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Smart Technologies for Waste Processing from the Automotive Industry

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SMART TECHNOLOGIES FOR WASTE PROCESSING FROM THE AUTOMOTIVE INDUSTRY

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ABSTRACT

The monograph presents the results of the scientific research activities of UNIVNET – University and Industrial Research and Education Platform of the Recycling Society. The monograph summarizes the results of activities in assessing the condition, forecasting the generation of waste and developing new technologies for the material and energy recovery of selected types of waste from the automotive industry.

The content of the monograph is fully in line with the European Union's waste management policy, which is aimed at reducing the negative impacts of waste on the environment and human health, while at the same time effectively increasing the recovery of waste in the form of secondary raw materials and energy. The transition to a circular economy requires changing entire value chains, from product design to new business and market models, including new ways of turning waste into resources to changing consumer behaviour. It presupposes a complete systemic change and innovation not only in technology, but also in organization, society, funding methods and policy formulation.

The Slovak Republic is currently facing many environmental challenges. We have problems with air quality, low waste recycling rates, but also with the protection of ecosystems. The basic vision, defined in the Strategy of Environmental Policy of the Slovak Republic up to 2030, is to achieve a better quality of the environment and a sustainable circular economy.

The monograph is divided into eight logically consecutive chapters. The individual chapters are devoted to the analysis of waste quantities, treatment capacities, forecasts of waste change in connection with the advent of electromobility, preparation of waste for reuse, design of technology for the recovery of glued laminated glass, recycling of metal-bearing waste from accumulators, development of sound and thermal insulation materials from waste, recycling of rubber, rubber and plastics, and finally options for energy recovery of waste. Several of the solutions presented are original solutions of the authors of the monograph and are subject to their copyright in the form of patents.

The monograph provides the necessary information on the state and problems of waste management in the automotive industry and is an inspiration for those who are engaged in minimizing and recovering waste from their production, operation and processing of old vehicles.

Keywords: waste, recycling, waste recovery, recycling technologies, automobile industry, circular economy, lithium batteries, composite materials, sound and thermal insulation materials

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Introduction

Dear readers, waste management specialists and students,

This is another issue in the series of books prepared by the UNIVNET association - University and Industrial Research and Education Platform of the Recycling Society. The publication sums up the results of activities related to the assessment of state, waste generation forecasting and development of new technologies for material and energy recovery of the selected types of waste from the automotive industry in 2021.

The UNIVNET association was established upon an agreement between the Ministry of Education, Science, Research and Sport and the leader of the association – Slovak University of Technology in Bratislava (STU BA). In addition to STU BA, the association includes four other universities and the Automotive Industry Association of the Slovak Republic (ZAP SR).

The EU waste management policy focuses on the reduction of negative impacts of waste on the environment and human health and, at the same time, on the improvement of waste recovery efficiency in the form of secondary raw materials and energy. In order to switch over to circular economy it is necessary to implement changes in the entire value chain, from the product design up to new business and market models, including the new methods of waste conversion into resources, up to the change of consumer behaviour. This foresees a complete systemic change and innovation not only in the field of technologies, but also in organization, society, financing methods and formulation of policies.

The Slovak Republic is currently facing many environmental challenges. We have problems with air quality, low level of waste recycling and also with the protection of ecosystems. The basic vision defined in the Strategy of the Environmental Policy of the Slovak Republic through 2030 is to achieve better environmental quality and a sustainable circular economy.

The publication we present to you is divided into eight logically related chapters. Individual chapters are devoted to the analysis of waste quantities, processing capacities, forecasting of the waste change in relation to the launch of electromobility, waste preparation for reuse, design of technology for the recovery of laminated glass, recycling of metal-bearing waste from accumulators, waste from sound-proofing and thermal insulation, recycling of rubber, natural rubber and plastics, and finally the possibilities for energy recovery from waste.

I believe that this publication will provide you with the necessary information on the state and issues of waste management in the automotive industry and becomes an inspiration for those who deal with the minimization and recovery of waste generated in their production, operation, and processing of old vehicles.

Dr.h.c. prof. Ing. Ľubomír Šooš, PhD.
Editor

Analysis of the quantities and processing capacities of waste generated in the automotive industry

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1 Analysis of the quantities and processing capacities of waste generated in the automotive industry

1.1 Introduction

The Automotive Industry Association of the Slovak Republic (ZAP SR) is one of the partners of UNIVNET – University and Industrial Research and Education Platform of the Recycling Society, an association recognized by the Ministry of Education, Science, Research and Sport of the Slovak Republic, the Ministry of Economy of the Slovak Republic and the Deputy Prime Minister's Office for Investments and Informatization of the Slovak Republic as the national platform for the area of recycling and waste recovery with its application outputs in industry sectors. The study "Analysis of the quantities and processing capacities of waste generated in the automotive industry" **contributes to the execution of prognostic and research and development activities in the search for new technologies and methods for the maximum efficient recovery of waste, especially in the automotive industry**, with the aim to minimize negative impacts on the environment and save the primary resources of energy and raw materials. In the long term, ZAP SR perceives the deteriorating situation in the area of processing waste from industrial production and end-of-life vehicles and the issue of wastes is gradually becoming one of the pillars of competitiveness. The results of studies should assist in the search for solutions in cooperation with all competent and involved parties. ZAP SR is prepared for further cooperation and discussion about this issue, especially with the responsible officers of the Ministry of Economy, Ministry of Environment, Ministry of Education and professional organizations. Data from the study mapping the needs of industry and processing capacities of individual types of waste provide a more realistic perspective of the issue of waste processing from the automotive industry and represent an important source of information in the search for solutions and improvement of the waste management situation.

1.2 Main objectives of the study and methods

The main objective of the study was **to map the needs of industry** and **processing capacities** within waste management in Slovakia. An analysis of the waste quantity was carried out on the basis of waste reports for 2019 and 2020. Members of ZAP SR were addressed by letter. Groups of waste types were determined after examination of delivered waste reports and missing data were again requested from the manufacturers from the relevant groups of waste types. At the same time, an analysis – **mapping of processing capacities** – was performed. Mapping the needs of the automotive industry could be carried out with the use of data from the relevant ministry which receives annual Reports on waste generation and management.

Since the information contained in these reports is not further analyzed, there is no available study concerning the reported quantities and future projections. We have decided to proactively respond to this situation by requesting the necessary data directly from the **waste producers** – production companies in the automotive industry.

1.3 Needs of industry

The production facilities of ZAP SR members were officially asked by letter (e-mail) to provide data about the types and quantities of waste in the form of mandatory reports which they send to the Ministry of Environment of the Slovak Republic under the Act on Waste No. 79/2015 Coll. and the Decree of the Ministry of Environment of the Slovak Republic No. 366/2015 Coll. on the mandatory evidence and reporting obligations. Except forecasts when the producers provided us with a summary table in MS Excel format, we have gained data from the delivered forms in .doc or .pdf format – a form titled "**REPORT ON WASTE GENERATION AND MANAGEMENT**", Annex No. 2 to the Decree No. 366/2015 Coll.

During the performance of our study, the template of the form Report on waste generation and management which also includes other details about the method of its filling in, was available in the electronic collection of laws on the portal Slov-Lex, Annex No. 2, direct link to the form in .pdf format: https://www.slov-lex.sk/pravne-predpisy/prilohy/SK/ZZ/2015/366/20210101_5270640-2.pdf

The data analyzed in this study were drawn directly from the Reports from **waste producers**, manufacturing companies from automotive industry, which we have addressed. **A waste producer** is every original producer whose activity results in waste generation, or who carries out the modification, mixing, or other operations resulting in a change in the nature or composition of this waste. If the waste records are kept for every establishment, if it concerns a transferring station, storage of excavated soil or mobile collection, this item will be filled out in accordance with the item Establishment/plant, in the Waste registration sheet. If the waste records are kept for every waste generation site in compliance with the issued consent or only for every generation site, the report will be filled summarily for all generation sites in the relevant district and the item Establishment/plant will include the name of the relevant district; item Address (street, municipality, post code), need not be filled in.

In order to draw up the .xls table necessary to perform the analysis of data from the reports, we have focused on the following sections in the report forms.

- Waste code according to the Waste catalogue (column 2), waste code according to the current Waste catalogue.
- Waste name according to the Waste catalogue (column 3), waste name according to the Waste catalogue.
- Waste category (column 4), waste category according to Waste catalogue.
- Y-code (column 5), hazardous waste must be specified with a Y-code according to tables 1, 2 and 3. If it is possible to assign more codes, only the code of the most hazardous compound, in terms of human health and environment, will be assigned.
- Weight of waste (column 6); if it concerns the disposal of waste, the summary quantity of waste disposed of which has the same waste code, handling code,

and organization in the period for which the yearly report is submitted, that is, waste disposal in 2020.

Weight of waste with the **same waste code** was added up, even though in the form this waste was specified in two or more lines due to other handling code and organization, because we did not analyze the way this waste was handled.

1.3.1 Results of the first contact with producers

The delivered reports were processed in an .xls table, approximately 27 records from 2019, and 29 records from 2020, for a total of 56 records from the two years 2019 – 2020. The total number of waste types in the reports was approximately 189, out of which the category N – hazardous waste, 86, and O – other waste, 103. In order to get a representative sample of data about the quantities and types of waste, we decided to address specific companies, members of ZAP SR, and non-member production facilities. Figures from the most recent data are specified in the following section in tables and charts.

1.3.2 Identification of the groups of waste types and results of the second contact with producers

In order to get a representative sample of data about the quantities and types of waste, we decided to address specific companies, members of ZAP SR, and non-member production facilities.

Based on data gained about the waste types in the first phase we could determine the indicative groups of waste – these are not the groups according to the Waste catalogue published at ISOH's web page [1] (Katalóg odpadov, 2021).

a) Car plants
b) Rubber/metal
c) Smelter/casting
d) Pressing
e) Assembly of groups
f) Tools
g) Metalworking
h) Foams
ch) Plastics/press
i) Surface finishing
j) Glass
k) Light fittings
l) Textile
m) Forgings

The selection of sample, reference producers for the given group of producers based on the activity, and production portfolio was carried out after the analysis of data about the waste categories gained after the first contact with ZAP SR member plants.

The data currently acquired (we already have more recent data, they will be included in successive reports) include the quantities of waste from 23 plants Table 1.1
Values for the number of waste reports from the automotive industry
in the Slovak Republic in 2019/2020 (main plants including other plants and spin-off plants).

Table 1.1
Values for the number of waste reports from the automotive industry
in the Slovak Republic in 2019/2020

Values	
Number of Producers, spin-off plants, plants	41
Number of Company Registration Numbers	32
Number of ZAP SR members	26
Number of “Did not send report”	8
Number of Replies from the producers at main plants	23
Number of Replies from spin-off plants, and plants	11
Number of Reports for 2019	33
Number of Reports for 2020	34

The individual producers were contacted in **October 2021** by e-mail, and then **during November 2021** we made phone contact with those that did not send any reply or in cases where we needed additional information and specifications regarding the data submitted.

Furthermore, **the data within the group of producers** can be processed in such way, that, based on the total number of employees in the group (CPZS), the number of employees in the selected plant or plants in the given group (PZVP) of which we have data about the quantities of specific waste type according to the Waste catalogue ISOH (for example, the waste code according to Waste catalogue 070213 – waste plastic, category O – other waste), we will calculate the coefficient which we will then use to calculate the approximate quantity of waste of the same type for all plants in the given group, that is, producers involved in the same activity with a comparable production portfolio.

This is only a rough estimate of the quantity, should the relevant plant actually report this type of waste.

Seasonal waste
This usually concerns the same waste codes in both analyzed years of 2019 and 2020; individual plants specifically reported certain types of waste only in 2019 or in 2020. For example, in 2019 the company Schaeffler Skalica, spol. s.r.o. did not report any waste under code 110105 – acidic pickling solutions, and in 2020 it reported 0.640 tonnes. In 2019 it reported zero quantity of waste under code 150202 – absorbents, filter materials, and in 2020 it reported 413.700 tonnes.
In some cases, this could result from the submission of an incorrect, incomplete report or a poor scan of the original – when 1 or more pages are missing. For instance, in 2019 the company THORMA Výroba, k.s. Fiľakovo, in the LC district, reported 1 562 tonnes of waste in 2019 under the code 120121 – spent grinding tools, and in 2020 it did not specify this type of waste.

