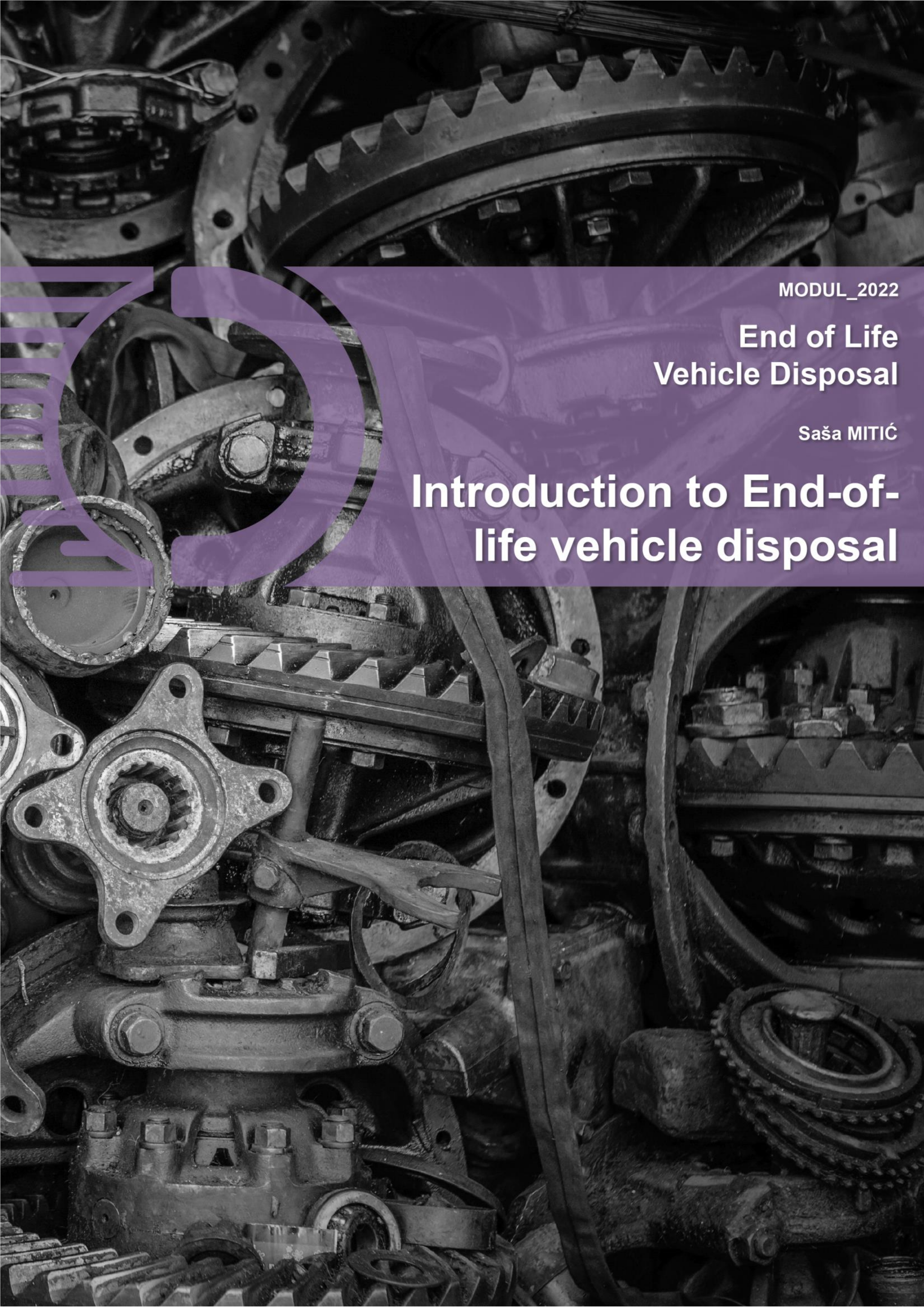

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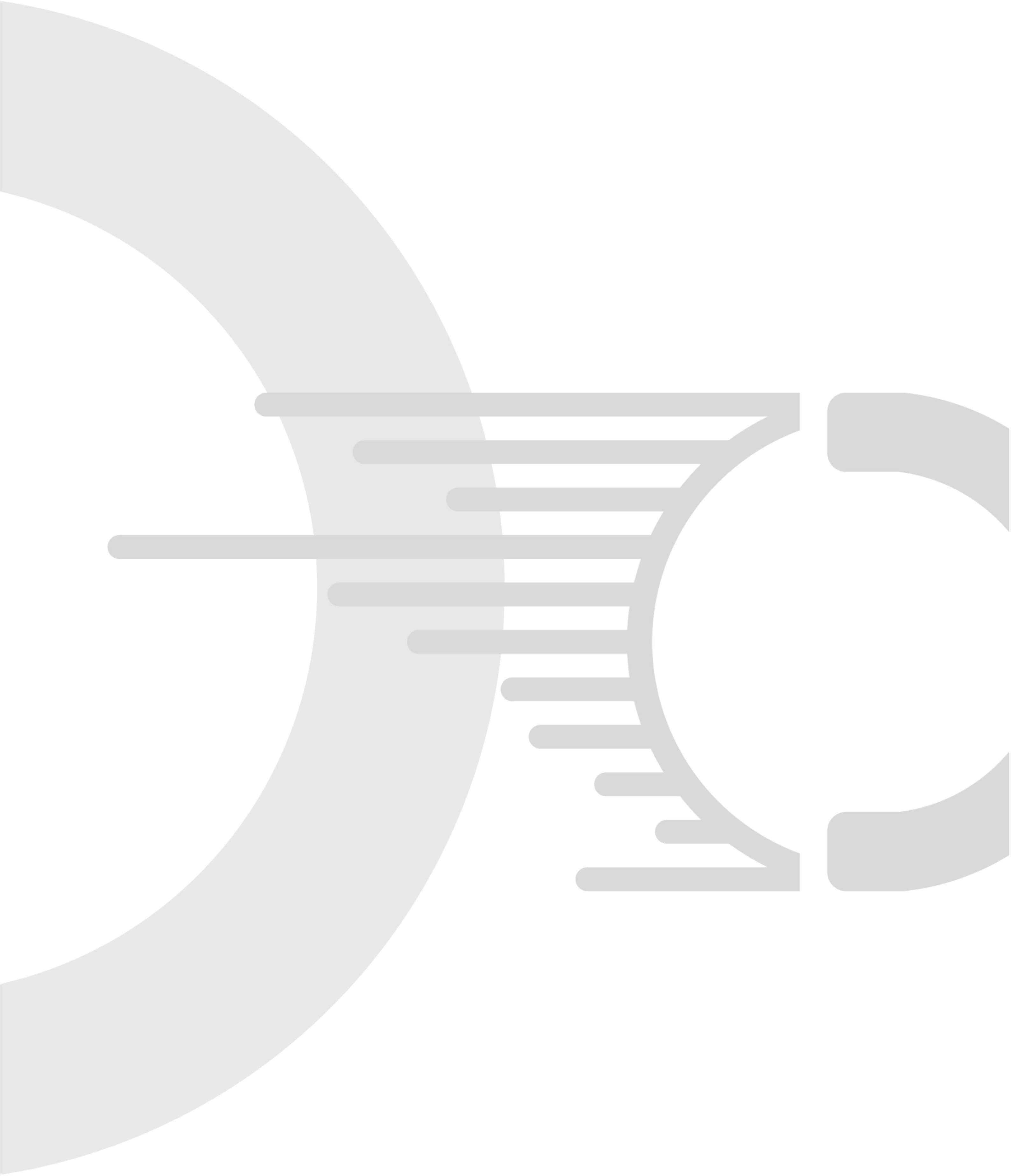
## End of Life Vehicle Disposal

Saša MITIĆ

# Introduction to End-of-life vehicle disposal



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## End of Life
## Vehicle Disposal

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# Introduction to End-of-life vehicle disposal

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# 1. INTRODUCTION

The automotive industry, along with the energy production industry, is a basic contributor to development of humankind in the last century. An ever-increasing number of people directly or indirectly becomes a participant in industry chain, which is linked with the production of road vehicles.

On the other hand, the development of humankind dictates the ever-growing need to use road vehicles in everyday life and in performing work tasks. Contributing to this is the constant growth of produces and sold vehicles, as well as vehicles in use.

However, automobile industry is exposed to numerous serious challenges, which mostly relate to the impact of automobiles and automobile industry on the environment. Vehicles during their life cycle affect the environment in several ways:

- Through energy consumption and other resources;
- By generating waste during production and use;
- By disposal at the end of their life.

All the listed ways of impact of vehicles on the environment during their entire lifetime represent a great burden imposed on humanity through production, use and disposal of vehicles.

The increase in number of vehicles in use directly impacts in the growing number of side-effects on the environment via all three influential factors. While the first two factors are a subject of thought for many years now and a constant progress in reducing the effects of actions is noticeable, disposal of end-of-life vehicles is relatively new area of research. Namely, only in the last two decades we become aware that the huge number of vehicles after their use is uncontrollably disposed of and this impacts the environment in various ways. Because of this, it was very important to design an appropriate global action strategy in this area.

In order to become aware of the problem of disposing of end-of-life vehicles, it is necessary to present some statistical data related to the current number of vehicles.

## 1.1. STATISTICAL INDICATORS FOR VEHICLE MARKET

Monitoring the condition of the active fleet over the years gives us accurate data on the number of vehicles in use, as well as the constant trend in growth. Beside the number of registered vehicles, the monitoring of newly produced and sold vehicles is of great importance, because by comparing the data it is easy to find the number of vehicles that come out of use each year, and in that way represent a group of vehicles that have ended their life cycle.

The production of automobiles constantly grows. After the Second World War, when the general world development and the restoration of the destroyed industry led to a huge increase in production and monitoring of the produced vehicles, a significant and constant increase was noticed. From starting 10 million units in 1950, we have arrived at 58 million units in 2000. In the last fifteen years, the growth in number of produced vehicles has increased to around 90 million units in 2014 (see figure 1), which represents a growth of over 50%. Last estimates show that in 2016, 95 million units were made, which shows further increase in production.

The only decline in vehicle production since data has been monitored was recorded in 2008 and during 2009, because of the global financial crisis, which shook all branches of industry and trade. However, since 2010 the growth of produced vehicles has made up for all the shortcomings of the previous year, and a stable trend of growing number of produced vehicles is continued.

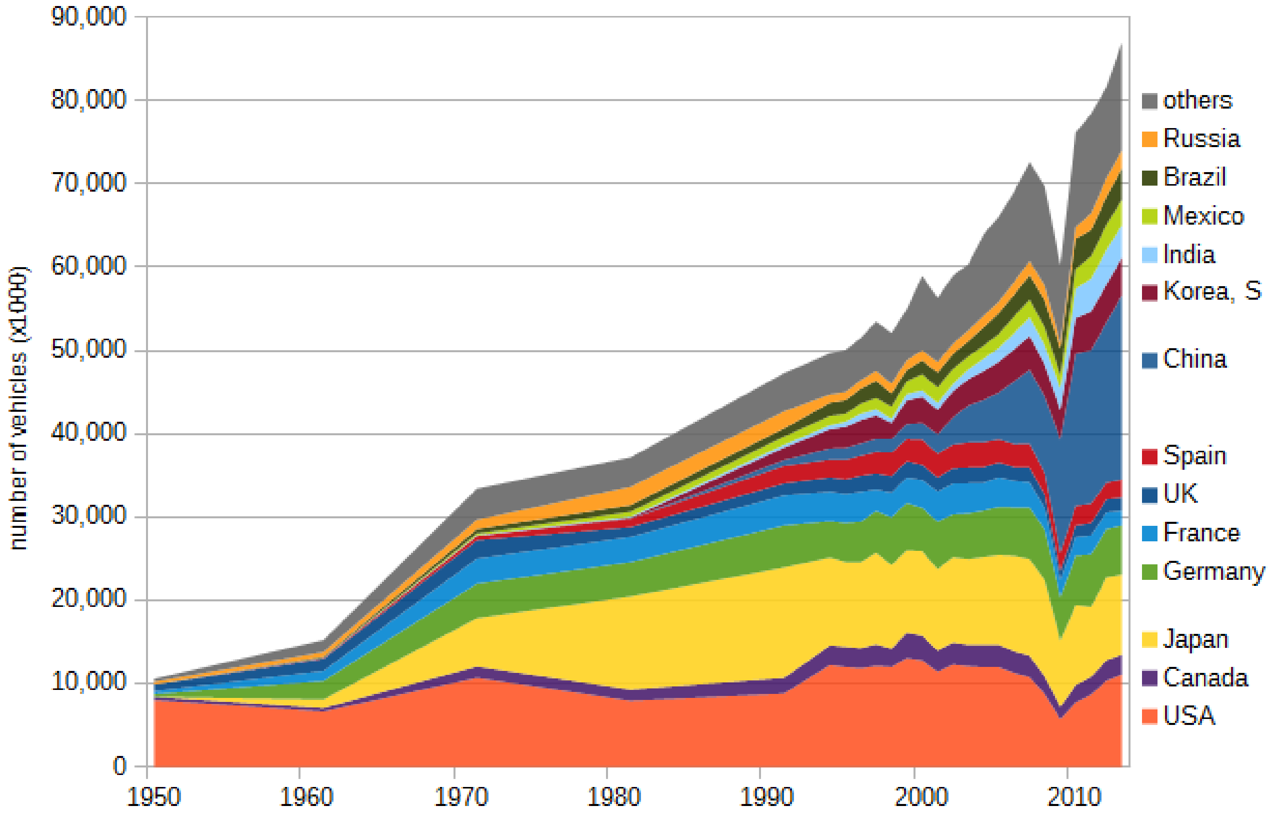

*Figure 1 - World production of vehicles in period 1950–2014*

In addition, all actual prognosis indicates that the trend of growing number of produced vehicles will continue in the coming period.

Trend of produced vehicles fully corresponds to official data on the number of sold vehicles in the same time period. Data on the number of sold vehicles is shown in the Figure 2.

However, maybe, it is most interesting to analyse the statistical data on the growth of vehicle in use. By looking at the official data for the last ten years, total number of vehicles in use in 2005 was around 892 million units, and that number would reach 1 billion 282 million units in 2015. That shows an increase of over 30% in just ten years.

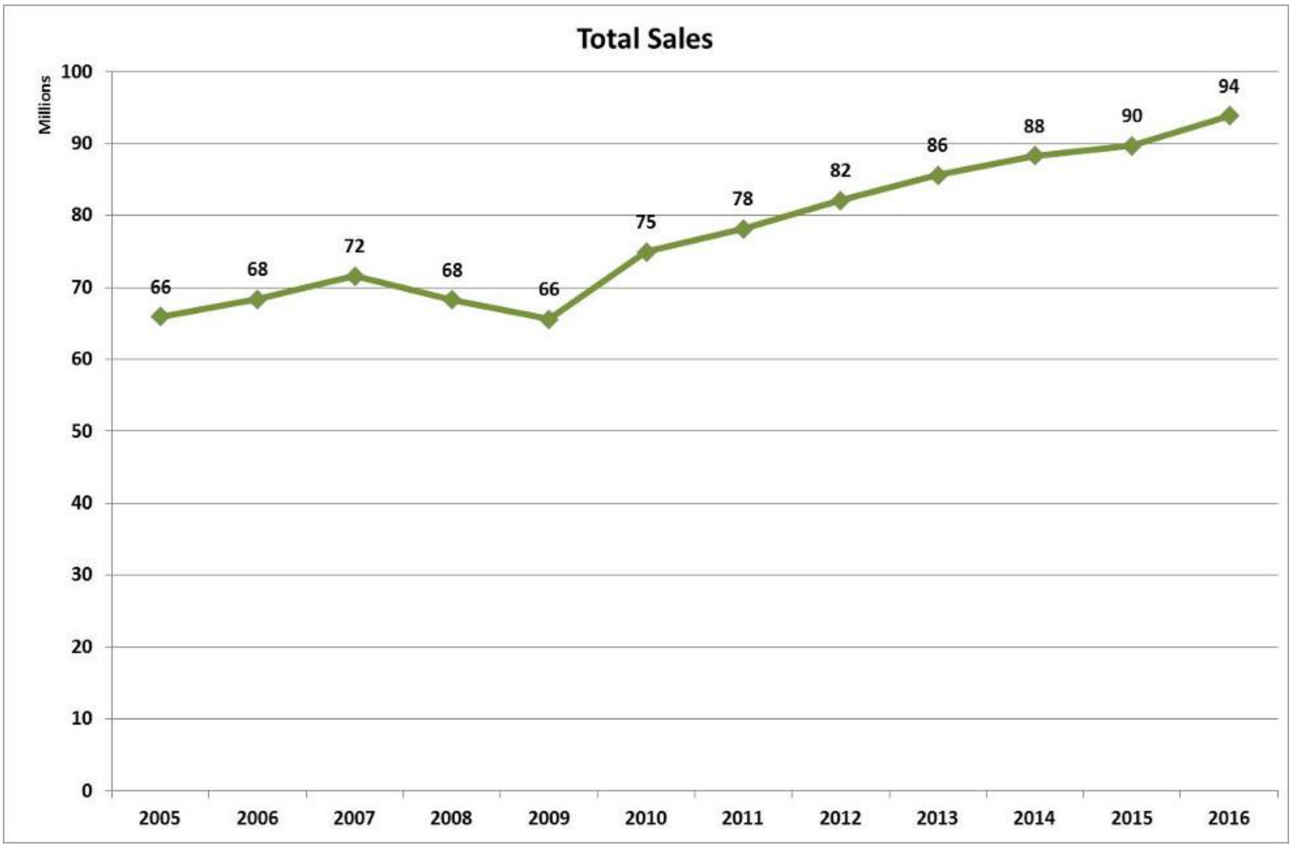

*Figure 2 - Number of vehicles dold in period 2005–2016*

The last 20 years have brought significant changes in the field of distribution of manufacturers. While in 20th century the primacy in production belonged to the United States of America, European countries (especially Germany, France, Spain, Italy, and the Great Britain), Japan and South Korea, the trends of reducing production costs led to the sudden relocation of production capacities to other countries at the end of the 20th century, South America, and Asia, especially in China. This somehow led to an even distribution of production facilities between North and South America, Europe, and Asia.

# 2. PROBLEMS OF VEHICLES AT THE END OF THEIR LIFE CYCLE

Since the end of the 19th century, vehicles slowly enter human use. Since the half of the 20th century, vehicles became standard and an integral part of human life, by making work and life easier through years, which inevitably led to the use of an increasing number of vehicles. Unfortunately, as humanity always gives precedence to production instead of the problem of end-of-life vehicle disposal, the increasing number of vehicles and not regulating their waste could create huge problems and even hazards.

## 2.1. ENVIRONMENTAL IMPACT

Although they are valid consumer products, properly used vehicles can last and serve for many years. However, with the gradual appearance of an increasing number of manufacturers and models, especially today, a man has a possibility of choosing from wide variety of vehicles, and a game of dominance is imposed on the manufacturers. In order to survive, manufacturers force each other to produce the best possible vehicle to the greatest extent and in the shortest possible time, in order to force the buyer or consumer to buy their product. Variation of vehicles, new and better, better looking models of the same type have an additional impact on the consumer. As new models become better in many aspects than their predecessors, that is how the consumers decide to buy a new vehicle. By losing the need for old vehicle, and with a goal making personal profit, the old vehicle is sold. Since new vehicles with better performance become more expensive, consumers with lower financial status are forced to buy that old vehicle. This process continues until the last consumer, that is, the owner could not sell his vehicle, that is, there would be no one to sold it to. It is then when the vehicle becomes unprofitable to the owner, therefore he usually “throws it away,” that is, disposes it in his own environment. This procedure inevitably leads to environmental pollution. For example, corrosion can lead to tank damage, which could leak the fluids on the environment, such as freon from the air conditioning system or oil from the braking system, or from the gearbox or main transmission. Glass may crack, scattering small pieces that can cause injury to living things.

The same fate is shared by vehicles involved in more serious traffic accidents, which repair would be unprofitable. Vehicles with light damage are repaired and are subject to resale process until they reach the last owner.

