Recycling system. In Proceedings of the 2018 International Forum on China Automobile Material Invitation (IFAM 2018), Tianjin, China, 28–30 March 2018.
2. Georg, M. European End-of-life Vehicles Directive, 20 years' experiences-continuous adjustments. In Proceedings of the 2017 International Forum on China Automobile Material Invitation (IFAM 2017), Tianjin, China, 11–13 May 2017.
3. Zhang, N. New Journey of China's Automobile Industry under the New Round of Industrial Change. In Proceedings of the 2018 International Forum on China Automobile Material Invitation (IFAM 2018), Tianjin, China, 28–30 March 2018.
4. Zhao, Q.; Chen, M. A comparison of ELV recycling system in China and Japan and China's strategies. *Resour. Conserv. Recycl.* **2011**, *57*, 15–21. [CrossRef]
5. Cheng, Y.W.; Cheng, J.H.; Wu, C.L.; Lin, C.H. Operational characteristics and performance evaluation of the ELV recycling industry in Taiwan. *Resour. Conserv. Recycl.* **2012**, *65*, 29–35. [CrossRef]
6. Li, W.; Bai, H.; Yin, J.; Xu, H. Life cycle assessment of end-of-life vehicle recycling processes in China—Take Corolla taxis for example. *J. Clean. Prod.* **2016**, *117*, 176–187. [CrossRef]
7. Zhou, F.; Lim, M.K.; He, Y.; Lin, Y.; Chen, S. End-of-life vehicle (ELV) recycling management: Improving performance using an ISM approach. *J. Clean. Prod.* **2019**, *228*, 231–243. [CrossRef]
8. Sato, F.E.K.; Furubayashi, T.; Nakata, T. Application of energy and CO2 reduction assessments for end-of-life vehicles recycling in Japan. *Appl. Energy* **2019**, *237*, 779–794. [CrossRef]
9. Petronijević, V.; Đorđević, A.; Stefanović, M.; Arsovski, S.; Krivokapić, Z.; Mišić, M. Energy Recovery through End-of-Life Vehicles Recycling in Developing Countries. *Sustainability* **2020**, *12*, 8764. [CrossRef]
10. Rovinaru, F.I.; Rovinaru, M.D.; Rus, A.V. The Economic and Ecological Impacts of Dismantling End-of-Life Vehicles in Romania. *Sustainability* **2019**, *11*, 6446. [CrossRef]
11. White Paper on Vehicle Hazardous Substances and Recycling Management. 2020. Available online: https://www.miit.gov.cn/jgsj/jns/gzdt/art/2020/art_54eae7f9696a4d288acec0f9b499f6bc.html (accessed on 5 December 2020).
12. Zhang, C.; Chen, M. Designing and verifying a disassembly line approach to cope with the upsurge of end-of-life vehicles in China. *Waste Manag.* **2018**, *76*, 697–707. [CrossRef] [PubMed]
13. van Schaik, A.; Reuter, M.A. The optimization of end-of-life vehicle recycling in the European Union. *J. Miner. Met. Mater. Soc.* **2004**, *56*, 39–43. [CrossRef]
14. International Organization for Standardization (ISO). *Road Vehicles—Recyclability and Recoverability—Calculation Method (22628)*; International Organization for Standardization (ISO): Geneva, Switzerland, 2002.
15. Yan, W. Talking about the Quality Management of Automotive Components and Parts. *Auto Expo* **2020**, *2*, 14.
16. Zhao, Q.; Chen, M. Automotive Plastic Parts Design Recycling Research and Development in China. *J. Thermoplast. Compos. Mater.* **2015**, *28*, 142–157. [CrossRef]
17. Kathy, X. Development direction of high value utilization technology in automobile recycling plastics industry. In Proceedings of the 2017 International Forum on China Automobile Material Invitation (IFAM 2017), Tianjin, China, 11–13 May 2017.
18. Shen, J.; Chen, M. The Research of Design Rules for Automotive Products facing Recycling and Dismantling. *Automob. Parts* **2009**, *3*, 29–35.
19. Bahadori, A. Compatibility in Material Selection. In *Corrosion and Materials Selection: A Guide for the Chemical and Petroleum Industries*; The Technical Policy for the Recovery of Automobile Products 2006; John Wiley & Sons: Hoboken, NJ, USA, 2014; pp. 295–335. Available online: http://www.gov.cn/jrzg/2006-02/14/content_191122.htm (accessed on 10 December 2020).
20. Shalaby, R.M. Effect of rapid solidification on mechanical properties of a lead free Sn–3.5Ag solder. *J. Alloy. Compd.* **2010**, *505*, 113–117. [CrossRef]
21. Wang, J.; Xue, S.; Lv, Z. Effect of gamma-ray irradiation on microstructure and mechanical property of Sn63Pb37 solder joints. *J. Mater. Sci. Mater. Electron.* **2018**, *29*, 20726–20733. [CrossRef]
22. Zhao, S. *Theoretical Research and Implementation of Automatic Generation of Automobile Component-And Part-Disassembly Sequence*; Chongqing University: Chongqing, China, 2005.
23. Fang, H. *Research on the Key Problems in the Recovery of Automobile Products for Circular Economy*; Hunan University: Changsha, China, 2009.
24. Huang, H. Research on Methodology of Modular Design for Recycling. *Trans. Chin. Soc. Agric. Mach.* **2006**, *37*, 144–149.
25. Quan, N.; Xia, X. Study on modular design of active recycling-oriented automobile product. *Wuhan Univ. Sci. Technol.* **2014**, *33*, 148–150.
26. Takafumi, E. Green Supply Chain in Japanese Auto Parts Industry. In Proceedings of the International Forum on China Automobile Material Invitation (IFAM 2017), Tianjin, China, 11–13 May 2017.