We can use the "**coefficient 1**" calculated by the division of the total number of employees in the group of plants (CPZS) by the number of employees in the selected plants (PZVP) from which we have data about the quantities of waste (for example, see Table 1.2
Calculation example of the coefficient 1 and 2 for 2019 for the group Lighting Fixtures for HELLA Slovakia and SLUŽBA NITRA) and use the resulting "coefficient 1" to calculate the quantities of waste in plants from which we have no data, but we know the number of their employees.

$$coefficient\ 1 = \frac{\text{CPZS}}{\text{PZVP}}$$

$$coefficient\ 2 = \frac{5495}{1986} = 2{,}767$$

We could also apply the "**coefficient 2** – ratio (average) of waste per employee" and the result might be more accurate (Table 1.2
Calculation example of the coefficient 1 and 2 for 2019 for the group Lighting Fixtures).

$$coefficient\ 2\ (average, ratio) = \frac{average\ A + average\ B}{\text{number of averages}}$$

$$coefficient\ 2 = \frac{3{,}50 + 1{,}28}{2} = 2{,}39$$

Calculation example for the group Lighting fixtures for 2019

Through this calculation and by the application of a coefficient we can estimate the total quantity of waste in all plants, including those from which we have no real data about the quantity of reported waste.

Table 1.2
Calculation example of the coefficient 1 and 2 for 2019 for the group Lighting Fixtures

Plant	Number of employees	Number of employees in the selected plants	Coefficient (total number of employees/ number of employees in reference plants)	Quantity of waste (t) 2019	Coefficient, ratio (average) of waste per employee
HELLA Slovakia Lighting s.r.o.	1 751	1 751		6142.000	3.50771
SLUŽBA NITRA, s.r.o.	235	235		302.000	1.285106
SEC spol. s r. o.	210			503.246	
ZKW	2 376			5 693.866	
CEMM THOME SK, spol. s.r.o.	923			2 211.885	
	5 495	**1 986**	**2.767**	**14 852.996**	2.396408

The application of the coefficient used for the calculation of the specified waste 070213 – waste plastic (mixed plastics) in 2019 shows the accuracy of coefficient 1 and 2.
Group: Lighting Fixtures
Year: 2019
Type of waste: 070213 – waste plastic (mixed plastics)

- an example of a calculation using a coefficient – a calculation using the coefficient calculated from the total number of employees in the group and the number of employees in the selected reference plants

12152 tonnes of waste = 4391.919 tonnes of waste (070213) reported from the two selected plants in 2019 x coefficient of 2.767

$$4391{,}919 \text{ tonnes} \,.\; 2{,}767 = \mathbf{12.152} \text{ tonnes of waste}$$

- an example of calculation using a coefficient – calculation using the coefficient calculated from the average quantity of waste per employee (Quantity of waste (t) 2019/Number of employees in the plant)

10 496 tonnes of waste = 4391.919 tonnes of waste (070213) reported from the two selected plants in 2019 x coefficient of 2.39

$$4391{,}919 \text{ tonnes} \,.\; 2{,}39 = \mathbf{10.496} \text{ tonnes of waste}$$

The difference is **1656** tonnes of waste of the given type which represents approximately 13% inaccuracy.

Waste code according to the waste catalogue	Vehicle producers	Rubber, metal	Smelters, casting	Pressing	Diverse groups	Tools	Metalworking	Foam	Plastics, pressing	Surface treatments	Glass	Lights	Textile	Forgings	Recalculation using the 2019/2021 coefficient for all groups together
Total	117 661.20	40 220.78	1 301 330.62	771 863.73	245 924.13	0.02	228 496.71	240.66	3 515 974.66	22 547.06	0.00	31 267.78	3 568.51	35 240.54	6 314 336.41
150101	30 614.01	2 018.89	3 770.80	7 375.07	74 276.01	0.00	4 872.29	111.47	963 703.15	157.08	0.00	1 285.91	1 690.04	2.91	1 089 877.63
070213	223.89	3 947.47	13.96	10 730.41	49 593.60	0.00	99.92	0.00	810 123.20	0.00	0.00	20 643.72	0.00	0.00	895 376.16
150202	3 204.57	423.99	798 929.17	2 169.64	1 787.48	0.00	1 450.65	0.00	9 139.04	59.80	0.00	87.46	10.09	51.41	817 313.30
150106	3 144.01	0.00	6 728.07	8 431.61	14 699.93	0.00	759.21	0.00	592 703.39	0.26	0.00	1 869.90	0.00	22.39	628 358.78
120102	0.00	0.00	371.55	443 649.66	0.00	0.00	134 634.23	0.00	7 076.88	6 824.53	0.00	403.34	0.00	660.13	593 620.33
150102	433.20	739.17	1 124.96	1 404.83	10 866.64	0.00	1 303.38	0.23	258 926.88	87.99	0.00	2 420.57	229.96	1.97	277 539.78
150103	8 529.04	1 389.59	1 410.63	10 435.26	15 380.85	0.00	4 217.52	0.00	201 285.10	95.94	0.00	1 151.24	171.77	391.64	244 458.57
191001	0.00	1 397.54	0.00	3 526.69	0.00	0.00	18.74	0.04	213 437.61	0.00	0.00	0.00	0.00	0.00	218 380.61
190805	15.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	203 025.31	0.00	0.00	198.11	0.00	0.00	203 238.74
190809	324.24	83.60	0.00	303.10	186.69	0.00	120.24	0.00	192 874.05	0.00	0.00	36.36	36.48	0.00	193 964.77
100910	0.00	0.00	173 042.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	173 042.42
191202	0.00	0.00	0.00	168 730.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	168 730.24
100903	0.00	0.00	130 939.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	130 939.47
120101	2 795.05	1 039.21	0.00	9 775.22	14 775.98	0.00	34 711.02	0.00	0.00	121.10	0.00	0.00	0.00	11 426.58	74 644.15
130502	195.13	0.00	71 616.75	159.14	59.95	0.00	249.17	0.00	0.00	94.25	0.00	0.00	17.10	0.00	72 391.50
100908	0.00	0.00	57 414.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	57 414.93
170405	634.63	0.00	1 773.38	308.74	2 935.42	0.00	404.38	0.00	14 342.29	235.34	0.00	45.61	0.00	17 747.88	38 427.66
191203	0.00	0.00	0.00	37 523.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	37 523.12
150104	119.63	0.00	0.00	0.00	32 758.56	0.00	353.77	0.00	261.03	0.00	0.00	0.00	23.14	0.00	33 516.13
120104	18.66	0.00	35.75	30 246.61	0.00	0.00	2 013.27	0.00	0.00	0.00	0.00	392.83	0.00	0.00	32 707.11
120114	0.00	0.00	0.00	2 917.98	0.00	0.00	20 895.48	0.00	0.00	0.04	0.00	0.00	0.00	184.54	23 998.04
120301	4 382.23	0.00	0.00	16 470.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	20 852.75
130507	1 247.98	0.00	0.00	0.00	15.90	0.00	0.00	0.00	14 893.36	0.00	0.00	0.00	0.00	4 035.53	20 192.77
130802	742.57	0.00	0.00	6.25	0.00	0.00	11 567.61	0.00	5 916.74	0.00	0.00	31.41	0.00	0.00	18 264.58
100906	0.00	0.00	15 175.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15 175.52
150110	5 360.61	1 249.94	1 446.27	619.90	1 051.03	0.00	529.81	0.00	4 527.46	210.15	0.00	37.66	0.48	11.21	15 044.53
110502	0.00	0.00	14 713.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14 713.90
191204	26.62	11 384.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11 411.31
160305	0.00	3 868.29	1 352.66	0.00	307.79	0.00	0.00	0.00	5 800.72	0.00	0.00	0.00	0.00	0.00	11 329.46
161001	50.65	8 328.07	0.00	197.07	1 918.17	0.00	0.00	0.00	0.00	0.00	0.00	0.44	0.00	1.52	10 495.93

Fig. 1.1 Example of a calculation table in MS Excel format

The reports contain about 166 types of waste (the column Waste code according to the Waste catalogue), for example for the waste no. 150101 – paper and cardboard packaging (packaging, paperboard) there is a total of 1 085 300 tonnes of waste in all 14 groups of waste; plants in the group Plastics/press reported the majority of this waste type (963 703 t); in case of zero values we do not have the reports of the selected groups yet or this type of waste is not reported by plants in the given group, or they report zero values.

Note: 166 plus about 15 types of waste were reported from the plants in the automotive industry which we did not include in the selected group, but the selected plants did not include these types in their reports.

The main recommendation is to determine the possible use of the data obtained for the calculation of estimates and forecasting the quantities of waste, or the necessary processing capacities within the cooperation of partners in the UNIVNET association and EUBA. We currently do not have information about the real summary quantities of individual waste types in the given period and cannot provide realistic estimates of the need for processing capacities in Slovakia. The lack of an effective system of collection and automated evaluation of data about waste cannot be substituted by temporary initiatives implemented by associations such as UNIVNET or individual industry representatives, such as ZAP SR. Data acquired from the producers and processors could be assessed further by experts from EUBA, they could propose further use for them, determine possible calculations or formulae, in order to get the data which we can then use to prepare a draft strategy in this field as soon as possible.

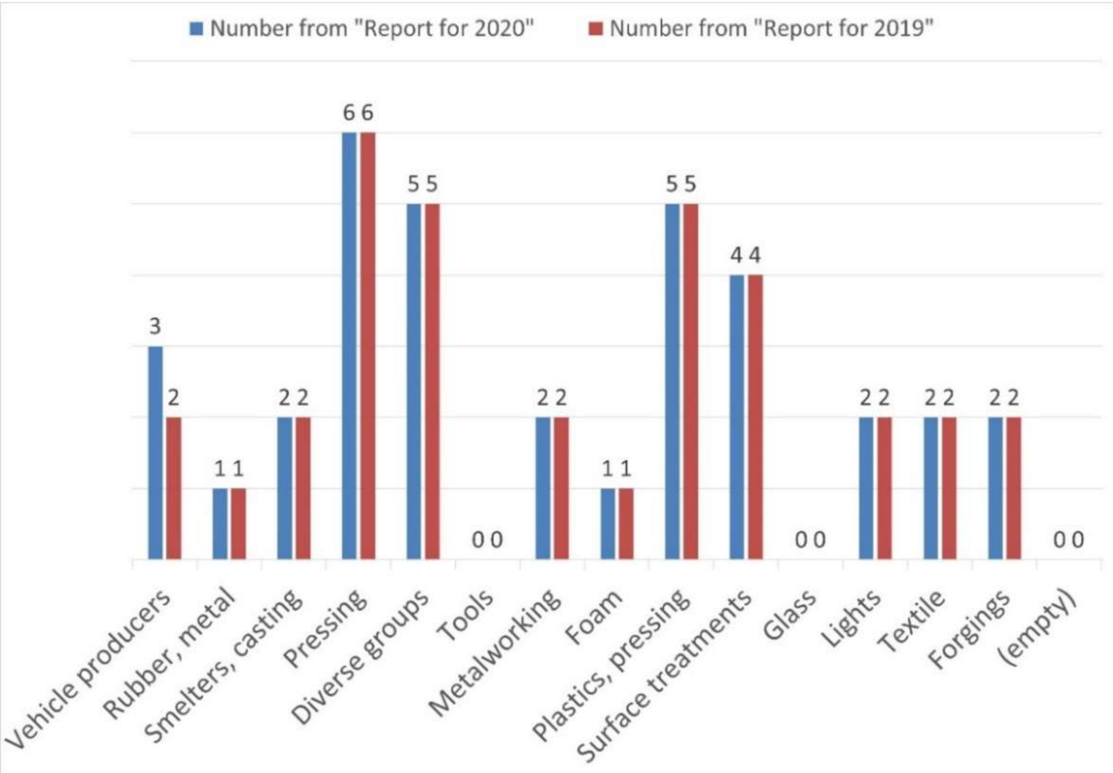

Fig. 1.2 Number of reports from the given groupings in the relevant year 2019/2020

We have gathered reports from one to six plants, Fig. 1.2 Number of reports from the given groupings in the relevant year 2019/2020. In some groups we are still searching for data – waiting for the reply form from the selected plant which had been contacted in writing as well as by phone. The majority of data is from the six selected plants in the grouping, Pressing.

The quantity of waste from the automotive industry in all categories derived from data provided by the selected companies in 2019 amounted to 120 235.174 tonnes and in 2020 it was a total of 157 220.949 tonnes, see Fig. 1.3 Report on waste generation and management, column 6, weight of waste in tonnes.