One of the main problems of impact of motor vehicles on the environment are the internal combustion engines which run of traditional natural fuels (fossil fuels), that is, air pollution. In addition, materials that are part of the vehicle, after the end of their useful life, if they are not treated in a proper way, can have a negative impact on the environment. Table 1 shows how a motor vehicle impacts the environment during its life cycle.

*Table 1 - Impact of motor vehicle on the environment during its life cycle*

| Environmental component | Pollution type | Impact level |
|---|---|---|
| Air | Gas emission, particles, dust | High |
| Global warming | Greenhouse gases ($CO_2$, $HO_x$, $CH_4$ ...) | High |
| Underwater | Waste oils, fuel, paint, emulsion, heavy metals and other | High |
| Land use | Wild landfills and components in natural environment | High |
| Soil pollution | Waste oils, heavy metals, plastic, general waste | High |
| Surface water | Waste oils, fuel, paint, emulsion, heavy metals, and other | High |
| Noise | Production processes, transport | High |
| Biodiversity | Damage to or disappearance of the eco-system | Medium to High |
| Natural riches (resources) | Depletion of non-renewable resources, high load on renewable resources | High |
| Ozon layer | Hydrogen fluorides | High |
| Waste | All aspects: gaseous, liquid, solid, hazardous | High |

## 2.2. FADING OF RAW MATERIAL RESOURCES

It is known that a vehicle is an assembly with huge number of parts. Those parts differ in many ways: material, shape, size, percentage composition, connections, functions and many more.

With the largest share, steel represents the basic material for automobile production, and it is obtained by processing iron received from mines. By having this natural relation, it can be said that steel is dependent on iron ores in mines, therefore, vehicle production is in the same way dependent. With the increased demand for vehicles, the consumption of steel also grows as well as ores in mines. Question arises, what will happen when the mines are empty? At the same time, it should be noted that vehicles are not the only product made of steel. Today, plastic largely replaces metal components on vehicles, but the entire vehicle cannot be made of plastic. Even if it were the case, there are other numerous industries which do not have an alternative to steel.

According to the statistical data for 2018, from total steel production in the world (1.826 billion metric tonnes), 51% went to the construction and infrastructure sector, 15% on machine equipment, 12% on automotive industry, 11% on metallic products, 5% on transport and 3% on household items and electrical equipment respectively (Figure 3).

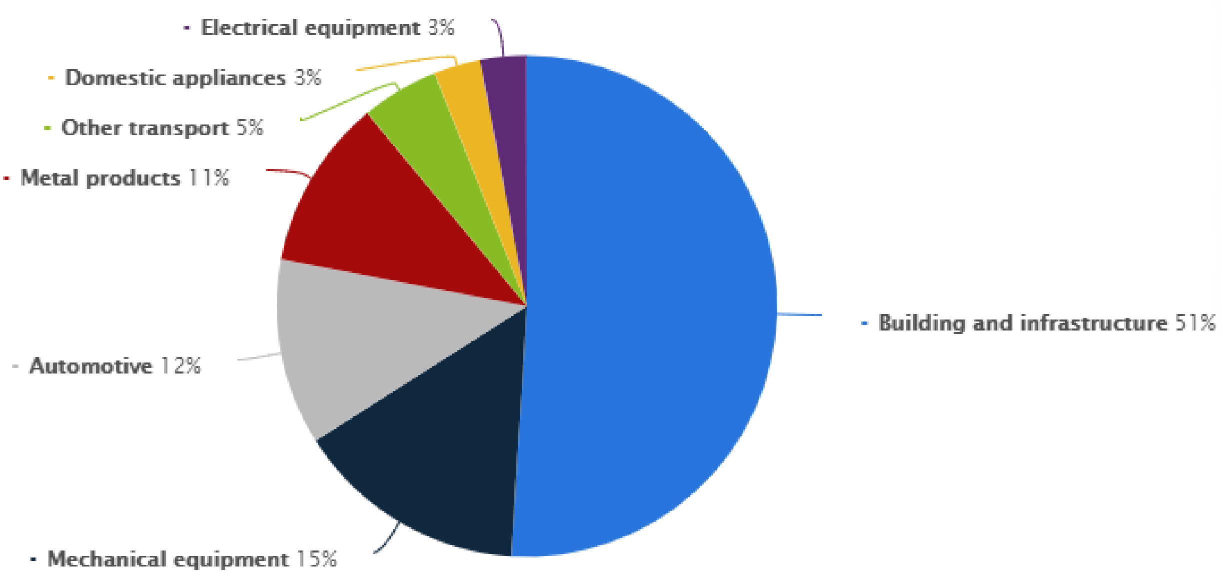

*Figure 3 - Percentage consumption of steel by sectors of industry for 2018*

If we were to convert this into numbers, 225.6 million metric tonnes of steel were spent on automotive industry, which is not a lot in comparison to infrastructural sector which demanded little less than a billion metric tonne of steel (931.26 million metric tonnes). In addition, for 2018, estimated reserves of “pure” iron are 84 billion metric tonnes (Figure 4).

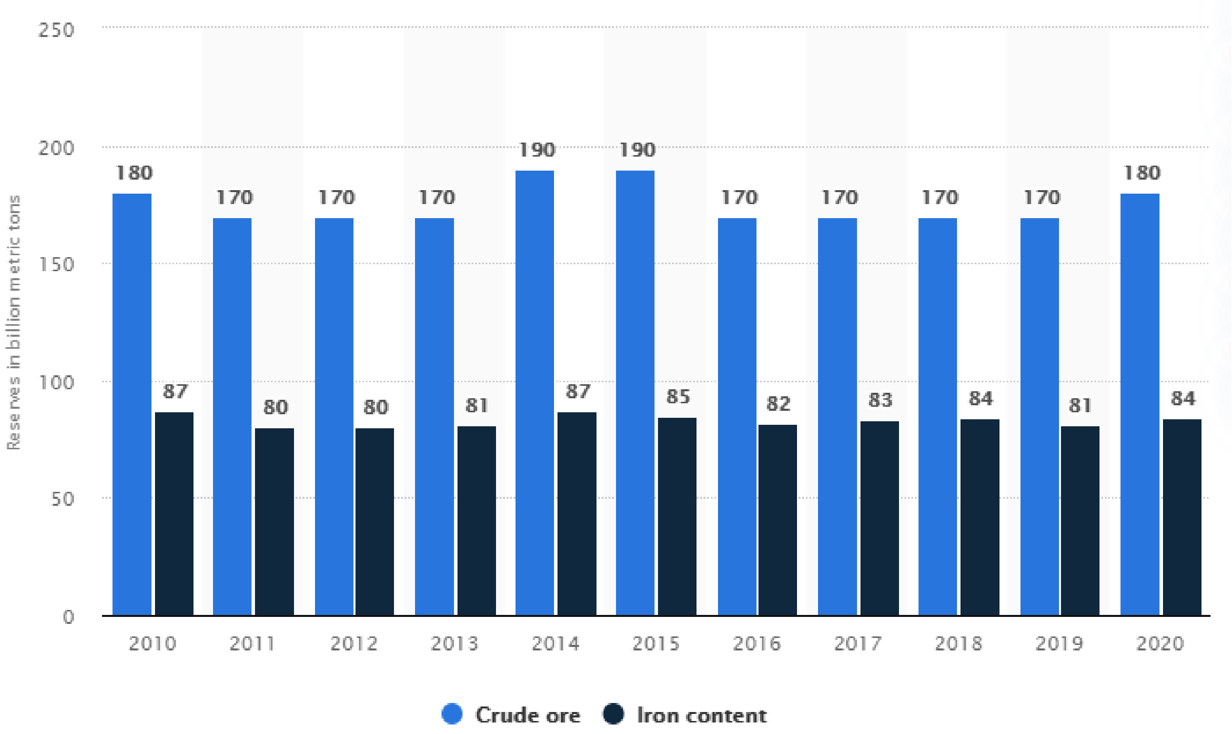

*Figure 4 - Estimated reserves of pure and iron ore*

Considering that from 1.6 tonne of iron, one tonne of steel is received, from 84 billion metric tonnes of iron, we would get 52.5 billion metric tonnes of steel. Under the assumption that all mentioned industries hold the same demand percentage annually, automotive industry would spend its percentage reserves in 232.7 years, but this number is only valid for the aforementioned assumption. This number is huge, but with rapid advancement in technology, without the application of recycling processes, this number could drop quickly.

## 2.3. ACCUMULATION OF VEHICLES AT THE END OF THEIR LIFE CYCLE

All those indicators undoubtedly show the importance of research and formation of the global strategy for treating end-of-life vehicles, because based on presented data with a conclusion that in 2015 over 40 million vehicles ended their life cycle. Of that number, about 10 million end-of-life vehicles are recycled annually in the countries of the European Union. By ignoring these indicators and not taking appropriate measures, the whole planet could very soon become one giant junkyard. Therefore, the question of “storage” arises if the vehicles were to be treated in the manner described above, that is, left in the environment to rot.

Illustratively, and to get a sense of the magnitude of the problem, if all those vehicles were of dimensions as *Fiat Punto* (length 3.84 meters, width 1.66 meters), for that year, all vehicles that have ended their life cycle would take up an area of around 255 million square meters, which is the equivalent of approximately 51,000 average football pitches. The area would certainly be larger because the total number of vehicles also include large ones such as trucks and busses. This would undoubtedly lead to significant environmental pollution.

However, the situation shows that the real number is probably smaller from the officially presented one. This is primarily related to the mass export of used vehicles from the countries of the European Union to other European countries that are not members of the Union (Eastern Europe, Russia, etc.), as well as some North African countries. It is obvious that the profit made in this way is much larger and that the European countries solve the problem of used vehicles this way, but still the problem what will happen to these vehicles at the end of their life cycle remains.

# 3. TERMS AND DEFINITIONS

For easier understanding of the matter, several terms regarding the process of disposing the end-of-life vehicles have been standardized. Those terms and their definitions are used within the framework of international regulative which deal with this matter, that will be discussed later in this chapter.

***vehicle mass - $m_V$***

Represents the complete vehicle shipping mass, as specified in ISO 1176, plus the mass of lubricants, coolant (if needed), washer fluid, fuel (tank filled to at least 90 % of the capacity specified by the manufacturer), spare wheel(s), fire extinguisher(s), standard spare parts, chocks, standard tool-kit;

***re-use***

Represents any operation by which component parts of end-of-life vehicles are used for the same purpose for which they were conceived;

***recycling***

Represents the reprocessing in a production process of the waste materials for the original purpose or for other purposes, excluding processing as a means of generating energy;

***recovery***

Represents the reprocessing in a production process of the waste materials for the original purpose or for other purposes, together with processing as a means of generating energy;

***dismantlability***

Represents the ability of component parts to be removed from the vehicle;

***reusability***

Represents the ability of component parts that can be diverted from an end-of-life stream to be reused;

***recyclability***

Represents the ability of component parts, materials or both that can be diverted from an end-of-life stream to be recycled;

***recyclability rate $R_{cyc}$***

Represents the percentage by mass (mass fraction in percent) of the new vehicle potentially able to be recycled, reused or both;

***recoverability***

Represents the ability of component parts, materials or both that can be diverted from an end-of-life stream to be recovered;

### *recoverability rate $R_{cov}$*

Represents the percentage by mass (mass fraction in percent) of the new vehicle potentially able to be recovered, reused or both.

Figure 5 shows an illustrated overview of the scope of covering the field regarding the disposal of end-of-life vehicles according to the previously mentioned terms and their definitions.

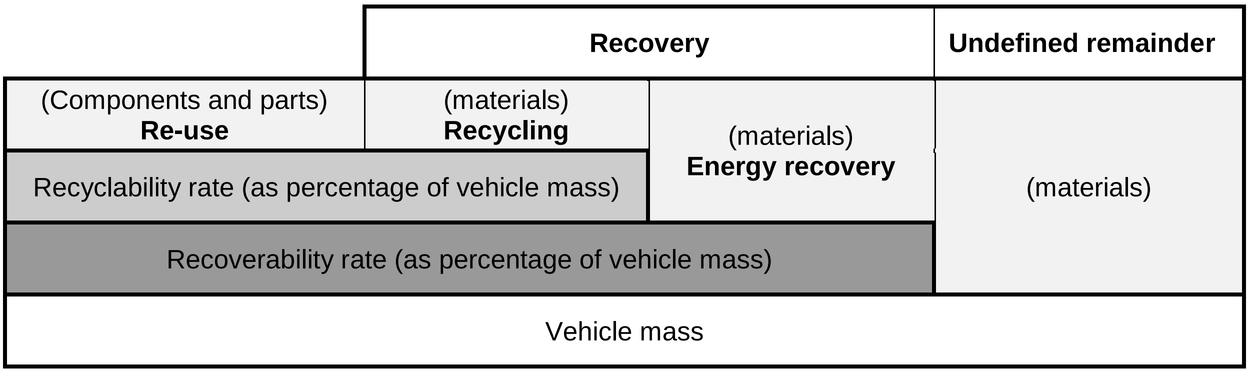

*Figure 5 - Important terms – overview*

# 4. THE CONCEPT OF SUSTAINABLE DEVELOPMENT

Every consumption of resources and every degradation of the environment has its limits; therefore, a further development must be a sustainable development, that is, there must be harmonized development for sustainable future. The term sustainable development represents the possibility of further developing existing and next generation, which would indicate that whatever damage done today is transferred to next generations.

The consumption of natural resources, as well as leaving the nature itself to regulate the problem of generated waste is with the development of industrial production even more intensified, so the environment cannot remain without consequences for future generations.

Apart from the production process alone represents new requirements and challenges on a daily basis, the process of treating vehicles (recycling of vehicles) also requires a lot of improvement, in order for it to follow the development of automotive industry. Recycling process of vehicles encompasses methods with which enables the obtaining of final products, that is, materials such as: metal, plastic, tyres, glass and other.

All these procedures are an integral part of industrial logistics in the area of production, that is, vehicle its component recycling. Gained knowledge and experience in research related to processes of development, production and exploitation of passenger vehicles are applied more and more in other industries as well. In designing the construction and product manufacturing, attention should be paid to energy efficiency and environmental protection. The products and their use should be manufactured in a way that they could be recycled, that is, they could be reused for similar or same purpose. By recycling of products, natural resource consumption is reduced, while also prolonging the life of landfill, therefore, preservation of the environment is possible.

Important task of environmental protection and improvement to environmental protection and suitable development is increase of control of waste generation. The most suitable way to reduce the amount of waste generated is to reduce the consumption of raw materials and to increase the rate of use of waste, that is, to apply the recycling process on the generated waste. Even if this is conceptually very simple, the implementation of waste management in modern technological society is very difficult and complex.

If waste management were to be a sustainable process, following factors must be considered:

- Environmental factors,
- Social factors,
- Economic Factors.

Figure 6, shows the factor which must be fulfilled in order for the waste management to be sustainable.

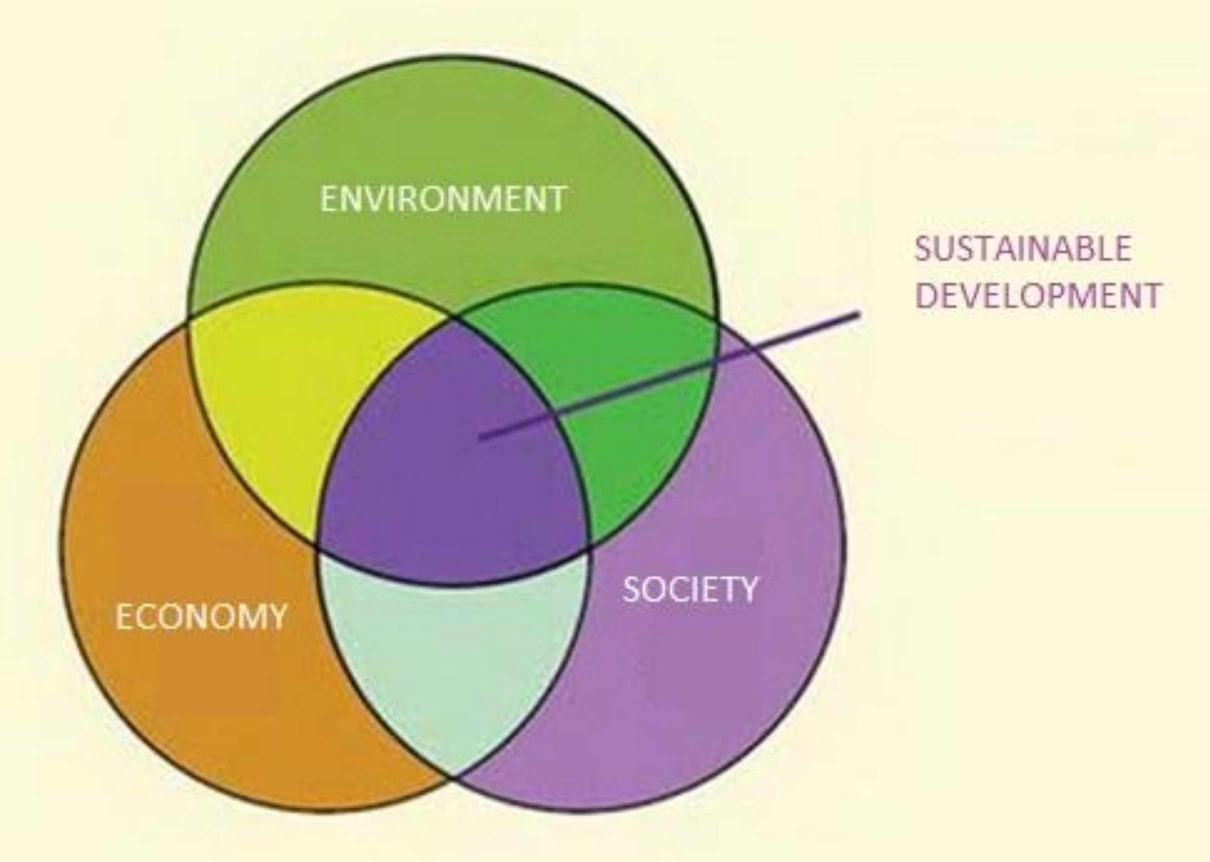

*Figure 6 - Factors for sustainable development*

Recycling promotes sustainability. For an activity to be sustainable, it must be justified economically and that it is not bad for the environment by enabling a service to a community with safe and responsible behaviour. Today's industries are moving towards sustainable processes as the world faces material shortcomings, rising costs and stricter environmental laws. Automotive industry and its products are the majority user of natural resources and are a source of emissions of harmful gasses. To reduce the energy consumption and the emission of harmful gases, which produce greenhouse effect, the industry is using lighter materials for the production. These materials include polymers, composites, high and medium strength steels, aluminium, and magnesium. The increased interest in hybrid vehicles will lead to an increase in the need of new materials, such as lithium, cobalt, and nickel. At the same time, regulative calls for a higher recycling rate of abandoned vehicles and their parts.

Replacing the conventional steel, which is recyclable, with lighter materials will lead to a reduction in the percentage of recycling vehicles, even though lighter materials would be recycled with the same recycling rate. Lighter materials and materials used for the production of batteries for hybrid vehicles are expensive, and if they are not recycled, they could become a resource with limited availability. Inappropriate disposal of these materials can have opposite effect on the environment. Therefore, the recycling of these materials is paramount for the sustainability of the automotive industry and its suppliers. Dismantling certain parts and materials from abandoned vehicles is an important step towards recycling these materials and parts.

If the recycling industry is not economically feasible, the world may face greater challenges in the preservation of the environment, and the reduction of quality waste may lead to use of ores for the production of final metals. Without the sustainable systems for recycling, it is estimated that there would be limitation in availability of the number of non-ferrous metals, according to the current designed use on the market. Increasing the recycling rate, ferrous metals would be necessary, especially aluminium, magnesium, cobalt, and nickel.

Efficient and economical solution for recycling of current and future residuals from the recycling process is necessary to improve the sustainability of the automotive industry and its suppliers. In order to produce the highest quality products at the lowest prices, the solution will most likely be an integrated system consisting of various technologies.

## 4.1. VEHICLE LIFE CYCLE PHASES

Based on the nature of the process, vehicle life cycle consists of four basic phases:

### *Research and development*

This phase includes all research and development processes in various fields, such as, the market, product, technology, business strategy and others. The output results of this phase are market position and commercial policy, technical documentation necessary for the production of automobile, instructions for managing production and business processes, as well as economic parameters. Development phase represents the support of knowledge in the whole cycle.