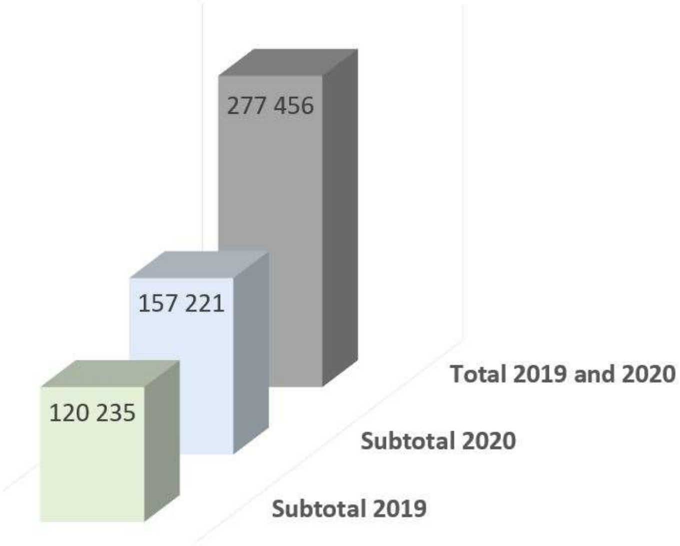

Fig. 1.3 Report on waste generation and management, column 6, weight of waste in tonnes

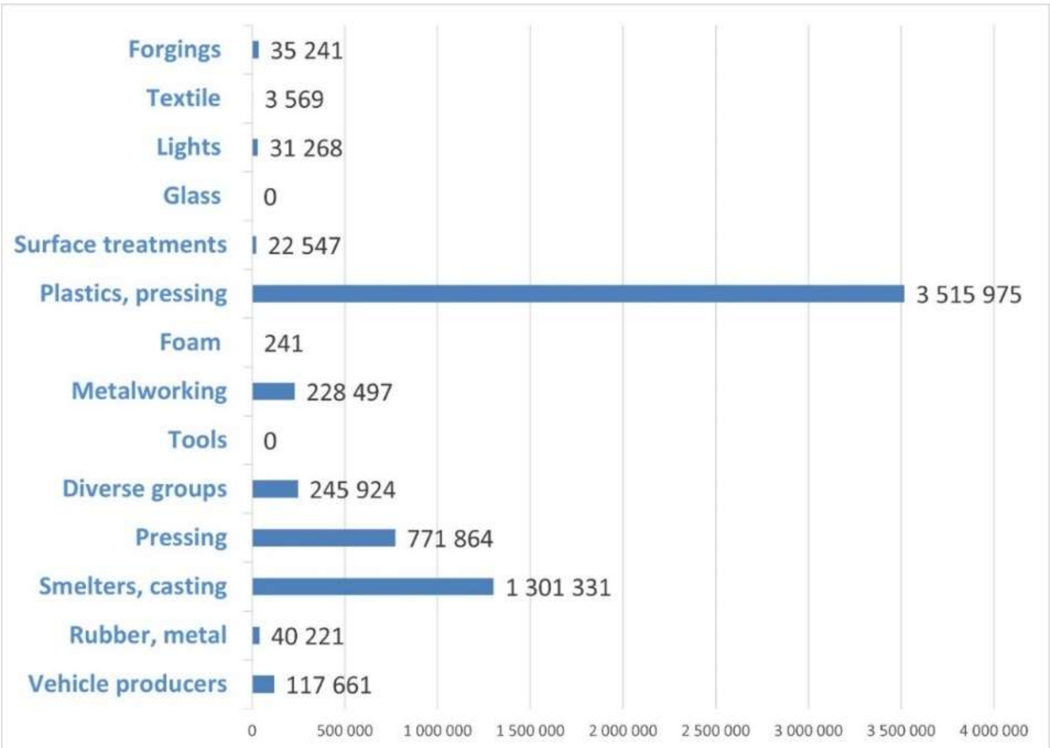

Fig. 1.4 Calculation of the total quantity of waste for individual groups of waste with the use of the coefficient together for the years 2019/2020

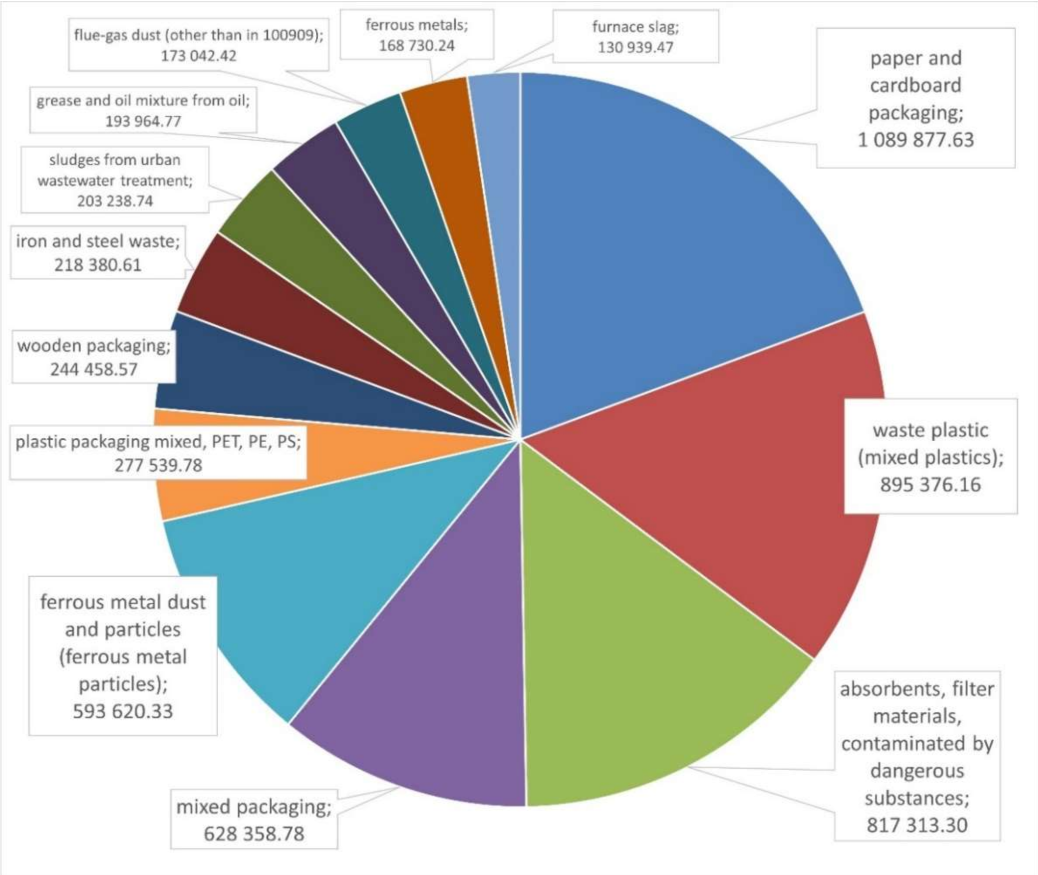

Fig. 1.5 Selection of waste types by the greatest number in tonnes

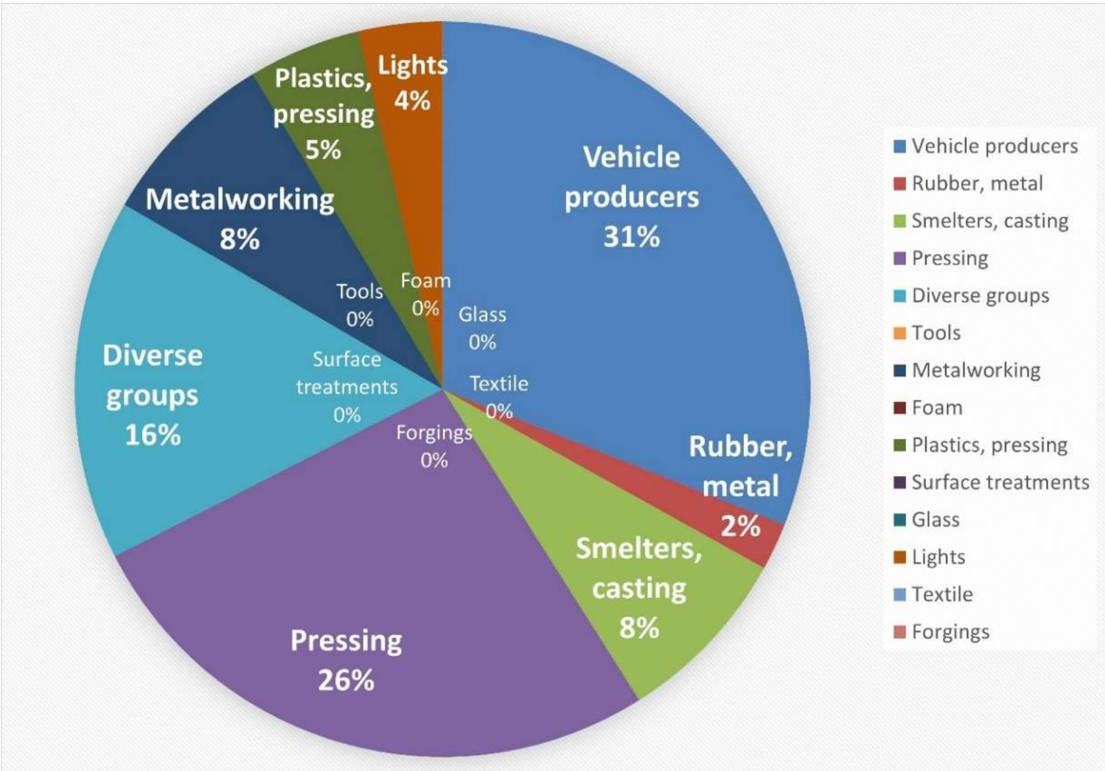

Fig. 1.6 Quantities of waste according to groups in % in 2019/2020

Table 1.3
Selection of waste types by the greatest number in tonnes

Selection of waste types according to the reported quantity of waste and quantity calculated with the use of coefficient 1 by the greatest number in tonnes together for all groups in 2019/2020	**Quantity in tonnes**
paper and cardboard packaging (packaging, paperboard)	1 085 300
waste plastic (mixed plastics)	895 376.2
absorbents, filter materials, including oil filters, wiping cloths, clothing contaminated by dangerous substances	816 095.4
mixed packaging	627 972
ferrous metal dust and particles (ferrous metal particles)	503 678.2
plastic packaging (under this number the companies report various waste plastic – mixed, PET, PE, PS polystyrene)	276 366.6
wooden packaging	240 103
iron and steel waste	218 380.6
sludges from urban wastewater treatment	203 238.7
grease and oil mixture from oil/water separation containing only edible oil and fats	193 959.6
flue-gas dust other than those mentioned in 100909	173 042.4
Ferrous metals	168 730.2
furnace slag	130 939.5

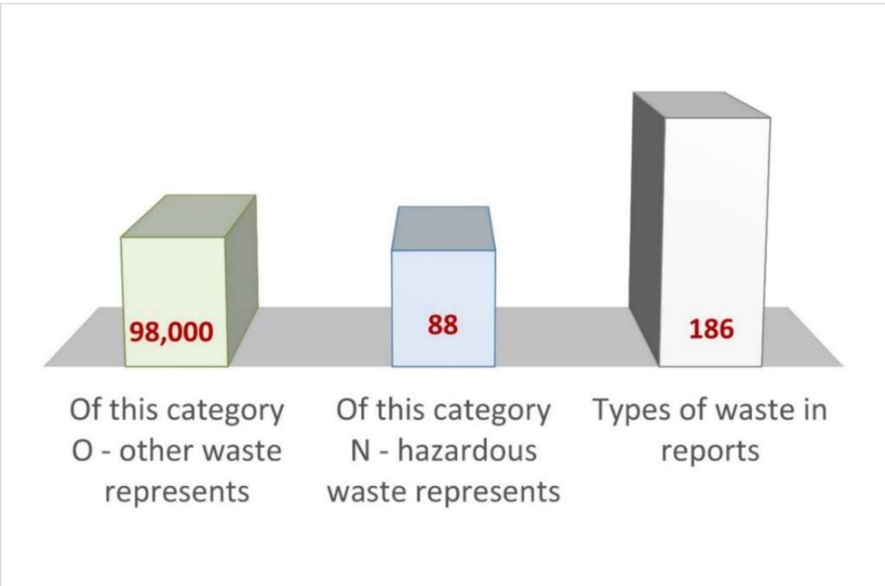

Fig. 1.7 Number of waste categories reported by the selected producers in the automotive industry in the Slovak Republic for years 2019/2020, in the study of ZAP SR 2021

It is also necessary to examine which specific types of waste are reported by the producers in the form for waste generation reporting under the given codes. We do not know whether there is a manual for the Waste catalogue specifying what falls under which code. For example, under the code no. – the official name from the Catalogue (its designation used by producers in the form is specified in brackets), N – hazardous waste, and Y-code, different companies specify different codes. These are in tables 8, 9, 12, 13.