### *Production*

This phase includes a wide spectre of production processes, starting from the production of parts and assemblies to the production of a complete vehicle.

### *Use*

The phase of vehicle usage integrates all pre-sale, sale, and after-sale processes, that is, promotional activities, sale, service in both the warranty and out-of-warranty periods, communication with buyers and other.

### *Recoverability*

At the end of the vehicle’s useful life, the used vehicle recovery phase begins, which includes all processes of dealing with vehicles at the end of their useful life, such as: take-over from the last owner, issuing of certificates for pre-registration, dismantling, preparation of materials for reuse, delivery of parts for reinstallation, delivery of materials for the production of new product, energy, and shipment to the warehouse of useless waste. The material that cannot be used by returning it into the cycle must be permanently stored in accordance with regulation, at the appropriate landfill.

## 4.2. OBJECTIVES OF VEHICLE LIFE CYCLE MANAGEMENT

In order to reduce the amount of waste and the negative impact waste has on the environment, it is of great importance to introduce specific measures, which should be adhered to. Hierarchy of waste management represents measures, that is, rules, which if adhered to, could reduce the amount of waste being disposed of on landfills. Figure 7 shows a pyramid of vehicle life cycle management objectives.

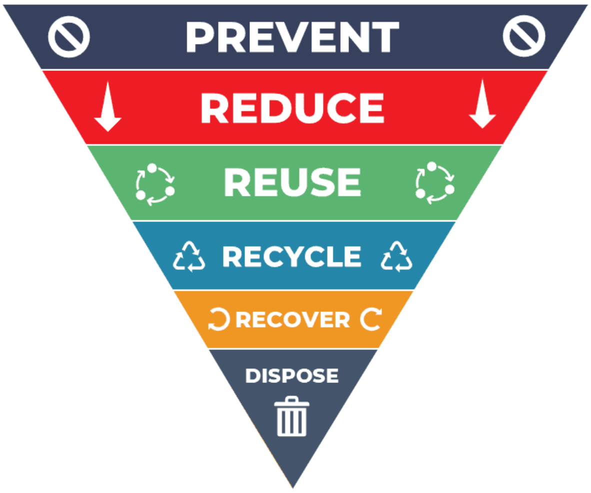

*Figure 7 - Pyramid of objectives of vehicle life cycle management*

***Prevention*** is a basic objective and a foundation of the pyramid. With appropriate vehicles design, as well as the design of adequate technological processes, conditions are created for a longer life of a vehicle, as well as for minimizing permanent waste in the phase of use at the end of the vehicle's life.

***Reduction*** is a layer of the pyramid and a second objective in terms of importance. Reduction is secured in the phase of vehicle and technology development, but also during the processes in production and use phase, through reduction of the number of materials, especially hazardous ones.

***Re-exploitation*** means the return of parts of end-of-life vehicles in phase of reuse, in their original state or after reparation, that is, by using production processes that allow the part to be used for the same purpose.

***Recycling*** is the preparation of material and its return into production cycle. Prepared materials are used to produce new parts for vehicles and/or the production of some other products.

***Energy recovery*** is the last usable layer of the pyramid, and is related to exploitation of heat released by burning materials that cannot be reused in shape of parts and cannot be used for new production, but are suitable for obtaining heat energy at the same time. Therefore, the amount of material, which cannot be used in any of the mentioned ways, must be as small as possible. Consequently, the storage of waste must be in accordance with regulations.

# 5. VEHICLE RECYCLING

Vehicle recycling is a collection of activities, which ensures the reuse of waste materials. End-of-life vehicle recycling includes the recycling in the narrower sense, recovery, and reuse.

Following strategic goals are achieved with recycling:

- **Saving of raw materials** – all new materials come from nature and there is a finite amount of them;
- **Energy savings** – there is no energy consumption in primary processes, nor in transport, which follows those processes, and additional energy is obtained by burning non-recyclable materials;
- **Environmental protection** – waste materials degrade the environment; therefore, environment is protected with recycling;
- **Opening of new jobs** – processes in the recycling of materials imply the investment of knowledge and work, which creates the need for new jobs.

As for the materials for recycling, regarding the possibility of reuse, materials can be:

- **Recyclable** – can be reused in the production process;
- **Non-recyclable** – cannot be reused in the production process, but they can be used for obtaining energy by burning, or they can be stored in an environmentally safe manner;
- **Dangerous/hazardous** – materials, which are harmful to humans and the environment;
- **Harmless** – materials, which are not harmful to humans and the environment.

10 to 15 thousand different parts are being installed into new modern vehicles. They are built from huge number of different materials. Choosing the material during design process and the production of motor vehicles is an extremely important aspect for the ecology. The request for zero waste in these phases of the life cycle of the motor vehicles represents a complex task for researches and designers, primarily in the development of new materials and use of modern technologies. In addition, the request for simplicity of dismantling the motor vehicles at the end of its life and safe separation of materials confronts the problem of vehicles safety and the economy of its recycling.

In the previous 15-20 years, a considerable number of research was done as to improve the percentage of recycled end-of-life vehicles, also including the processes of dismantling of vehicles and improvement in reuse of the same materials. However, most effort has been invested in the development of technologies for the separation and processing of non-metallic materials, such as, polymers, from the remains of cutting products.

The design of motor vehicles, in addition to a whole series of requirements, should also satisfy the requirement of vehicle recycling at the end of its life without residues, which represents the ultimate objective in the coming decades. In order to realize this, the development of new materials that are incorporated into the vehicles, the development of new fuels and drives, as well as the development of new production and recycling technologies are being approached.

Driving force, criteria, and the concept of recycling of end-of-life vehicles are the results of influencing factors that change over time. For example, the development of electric arc furnaces in the 1960s and 1970s of the last century dramatically increased the use of chassis (shells) of vehicles as input components. Later, the production of high-quality steels required the use of vehicle components which do not contain the so-called ferrous metals, which caused the magnetic separation of ferrous and non-ferrous metals. Furthermore, the separation and recovery of aluminium from end-of-life vehicles has shown greater energy efficiency than the production of aluminium from ore.

Recycling options of end-of-life vehicles depend of the materials used during the production of vehicles, as well as the assembly of components. The structure (composition) of vehicles moves toward light materials, such as, aluminium and materials from polymer. For example, in 1965, in the total weight of the European vehicles, there was about 82% of ferrous and non-ferrous metals (with only 2% aluminium) and 2% plastic. In the mid-80s, the content of ferrous and non-ferrous metals was around 74-75% (with approximately 4,5% aluminium), while the share of plastic materials increased to 8-10%. The use of light materials (aluminium and plastic materials) improved fuel and vehicle economy, as well as reduced the exhaust gases emissions. It was believed that reducing the vehicle’s weight by 100 kilogrammes results in fuel savings of 0,7 litres on 100 kilometres. However, introduction of light materials in vehicles and savings on mass compensates for the increase in mass that happened with new requirements for comfort and safety, that is, with introduction of new components and systems in vehicles.

Average composition of vehicles from European Union in 1998 is shown on Figure 8, which clearly indicates the increase of aluminium content (nearly 8%) in total weight of the vehicle. Ferrous and non-ferrous metals (zinc, copper, magnesium, and lead) make up around 67,5% of the vehicle. These number also show an approximate share of plastic materials of around 9,3% of the total weight of the vehicle, its application in vehicle chassis components as the main type of plastic materials being used (polyvinyl chloride, polypropylene, polyurethane rubber, etc.).

Considering the average vehicle life is between 12 and 15 years, the composition of vehicle in Figure 5 should have entered the recycling process in this decade in the countries of European Union.

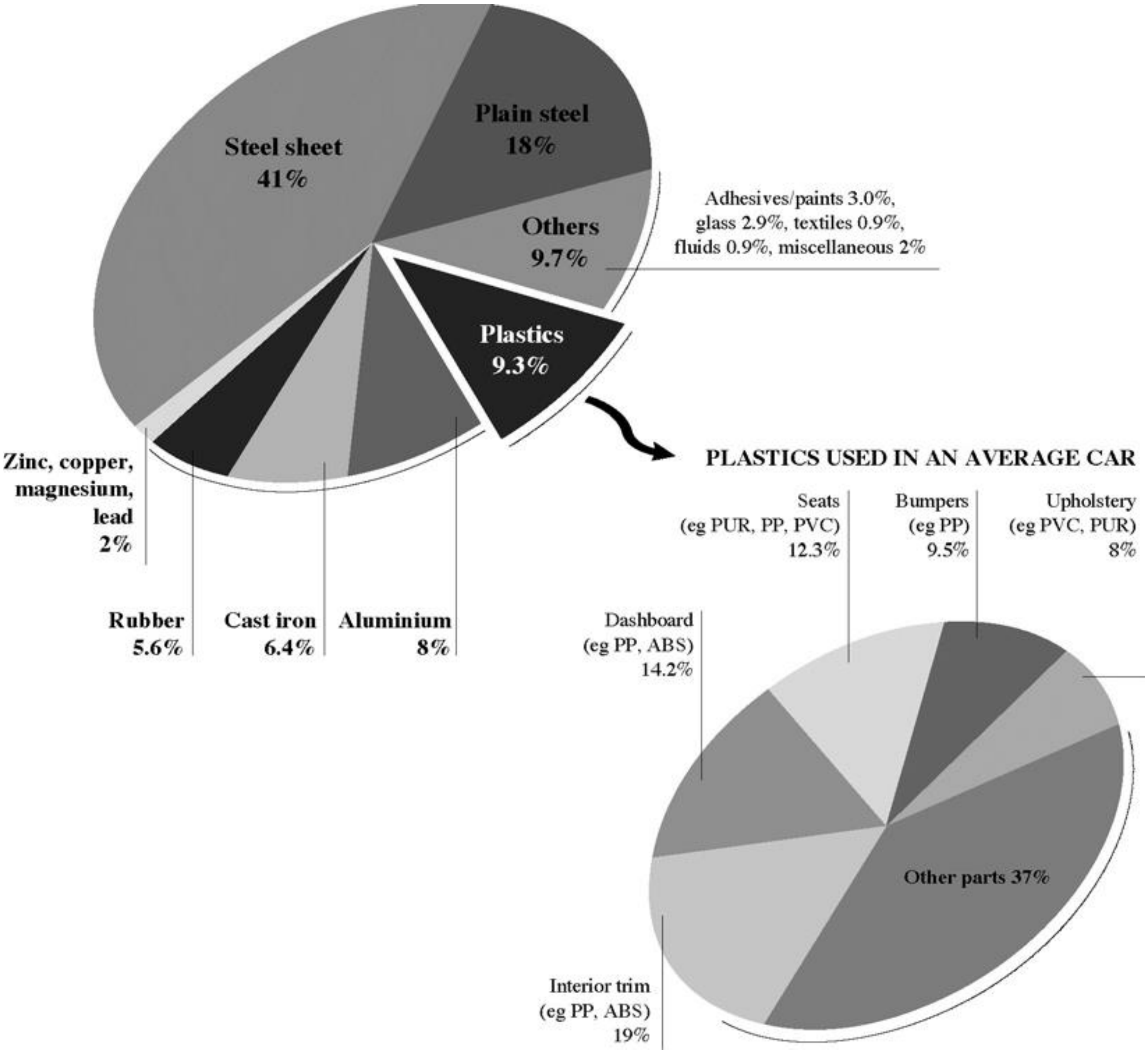

*Figure 8 - Materials used during the vehicle production in European Union (1998)*

## 5.1. RECYCLING STRATEGIES

According to the method of returning the material to the process of reuse, recycling can be divided into two groups:

- Collection of materials for recycling in primary products (Primary recycling);
- Collection of materials for recycling in secondary products (Secondary recycling) – recycling by which conventionally non-recyclable materials are processed using new technologies to the maximum possible utilization.

### 5.1.1. COLLECTION OF MATERIAL FOR RECYCLING IN PRIMARY PRODUCTS

This process relates to the recycling of uncontaminated waste material within the industrial production sector, by which, after appropriate preparation of the material, it is used to obtain new products, or by refinishing the used products, their reuse is enabled. For this type we can also include:

- Dismantling and repair of parts for reuse;
- Separation of individual parts from residue of materials after cutting, high cleanliness and without degradation of both physical and chemical properties, with the desire to continue using those materials and combining them with materials that are used for the first time or other plastics.

### 5.1.2. COLLECTION OF MATERIAL FOR RECYCLING IN SECONDARY PRODUCTS

This process relates to recycling by which the conventional unrecyclable materials are processed by using new technologies to the maximum possible utilization. It makes the production of secondary products from cutting residue. We strive towards this process because of the thermoplastic residue in the cutting machines after cutting. Extensive research regarding the secondary recycling residue from cutting material was conducted by the American Institute for Energy Conservation and Conversion. Thermoplastic represents about 70-80% of total plastic in cutting residue. Thermoplastic can be melted and by means of moulds used for the production of various products without the need for the raw material to be of high purity. Products, such as, benches in parks, poles for lampposts, light-signalling equipment for road traffic and other construction materials can be made from the waste enriched in plastic by using the best technologies for extrusion and casting. The quality of the product that can be made in this way can be improved by partially extracting unwanted components (like glass, gravel, or metal) and adding plastic and other additives. The appearance of the product can be improved my mixing layers of recycled materials with other clean materials. The presence of hard materials in waste material (gravel, metal, and glass) can, however, damage the equipment for casting and increase the cost of its maintenance.

Key limitations of this type of recycling are that the market for these kinds of products is small and costs of production of secondary products is not negligible. As the result, secondary products are in best case only marginally competent to most cases compared to parts made from cheap unrecycled materials (wood, sand, gravel). Concerns connected to this method of recycling are residues after cutting because those contain different substances which could cause problems, including heavy metals, polychlorinated biphenyl (cooling liquid for transformers, banned in the USA in 1977, and in Europe in 2001). Purifying plastics from these materials can cost pretty much considering the relatively high costs, while the market price of materials from which secondary materials are made is low.

Changes in the composition of residue after crushing require the process of treatment to include high tolerances so the product would meet the requirement and so the rejection does not occur. Improvement of specific materials can be necessary in some cases.

Various experiments were conducted in 1985. One of them was an attempt of separation of plastic from cutting residue. In these experiments, floating parts (parts lighter than water) and parts of medium size from water would be send to a gravitational separator, which consisted of a number of physiological cells, from which each maintained a certain level of specific gravity. Even though the procedure did not produce separated plastic in high concentration, the tests have shown that certain part of plastic can be concentrated in various groups.

Grouping of various cutting residues is necessary to improve the recycling sustainability, even though this method may not be the best or the best approach from the economy standpoint.

Many technologies that are more advanced have been developed and tested since them. Equipment developed for recycling plastic from heavy city waste can be adjusted for this type of recycling of plastic from pressing (cutting) residue. This equipment is made by the following companies: *Mitsubishi Revezer*, *Klobbie*, *FN machine*, *Flita System*, *Remaker*, *Regal Converter* and *Kabor K board*. Institute for Energy Conservation and Conversion marked the use of cutting residue as an additive for “polymer-concrete.” Conclusions have shown that this concrete had lower strength that the conventional one.

## 5.2. VEHICLE RECYCLING INFRASTRUCTURE

The improvement of economic aspect of vehicle recycling requires detailed and integrated approach. Different participants in the chain of recycling processes have to cooperate in order to harmonize the connectivity of processes, quality control and science, which supports procedures of recycling processes, to implement the efficient approach. That approach must be in accordance with international and local regulations, but also meet market requirements.

As mentioned previously, end-of-life vehicle recycling encompasses reuse, recovery, and recycling in the narrower sense, and with time, it has become as the “3R” concept around the world (*Reduce-Reuse-Recycle*). The first “R” relates to waste reduction, in order to extend the life cycle of vehicles, reduce raw materials, and to reduce energy. The second “R” relates to use of parts and individual assemblies again. That part that has not failed, that is, that can still be used, is returned as used part on the market and is installed in some other vehicle (gearbox, lights, power unit, seats…). The third “R” refers to turning the other parts into raw materials from which they were obtained. “3R” concept was upgraded to “5R”, and it was improved by *Toyota*, which added a process of cleaning of materials for easier recycling process and energy recovery from waste. In this way, they reduced the deposited materials by 20-25%.

When a vehicle reaches a specific number of years (life cycle of vehicles is estimated to 12-15 years), most often it is bought by companies that do dismantling of vehicles. Those companies from bought vehicles use working parts and sell them on the used parts market. By returning those parts on the market, they make profit (second “R”). The rest of vehicles are bought by processing companies. In those companies, the vehicle is shredded, and it different processes ferrous and non-ferrous metals are separated for further recycling. After these processes, what remains is 20-25% of the total vehicle weight, and that remain is the weakest link in the recycling process. Average composition of remains that is disposed at landfills is shown on Figure 6. Those remains are considered as hazardous waste, because of the chemical composition, but it can also be considered as an energy source. The remains can be recycled or disposed of. Currently, because of the recycling costs, the best option is disposal of vehicle. Guided by this, vehicle manufacturers make the vehicle in such a way that: it has a reduction in the energy used, easy disassembly or parts (dismantling), recycling, and reduction of toxic metals.

The global scheme of vehicle route, which starts from the manufacturer and ends with the disposal of residues at the vehicle's end of the life, is shown in Figure 9. The last owner represents the first link in the chain of the vehicle's life cycle. After deregistering the vehicle from the register of registered vehicles, owner can deliver their old vehicles to dealers of used cars, who can then deliver them to collection and dismantling companies. Otherwise, deregistration of a used vehicle can be done by the owner himself, but it can also be done on behalf of the owner by a used vehicle dealer or companies for collection and dismantling, all depending on the local regulations in the country.

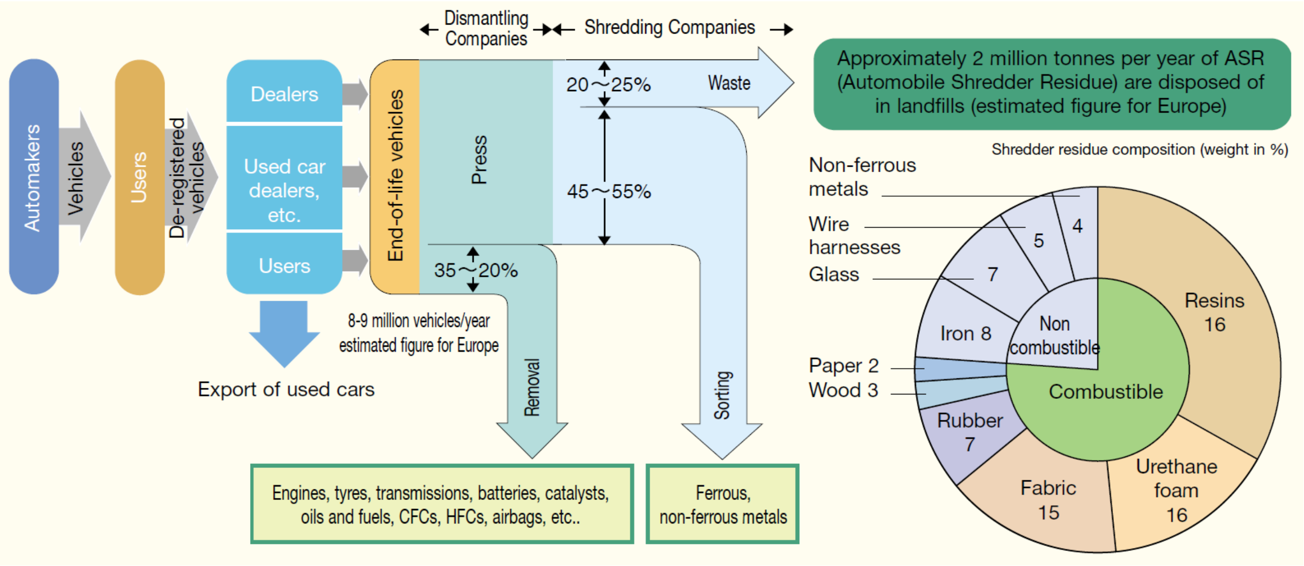

*Figure 9 - Disposal route for end-of-life vehicles*

Recyclability rate of end-of-life vehicles is higher by 75-80% than that of simpler products, such as glass packaging, old paper and/or tin cans.

Residues from the cutting process represent a weak spot in the end-of-life vehicles recycling process, not only in the European Union, but in general in automotive industry across the world. Around 2 million tonnes of residue after the cutting process are generated annually in the countries of the European Union. In fact, that represents less than 1% of waste generated in the European Union. Residue after the cutting process, if they contain enough toxic substance can be classified as hazardous waste in many countries, and they can be considered as energy source if they contain more than 7% combustible substances. (See Figure 9).

All the elements of the infrastructure of vehicle recycling, with its processes, flows of material and economy parameters are shown in Figure 10. The elements involved in the processing of end-of-life vehicles are clearly indicated, and the products of the process representing income (dismantling components and scrap metal) and cost (cutting residues) are also shown.

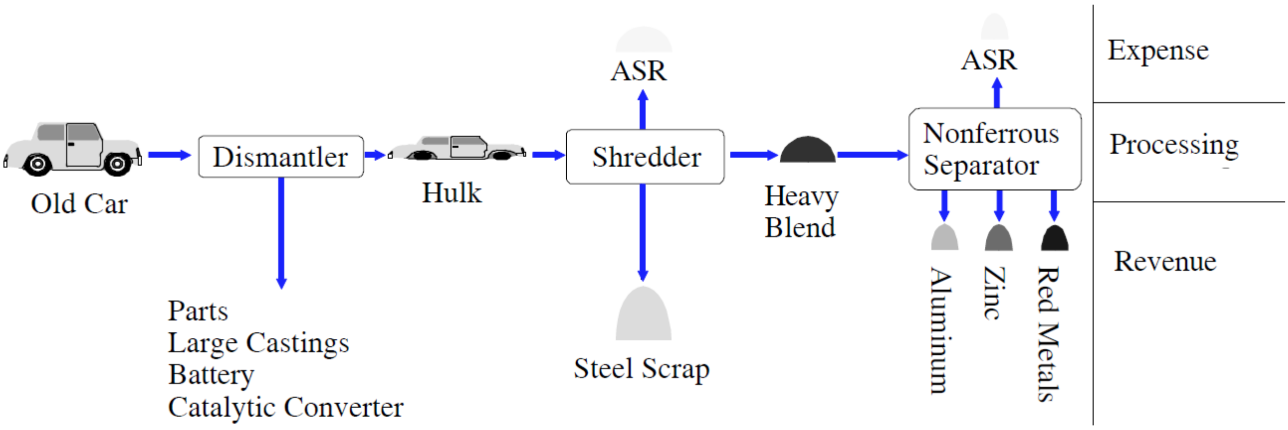

*Figure 10 - Elements of vehicle recycling infrastructure with processes, material flow and economy elements*

For residues after the shredding process, two options could be applied:

- Recycling / recovery;
- Disposal of residues to landfills.

In addition to the above, apart from the vehicle-recycling infrastructure shown in the Figure 10, it is interesting to note that there is always a possibility to include some new processes in these elements of the infrastructure, which contribute to better usability of useless residue, that is, they could increase the recyclability and recoverability rate of vehicles. Figure 11 shows an example of one such recycling infrastructure, where additional appropriate treatment, in this case pyrolysis, was performed on the cutting residues. As the result of the treatment, oily residues were obtained, which are suitable as energy renewables, but solid residue is also obtained which is disposed on landfill. This increased the income generated by the recycling process and reduced the costs of residues that are disposed on landfills.

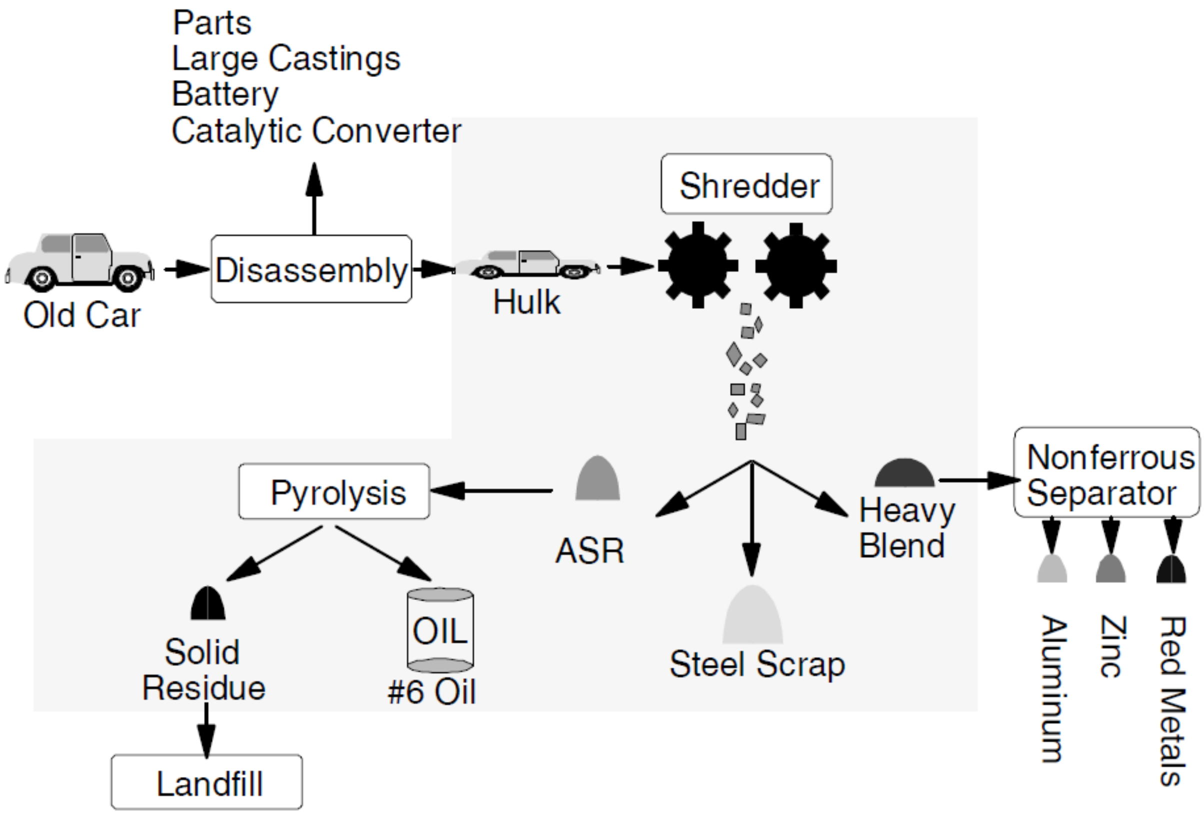

*Figure 11 - Vehicle recycling infrastructure with additional processes*

Today, the world has developed a large number of companies that are involved in the process of disposing of end-of-life vehicles. As previously shown through figures of existing vehicle-recycling infrastructures, such facilities can deal only partially with a part of the intended operations, or else they can cover the entire range of recycling, from the collection of vehicles from the end user to the disposal of residues on landfills. Therefore, their structure, capacities, and number of employed personnel can be very different, so it is difficult to make a comparative analysis.

For example, Figure 12 shows the layout of one facility for end-of-life vehicle recycling (in the narrow sense), which deals with cutting, separating, and processing vehicles and components after dismantling, while Figure 13 shows a photograph of the real facility with approximately the same recycling infrastructure.

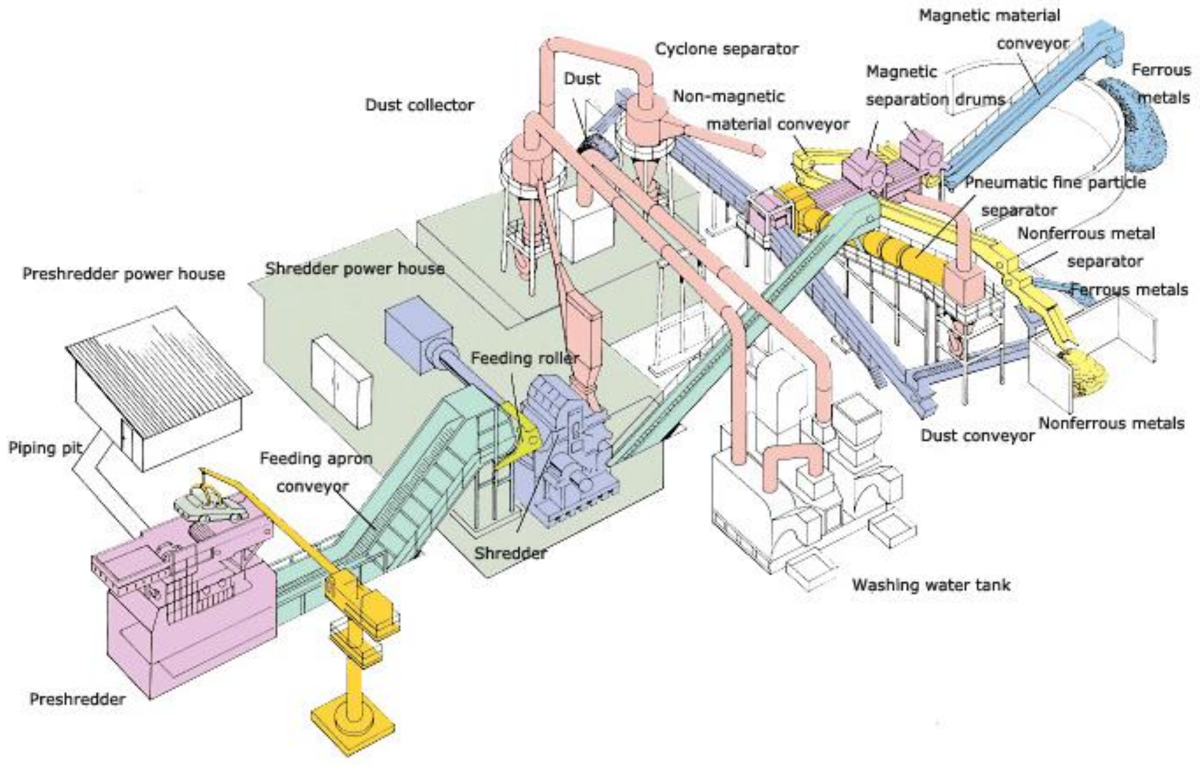

*Figure 12 - Layout of an end-of-life vehicle recycling facility*

*Figure 13 - Real facility for end-of-life vehicle recycling*

The choice of vehicle-recycling technologies with the objective of sustainable waste management depends on many factors, and the most important ones are:

- Price,
- Amount,
- Type,
- Quality and location of landfills and recycling facilities.

Vehicle recycling process is a complex process due to large number of various materials that are in its composition. Recycling of end-of-life vehicles is performed chronologically, usually in six main phases:

- Handing over the vehicle for recycling,
- Draining of work fluids,
- Dismantling the vehicle into components,
- Shredding,
- Separation,
- Processing.

Companies dealing with collecting and dismantling are focused on dismantling of valuable components from vehicles, such as the engine, batteries, oil and fuel, airbags, etc… Even though, such companies are necessary for the reduction of waste generated by end-of-life vehicles, they are primarily small companies that are mostly interested for the components, which can be reused, recovered, recycled, or sold.

### 5.2.1. HANDING OVER OF VEHICLES FOR RECYCLING

After the vehicle finishes its life, that is, it is no longer able to be used, is handed over for recycling.

After deregistration of the vehicle from the registry, owners can deliver their vehicles to used vehicle dealers, who in turn deliver them to collection and recycling companies.

### 5.2.2. DRAINING OF WORK FLUIDS

After deregistering the vehicle from the registry of registered vehicles, the first step in the recycling process is to drain all the fluids from the vehicle. This refers to draining of the following: drive fuel, engine oil, transmission oil, brake oil, coolant, windshield washer fluid, differential oil.

*Figure 14 - Draining of fluids from the vehicle*

Apart from these fluids, battery is also removed from the vehicle. The reason for draining fluid and removing the battery is to prevent a potential fire, easier disposal of vehicle on landfill, but also easier dismantling of parts. If the fluids were not drained, most of it would leak out, and in contact with soil would destroy the living world on that spot. Fluid leaking from one vehicle would not cause much of a problem, but on landfills all over the world there a hundred of millions of vehicles, and that would cause enormous pollutions.

Fluids from tanks at accessible places, such as the coolant and windshield washer fluid are removed by using the vacuum drill (by punching or drilling). When draining the oil from the engine and gearbox, the oil is immediately collected in special balloon containers, from which the oil is transferred by means of a compressor into large containers for storing engine oils, which fall into the category of hazardous waste, and are further handed over to certain companies dealing with the treatment of oils. A free-fall can also be used for draining the mentioned fluids.

After draining of fluids from vehicles, they are separated and stored in special containers (preferably in metal barrels).

When the fluids are separated from vehicles, tanks in which they were located are additionally cleaned to remove any residual impurities.

### 5.2.3. DISMANTLING

After the vehicle is, free from various fluids and hazardous substances, all companies for disassembly begin to dismantle the vehicle. Very often, the case that the dismantling is done directly on junkyards, from where the components can be reused (recovered or repaired) or just as they are delivered to used parts market. Used parts that can be reused are much cheaper from new ones and are available to everyone. Direct use of a part (door or a bonnet) also saves energy that would be invested to produce and assemble such a part.

Recovery and repair of specific parts from dismantled vehicles at junkyards or at service stations of used parts are an important member of the whole recycling infrastructure. Many parts have been repaired to enable lower post-sales costs of vehicle maintenance for domestic market. For example, more than 90% of starter-motors and alternators are repaired. Other parts of the automobile, which are commonly repaired, are engine, gearbox, braking system and water-pump. The repair process consists of opening a part and disassembling, controlling, repairing, and replacing smaller parts, as well as retesting the repaired part, so that it can be asserted with certainty that the repaired part meets all the prescribed characteristics.

*Figure 15 - Vehicle dismantling*

Catalytic converter (catalysator) is an integral part of an exhaust system on vehicles. If it functions correctly, it can be reused as a used one. Catalytic converters, which failed, when opened, must be carefully disassembled because there are materials inside that are worth more than gold (palladium, rhodium, platinum). Mentioned noble metals from the catalytic converters are recycled. They can end up on various markets and products (they do not stay in automotive industry).

The tyre can be reused, but that depends on the condition and level of wear. They are mostly removed and sent to specialized companies for their recycling. Part of removed tyres from vehicles are used as alternative fuel in power plants, and the other part is mechanically processes and reusable tyre is created, and from "speed bumps" are made from recycled rubber. However, rubber from a tyre can have a very harmful effect on the environment.

Worn-out tyre does not mean that it cannot be used. There are companies that do the so-called tyre rethreading, and is usually done on truck tyres. It is a matter of removing the old, worn tread and pouring and profiling a new treat, so that the rethreaded tyre is fully functional for further normal use.

*Figure 16 - Tyre rethreading*

In dismantling process, the windows are also removed from the vehicle. Two types of glass are installed on vehicles:

- Tempered glass – when broken, it breaks into small pieces and is used for the side and rear windows;
- Laminated glass – when broken, it stays whole and protects the driver and other participants in traffic from possible injuries it is used for windshields.

Because the laminated glass cannot be used multiple times, it is removed with the shortest possible procedure, however if there is an order for such a glass as a spare part, it is carefully removed.

Glass on vehicles can be reused, regardless of whether it is broken or not. The glass is sent to specialized companies that grind them, thus transforming them to silicone sand, and then use it either as filling sand in construction, or they heat the sand to get glass again. The process is more complicated than the production of household glass.

Windshield glass consists of two layers of glass, which are connected with polyvinyl butyral. This interlayer helps with traffic accidents because it prevents the shattering of the windshield glass when it breaks, therefore, preventing any serious injuries of driver and other participants in traffic. During the recycling process, the interlayer is separated from the rest of the glass, in most cases, the windshield glass is first shredded and only then, the resin of polyvinyl butyral is separated. Separated layer can be recycled and used in the production of adhesives. This procedure is very expensive, so companies from the automotive industry that deal with the production of glass have contracted with recycling centres to recycle their windshields after replacement.

However, dismantling of end-of-life vehicles is often done inappropriately (the use of inappropriate tools, “self-thought,” that is, ignorance of the process of dismantling of components with all its specifications, speed during work in order to achieve the highest possible profit…), which usually leads to the opposite effect – increase in quantity and danger of this type of waste for the environment.

After the removal of the “interesting” components, the remains of end-of-life vehicles are handed over to companies that deal with cutting, as well as further treatment of the remains and disposal of scrapped and unusable remains.

### 5.2.4. SHREDDING OF METAL (CUTTING)

When the process of dismantling of vehicle is completed and when all the components that can be reused through the used market are separated, the rest of the vehicle is transferred to companies, which specialize for the next phase, shredding.

The process of shredding the remains of vehicles starts with loading the components or the shell of a vehicle for recycling into the pre-cutting machine (pre-shredder). There are also companies that compress vehicle bodies (shells) into a four-sided prism, and deliver them to recycling facilities.

The loading is done with a crane, which loads the material by grabber claw or a magnet. In the pre-shredder, a very rough cutting of the shell or compressed prism is actually done, to make smaller pieces of one-fifth of the original volume. Such parts are transported via conveyer belt of roller (feeding apron conveyor) to cutting machine (shredder). In the cutting machine, at the same time, the roughly cut parts are further crushed into parts the size of a human hand and the dust is removed to the area for its storage (Dust Collector). After shredding, the shredded material is transported to pneumatic separator. There, the material is transported through a high-diameter tube, through which compressed air also goes. Compressed air circulation raises the always-present dust and metal particles and takes them to a filter where the dust particles are redirected towards the dust collector, and metal particles are separated on particles made from ferrous and non-ferrous metals, and in accordance with this, they are piled up on different places. Metal parts that exit the pneumatic separator go through magnetic drums, where the separation of ferrous and non-ferrous metals is done. Non-ferrous metals are extracted with magnets, while the ferrous metals are often separated by using electricity separators. Due to a magnetic field, ferrous metals stay in the drum and are rerouted to a single pile, while non-ferrous metals will continue the transport to their storing place.

Piled-up ferrous metals are transported to foundries, where they are put in blast furnaces under high temperatures and are melted together with iron ores, and they come out again as steel ready for use.

Non-ferrous metals are sorted or separated on the spot, or they are sent to special companies, which do these processes.

After those spent scraps are cut, obtained materials (cutting residue) undergo a series of physical and mechanical separations with a goal of separating ferrous and non-ferrous metals, as well as a series of processes of applying different recycling technologies, with an objective of obtaining materials that can be further used.

### 5.2.5. CUTTING RESIDUE

Cutting residue represent a very complex heterogenic compound of materials, which is very hard to separate. In these residues, the following can be found: moisture, wood, metal, glass, sand, dirt, automobile fluids, plastic, foam, rubber, textile, fibers and other. In addition, it is known that certain amounts of heavy metals, chemical elements and combustible materials are found in the residue. About 15 million tonnes of this waste is obtained annually through recycling processes.

### 5.2.5.1. RECYCLING OF CUTTING RESIDUE

Extraction of materials from complex mixtures (such as residues from cutting facilities), require several layers of separation and cleaning, including the following:

1. Concentrating specific materials into groups that are easier to manipulate;
2. Separating specific materials from waste;
3. Cleaning of separated material from dust and other harmful substances.

### 5.2.5.2. MATERIALS THAT CAN BE RECYCLED FROM THE CUTTING RESIDUE

As mentioned previously, cutting remains contain, among other materials, plastic, rubber, glass, and various metals. These materials are potentially recyclable. Problems with separation and recycling of these materials (excluding metals) are:

- Lack of economic technology for separation of these materials from waste in high concentration, in order to enable their use for adding value to specific products, and not only as supplements (in small percentages). These technologies should have a good way of removing harmful substances from the waste at a satisfactory level;
- The lack of market for sale of recycled materials and their real price;
- The creation of insufficient amounts at certain place in order to justify the profitable business.