150110	packaging containing residues of, or contaminated by dangerous substances (Packaging with the residues of dangerous substances)	N	8, 9, 12, 13

The reports included a total of 181 different types of waste, out of which 97 belonged to the category O – other waste and 84 to the category N – hazardous waste (graphically represented in Fig. 1.7 Number of waste categories reported by the selected producers in the automotive industry in the Slovak Republic for years 2019/2020, in the study of ZAP SR 2021).

1.4 Processing capacities

1.4.1 Data analysis from the form Report on the processing of old vehicles

We have gained all data for 2020 from 47 processors (businesses/plants). The sum of processed old vehicles for all generation sites, establishment/plant in the same or different district of SR is 51 955, a total of around 53 636 tonnes (Fig. 1.8).

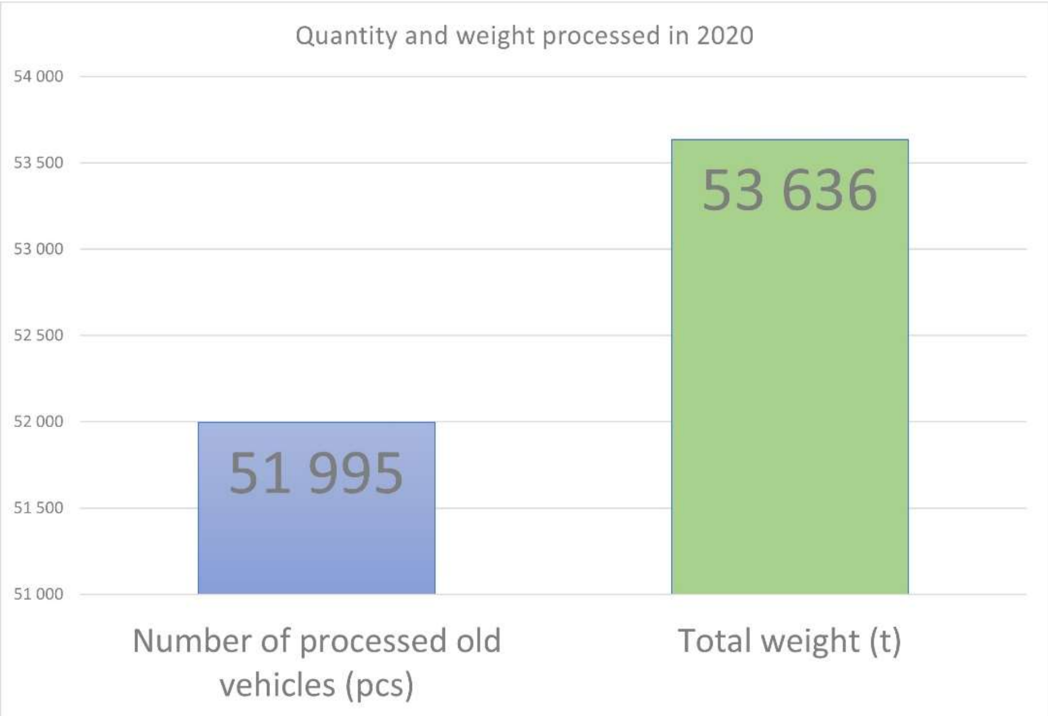

Fig. 1.8 The number of processed old vehicles and total weight in 2020

We have data from 47 businesses/plants, the number of processed vehicles is, on average, around 1106 pcs/plant, the total weight of processed old vehicles is on average about 1 141.182 tonnes/plant.

From Table 1 Total recovery (D1=B1+C1)
Batteries
Fluids (except for fuels)
Oil filters
Other materials from purification (except for fuels)
Catalytic converters
Metal parts
Tires
Large plastic parts
Glass
Other materials from disassembly

From Table 2 Total recovery (D2=B2+C2)
Scrap metal (steel)
Non-ferrous materials (aluminum, zinc, lead, etc.)
Light fraction from shredding (1) to be filled in only for crushing plants
Other

From the form Report on the processing of old vehicles, **Table 1**: Materials (in tonnes per year) obtained from **drainage** of old vehicles (removal of contaminants) and **disassembly** of old vehicles recovered in the same member state; we have added up data from the column Total recovery (D1=B1+C1) for individual Materials from **drainage** of old vehicles and disassembly.
From the form Report on the processing of old vehicles, **Table 2**: Materials (in tonnes per year) obtained from **crushing** of old vehicles and disassembly of old vehicles recovered in the same member state; we have added up data from the column Total recovery (D2=B2+C2) for individual Materials from **crushing** of old vehicles and disassembly.
Data listed in the following charts were derived from the form Report on the processing of old vehicles, **Table 4**: The total re-use of parts of old vehicles, recovery of waste from the processing of old vehicles and recycling (in tonnes per year), recovered in the same member state, D2 + D2 + F2 (Total recovery of the exported parts of old vehicles).

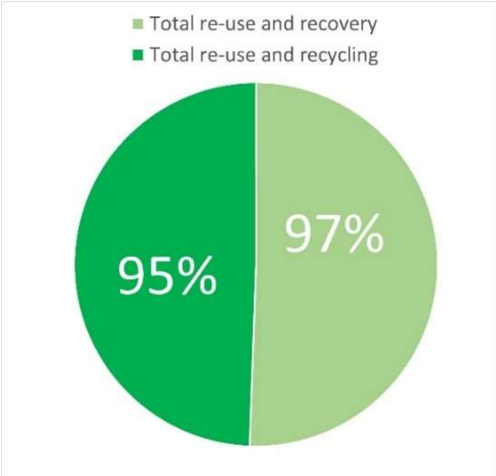

Fig. 1.9 Total reuse, recovery and recycling, 2020

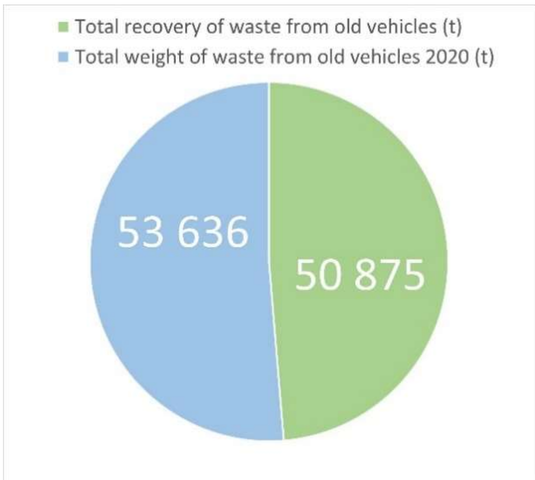

Fig. 1.10 Total recovery and weight of waste, 2020

The total re-use and recovery in 2020 represented approx. 97%, and the total re-use and recycling was 95% from the total quantity of waste specified in the reports (Fig. 1.9). According to data from the reports, the total recovery in proportion to the total weight of waste from old vehicles per 2020 was 50 875 tonnes from 53 636 tonnes of waste.

1.5 Conclusions and recommendations

The study "**Analysis of the quantities and processing capacities of waste generated in the automotive industry**" was carried out following the analytical study titled "Analysis of the recycling process of old vehicles and the state of processing and recovery of waste from old vehicles" (2019/2020), which formed the initial database necessary to carry out the tasks within the UNIVNET association. Analysis of the quantity of waste was carried out **on the basis of waste reports submitted in 2019 and 2020** from the selected producers in the automotive industry. We currently do not have information about the real summary quantities of individual waste types in the given period and cannot provide a realistic estimate of the need for processing capacities in Slovakia. The lack of an effective system of collection and automated evaluation of data about waste cannot be substituted by temporary initiatives implemented by associations such as UNIVNET or individual industry representatives, such as the Automotive Industry Association of the Slovak Republic (ZAP SR). We have successfully obtained **accurate information from the reports on the processing of old vehicles in 2020**.

The main recommendation is to determine the possible use of the data obtained for the calculation of estimates and forecasting the quantities of waste, or the necessary processing capacities within the cooperation of partners in the UNIVNET association and EUBA.

The current system of collection of information about waste and its processing for the purpose of assessment of the state and planning of processing capacities in the Slovak Republic is insufficient. We currently do not have information about the real summary quantities of individual waste types in the given period and cannot provide a realistic estimate of the need for processing capacities in Slovakia. The lack of an effective system of collection and automated evaluation of data about waste cannot be substituted by temporary initiatives implemented by associations such as UNIVNET or individual industry representatives, such as ZAP SR. Data acquired from the producers and processors could be further evaluated by experts from EUBA; they could propose their further use, determine possible calculations or formulae, in order to obtain the data which we can then use to prepare the draft strategy in this field as soon as possible.

The study "**Analysis of the quantities and processing capacities of waste generated in the automotive industry**" was carried out following the analytical study titled "**Analysis of the recycling process of old vehicles and the state of processing and recovery of waste from old vehicles**" which formed the initial database necessary to carry out the tasks within the UNIVNET association. This initial study was executed in two stages. **Stage No. 1** Analysis of the composition of material and its subsequent utilization – recycling or disposal. The material processed within the first stage includes data on the environmental and social benefits of recycling old vehicles, the expected numbers of phased-out vehicles per year that are intended for processing, the material composition of individual parts and their quantity, the plants necessary for processing or disposing of waste, the logistics of collecting and transporting materials for further processing, and a proposal to create an information system for monitoring the waste stream arising from old vehicles. **Stage No. 2** the period from August to November 2020 consisted of data collection from **37 processors of old vehicles** authorized by the Ministry of Environment of the Slovak Republic. The **analysis of the current state of processing and recovery of waste from old vehicles** was drawn up on the basis of data on the actual yearly capacities of every old vehicle processor, the level of processing/recovery of waste, the waste stream of hazardous substances and materials (consumers), and the waste stream of other materials (consumers). We collected data on materials intended for dumping, materials that currently cannot be recovered in an ecological manner and on the economic efficiency of old vehicle processing, and the conditions for achieving it. Within the second stage we further examined the state of cooperation between processors with the Producer Responsibility Organizations (OZV). The remarks and proposals of the processors with regard to the relevant legislation were also collected.

The Automotive Industry Association of the Slovak Republic (ZAP SR) is one of the partners of the UNIVNET association, which was recognized by the Ministry of Education, Science, Research and Sport of the Slovak Republic, the Ministry of Economy of the Slovak Republic and the Deputy Prime Minister's Office for Investments and Informatization of the Slovak Republic as the national platform for the area of recycling and waste recovery with its application outputs in industry sectors. The study contributes to the execution of prognostic and research and development activities in the search of new technologies and methods for the maximum efficient recovery of waste, especially in the automotive industry, with the aim to minimize negative impacts on the environment and save the primary resources of energy and raw materials.

Acknowledgements

This paper was drawn up within the project of the University and Industrial Research and Education Platform of the Recycling Society – UNIVNET, No. 0201/0004/20. The authors would like to acknowledge the support of the Ministry of Education, Science, Research and Sport of the Slovak Republic.

1.6 Bibliography

[1] ISOH. (2021). Dostupné na Internete: Register autorizovaných spracovateľov: https://www.isoh.gov.sk/uvod/registre/register-spracovatelov.html

[2] Katalóg odpadov. (2021). Dostupné na Internete: ISOH: https://www.isoh.gov.sk/uvod/registre/ciselnik_katalog_odpadu.html

[3] BADIDA, M. – ŠOOŠ, Ľ. et al.: Analysis of the state, forecasts and new technologies of waste recovery in the automotive industry. - Lüdenscheid (Nemecko): RAM-Verlag pp. 190, [print]. ISBN 978-3-96595-008-5.

Electromobility, circular economy, structural effects of automotive on the economy of the Slovak Republic, science, research and their barriers in the automotive value chain

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2 Trends of structural effects of electromobility on the economy of the Slovak Republic and the potential of waste for the circular economy

2.1 Introduction

The intention to gradually transfer the structure of the car “fleet” in Europe towards the use of electric vehicles is one of the biggest technological challenges for the operators involved in the entire life cycle of cars (LCC). A time-lag in bringing about **electromobility** will affect the entire LCC in the Slovak Republic (hereinafter SR): from production, operation, up to processing of end-of-life vehicles (ELV). Under the influence of the growth of scarce raw materials and their prices, but especially for the purpose of emission reduction in the entire LCC and under the influence of EU regulation, it is generally expected that electrically powered vehicles will become a dominant type of so-called light vehicles by 2050. If we strip out the emissions related to power production in the use of such cars, electric cars, as compared to vehicles with petrol, diesel or hybrid drive, will have a significant impact on the reduction of the total volume of greenhouse gases.