### 5.2.5.3. SEPARATION OF MATERIALS FROM CUTTING RESIDUE

The separation of material is achieved by using a variety of material properties. These different properties can be physical (size, shape, colour, porosity, density, and strength), chemical (solubility, hydrophobicity, hydrophilicity, and reactivity), and electrical (resistance and dielectric constant). Similar properties of different materials complicate the process of separation and make it difficult to manage it, therefore, they place limitations on material cleanliness which could be extracted from waste. Very often there is an overlap of the properties of plastic materials in the waste. One of the reasons of that overlap is the mass use of polymers in various formulations. Polypropylene can be found in the following shapes: homopolymer, copolymer, polypropylene filled with talc, polypropylene filled with calcium carbonate etc. Different amounts of additives, modifiers, plasticizers, are added to resins in order to achieve the desired properties.

Recycling of materials from residue from cutting is more complex due to unwanted substances in residues (polychlorinated biphenyl, heavy metals, and combustible materials). From time to time, new materials could also appear in residue, and it is expected that there will be more and more of them. Except for non-ferrous metals, there is little probability of recovering material at a satisfactory level of purity from the residues in a single process. Extraction of specific materials during the recycling process (plastic and metal) requires following steps as a minimum:

1. Separation of polymers from waste;
2. Separation of plastic and rubber from polymer concentrator;

3. Separation of wood and rubber from plastic;
4. Separation of types of plastics;
5. Extraction of unwanted materials from separated materials.

### 5.2.5.4. MECHANICAL SEPARATION FACILITY

Figure 17 shows one recycling facility with a mechanical system of separation, by using the equipment which is mostly used for cutting machines, for isolation and grouping of certain wanted materials (polymers and metals) for further processing. The initial concept of the facility could process two tonnes of waste per hour. Over 90% of polymers larger than 6 milometers are separated from waste, while there was a 90% success rate for separating ferrous and non-ferrous metals larger than 6 millimetres.

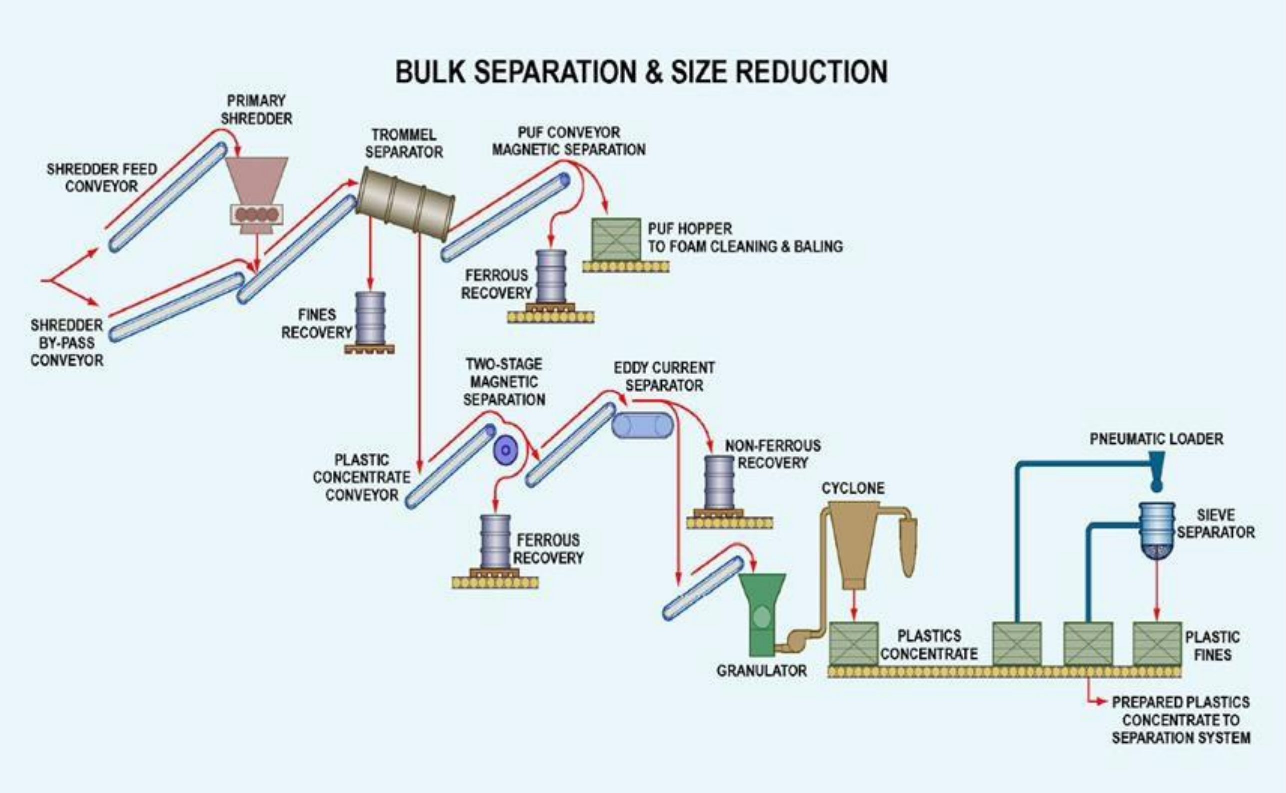

*Figure 17 - Facility for separation and processing of cutting residue*

Operations within the facility for mechanical separation may differ from some other facilities of the same purpose, but some basic steps in the processing of cutting residues are as follows:

1. Big chunks of metals, rocks, and polyurethane foam, are removed manually (In full scope process, big chunks of metals, rocks and foam can be separated with lattice panels and then proceed to the extraction of metals and foam);
2. Residue from the cutting process is crushed to a size of 25 millimetres and then transferred to two-layered lattice. In the first step, material smaller than 6 millimetres are removed. In the second step, thin parts are removed through adjustable slits. In this step, there is mostly plastics, rubber, metals of smaller dimensions, foam, and fiber;

3. Larger parts of materials leave the area with lattice. These materials are mostly soft polyurethane foam, which is pressed in the cutting machine and is larger in comparison to other materials at the outlet from cutting process. In this part, there is also textile, fiber, and some plastics and metals which are larger than opening on the lattices;
4. Large materials go over a magnet in order to extract non-ferrous metals;
5. Part of materials, which passes through slits, mostly parts rich with polymer also go where the magnet is located, in order to extract non-ferrous metals from them by means of screw separator with electricity (additional mechanism for extracting non-ferrous metals);
6. Concentration of polymers from which metal is extracted further branches to average size from 6 to 10 millimetres and is further processed on vibrating slab in order to remove small impurities, and them with the help from air, the residue parts from polyurethane foam are removed.

### 5.2.5.5. OTHER WAYS OF MECHANICAL SEPARATION FROM CUTTING RESIDUE

Mechanical systems like gravitational separators, electro-static separators, vibrating lattices and quick sorting systems (paint, infrared beam, x-ray, and UV radiation), mostly rely on difference in some of the material properties. Due to many types of materials in waste and their similar properties, such equipment cannot separate all residues. However, some of these machines can be used for purifying the specific groups of materials separated from waste.

#### ***Gravitational separator***

Gravitational separators are based on the differences in material density for separation of solid particles from homogenic compound of solid substance. Due to the heterogeneity of waste, many particles have the same properties, so it is very difficult to perform separation.

#### ***Electro-static separator***

The size of electro-static charging of plastics depends on the electrical properties of plastics as a material, but also depends on air humidity, contact surfaces, handling, surface roughness and surface friction properties. Plastic is considered dielectric material because it is a bad conductor, which can withstand an electrostatic field with minimal thermal energy dissipation (dielectric losses). Key electrical properties, which regulate electro-static behaviours are dielectric constant and surface resistance. A lot of research has been done on this topic, but only a few facilities have been built that work according to this principle. There is one separator of this kind in Canada, however it did not have the best performance. It did not separate rubber from plastic, it was very dependent on size, thickness, and mass of the particle. It was practically useless. The *Hitachi* company, has manufactured a highly efficient electrical separator in 2001. The main drawback was the production of insufficiently pure polymer. These separators are very sensitive to moisture, and this is the reason why this process is even more complicated.

### *Burning of cutting residue for energy*

Burning could be a cost-effective technique for cutting residue disposal given that the energy efficiency is half that of coal. Cutting residues can burn without any additional fuel. Because of the increased use of polymers in vehicles and other long-lasting parts, the energy value of cutting reside keeps growing. Reside have little sulphur. Some studies have addressed this topic, and waste processors have produced several incinerators. This type of recycling was very common in the 1980s. However, today not even one exists.

By burning, a reduction of over 50% in weight and 75% in volume of cutting residue can be achieved. This method is not accepted due to combination of economical, ecological, and logistical problems, which include:

- Disposal of cutting remains on landfills is cheaper from burning;
- Environmental concern is still present, because the residues contain unwanted substances, including chlorinated materials and heavy metals;
- Cutting residues have a high ash content (50%) and different moisture content (25%).

Although there is technology to purify hydrochloric acid, purification of these compounds can be very expensive, especially when they are present in high quantities, which can be the case for the rest of the cutting process. By burning this acid, corrosive flue gas would be created, which would increase the costs of maintaining the incinerator. For chlorine is also suspected that it increases the risk of creating dioxins and benzofurans during combustion. In addition, complicated procedure of issuing permits for incinerators may cause even greater costs of this type of recycling. The price of burning waste additionally grows if the residues contain polychlorinated biphenyls, which burn at high temperatures (1,095°C). Blast furnaces used for burning these types of materials are very expensive to build and maintain. Reaching these temperatures would require additional fuel and additional operational costs. The profitability of incineration mainly depends on the location and type of waste, the costs of local landfills, the composition of heavy metals and the type of incinerator. Location, construction, and work can also be the subject of dispute, so it is clear why there are no more facilities like this.

### *Chemical recycling*

Chemical recycling could be used for obtaining products with additional value (monomers, light hydrocarbons, liquid, or gaseous fuels) from waste parts based on hydrocarbons (plastics, rubber, paper, and wood). Plastics and rubber are the main source for these products. Processes, which could be used for chemical recycling include pyrolysis, gasification, hydrolysis, selective dissolution, hydrogenation and depolymerization.

### *Thermo-chemical processes of converting waste into fuel*

Pyrolysis is thermal treatment of organic material waste in low oxygen environment. It is a well-known technique for the production of fuel and chemicals from organic raw materials, such as wood, coal, plastic, rubber, and municipal waste. In case when polyethylene is used as raw material, hydrogen, benzene, methane, ethylene, and propane are obtained. Main products of the pyrolysis of polyvinyl chloride are benzene, acetylene, styrene, and hydrochloric acid. From pyrolyzing polystyrene, styrene, benzene, toluene, and methyl styrene are obtained. The assumptions are that a mixture of polyethylene, polyvinyl chloride and polystyrene could be obtained by pyrolysis of cutting residues.

Some of the problems that occur during the process of pyrolysis of plastics are:

- Pyrolysis of plastics requires several pyrolysis of hydrocarbons due to bad characteristics of heat transfer of plastics;
- Carbon residues created by pyrolysis of plastic have tendency to stick to the walls of the reactor;
- Some types of plastics produce high-viscose material during heating, which makes pumping difficult.

Pyrolysis on high and low temperature, as well as pyrolysis at various pressures, including atmospheric sub pressure, processes used during the processing of cutting residue. In these cases, by the process of pyrolysis, oil, gas, and solid residue are obtained. The observations based on these tests are as follows:

- Iron makes a quarter of solid part;
- Copper makes 5% of solid part, and most of the copper was in elemental form;
- Concentration of polycyclic aromatic hydrocarbons was reduced for more than 90%, and the concentration of polychlorinated biphenyls was reduced by 99%;
- Due to the present of heavy metals (cadmium, nickel, zinc) solid residue could not be disposed of on landfills.

### *Gasification*

Gasification is a thermal-chemical process of high temperature which can transform organic content of waste into gaseous mixture, primarily carbon-monoxide, oxygen, carbon-dioxide, and some lighter hydrocarbons. In addition to organic waste, water, and air (or oxygen) are added to the reactor. However, the amount of air or oxygen added are limited in order to achieve the partial oxidation of organic waste and to increase reactor temperature up to desirable 500 ÷ 1.500°C, depending on the process.

There are three types of reactors for gasification. These processes are developed for the production of gaseous fuels from sold fuels, such as coal. By gasifying the residues from the cutting process, the following products can be obtained:

- Gaseous mixture consisting of carbon-monoxide and oxygen and some light hydrocarbons;
- Reduced metals (iron, copper, aluminium).

There are many facilities in the world that work on the principle of gasification.

### 5.2.6. DISPOSAL ON LANDFILLS

Recycling, above all, belongs to activities related to industrial production, where it is based on trustful (approved) technologies. Although many alternative options were considered (physical separation, incineration…), it turned out that the most suitable way is to dispose of the residue on landfills.

Fraction that remains after previously mentioned processes is ecologically safe to be disposed of on landfills, but can also be used as construction material for filling or as a covering layer. This process greatly reduces the amount of waste that goes to the landfill. In addition to protecting the environment, the lifetime of the landfill is also extended, which is estimated to be 50 years.

However, costs of disposing the residue on landfills are not low and they differ from country to country. An overview of the costs in some countries of the European Union and the world, which are most active in the matte of waste disposal, are given in Table 2.

*Table 2 – Costs of disposing the cutting process residues on landfills*

| Country | Cost ($/t) |
|---|---|
| Countries of the European Union | |
| Austria | 140 |
| Belgium | 55 |
| Denmark | 70-110 |
| France | 40-60 |
| Germany | 60-170 |
| Italy | 75-80 |
| The Netherlands | 70-90 |
| Spain | 20-60 |
| Sweden | 90-100 |
| The United Kingdom | 30-35 |
| Poland | 25-30 |
| Czech Republic | 30 |
| Other countries | |
| Australia | 20 |
| Japan | 135-160 |
| Norway | 50 |
| USA | 50-60 |
| South Africa | 25-40 |
| Switzerland | 120 |

As it can be seen, the costs of disposing in Germany are at least twice as much than those in the Great Britain. High costs of disposing the reside on landfills are the main driver of directing the residue from the cutting process from disposal in landfills to more economically and environmentally efficient processes.

***Example:***

Cutting companies in Germany are directly responsible for the reduction of residue remains of the cutting process, as well as the damage inflicted upon the environment, which is the result of disposal in landfills. The environmental protection strategy of the German automotive industry is based on the model in which the interested parties of the automotive industry strive for minimizing the impact of vehicles on the environment during their life. Strict regulations in Germany regarding waste resulting from end-of-life vehicles can be explained and justified, among other things, by the important role of the automotive industry in the country’s economy.

## 5.3. RULES DURING THE RECYCLING PROCESS

The most important tasks of the vehicle manufacturers must be: reduction of used energy, easy disassembly, appropriate recycling process and the use of less toxic metals.

As for the recycling, the most important is the following:

1. Elimination of toxic elements, such as: chromium, mercury, lead, halogen polymers and similar. After processing in the mills of the previously disassembled vehicle, heavy/toxic metals are mostly categorized as residue, because during the burning process, chlorinated and fluorinated polymers may lead to creation and emission of products, that are highly toxic for the environment, and greatly damage the ozone layer;
2. Designing key structural components from basic alloys, where we should strive to reduce the weight and number of parts. Select standard alloy families based on common aluminium-based alloying elements as base (*Al*, *AlCu*, *AlMn*, *AlSi*, *AlMg*, *AlMgSi* и *AlZn*);
3. Avoiding the uncommon alloying elements. These alloys have desirable properties. For example, adding lithium increases the specific stiffness, and tin enables excellent plastic shaping. However, limit concentration of these elements in basic alloys is less than 0,05%, and small number of components with uncommon alloying additives can make the aluminium recycling system harmful;
4. Securing the market for each recycled material and promotion of importance and possibilities of recycling of old automobiles in each branch of industry;
5. Construction of components so that after processing by cutting, pieces made of one material are obtained;
6. Rational use of composite materials. Strengthened plastic, ceramic composites with metal matrix and some other rare combinations can have physical and functional characteristics, that enable them a significant use value (shapes, which are impossible to obtain by using steel are very easily achieved using composites, they are lighter than steel);
7. Encouraging separation of different materials after cutting to the greatest extent

possible. Construction of new facilities for processing in which the treatment of aluminium and steel will be done separately, and if possible, individual alloys as well.

## 5.4. RECYCLING OF MODERN MATERIALS

All previously mentioned procedures regarding the disposal of end-of-life vehicles are functional for many years now, therefore, the number of companies for taking over vehicles and dismantling them, facilities for recycling materials and landfills for disposing of the remains of the recycling process is increasing and is becoming better organized. That is why we say with certainty that the vehicle recycling process has entered “a routine” flows and that protocols and materials flows are clearly and precisely defined.

However, challenges constantly arise, and primarily regard the innovative technologies and modern materials, which are being used in automotive industry today. Although the technologies and materials being installed today in vehicles will appear in 10 to 15 years in the recycling processes, it is the right time to start with analyses, examinations and defining the way to include those components in the recycling process, in order to fulfil the given criteria of vehicle mass that needs to be recyclable.

In this regard, it is perhaps most interesting to present two real examples of modern technologies and materials that are taking an increasingly important role in the automotive industry and to see what are the trends of their recycling process at the end of the vehicle’s life. Those are composite materials, which play an increasing role in vehicle production, especially chassis components (due to low specific weight and high strength), as well as lithium-ion batteries, as the backbone of the expansion of electric and hybrid vehicles.

### 5.4.1. COMPOSITE MATERIALS

Although parts made from composite materials have a long-life, the first generation of such parts, for example windmills, are coming to the end of their life. This starts the theme of recycling of composite materials as problems we need to additionally research and relatively quickly solve at least partially. It is expected that the use of composite materials in the future will grow, so it is necessary to dedicate to recycling before a large number of parts made from composites come to the end of their life. Due to the fact that the material is strong, durable, and non-homogeneous, it is very difficult to recycle.

One more reason for solving the question of recycling of composite materials represent the laws of the European Union which prohibit the disposal in landfills and regulate what will happen to products at the end of their life. Legislation strives to increase the responsibility of manufacturers, increase the recycling rate, and reduce the availability of landfills. The Circular Economy Package of the European Union and proposed changes to the Directive 2008/98/EC limit the city waste in landfills to 10% by 2030, but it is not clear how this applies to industrial and construction waste other than packaging (75% has to be recycled by 2030).

It is important to note that using composite materials reduce the weight of vehicles, and they can improve aerodynamic properties by changing the shape of the vehicle, which can help vehicle manufacturers in fulfilling the limit of 95 grams of carbon-dioxide per kilometre for a fleet of vehicles. On the other hand, Directive 2000/53/EC requires that 85% of the vehicle mass can be recyclable or reused, and 95% reused, recycle, or return to the original state. Composites strengthened with carbon fibers have the highest potential to reduce vehicle mass, but their current price and lack of solution for recycling inhibits their widespread application.

Generally, the development of composite industry can be divided into five epochs:

1. 1932-1946, the beginning of the industry. Application: *Fiberglass™*, composite chassis (*Stout Scarab*). Processes: Resins were developed and manual lamination.
2. 1947-1960, small scale application phase. Application: commercial composite chassis, composite panels (in trucks), helicopter blades *Alouette II*. Processes: use of short fibers, developed carbon fibers, *spray-up* process, pultrusion.
3. 1961-1978, industrial application phase. Application: Thermoplastics strengthened with glass fibers, glass matte, commercial wind turbine blades. Processes: developed Kevlar fibers, C-glass process of high strength.
4. 1979-1996, phase of corrosion resistance. Application: Tanks made from composites, windows from fiberglass. Processes: continuous laminates from fibers of strengthened thermoplastics, and thermoplastics with other fibers, the process of resin infusion.
5. 1997-2014, phase of hybrid technology integration. Application: commercial wind turbines, commercial aircraft, parts of automotive structures, electronics. Processes: hybrid technologies for moulding.

There is also a sixth phase, conceived in the first two decades of the 21st century, and that is the phase of recycled composite. Composite recycling represents a topic, which was the most researched in this period.

### 5.4.1.1. COMPOSITE MATERIALS IN AUTOMOTIVE INDUSTRY

Composites in automotive industry are used for sport vehicles due to high performance and low mass. Now they are used in electric vehicles, where the lower mass ensures a higher autonomy. One of the reasons for the development of recycling is that in the automotive and aviation industries carbon fiber parts are made on a large scale and large percentage of new materials go to waste (sometimes 20 to 40%).

*Volkswagen Golf* from 2016 has carbon parts (seat carriers, floor) and chassis (front fenders and boot lid). Using the composites reinforced with carbon fibers reduces the weight of the vehicle by about 30%. Recycled fibers are used, for example, for C-pillar for *BMW i7*, boot lid carrier for *Mitsubishi Rayon*, or for a roof for *BMW i3* series.

Light construction can reduce the fuel consumption and harmful gases emissions from aircraft and automobiles. It is proven that reducing the mass (structure) of 10% leads to fuel consumption reduction of 6-8%.

### 5.4.1.2. FIBER TYPES

95% of composites use glass fibers as reinforcements. They have high strength and low density resulting in high strength to mass ratio. In 2010, 3.82 million tonnes of glass fibers were produced in the world, and that number is predicted to grow.

Carbon fibers represent only 1.5% of the total market of composite materials in regards to mass, but are over 20% of net value of that market. In 2010, 33 thousand tonnes of carbon fiber were produced in the world, and even 63.5 in 2016. It is believed that an increase of 10-13% will occur in the coming years, to reach 117 thousand tonnes in 2022.

### 5.4.1.3. MATRIX TYPES

Duromers accounted for 83.3% of the global matrix market in 2015. Epoxy and polyester resins are most often used.

### 5.4.1.4. RECYCLING OF COMPOSITE MATERIALS

Composite materials recycling methods are divided into three groups: mechanical, thermal, and chemical recycling.

### 5.4.1.4.1. MECHANICAL RECYCLING

Mechanical processing of scrap materials made from composites is the usual step for two technical recycling due to the size ratio of composite parts and chemical reactors. By mechanical crushing (cutting) and fragmentation, the parts are shredded into smaller parts to obtain recyclate.

### 5.4.1.4.1.1. MECHANICAL CRUSHING (CUTTING)

Serves for material shredding and rough separation of fractions of fibers and resin. Most research is directed to glass fibers. This process can be divided into three steps:

1. Shredding – cutting at low speed or with crusher, to obtain particles with size of 50-100 millimetres, to pulverize the material;
2. Crushing – cutting at high speed or with crusher, to obtain particles with size of 10 millimetres – 50 micrometres, to crush the parts into fragments;
3. Classification – using cyclone and sieve, for the fragments to separate into resin-enriched powder and fiber fragments.

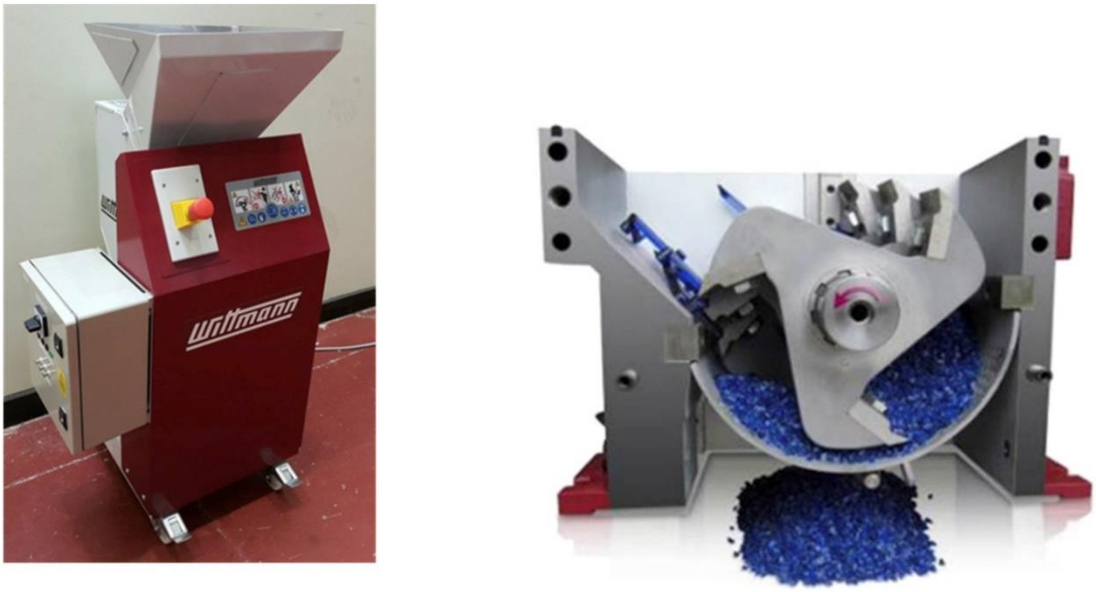

*Figure 18 - Device for mechanical crushing*

Recyclate in this case is the mixture of resin, filler, and fibers. Resin-enriched powders can be used as filler, but this is rarely done due to the low cost of new fillings. Mechanical properties are considerably reduced by crushing. When it comes to fiber recyclate, it still contains a certain percentage of resin, which means it is hard to tell what its properties are. The length of fiber varies, fragments are different (they can be in powder form, and they can be fiber tiles). The fibers obtained in this way can be used again, but the mechanical properties of the new composite material are significantly worse, due to the difficulty in binding the recycled material and the new resin. These difficulties are possible to overcome with certain procedures.

There are also economic and ecological advantages to this procedure. For starters, there is no pollution of air and water. No expensive equipment is required to apply this procedure. On the other hand, the main shortcoming is the low quality of recyclate in comparison to the original materials. Without the use of recyclate, the whole process can be unjustified or even unsustainable.

### 5.4.1.4.1.2. HIGH VOLTAGE FRAGMENTATION

High voltage fragmentation is an electro-mechanical process, which uses electricity to separate matrix from fiber. Its origins are from its application in stone mines, where it was used to separate minerals and crystals. The material is with this process shredded to small parts, which releases fiber.

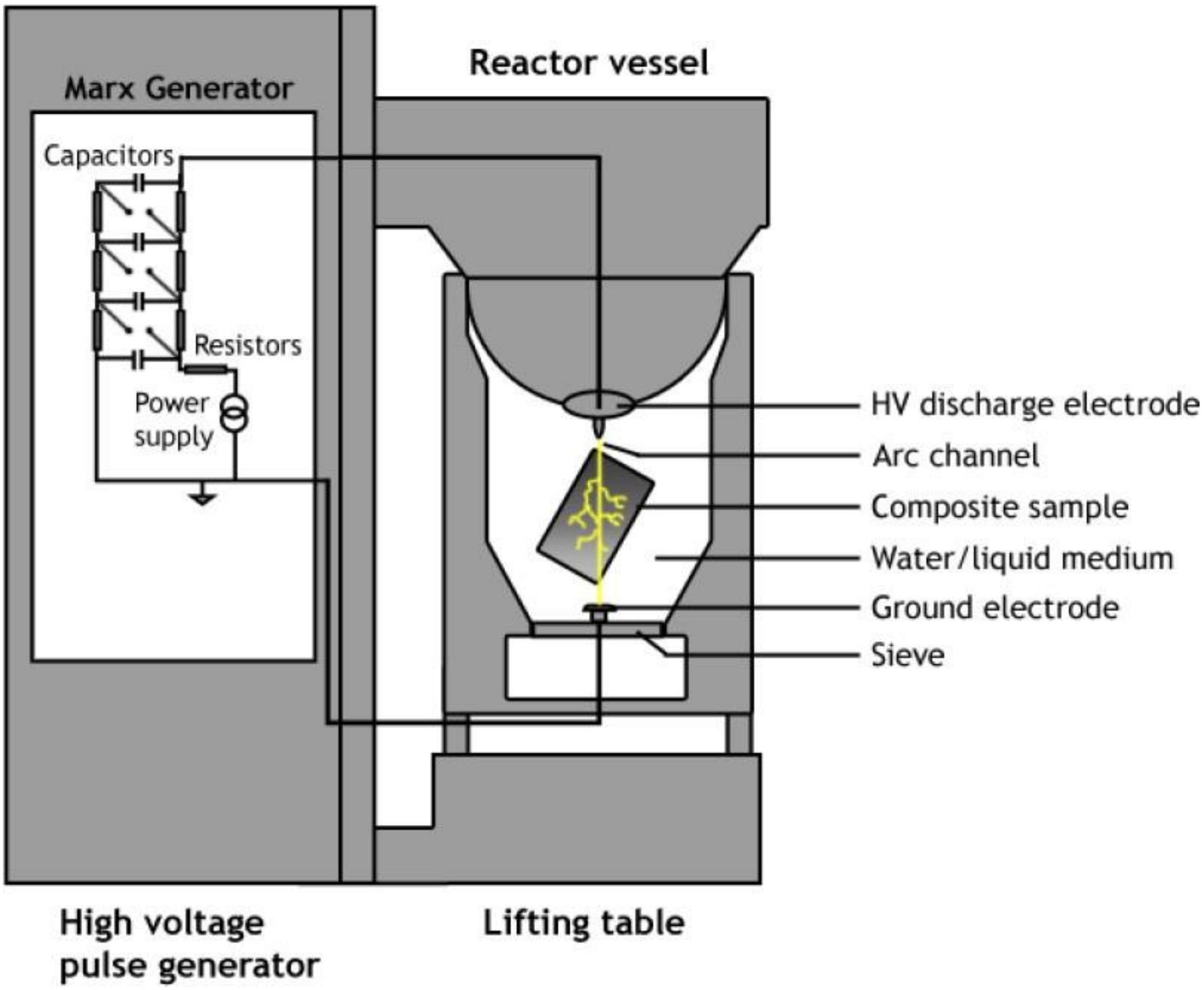

*Figure 19 - Device for high voltage fragmentation*

The equipment shown on Figure 19 is the equipment used for this method, whereby a repeating electrical discharge in dielectric liquid, mainly water, is used. Material that needs to be shredded is put between electrodes. A high voltage discharge occurs between the electrodes, with less than 500 nanoseconds passing between the two pulses. This creates a channel spark, which moves along the internal boundaries and weak regions of the material (such as, existing cracks). Channel spark generates a shockwave of high pressure and temperature and induces internal mechanical stress higher than tensile strength of solid materials. This separates the matrix from fibers and creates cracks, which leads to breakdown of the material.

Recyclate of this process are fibers in original form and parts of the matrix in the solution. Higher number of pulses leads to less resin remains. To remove the rest of the resin from the fiber, they are thermally treated twice on temperature of 400°C. The number of pulses impact the length, distribution of length and purity of fibers. It has been proven that the number of pulses (2000) creates smaller fibers with narrower distribution. When using 500 to 1000 pulses, badly separated parts of resin are obtained. The length of fibers obtained as the result of this process is somewhere between 2 to 9 millimetres.

Advantages of this methods are good separation of matrix from fibers for a relatively low price, higher quality of obtained fibers, longer fibers, higher distribution of fiber length, therefore, a smaller proportion of residual resin on the fibers. Shortcomings are the energy necessary for this process, average fiber quality (drop of about 20% in mechanical properties) and that the residues must be rinsed several times during the process.

### 5.4.1.4.2. THERMAL RECYCLING

Various methods are often combined in order to create better results, thus most pyrolysis processes are combined with gasification or burning to produce purer fibers. Basic difference between the methods is reflected in the amount of oxygen available during the process: if there is no oxygen, it is pyrolysis limited amount of oxygen means gasification; with excess oxygen, burning or incineration occurs. Excess heat from these processes is often collected and used as an energy source. Overview of methods is shown in Table 3.

*Table 3 - Overview of thermal recycling methods*

| Type of thermal recycling | Definition | Energy | Product |
|---|---|---|---|
| Burning | Complete burning;<br>Temperature: > 850 °C for common materials;<br>> 1100 °C for materials containing over 1% of halogenic substances | Exothermic;<br>30 MJ/kg on average | Energy and ash |
| Incineration | Controlled burning<br>Temperature: 450-600 °C | | Recycling of fibers and fillings and energy |
| Comparative processing | Burning and mixing the remains into cement<br>Temperature: 1050-2000 °C | | Energy, ash, and minerals, which can be used in cement |
| Pyrolysis | Thermal decay of polymers<br>(In an inert atmosphere)<br>Temperature: 300-800 °C | Endothermic;<br>23-30 MJ/kg<br>(5-10 MJ/kg for microwave pyrolysis) | Solid substances (50-75%): fibers, fillings, carbon soot<br>Liquids (10-50%):<br>Mixture of organic substances<br>Gaseous substances (5-15%):<br>Mixture of carbon-dioxide, carbon-monoxide, and hydrocarbons |

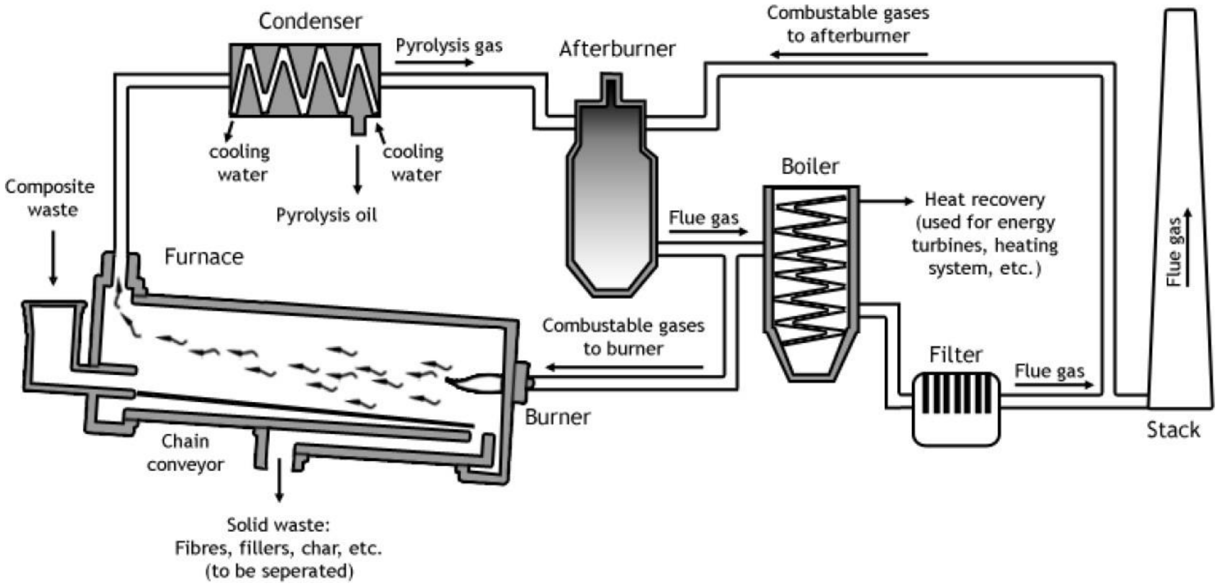

*Figure 20 - Pyrolysis facility*

### 5.4.1.4.3. CEMENT FURNACE (KILN) METHOD

Waste polymers strengthened with fibers is used as alternative fuel in the cement industry. 100% of composites waste is recovered as energy and pure materials, at which 67% of material is recovered. The use of this waste for cement does not impact the quality of the cement.

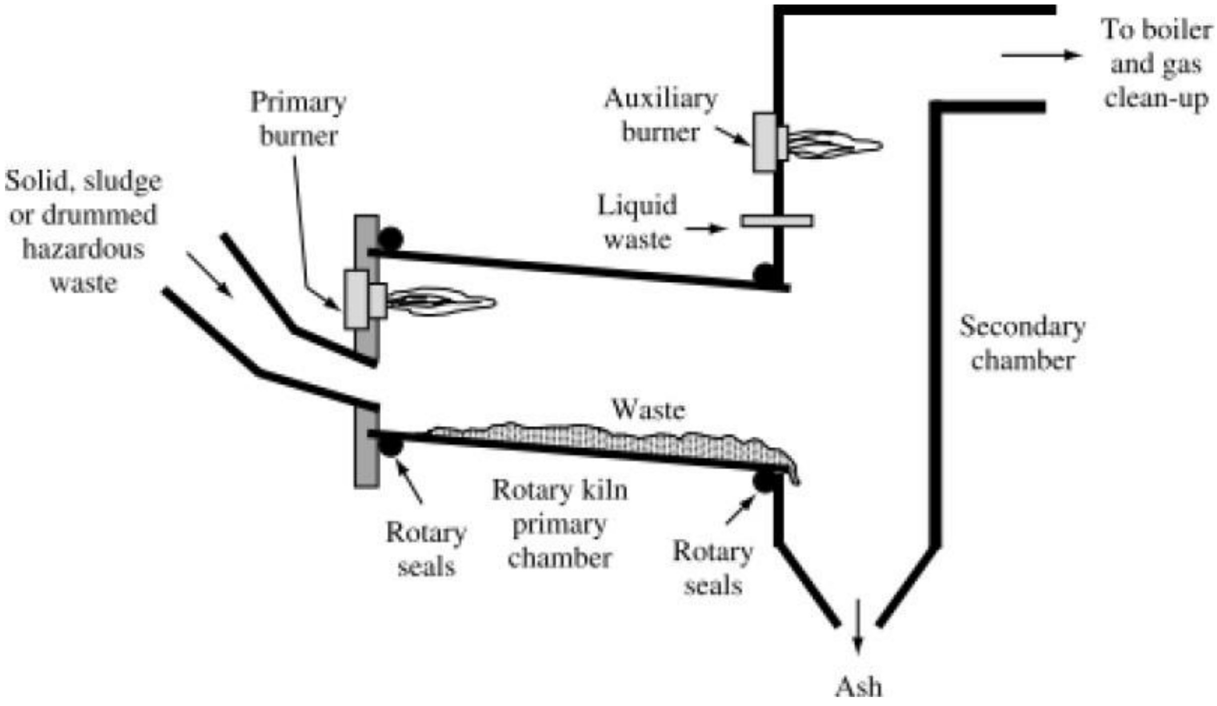

*Figure 21 - Cement furnace (kiln)*

### 5.4.1.4.4. CHEMICAL RECYCLING

It is often that this process is called solvolysis and it uses the chemical depolymerization of the matrix by using preheated solvents or mixture of solvents. Fibers do not dissolve and are released from resin to be collected. Solvolysis provides bigger number of possibilities thanks to a wide variety of solvents, temperatures, pressures, and catalysts. Depending on the solvent, solvolysis can be a hydrolysis (solvent is water), glycolysis (glycols) and acid fermentation (acids). This type of recycling can be applied on both carbon and glass fibers, but is not used for glass fibers, because of their low price and high degradation in properties after the process.

Reactive solvent, or a mixture with co-solvent or co-reactive solvent, is poured into a composite and it terminates specific bonds within the resin, which enables the separation of fibers, as well as resin monomers. In addition, this process avoids the formation of soot residues on fibers. Water is most commonly used, but alcohols are used as well. These two substances can be separated from the solvent by evaporation (water) or by distillation (alcohol). Fluid solvent can be steam, liquid, two-phase substance, or supercritical fluid, depending on the amount of solvent and temperature.

Relatively high temperatures and pressures are necessary for resin degradation, depending on the resin type. Polyester resins are mostly easier for solvolysis from epoxy resin; therefore, they can be processed at lower temperatures. Epoxy resins have been developed to be easier to recycle.

For the control of work conditions, additives and catalysts can be used, but they can be very harmful to mechanical properties of fibers, ecology, and health of workers. In addition to solvolysis at high pressures and temperatures, there is also solvolysis at low pressures and temperatures, where more aggressive solvents are used for it to be to work at low temperatures.

Solvolysis can generate pure fibers and fillings, as well as depolymerized matrix in the form of monomers or petrochemical raw materials. Gases are also products of solvolysis, but are rarely mentioned or analysed. For epoxy resins, the main product is phenol. Matrix materials of resin can be used to create new resins, while the other use includes new polymers, monomers, fuels, or other chemicals, degraded resins are also applicable as adhesives. As for carbon fibers, those are produced as a product of solvolysis, they retain more than 90% of the properties of the original fibers. The shortcoming of this process is the quality of the surface, considering that obtained fibers in new composites are easily extracted, which leads to failure. The advantage of solvolysis at low pressures and temperatures is in the control of chemical reaction, there are no secondary reactions and it is possible to extract more of epoxy monomers. Shortcomings are the process efficiency, which depends on the type of resin, which means that the separation of different types of composites before recycling is key.

### *Which method suits which composite material?*

When it comes to the use of methods from the point of view of the type of composite, an overview is given in Table 4.