Future production of these vehicles represents a big challenge, especially in terms of **technology, ecology, raw materials and economy**. It will have significant effect on the innovations in the entire LCC. The transition to electromobility, as well as other changes towards the new material structure of cars, will fundamentally change the supplies of components. In professional circles, it is generally expected that the number of components will fall by approximately one third and they also expect changes in the structure of suppliers and the overall structure of economies. This is especially true in relation to the intensification of supplies for the producers of electronic components and batteries.

Electromobility will “strengthen” the area of science, research and innovations especially in the two above-mentioned fields. It will gradually eliminate the consumption of fossil fuels and petroleum products and be the incentive in the development of new “fuel” infrastructure and energy consumption growth. It will also be the source of a new structure of waste generated during the use of vehicles and also in the phase of processing of end-of-life vehicles (ELV). Electromobility will bring new impulses for all phases of LCC. Early adaptation will be the prerequisite for the involvement in the creation of added value within the global and changing value chains.

Europe and its individual countries in 2020 recorded a **boom in the demand for electric cars** – battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV). The Nordic countries, followed by Luxembourg and Germany, lead the ranking of “fleet” penetration by electric cars. The share of registration of these vehicles in the SR compared to Europe is negligible.

SR lags behind Europe even in the current volume structure of cars in SR. This is caused especially by the growing importation of second-hand cars (earlier years of manufacture) which appeared during pandemic. Without the acceleration of action steps towards the increase of the share of BEV (Battery Electric Vehicle) – pure electric vehicle, and PHEV (Parallel Hybrid Electric Vehicle), fulfilling European obligations for the future will be endangered, and thus there will be insufficient reduction of the carbon footprint from the use of cars registered in the SR. At the same time, such composition will become the source for the processing of secondary raw materials, as well as for the generation of such waste during operation that will, for several years, copy the current structure of waste as well as the existing technologies for their processing in the SR or in Europe.

Despite the pandemic, in 2021, Slovakia maintained its leadership position with regard to the **number of produced cars per capita** (Press release of ZAP: Alexander Matušek, Chairman of ZAP SR: Slovakia lags behind in the country's green transformation. How to fulfil the EU's commitments? Bratislava, 13.1.2022). **The share of electric car production in the SR gradually increases.** Based on publicly available data, the share of electric and plug-in hybrid vehicles represented almost quarter of the production (23%) of Volkswagen Slovakia. The percentage of electrified car production of Stellantis Slovakia was 10% in 2020, and 13.5% in 2021. Production of petrol engines also prevailed in the production of Kia Slovakia in the previous year (eight out of ten engines were petrol aggregates).

In the following text we will be focusing on the major trends influencing the production inputs, material composition of cars and waste, changes and trends of impacts of the technological changes in the production of cars in the SR on the structure of SR economy and on science and research as a source of innovation potential of subcontractors in the automotive industry in the SR – the chapter presents the main findings of the study by Ochotnický, P. et al. (2021).

2.2 Specific features of circular economy in the automotive industry, main factors and consequences of technological changes for the economy of the SR

The new frameworks for the circular economy in automotive in the coming years will be influenced especially by two relevant factors:

- **political commitments within EU and national legislation (such as Fit for 55) with the emphasis on strengthening of the circular economy in the automotive industry,**
- **emphasis on the introduction of environment-friendly alternative propulsion technologies in car production.**

The importance of policies in the field of circular economy grows especially for environmental and ecological reasons, but currently even due to the disruptions in the global supply chains and the resulting growth of consumption and prices of energy inputs. The traditional model of linear economy is unsustainable in the long-term as it is based on a chain that is not closed. It is based on permanent extraction of resources from the environment that are then transported for further processing and subjected to treatment.

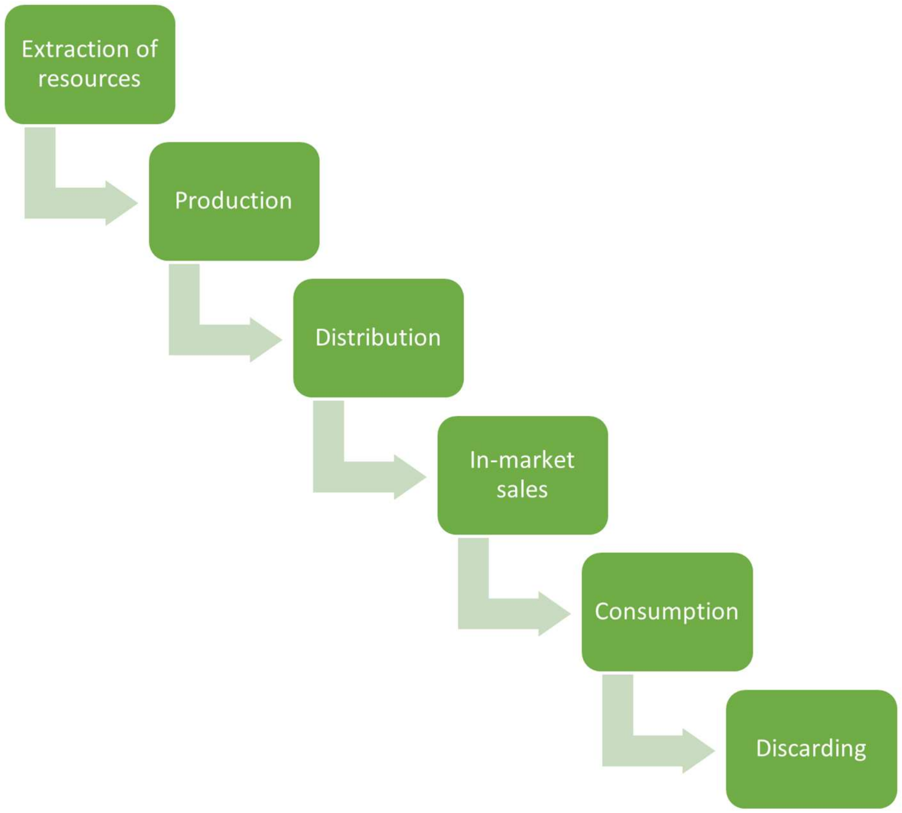


Fig. 2.1 Schematic of the linear economy
Source: self-elaboration according to the European Commission.

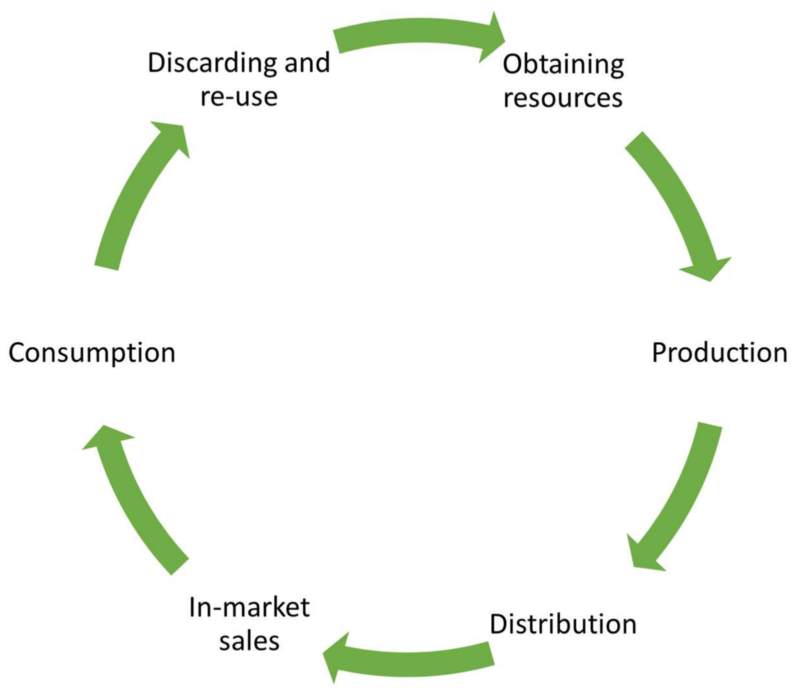


Fig. 2.2 Schematic of the circular economy
Source: self-elaboration according to the European Commission.

2.3 Circular economy in the automotive industry

The standard circular economy is based on the connection of the initial and final phase of linear economy into a circle, in which the waste from a product again becomes a resource. The standard model of circular economy saves the primary resources and in many cases it even saves energy compared to the production from primary resources (European Commission, 2020).

In comparison with the other sectors, the automotive industry has several specific features which use the specific processing technologies to return the waste from cars back to production.

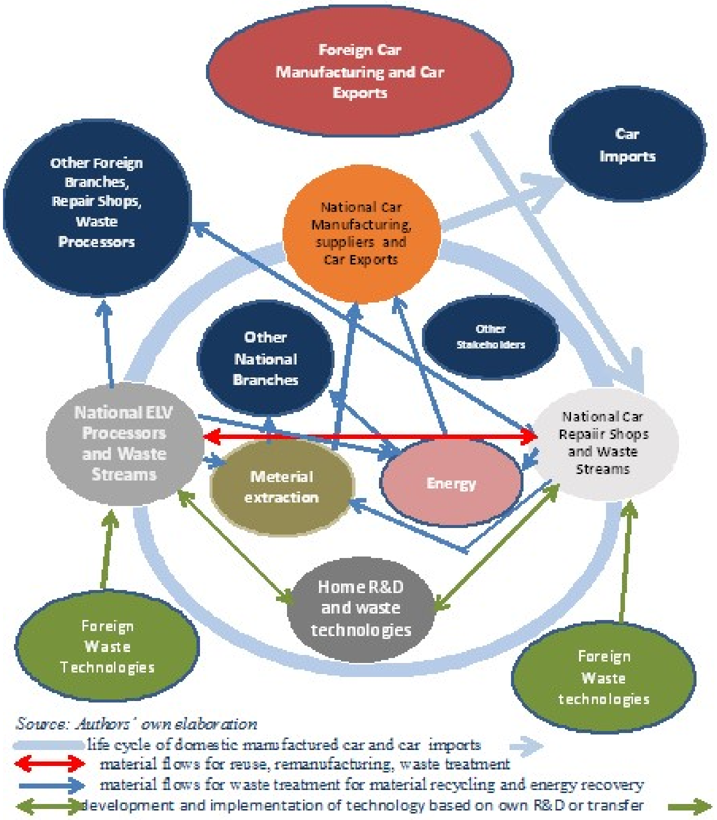


Fig. 2.3 Specific features of the circular economy model in the automotive industry

Car life cycle and the automotive circular economy has next concrete main specificities compared to other products or sectors: (a) car manufacturers are multinational corporations whose exports of components and imports of components exceed the borders and needs of cars in the EU countries where vehicles are manufactured, (b) cars today consist of approx. 30 000 or 20 000 components (for electric cars), which are differed through complex global tier 1 - tier 3 supply relationships and through complex globalized value chains, (c) intermediates, secondary raw materials and energy from treated waste and used cars have only a small potential to be a re-entry for car manufacturers themselves. Rather, they go anonymously to other sectors of the economy, as well as to exports.

This all makes it difficult to statistically and exactly evaluate the circularity impacts in the automotive industry on the national economy level. Whether volumes of re-extracted materials or energy from waste directly for car manufacturers.

Moreover, the waste from automotive industry, in the entire life cycle starting from the use of vehicles up to the end-of-life phase (ELV), are significantly different in nature, in comparison with the municipal waste, for example. Cars are characterized by a higher rate of re-usability or particularly high rate of technical recyclability of many of its components and materials. The objectives in terms of waste from discarded vehicles are therefore more ambitious and easier to meet as compared to municipal waste.

2.4 Electromobility challenges for Europe and SR

The EU automotive industry, as one of the accelerators of green Europe, and especially the Slovak Republic as the largest car manufacturer per capita in the world, has joined the basic document "Green Deal" – the European Commission's declaration on carbon neutrality and the "FIT FOR 55" action plan. The Action Plan contains 14 documents and commitments for member countries. They are aimed at reducing emissions from transport, building infrastructure for alternative fuels, reducing emissions from transport through renewable energy sources and fuels, a new structure of minimum tax rates based on the actual energy content and environmental properties of fuels and electricity. Also, one of the challenges of "EU new circular action plan" "aims to ensure that waste is prevented, and the resources used are kept in the EU economy for as long as possible".