*Table 4 - Applied methods depending on the type of composite materials*

| Fiber type | Resin type | Direct reprocessing | Mechanical recycling | Cement furnace | Thermal treatment | Chemical processing |
|---|---|---|---|---|---|---|
| Glass | Duromers | | x | x | | |
| | Thermoplastic | x | x | | | |
| Carbon | Duromers | | x | | x | x |
| | Thermoplastic | x | x | | x | x |

As for fiberglass with duromer matrix, *EuPC, EuCIA* and *ECTC*[1] consider co-processing in a cement kiln as the most suitable solution. Pyrolysis is mostly used because it is used in chemical industry, while the interest for solvolysis keeps growing, and it should be kept in mind that these two processes are complementary and it would be best to perform solvolysis and then pyrolysis to remove organic residues from the fiber surface.

Thermoplastic composites: Resin can be reshaped by heating. These composites are recycled by shredding parts into small particles. Those particles can be inserted in the machine for injection moulding with new materials for thermoplastic composites.

Duromer composites: Resin cannot be reshaped by heating. These composites are shredded, whereby the fibers and fillers are separated from the matrix. Obtained fibers can be used as strengthening agent for other application, while the matrix and the filling can be used as filling for other application.

Vitrimers: this is new and promising type of matrix from 2011, which is developed to serve as a bridge between processability and recyclability issues when comparing duromers and thermoplastics.

Rubber: Vulcanized rubber is also duromer and it plays a huge part in the industry. Disposed tyres can be used as input material for various parts.

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[1] *European Plastic Converters, European Composites Industry Association* и *European Composites Recycling Service Company,* respectively

*Table 5 - Tensile strength of composite materials depending on the process*

| Process | Preserved tensile strength of recycled carbon fibers when compared with new ones | Preserved tensile strength of recycled fiberglass when compared to new ones |
|---|---|---|
| Mechanical recycling | Around 50% | Around 78% |
| Pyrolysis | 36-93% | Usually around 80%<br>Or less around 52% |
| Pyrolysis assisted by microwaves | Around 80% | Around 52% |
| Chemical recycling | 90-98% | Usually around 95%<br>Or less around 58% |
| High-voltage fragmentation | Around 83% | Around 88% |

### 5.4.1.5. ALTERNATIVE APPROACHES TO THE PROBLEM

As for the alternative recycling methods, the use of microbes for the degradation of composites, microbiological systems for degradation of matrix in the controlled environments, etc… it being considered, although new results of these research cannot be found.

When it comes to improving the materials that are used for the composite, there are several ways we can do this: improving the design of materials so that the matrix and fibers have similar chemical properties, improving the resin recyclability, use of bio composites and bio nanocomposites, all of which take a lot of time.

Alternatives to recycling would be reuse, so that the initial part becomes a primary part of the new structure or product. For example, wind turbine blades can be used in bridge construction and similar. For such uses, it is necessary to keep in mind that there are few parts that already reach the end of their life, so that reuse is very limited, while on the other hand, reused materials will reach the end of their life and will have to be recycled.

Because there are a lot of types of composites, considering material, structure and use, there is not a single solution for all composites that solves all problems, rather, it is necessary to divide the solution into sectors with a focus on different types of composites.

### 5.4.1.6. STATE ON THE WORLD MARKET

Problems that exist for a wide application of composite recycling methods:

- Methods are not on the market, although they are technically feasible;
- Testing is expensive;
- Change in standards regarding composites is necessary;
- Obtaining licences for waste management;

- Health and safety requirements;
- Lack of investments;

Only a few companies in the world are recycling composites strengthened with carbon fibers:

- *ELG Carbon Fibre*, the United Kingdom;
- *CFK Valley Stade Recycling*, Germany;
- *Carbon Conversions* (previously *MIT-RCF*), South Carolina, USA;
- *Karborek*, Italy;
- *Carbon Fiber Recycle Industry Co Ltd*, Japan.

Fiberglass is processing by *Neocomp* in Germany. Some companies provide the equipment for including the recyclate into resins for spray-up technology or casting, for example, *Eco-Wolf* – from Florida, the USA, and *ADM Isobloc* from Germany. Dry carbon, aramid and other fibers that are waste (but not fiberglass) are processed by *Aptec Products* and *Davy Textiles* in the United Kingdom, as well as *Procotex* in Belgium and France. Dry fibers have limited commercial as infrastructure reinforcements or wood replacement products in recycled thermoplastics or with duromer matrix and other fillers.

#### 5.4.1.7. PREDICTIONS FOR THE FUTURE

It is expected that the technology for composites recycling will mature in time. That will include separation of strengtheners from the matrix or the recycling of the whole composite by processing the matrix along with strengthener. To improve the market opportunity for recyclate, it is necessary to either improve the recyclate or increase the tolerances of the production process by using more recycled fibers, matrix, or both.

It is considered that the composite recycling will play a major role in aviation and automotive industries. A very strong collaboration between universities and industry will be needed to reach the ultimate goal. Because carbon fiber composites have long lifespan, it will be some time before they become available for recycling. This means that the growth of recycling sector will lag behind the production of (carbon) fibers.

Currently the main driver for development is European legislation, which orders the procedures for composite recycling. High cost of recycling will be compensated by banning landfills and burning of composites, and by increasing the costs of manufacturing new composite components.

### 5.4.2. LITHIUM-ION BATTERIES

Lithium-ion batteries currently dominate the market of electric vehicles, thanks to their high energy, power, and long life. Millions of electric and hybrid vehicles driven by lithium-ion batteries very soon after leaving the production facilities get their owners and a big growth of that trend is projected. According to research, lithium-ion batteries have the largest growth and the largest share of investment in the industry. For example, considering the whole world, sale of lithium-ion batteries grew from approximately 16% a year from 1996 to 2016, in 2016 the world market of these type of batteries was worth over 20 billion dollars; there is an estimate that the market will be work around 40 billion dollars by 2025. Price for energy obtained from these batteries has considerably dropped in the last 10 years, in 2005 a price for one kilowatt/hour was 1000 dollars, while the price of kilowatt/hour in 2016 was only 200 dollars. This drop in price was due to the increase in production.

Lithium-ion batteries belong to class 9 in classification of hazardous substances, due to its unstable electrical properties and the risk of thermal spillage of not handled properly during transport. These batterie have to be subjected to certain international tests before delivery via land, sea, or air.

Huge number of vehicles is equipped or driven by lithium-ion batteries in order to mitigate environmental pollution and reducing energy use. Quick growth of use of lithium-ion batteries will lead to huge number of lithium-ion batteries that reached end of their life, which is estimated to 8 to 10 years. For the battery to reach its projected life, proper handling is necessary. There are three possibilities for end-of-life electric vehicle batteries, depending of their design, quality, and condition:

1. Recovery;
2. Processing;
3. Recycling.

Recovery and processing extend the use of lithium-ion batteries, and recycling ends their life. To be able to use the maximum value of lithium-ion batteries, ideal scenario would first include the processing or recovery, and then they should be recycled. Recovery is the most desirable scenario for end-of-life batteries in terms of maximizing the value and minimizing the consumption and emission of energy in the life cycle; however, this option is the strictest in terms of meeting the battery quality. Going directly from first use in a vehicle to recycling is less desirable from a lifetime perspective, due to underutilization.

Recycling is useful because lithium-ion batteries become a part of circular economy, instead of going to waste. Recycling returns valuable materials back to chain of value, partly mitigating the need for introducing new resources.

Change in place of use of batteries outside the automobile (second life) lies between these two scenarios, in terms of desirability. However, considering the ease of processing, recycling is probably the simplest and certainly the most widely applicable solution for lithium-ion batteries. It should be noted that, even if the batteries are refurbished first or repurposed, they will eventually be recycled. First two options only delay recycling.

#### 5.4.2.1. BATTERY REFURBISHMENT

Refurbishment refers to battery refurbishment of electric vehicles and their placing in their original spots (in vehicles). This requires that the batteries for electric vehicles have acceptable level of consumption and that they fulfil all *REM* requirements for power, energy, life cycle, etc. According to the American Consortium for Advanced Batteries (*USABC*), batteries are generally not suitable for use in electric vehicles when the capacity of power of the cells, modules, or packs is less than 80% of the original nominal value. Testing the whole battery pack could prove that only a small percent of cells cannot keep the necessary capacity, and throwing away the whole pack of batteries represent the unused life cycle. The idea behind this refurbishment is to replace failed cells or modules in packs and return the refurbished packs for use in electric vehicles.

#### 5.4.2.2. BATTERY REPLACEMENT

Refers to incorporation into other systems that implement lithium-ion batteries, whereby the batteries are reconfigured for use in less stressful systems (such as stationary storage).

When the battery is not able to maintain the desired capacity, incorporating it into another system the best solution. Use in other systems requires not only requires the change of damaged cells or modules, but also requires the reconfiguration of the module or the battery itself, including the establishment of new battery management systems for placement into other systems. However, refurbishment faces a number of challenges, including reliably assessing the battery or module, responsibility and costs of reconfiguration must be compared to new and less expensive batteries.

Replaced batteries can be used in various systems, such as back-up generators, integration of renewable sources of energy and charging of electric vehicles. One example uses *Nissan's* modified lithium-ion batteries for electric vehicles for *kStorage* system; *kStorage Home* is an integrate solar house system for storing energy which represent a reliable solution for efficient power supply of companies that have large needs for the consumption of electricity. The largest systems for storing electricity in Europe, that uses lithium-ion batteries is *xStorage Building*, which stores electricity at Johan Cruyff Arena, which is the home to Ajax football club from Amsterdam, it uses 280 *Nissan LEAF* batteries. Another example, *General Motors* used five retrofitted *Chevrolet Volt* batteries together with solar panels and wind turbines that powered *GM* headquarters. Installation into infrastructure is another option for retrofitted batteries. In order to demonstrate the application, *Renault* batteries were placed on motorways in Belgium and Germany in August 2017.

#### 5.4.2.3. RECYCLING THE LITHIUM-ION BATTERIES

Recycling is the third option that can and must be used on all batteries. Multitude of chemical materials used in today's electric vehicle batteries, increase the complexity of recycling, and presenting several technical and economic obstacles that must be overcome in order to enable the mass recycling of automotive batteries. Lithium-ion packs are of complex structure, which consists of multiple modules in which numerous, prismatic, or cylindrical cells are connected in a variety of parallel and serial configurations (welding, bonding of wires, and mechanical bonding are common techniques used within the modules and pack of lithium-ion batteries). The structure of lithium-ion packs, modules and cells considerably differs from manufacturer to manufacturer.

There are three different processes of battery recycling:

1. Pyrometallurgical process;
2. Hydrometallurgical process;
3. Direct recycling process.

First two methods are established and working on an industrial scale, and third is currently in the laboratory phase. New approaches to all three categories are a subject to extensive development in the industry.

*Figure 22 - Recycling processesof lithium-ion batteries*

## 5.4.2.3.1. PYROMETALLURGIC PROCESS

Pyrometallurgic process is a process of melting on high temperatures, which usually includes two steps. First, lithium-ion battery is burned in the smelter, where the compounds are broken down, and organic materials light plastics and separators are burned away. Then, new alloys are created by reducing carbon. In next steps (often hydrometallurgical), metal alloys are further separated in order to get pure materials. In this process, only expensive metals (cobalt, nickel, or copper) are recycled with highest efficiency. Anode, electrolyte, and plastic oxidize and provide energy for the process. Lithium is in the slag fragments and can be obtained by additional processing, and recently the value of lithium grew, so its extraction is profitable for some recycling processes. Aluminium serves as a reductor in the furnace and reduces the need for fuel.

Pyrometallurgic processes have created relatively successful business model until today, because of the high cobalt content in lithium-ion batteries used in portable electronics. However, in batteries for electric vehicles we strive for a lower cobalt content,

Main advantages of pyrometallurgic processes are:

- Simple process;
- Sorting and crushing are not necessary.

Main disadvantages are:

- Production and high energy consumption during the melting process;
- Alloys require further processing, which increases an overall cost of recycling;
- Many materials cannot be recovered (for example, plastic, graphite, aluminium).

#### 5.4.2.3.2. HYDROMETALLURGICAL PROCESS

In this process, recovery of material is done by the use of water chemistry, by rinsing in acids (or bases) and further concentration and purification. For lithium-ion batteries, ions in solution are separated with different technologies (ion exchange, solution extraction, chemical deposition, electrolysis etc.) and deposited as different compounds.

Main advantages of the hydrometallurgy process are:

- Materials of high purity can be created;
- Most contents of lithium-ion batteries can be recovered;
- Possible work on low temperatures;
- Lower emission in comparison to pyrometallurgic process.

Main disadvantages of hydrometallurgical processes are:

- Need for sorting, requires dedicated area for storage and increases costs and complexity of the process;
- Harder separation of new elements (cobalt, nickel, manganese, iron, copper, and aluminium) in the solution, due to similar properties that could lead to increase in costs;
- Costs of waste water treatment and accompanying costs.

### 5.4.2.3.3. DIRECT RECYCLING PROCESS

Direct recycling is the method of recovering, which directly collects and recovers the active materials of lithium-ion batteries, retaining their original structural compounds.

In this process, battery contents are separated, primarily by using physical methods of separation, magnetic separation, and mild thermal separation, in order to avoid chemical breakdown of the active substances, which are the main goal for recovery. Purified active materials, and surface imperfections are repaired by re-bidding or with hydrothermal processes. However, cathodes may be a mixture of more active substances, and separation can, but also cannot be economical.

Main advantages of direct recycling method are:

- Relatively simple procedure;
- Active materials can be used directly after regeneration;
- Considerably lower emission and lesser secondary pollution, in comparison to pyrometallurgy and hydrometallurgy.

Main disadvantages of the direct recycling process are:

- Strict sorting/pre-processing is necessary, based on exact chemistry of active substances;
- Guaranties of constant high purity and intact crystal structure;
- Unproven technology, which only exists in laboratory conditions;
- Significant sensitivity to waste input variations;
- Inflexible process.

*Figure 23 - Recycling facilities for lithium-ion batteries in the world*

# 6. A SYSTEMS VIEW OF VEHICLE RECYCLING

One of the ways to consider the strategy initiated by the increase of vehicle recycling is to start considering the existing methods the recovery of resources from old vehicles. Figure 24 shows the way in which the vehicle recycling process is currently carried out in most of the world. This diagram represents main actors in the vehicle recycling process:

- end-user,
- dismantling companies,
- shredding companies,
- non-ferrous metals treatment companies,
- market for used parts and scrap metals.

Smaller activities within this infrastructure are not shown. These smaller operations and interactions include the processing and treatment of lead-acid car batteries, catalytic converters, airbags, and fuel tanks.

Dismantling companies can choose not to resell large metal parts (for example, engine blocks and gearbox housing) on the market of used parts, but can simply sell them on the market of waste metals (“old iron”). Nevertheless, the picture captures the main interactions in the vehicle recycling infrastructure.

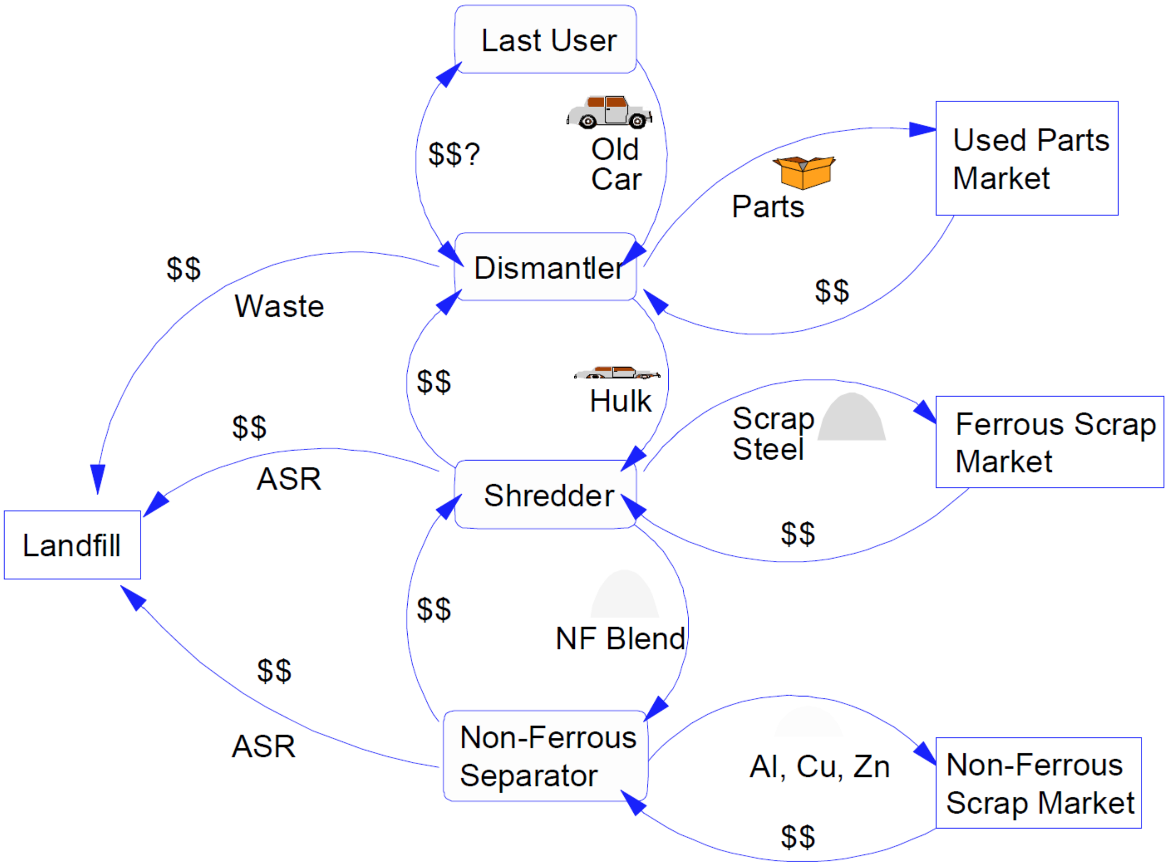

*Figure 24 - Existing mechanisms for resource recovery of vehicle materials*

Unlike the usual overviews of this infrastructure, the Figure 24 however, shows not only the flow of materials through the infrastructure, but also includes economic flows that follow these material flows. This figure makes explicit the feature of recycling that is most commonly forgotten: ***nothing is truly recyclable if there is no market for the recycled products.*** Collecting and generating recyclate is no guarantee that there is a demand for the resulting resource. Similarly, participant interactions in the recycling infrastructure will occur only if the financial incentives are big enough.

By considering the Figure 24, the only financial flow, which direction is uncertain, is the flow between the dismantler and the last user. Depending upon the situation, the dismantler may pay for, or be paid to take, the old vehicle. After that, however, the transfer of resources must be accompanied by a reciprocal flow of financial means, while the transfer of waste requires a parallel flow of cash.

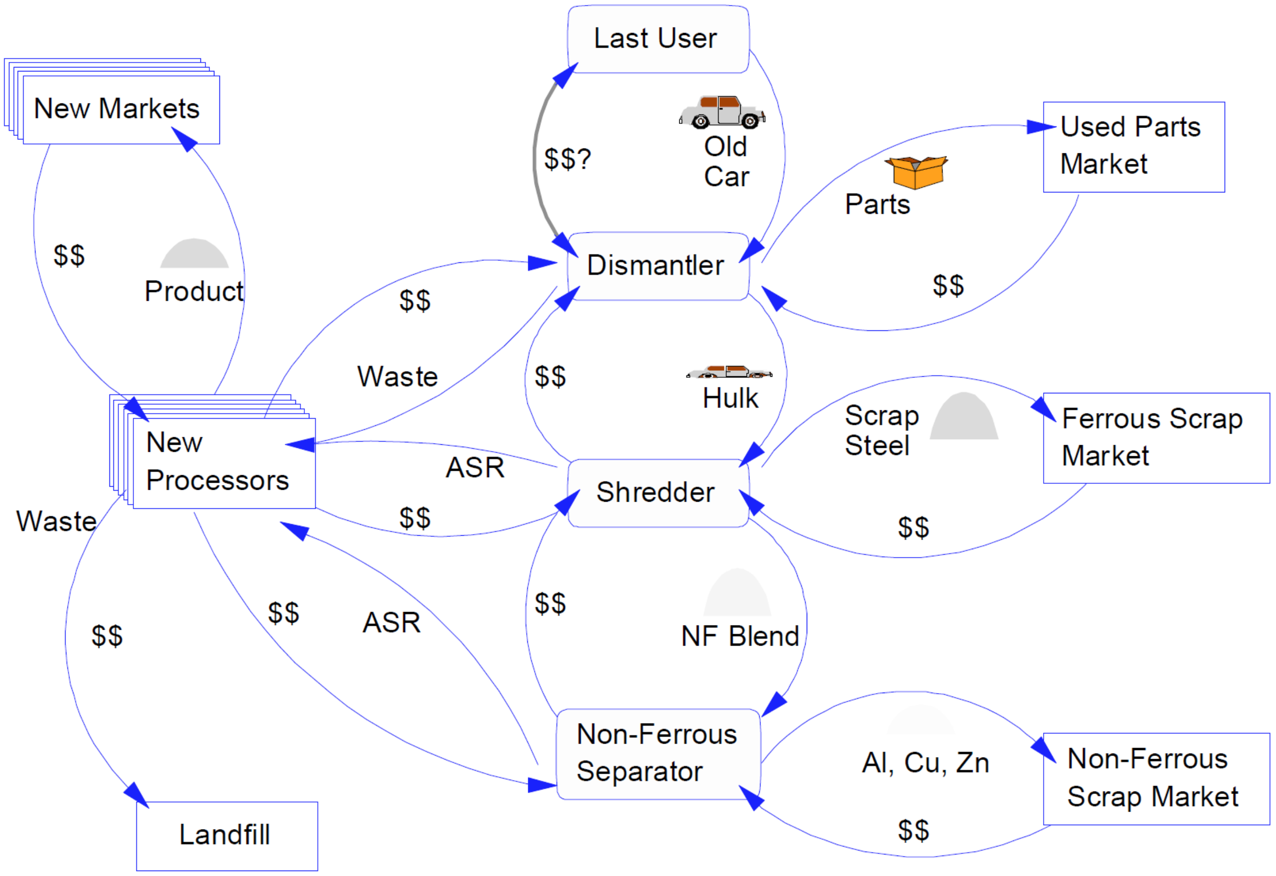

Figure 25 - Machanisms for expanding resource recovery of vehicle materials

Efforts to increase the amount of the automobile recycled depend either upon increased effort by the existing processors, or the participation of one or more new processors. Generally speaking, most of the initiatives in the area of increased automobile recycling are targeted at the introduction of processes and mechanisms that lead to increased recovery of the polymeric fraction of the automobile. These new processes are likely to rely upon the existing recycling infrastructure to supply the necessary feedstocks, either in the form of plastic parts removed by the dismantler or in the form of automobile shredder residue (ASR), the blend of chopped materials separated from the ferrous and nonferrous scrap metals. Figure 25 presents this potential expanded recycling framework. It is important to note that not only are new processes required, but also new markets for the materials extracted.

The maze of linkages represented in Figures 24 and 25 in-detail demonstrates the complexity of the infrastructure of vehicle recycling and the myriad interconnections and interrelationships between the actors. However, the important relationships between these actors are a reflection of some simple economic factors which can be presented in a fashion that begins to reveal crucial structural features of this market. In particular, the fact that recycling occurs in response to economic opportunity rather than technological necessity suggests a closer consideration of the economic transactions between the actors. By constructing a representation of the expenses and revenues of each participant, a clearer picture of the important aspects of the recycling infrastructure emerges.

Relations between participants in the Figure 25 can be represented in tabular form, which can be used for a clear definition of the necessary conditions for the successful recycling infrastructure. Figure 26 shows the flow of income and expenses within the recycling infrastructure, that includes not only the major interactions represented in previous figures, but also alternative flows of material (for example, sale of large metal parts on the waste metal market - “old iron”, instead on the used parts market).

In Figure 26, “+” signifies an income-generating transaction by the actor in that row, while “-“signifies a purchasing transaction by the same actor. The column in which “+” or “-“ appear shows which other actor participated in the transaction. In other words, each “+” or “-“, corresponds to a purchase or a sale by the participant in the row in which the symbol appears with the actor in whose column the symbol appears.

| | | Source of Income / Recipient of expense | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Participant | *A* | *B* | *C* | *D* | *E* | *F* | *G* | *H* | *I* | *J* |
| *A* | Last user | *-V* | +/- | | | | | | | | |
| *B* | Dismantler | -/+ | *-P* | + | | ? | + | + | + | | - |
| *C* | Shredder | | | *-P* | | ? | | + | | | - |
| *D* | Non-ferrous separator | | | | *-P* | ? | | | + | | - |
| *E* | New participants in the process | | ? | ? | ? | *-P* | +? | +? | +? | + | - |
| *F* | Used parts market | | - | | | -? | *+V* | | | | |
| *G* | Ferrous scrap market | | - | - | | -? | | *+V* | | | |
| *H* | Non-ferrous scrap market | | - | | - | -? | | | *+V* | | |
| *I* | New scrap market | | | | | - | | | | *+V* | |
| *J* | Landfill | | + | + | + | + | | | | | *-P* |

*Figure 26 - Tabular overview of asset flows within a stylized automobile recycling infrastructure*

When actors process resources to extract valuable products, a “*-P*”, which signifies the costs of that processing, appears in the gray box for that actor. Thus, a “*-P*” appears in the rows for the dismantler, the shredder, the non-ferrous metals separators, the potential new processor, and the landfill operator. For these actors, their row in the table can be thought of as an operating balance sheet. On the other hand, a “*+V*” represents the value of the resource flowing into the relevant market, or a “*-V*” from the last user. This value may be a true market value, or may represent the opportunity cost that the holder of the resource faces if he is unable to sell the resource. In either case, this “*V*” term represents the upper limit on the price that the resource would reach on the open market.

Finally, if there are free markets, the off-diagonal elements of the matrix (representing the transactions between actors) must be symmetric, i.e., for every buyer there must be a seller. This symmetry has a further implication: it couples the economics of all the recycling participants and introduces the critical operating constraints on the system. In particular, the net sum of income and expenses in each row representing a recycling processor (the dismantler, the shredder, the non-ferrous separator, and the hypothetical new processor) must be positive if the activity in that row is sustainable; i.e., each participant must make an economic profit. In addition, for each row representing a market, the net cost must be offset by the market value of the resource (parts, scrap metal, or other product) or the market will not absorb the product of the processors. An additional implication is that, in the absence of other market initiatives, the value of these resources cannot exceed the value of virgin resources. Finally, the sum of the diagonal elements must be greater than or equal to zero, or the entire recycling infrastructure represents a net economic loss.

This systemic overview of the asset flows within the recycling infrastructure is an important basis for the analysis of potential strategies directed toward the increase of vehicle recycling. For example, while the increase of landfill costs may lead to the increase of recycling price (because the participants in the process will try to change their business policies and limit their costs towards the landfill), this table shows that such changes in process will only occur if the change in the process costs “*P*” is increased to reduce total landfill costs and increase income from recycling process. If these changes are not sufficient, then increases in landfill costs will not lead to increases in recycling costs – rather, such price increases will reduce the profitability of existing participants in the process, possibly fatal. Similarly, efforts to increase the flow of old automobiles into the system, by imposing landfill certification procedures (and imposing of fines if the certificates are not obtained) can only lead to the reduction of price paid by (or even paid taxes) the dismantling company to take over the vehicle (considering that such strategies substantially reduce the value “*V*” of the old vehicle to the last user).

## 6.1. IMPLICATIONS FOR DIFFERENT RECYCLING POLICY OPTIONS

This analysis suggests that real questions for increasing the need for recycling, as well as appropriate focus on strategy, lie along the diagonal in Figure 26. While strategy makers can place themselves on the transaction market, the history of such actions in the material markets has not been encouraging. The frequency of such pledges has resulted in the development of a large bureaucratic system that must supervise such transactions and the development of the black market. History teaches us that, whenever possible, the strategy should be directed to reduce the costs of the production technologies ("*P*" in Figure 26) and to increase the market values of the resource which are managed within the infrastructure of the recycling process ("*V*" in Figure 26).

For example, even the certification on disposal can increase the effective value of the vehicle, it does it by introducing the action during the transaction (the exchange of vehicles for certificates). According to this, even if it can increase the recycling rate, it can also enable the recycling company to obtain a significant income for the company itself, without increasing the recycling rate. Just by introducing the mean of following the transactions between the last owner and the dismantler, strategy makers can ensure that the effectively increased value of the old vehicle will be introduced into the infrastructure, by increasing the recycling rate.

Therefore, increasing the economic benefits from recycling, and thus increasing the recycling rate and type, must be implemented through actions that change the value of treated resources or reduce the processing and separation costs of those resources. Furthermore, those changes must be applied in such a way that they do not rely on tracking and control of transactions within the infrastructure. With these limitations in thinking, main strategic options that are available for increasing the recycling can be classified in the following way, in accordance with their impact to the transaction matrix.

- Value of the old vehicle;
- Processing costs for the existing and new recycling companies;
- Value of recycled materials and parts;
- Landfill costs.

### 6.1.1. THE VALUE OF OLD VEHICLES

Unlike the other resources in this infrastructure, the value of old vehicles is derived from the profitability of the rest of the infrastructure. According to some understandings, while there are markets for metal waste and refurbished parts independently from the vehicle recycling infrastructure, this infrastructure is the market for old vehicles. In the absence of alternatives, this infrastructure is threfore, in the position to dictate that value.

| | | Source of Income / Recipient of expense | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Participant | A | B | C | D | E | F | G | H | I | J |
| A | Last user | -V | +/- | | | | | | | | |
| B | Dismantler | -/+ | -P | + | | ? | + | + | + | | - |
| C | Shredder | | | -P | | ? | | + | | | - |
| D | Non-ferrous separator | | | | -P | ? | | | + | | - |
| E | New participants in the process | | ? | ? | ? | -P | +? | +? | +? | + | - |
| F | Used parts market | | - | | | -? | +V | | | | |
| G | Ferrous scrap market | | - | - | | -? | | +V | | | |
| H | Non-ferrous scrap market | | - | | - | -? | | | +V | | |
| I | New scrap market | | | | | - | | | | +V | |
| J | Landfill | | + | + | + | + | | | | | -P |

The source of values for the old vehicles come from values of parts and materials from which they are composed of. Their values can be increased by increasing the value of those materials and parts, but another strategy is to use materials in the vehicles that are easily separated and recycled, increasing the profitability of the rest of the recycling infrastructure by reducing production costs. This approach suggests that the responsibility for establishing and maintaining these values lies in vehicle manufacturers, suppliers of after-market parts, and users as well.

Vehicle manufacturer can increase the value of old vehicles by adjusting the recycling production process, which has an impact in choice of materials, designing the components, and the way how the vehicles is assembled (the ease with which assembled vehicles can be disassembled and different types of materials can be identified and separated). Component supplier can also work in tandem with the vehicle manufacturer in order to simplify the dismantling process, as well as to ease up the identification of materials that make up the components. Finally, the use can also maintain the value of the vehicle through maintenance and use of replacement components manufactured in accordance with these objectives.

It is very important to distinguish these actions from various instruments that have been used and proposed for use to supposedly raise the value of vehicles and promotion of recycling. Disposal system, which is institutionalized at some locations, increases the value of old vehicles through payment of cash to the last user, when the vehicle is given to be dismantled. However, although this increases the value of the vehicle to the last user, that value does not increase the value of the recycling infrastructure, which is the only one in a position to accumulate income derived from the conventional way of manufacturing vehicles. The alternative approach, searching for proofs of vehicle disposal before freeing the last user of obligation to pay tax on owning the vehicle, registration, and insurance, effectively reduces the value of the vehicle for the last user, while keeping the vehicle's value intact in the eyes of the dismantling companies. In this case, the dismantling company is in the position to accumulate a considerable income and again, to increase the amount of material recycled from the vehicle for no particular reason.

### 6.1.2. PRODUCTION COSTS OF THE EXISTING RECYCLING COMPANIES

The reduction of the production costs of the existing recycling companies requires the improvement to the applied technologies for dismantling vehicles and separation of available materials and components.

In cases of dismantling companies, this requires the transfer of information from the vehicle manufacturer to the dismantling companies, in the form of material specifications and manuals for dismantling. Such efforts are already underway, with the objective of satisfying the requirements of the German recycling initiative. Similarly, ISO and SAE have developed standards for marking plastic components, by means of which the composition of the material is identified, which is introduced as an obligation through the Directive 2005/64/EC and the UN Regulation No. 133.

| | | Source of Income/ Recipient of costs | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Participant | *A* | *B* | *C* | *D* | *E* | *F* | *G* | *H* | *I* | *J* |
| *A* | Last user | *-V* | *+/-* | | | | | | | | |
| *B* | Dismantler | *-/+* | *-P* | + | | *?* | + | + | + | | - |
| *C* | Shredder | | | *-P* | | *?* | | + | | | - |
| *D* | Non-ferrous separator | | | | *-P* | *?* | | | + | | - |
| *E* | New participants in the process | | *?* | *?* | *?* | *-P* | *+?* | *+?* | *+?* | + | - |
| *F* | Used parts market | | - | | | *-?* | *+V* | | | | |
| *G* | Ferrous scrap market | | - | - | | *-?* | | *+V* | | | |
| *H* | Non-ferrous scrap market | | - | | - | *-?* | | | *+V* | | |
| *I* | New scrap market | | | | | - | | | | *+V* | |
| *J* | Landfill | | + | + | + | + | | | | | *-P* |

In addition to such initiatives, alternative methods for removing of components and identifying the composition of materials can be explored. For example, plastic parts of the chassis do not have to be removed from the vehicle intact, if the only purpose of removal is to recover the material. Similarly, while marking can help in identification of the material composition, an automated method for obtaining such information can reduce mistakes during sorting, which is a critical problem of experimental facilities for dismantling and recovery of polymer materials today.

In the case of the shredder, the costs of processing are already quite low. However, as electric arc furnace steelmakers begin to explore the production of steel sheet, it will become increasingly important that the shredder achieve better control of material separation. While some tramp elements can be accommodated when making construction shapes (e.g., reinforcing bars and wires), the production of sheets is not easy, so in order to continue to supply scrap to these producers, the shredder will have to expend more resources to produce clean scrap from automobiles.

The problem of segregation has the potential to become a much greater problem for both the shredder and the non-ferrous processor as the ferrous fraction of the automobile decreases and the use of light metals increases. Current technologies for separation rely upon gross differences in density and electromagnetic properties of the various metal species. However, with increasingly sophisticated alloys, these producers will need to find ways to make fine distinctions between these alloys. In some cases, failure to achieve this degree of separation may even lead to saturation of low quality secondary markets, which could adversely effect the economics of the entire infrastructure.

Clearly, strategies directed at the development and an announcement of more effective separation technologies will be necessary to maintain and improve the economics for these existing processors.

### 6.1.3. PRODUCTION COSTS OF NEW RECYCLING COMPANIES

In order to establish new recycling facilities, it will be critical that the costs of the existing processes be reduced, or new processes be developed. The economic factors of the available processes for the extraction and recovery of polymers are not particularly attractive, even with great efforts for ensuring relatively clean supply resources. When the more likely feedstocks are processed, the economics are even less attractive.

| | | Source of Income/ Recipient of expenses | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Participant | | A | B | C | D | E | F | G | H | I | J |
| A | Last user | -V | +/- | | | | | | | | |
| B | Dismantler | -/+ | -P | + | | ? | + | + | + | | - |
| C | Shredder | | | -P | | ? | | + | | | - |
| D | Non-ferrous separator | | | | -P | ? | | | + | | - |
| E | New participants in the process | | ? | ? | ? | -P | +? | +? | +? | + | - |
| F | Used parts market | | - | | | -? | +V | | | | |
| G | Ferrous scrap market | | - | - | | -? | | +V | | | |
| H | Non-ferrous scrap market | | - | | - | -? | | | +V | | |
| I | New scrap market | | | | | - | | | | +V | |
| J | Landfill | | + | + | + | + | | | | | -P |

There are consortiums in the world today, with the objective of researching and developing of these technologies, from which some receive the support not only from the industry, but also from the government of countries. Such strategies are necessary in order to reduce the probable costs of new recycling companies.

### 6.1.4. THE VALUE OF RECYCLED MATERIALS AND PARTS

The maintenance of a healthy market for recycled materials and parts will rely upon sustaining the value of these recovered resources. This will require supporting the development of an infrastructure that can effectively remanufacture and distribute used parts, as well as support by the original equipment manufacturers for a market in secondary components. This may either require the direct participation of the OEMs in this market, or an acceptance of the loss of a certain fraction of the after-market parts market in order to support this industry.

| | | Source of Income/ Recipient of expenses | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Participant | | *A* | *B* | *C* | *D* | *E* | *F* | *G* | *H* | *I* | *J* |
| *A* | Last user | *-V* | +/- | | | | | | | | |
| *B* | Dismantler | -/+ | *-P* | + | | ? | + | + | + | | - |
| *C* | Shredder | | | *-P* | | ? | | + | | | - |
| *D* | Non-ferrous separator | | | | *-P* | ? | | | + | | - |
| *E* | New participants in the process | | ? | ? | ? | *-P* | +? | +? | +? | + | - |
| *F* | Used parts market | | - | | | -? | *+V* | | | | |
| *G* | Ferrous scrap market | | - | - | | -? | | *+V* | | | |
| *H* | Non-ferrous scrap market | | - | | - | -? | | | *+V* | | |
| *I* | New scrap market | | | | | - | | | | *+V* | |
| *J* | Landfill | | + | + | + | + | | | | | *-P* |

In the case of materials markets, direct action in the secondary markets will be difficult. There are substantial difficulties with establishing and maintaining the direct price supports for secondary raw materials, considering that the source materials market will always be able to supply a perfect substitute for recycled materials. Moreover, establishing the direct supports for recycled material prices begins to move the area of policy action off the gray diagonal, into the monitoring of transactions between buyers and sellers of recycled materials. For example, if one wishes to support the price of recyclate, one must have some way of guaranteeing that the material being sold is recyclate (rather than virgin) and is of the appropriate composition and quality.

This suggests that, rather than directly supporting the price of recycled materials, it may be appropriate to develop instruments which raise the cost of the alternatives to recyclate.

### 6.1.5. COSTS/PRICE OF A LANDFILL

The final area for possible policy action lies in the area of manipulating the cost of landfill. While there are some “real” economic bases for the price of landfill (land prices, processing, etc.), the price of landfill increasingly is a reflection of scarcity, usually as a consequence of local and national strategies. Difficulties in establishing landfills, including expensive procedure of acquiring licences and litigation processes, as well as government policies establishing varying grades of waste and associated disposal requirements, have led to a price spiral in landfill costs in many parts of the world.

| | | Source of Income / Recipient of expenses | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Participant | A | B | C | D | E | F | G | H | I | J |
| A | Last user | -V | +/- | | | | | | | | |
| B | Dismantler | -/+ | -P | + | | ? | + | + | + | | - |
| C | Shredder | | | -P | | ? | | + | | | - |
| D | Non-ferrous separator | | | | -P | ? | | | + | | - |
| E | New participants in the process | | ? | ? | ? | -P | +? | +? | +? | + | - |
| F | Used parts market | | - | | | -? | +V | | | | |
| G | Ferrous scrap market | | - | - | | -? | | +V | | | |
| H | Non-ferrous scrap market | | - | | - | -? | | | +V | | |
| I | New scrap market | | | | | - | | | | +V | |
| J | Landfill | | + | + | + | + | | | | | -P |

On one hand, such increases in cost can lead to increases in recycling, but only to the extent that the costs of processing and extraction, as well as the value of the recovered materials, lead to lower net costs than the costs of landfilling. Provided such technologies are available, then increasing landfill costs can be effective. However, there is a redistribution of income, since landfill operators (or tax collectors from landfill operators) will accumulate economic value that would otherwise add value to the recyclers. Moreover, if effective technologies are not available or if the loss in economic value is sufficiently great, then the imposition of such landfill costs will only serve to choke off recycling altogether by reducing the overall profitability of the enterprise.

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# End of Life Vehicle Disposal

Saša MITIĆ

# Introduction to End-of-life vehicle disposal

ISBN

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