For the European economy and especially for the economy of the SR as the car production leader, the automotive industry is extremely important and for this reason it is also necessary to improve its material balance in relation to the environment. According to the European Automobile Manufacturers' Association in 2020 the automotive industry in Europe accounted for the production of 17.6% of all passenger cars in the world. In 2018 it directly employed 2.6 million people and together with the associated sectors it had 12.6 million employees.

The average greenhouse gas emissions from the operation of new vehicles in 2020 reached 108.2 g CO_2 per km. The composition of vehicles in the SR is one of the most demanding in terms of emissions due to the lower purchasing power and high average age of cars. The widespread practice in the purchase of larger SUV models causes that even in the case of new registrations the levels of emissions from vehicles in the SR exceed the European average and represent one of the highest levels amounting to 121.8 g of CO_2 per km (European Automobile Manufacturers' Association, 2021).

According to the intentions of the EU countries, the material, technological and environmental aspects of the automotive industry will be significantly affected, especially by the diversion from vehicles propelled by fossil fuel combustion engine to electric cars, in particular. As a consequence of this trend, the material composition of the cars produced will change naturally and there will be a fall in the demand for components for combustion engines and related parts of the propulsion technology. The demand for battery cells or electric engines and their components will grow significantly. It is generally expected that the penetration of electromobility will reduce the number of components in passenger cars by about 1/3 and that it will give new impetus for the development of innovations and technologies within the entire LCC.

All of this has already had, and will have even larger impact on the changes in the European sectoral structure, changes in the supplies-customer relationships, but also on the operation of vehicles and structure of waste from the processing of ELV. Since the combustion engine will be replaced by other propulsion units, there will be a drop in the demand for supporting systems or products, such as air filters, sparking plugs, ignition coils, cam belts, oil filters or engine oil, alternator, and starter. The majority of electric vehicles will have one or only a few gears. The intake systems will also change, or the conventional exhaust loses its meaning.

On the contrary, electric cars require other components. For example, a set of batteries that will serve for driving, operation of heating and cooling and for the operation of all other lights and accessories. Furthermore, a power converter will be applied when the vehicle uses regenerative breaking, which converts the alternating current generated by electric engines to direct current. However, the main component is the electric motor as an alternative drive unit of the vehicle. The on-board battery charger and the system of battery management manage the flow of current to and from the battery. The charging port is another component which replaces the port for the conventional tank in a car with combustion engine.

The production of battery cells and electronics significantly increases demands on the consumption of rare earth or selected metal elements, as well as the demand for electricity during the operation of cars. Therefore, this will also change the structure of waste from the discarded vehicles at the end of the life cycle. Today it is debatable to state that the so-called “dirty” resources for the production of energy for car operation may eliminate or discriminate against the development of electromobility in terms of the total CO_2 emissions. This is due to the downturn of coal-fired power plants, increasing share of renewable resources in some countries. On the other hand, the current energy crisis represents an impetus for strengthening nuclear energy. However, in relation to the growth of prices and demand for energy, there are mainly ecological concerns and risks of the consequences of the remining of coal, and waterborne and road transport of liquified gas and oil.

There are several potential ways for the reduction of CO_2 emissions in the automotive industry. The most significant trends in the production are things such as electrified vehicles, lightweight structures, or “fleet” limits for the producers (Wellbrock, et al., 2020). The automotive industry is highly globalized, capital intensive, characterized by vertical integration and economies of scale (Schulze, et al., 2015). Behind the effort of the entire sector to direct its production program towards sustainability lies the economic consideration of return on investment. Since the sustainable solutions require investments into research and development, the investor has legitimate expectations in terms of the return on such investment.

With regard to the rapid, and to a certain extent even the forced start of electromobility, there are still some outstanding issues regarding the structure of supply chains, material consumption or the management of waste after vehicles are discarded (Casper & Sundin, 2020). Recycling capacities which are currently almost non-existent will be under a sharp onslaught at a time when the cars bought in years of rapid growth start to get discarded (Skeete, et al., 2020). The current high rate of technical recyclability and re-use of batteries (Pagliaro & Meneguzzo, 2019) will enable the significant reduction in the environmental risks in areas such as water pollution, pollution of soil, or depletion of natural resources (Cusenza, et al., 2019).

The study assessing the impacts of the increasing use of plug-in hybrids in the United States of America came to the conclusion that significant savings of fuels generate a total net social benefit, but also that the adoption of this technological change supports the economy at a macro level. Depending on the level of ambition of the scenario, prioritization of PHEV may bring a net annual social benefit in the range of USD 4.7 – 9.3 billion per year by 2035. Even more ambitious scenarios quantify the positive impacts in the amount of USD 26.5 – 34.2 billion per year. The aggressive scenario estimates the yearly increase in employment in the period 2015 – 2040 at the level of 52 thousand jobs, while in the same period the GDP is expected to grow, in average, by USD 6.6 billion (National Renewable Energy Laboratory, 2016).

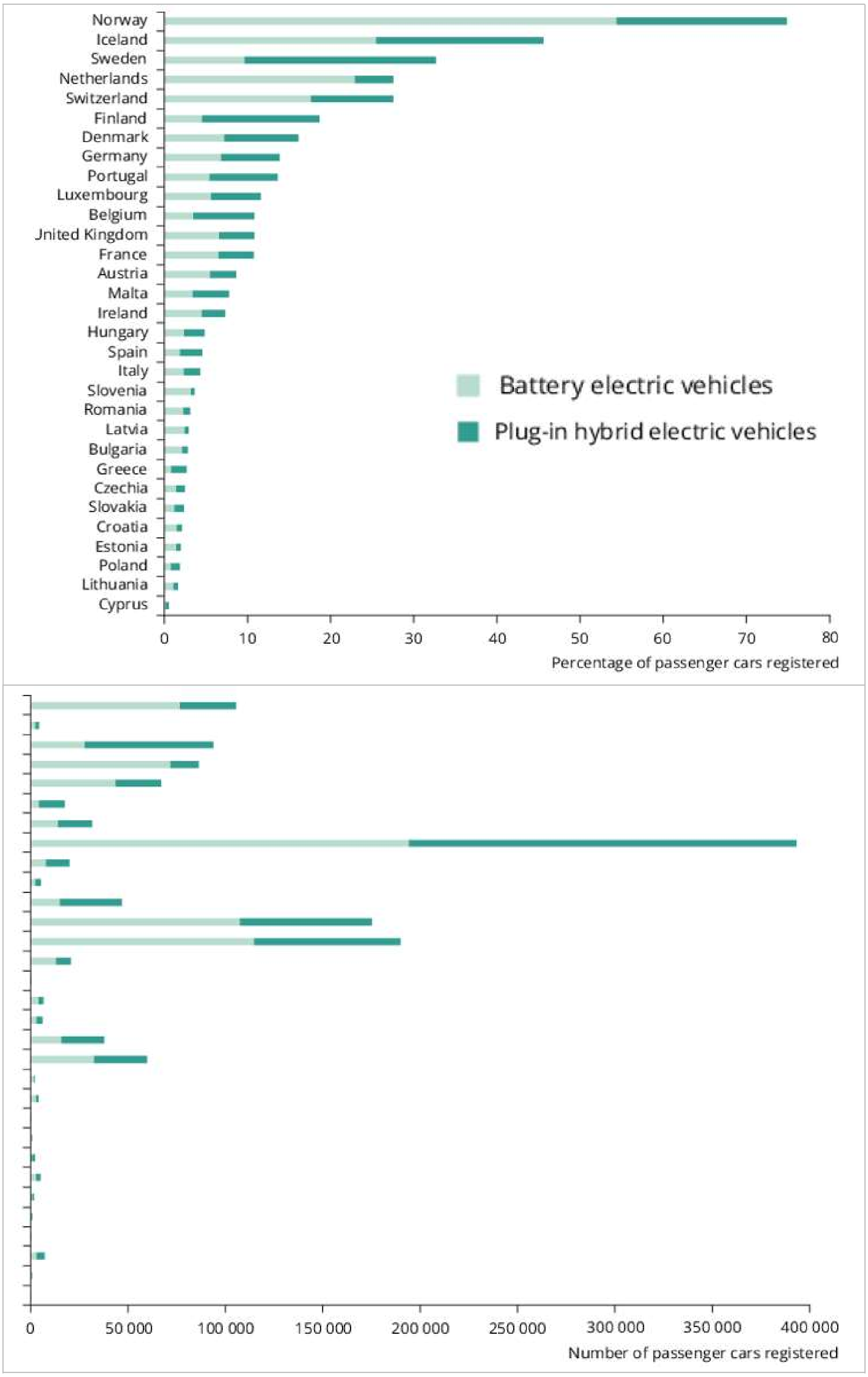
Yamada et al. in their article, Scenario Input-Output Analysis of the Diffusion of FCV and Alternative Hydrogen Supply Systems examine the economic and environmental impacts of replacing cars with combustion engines with cars with hydrogen propulsion. Environmental objectives and changes in consumer preferences create pressure on the fundamental change of the production program in the automotive industry. Conventional propulsion is being replaced with alternatives in order to meet the average limits for new vehicles.

In terms of analysis, this changes the structure of inputs and outputs, which is associated with changes in the cost rates and environmental intensity of the sector (Yamada, et al., 2019). In terms of inputs, provided that there is higher rate of penetration of hydrogen-driven cars on the market, there is a growth in demand for products made of glass, ceramic and earth. At the same time, the demand for electronic components also increases, since cars with alternative propulsion are characterized by higher digitization rate. On the contrary, we observe a decline in demand for conventional car components, such as gearboxes or clutches. As results from the final simulation, the transition from conventional to hydrogen propulsion is associated with the reduction of pressure on economic resources. However, in combination with the hydrogen production from fossil fuels through steam reforming, it does not bring any relief to the climate.

The substantial transition towards electromobility in Europe is clear from the following chart (Chart 2.1 Comparison of electromobility penetration with the EU), as in 2020, the purchase of BEV and PHEV dominated where there was registration of new cars, especially in Nordic countries.

Contrary to this trend, (according to the ZAP representatives) there was an increase of only 2026 newly registered electric and hybrid cars from a total number of newly registered passenger cars in SR in 2021 (Source: Ministry of Interior of the SR) in the amount of 75 608, or from the total number of newly registered vehicles amounting to 110 386. In the total quantity of 3.436 million of cars registered in the SR at the end of 2021, the share of registered electric and hybrid cars is still negligible (per mill).

Chart 2.1 Comparison of electromobility penetration with the EU



Source: The European Environment Agency (EEA).
https://www.eea.europa.eu/data-and-maps/figures/new-electric-vehicles-by-country

Based on the registry of the Ministry of Interior of the SR, during the pandemic in 2021, the total number of newly registered cars in Slovakia decreased compared to 2019 (134 703) by 24 317 vehicles and in the category of passenger cars (101 743 in 2019) by 26 135 vehicles. According to ZAP, there was a decline in the registration of owners that are natural persons and an increase in case of legal entities, since "the natural persons increasingly use financial products, such as credits or leasing, for the purchase of vehicles". ZAP (Press release of ZAP: Alexander Matušek, Chairman of ZAP SR: Slovakia lags behind in the country's green transformation. How to fulfil the EU's commitments? Bratislava, 13.1.2022.) in 2021 we also registered a negative trend represented by the growing portion of individually imported vehicles (new and used) by 3 846 vehicles compared to 2020. For individually imported cars there is a prevalence of vehicles older than 5 years (more than 60% of all individually imported vehicles in 2021). "These are mainly vehicles with the emission standard of EURO 5 and lower". "The age of individually imported vehicles also increased, as about 8 508 of the vehicles older than 15 years were imported".

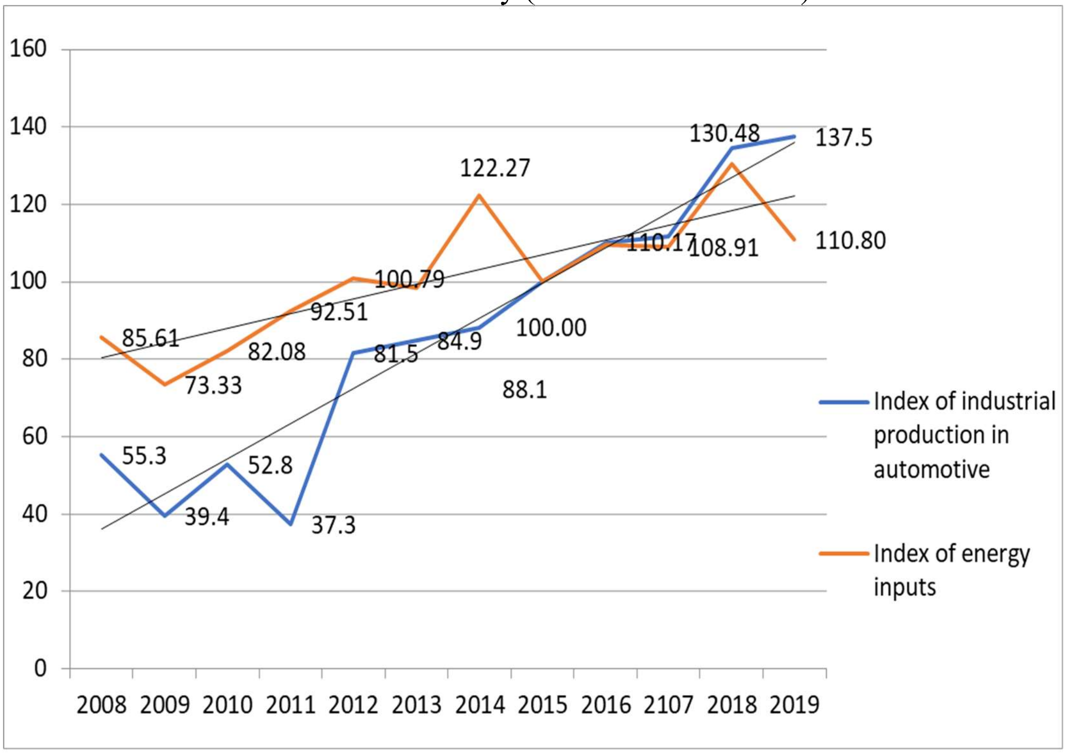
2.5 LCC and emissions

Despite the fact that the emission as well as the energy intensity of the automotive industry in the SR is decreasing, the potential of LCC for the reduction of CO_2 emissions in the SR is currently low. This is due to the low share of operation and sale of electric vehicles. The sales support of vehicles with alternative propulsion in the SR is also insufficient and, according to ZAP, without more significant support, Slovakia will not be able to fulfil its commitments to Europe. The same applies to the unfavorable situation in building the necessary infrastructure, as in 2020 there were 820 charging stations in Slovakia with the ambition to build 5 500 charging stations by 2025. It is estimated that in 2030 a total of 25 000 stations will be necessary. The positive trend, such as the reduction of energy intensity in the automotive industry in the SR, the energy mix, and the improvement of the environmental impact of the automotive industry is noticeable in the production of cars.

Despite the fact that the emission as well as the energy intensity of the SR's automotive industry is decreasing, the potential for the reduction of CO_2 emissions in the SR is low. This is due to the low share of operation and sale of electric vehicles. The sales support of vehicles with alternative propulsion in our country is still insufficient and, according to ZAP, without more significant support, Slovakia will not be able to fulfil its commitments to Europe. The same applies to the unfavorable situation in building the necessary infrastructure, because, in 2020, there were 820 charging stations in Slovakia with the ambition to build 5 500 charging stations by 2025. It is estimated that in 2030 a total of 25 000 stations will be necessary.

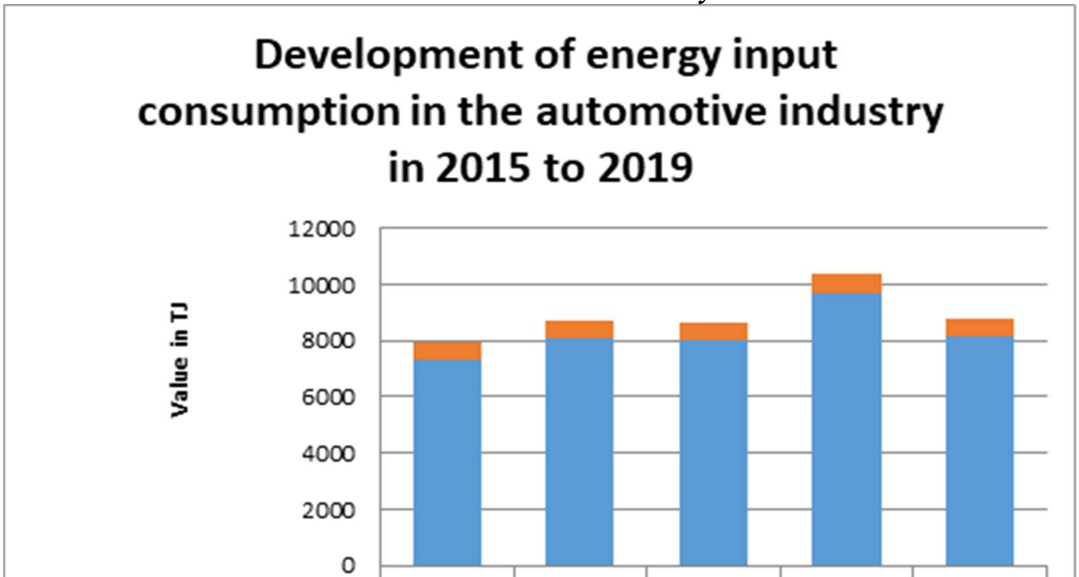
The positive trend, such as the reduction of energy intensity in SR's automotive industry, the energy mix, as well as the improvement of the environmental impact of automotive industry is demonstrated in the following charts.

Chart 2.2 Development of energy production and consumption in the SR's automotive industry (sectors C29 and C30)



Source: Self-elaboration of data from the Slovak Statistical Office.

Chart 2.3 Development of energy input consumption (TJ) in the automotive industry

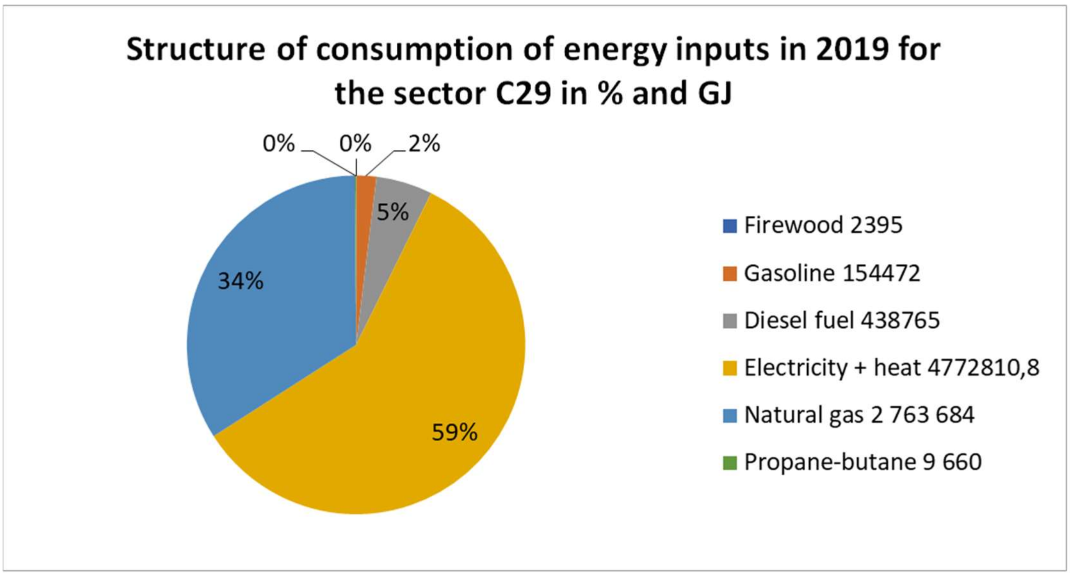


	2015	2016	2017	2018	2019
Total consumption in TJ for sector C30	640	632.7384	661.3744	664.56	653.8688
Total consumption in TJ for sector C29	7297.7468	8057.97	7984.2482	9693.4982	8141.7868

Source: Self-elaboration of data from the Slovak Statistical Office.

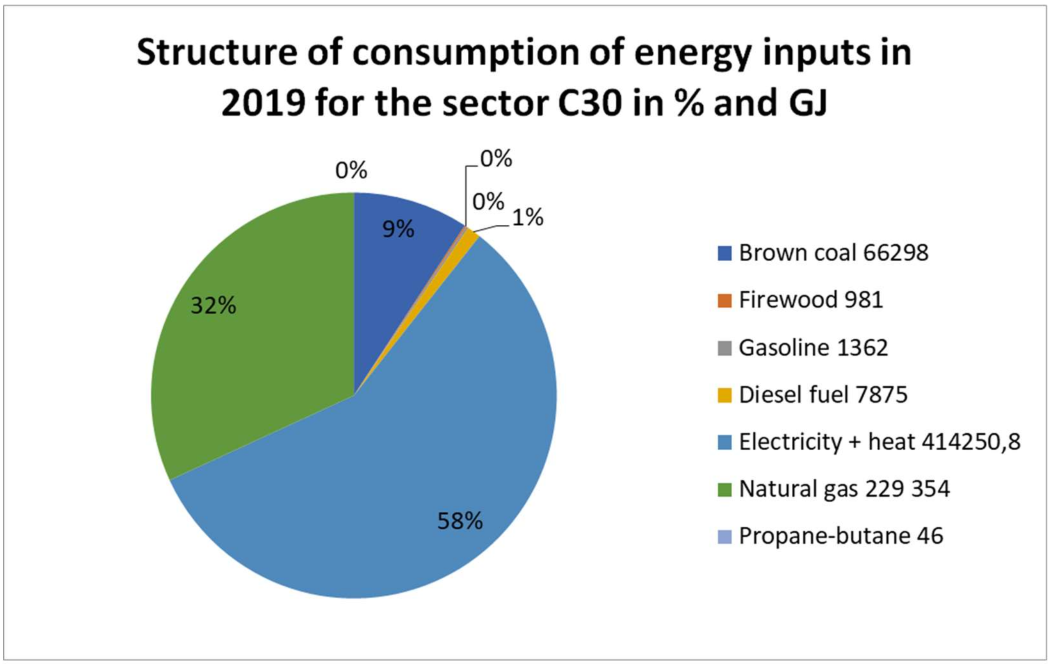
The energy mix in the Slovak sectors and sub-sectors of the automotive industry is based on the energy mix with the following dominant **main sources: electricity + heat and natural gas**.

Chart 2.4 Energy mix in sector 29, Manufacture of motor vehicles, trailers and semi-trailers



Source: Self-elaboration of data from the Slovak Statistical Office.

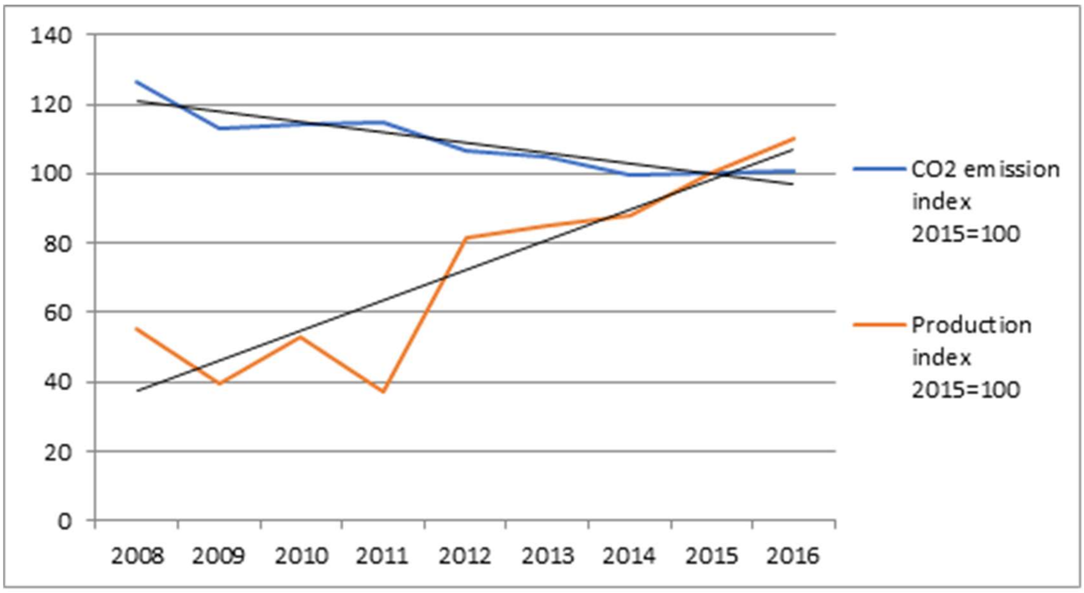
Chart 2.5 Energy mix in sector 30, Manufacture of other transport equipment



Source: Self-elaboration of data from the Slovak Statistical Office.

The available data from the ecological input-output tables of Eurostat through 2016, together with the above specified facts, confirm a clear long-term positive trend of the impact of automotive industry on the reduction of CO_2 emissions in the SR.

Chart 2.6 Trends of CO_2 emissions in the productionwithin the automotive industry (sector codes 29 + 30)



Source: Self-elaboration of data from the Slovak Statistical Office and Eurostat.

2.6 Analysis of trends in the development of inputs and production multipliers in the Slovak automotive industry

The automotive industry, its suppliers and research and development facilities, and not just in Slovakia, must face the above specified challenges. In this context, along with the response of the individual companies operating in this sector, the active involvement of public entities is also important, as they should support the development of competitiveness within the automotive industry, both in the medium and long term.

The action plan 2.0 expects the expenditures amounting to EUR 53 million for the establishment of a national network of ultra-fast charging stations within the urban infrastructure and in the form of subsidies for legal persons. In 2021, there were approximately 800 charging stations in Slovakia, and it is foreseen that more than 3 000 new ones should be built. Despite this, the chairman of ZAP SR states that the electromobility support in Slovakia is insufficient and that it is necessary to build almost 25 000 charging stations for electric cars. According to the EY study (2017), 90% of all innovations in the automotive industry currently come from the electrical engineering sector, which generates 35% to 40% of the vehicle value (EY, 2017).

Within the projecting of changes in the labor market it is especially challenging to forecast the skills, not the jobs. Many available studies indicate that the function of individual jobs is significantly changing. Many activities are being automated and there are demands for new activities in which the labor has comparative advantages compared to capital. Changes in the structure of vehicle production will also be reflected in the change of the structure of inputs in the automotive industry and subsequently they will be reflected in the generated effects of this sector. Therefore, in the following section we will examine the changes in the intensity of inputs in the Slovak automotive sector in an international context. We will use this knowledge in the next part of the research as a basis for shaping the forecast of the input development and its generated effects.

2.6.1 Intensity of inputs in an international context

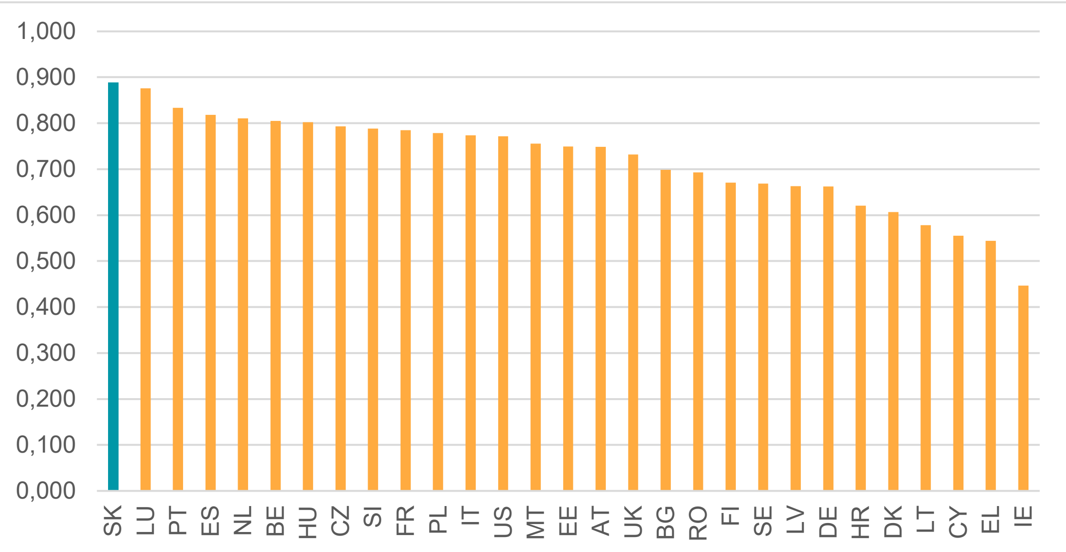
In the processing of the results, we have used data from the current Eurostat database, that is, what is referred to as the FIGARO version of input-output tables (Full International and Global Accounts for Research in input-Output analysis). It is a new statistical product of integrated global accounts for economic modelling. These tables interconnect the national accounts and data about business, commerce and jobs of EU member states and other selected countries.

Data used: FIGARO Tables, EUROSTAT (2021)

- Multi-regional input-output tables for EU countries and the rest of the world
- 2010 – 2017, 2018 – 2019 (data for fewer regions and more aggregated sectors)
- Data in current prices (in millions of euros)
- 46 countries, 17 countries
- Sectors x sectors
- Products x products
- 64 sectors and 64 products, 30 sectors and 30 products

Chart 2.7 clearly shows the total intensity of inputs per unit of production of the automotive industry in different countries. It is obvious that the Slovak automotive industry has the highest direct intensity of inputs, which is also related to the intensity of own intermediate consumption.

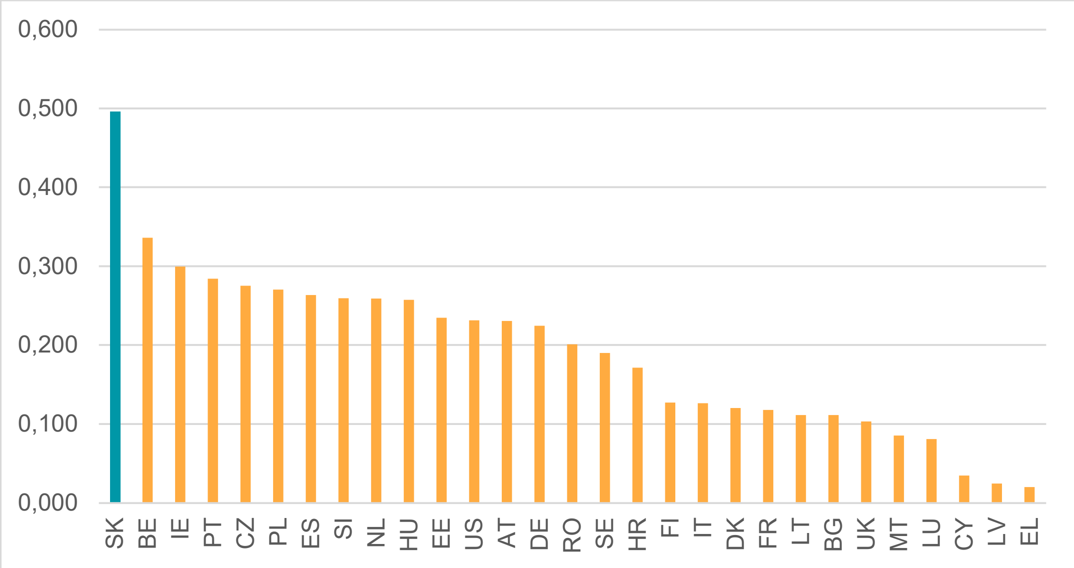
Chart 2.7 The total intensity of inputs per unit of production of the automotive industry, 2017



Source: EUROSTAT (2021) Figaro Tables, own calculations.

Chart 2.8 documents the high intensity of automotive industry in the SR with regard to its own intermediate consumption compared to other countries. This is especially due to significant specialization in the final production which is supported mainly by foreign demand. In comparison to Germany, another world leader in car manufacturing, it is almost double in value of the intensity of its own intermediate consumption.

Chart 2.8 Intensity of innate intermediate consumption – inputs from the automotive industry into the automotive industry

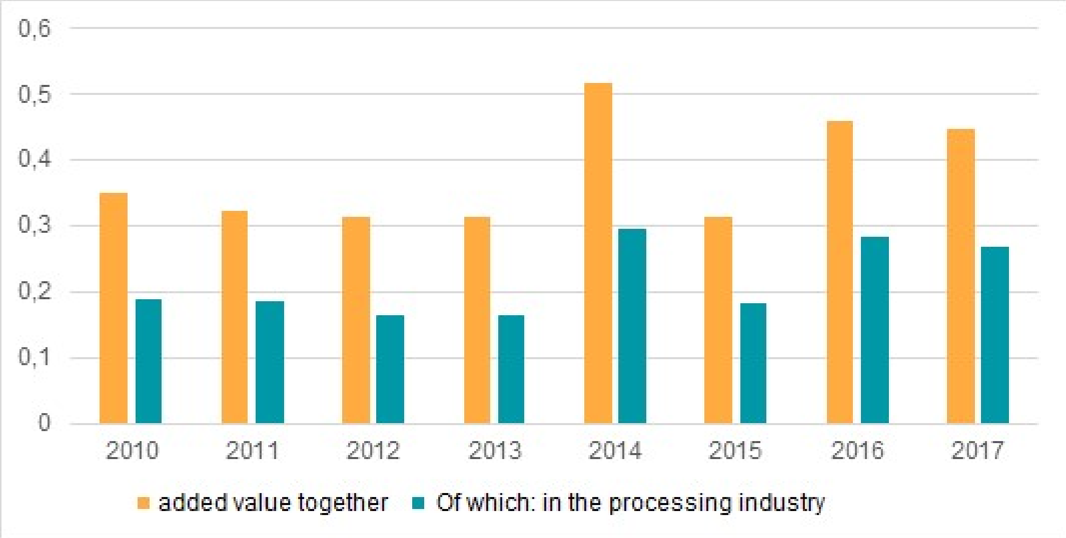


Source: EUROSTAT (2021) Figaro Tables, own calculations.

It is also interesting to observe the development of multipliers of added value in the Slovak automotive industry through time, as their value in the last monitored years 2016 – 2017 was higher than in 2010 – 2015 and more than half of the added value was generated in the processing industry (Chart 2.9). The automotive industry in Slovakia is traditionally characterized by lower values of added value multipliers, also due to the higher intensity of intermediate consumption already discussed.

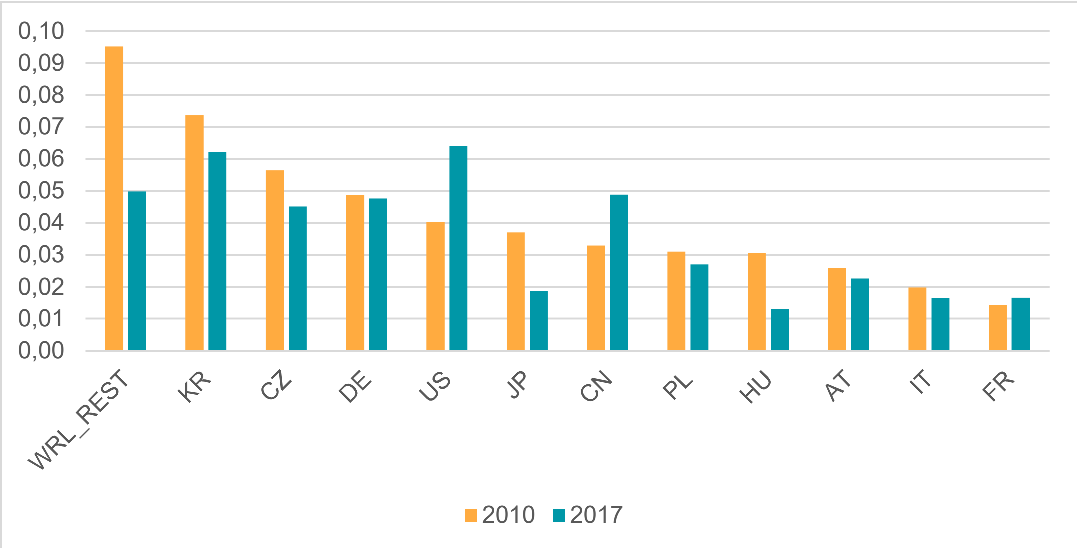
The development in the last two years can even indicate a gradual qualitative shift towards activities with higher added value. The value of the automotive industry added a value multiplier of 0.45 from 2017 means that production of the automotive industry in the value of EUR 1 million to its end use, generates an added value in the entire Slovak national economy amounting to EUR 450 thousand (in 2010 it was about 100 thousand EUR less).

Chart 2.9 Multipliers of added value of the Slovak automotive industry



Source: EUROSTAT (2021) Figaro Tables, own calculations.

Chart 2.10 From where we import added value and how this changed between 2010 and 2017



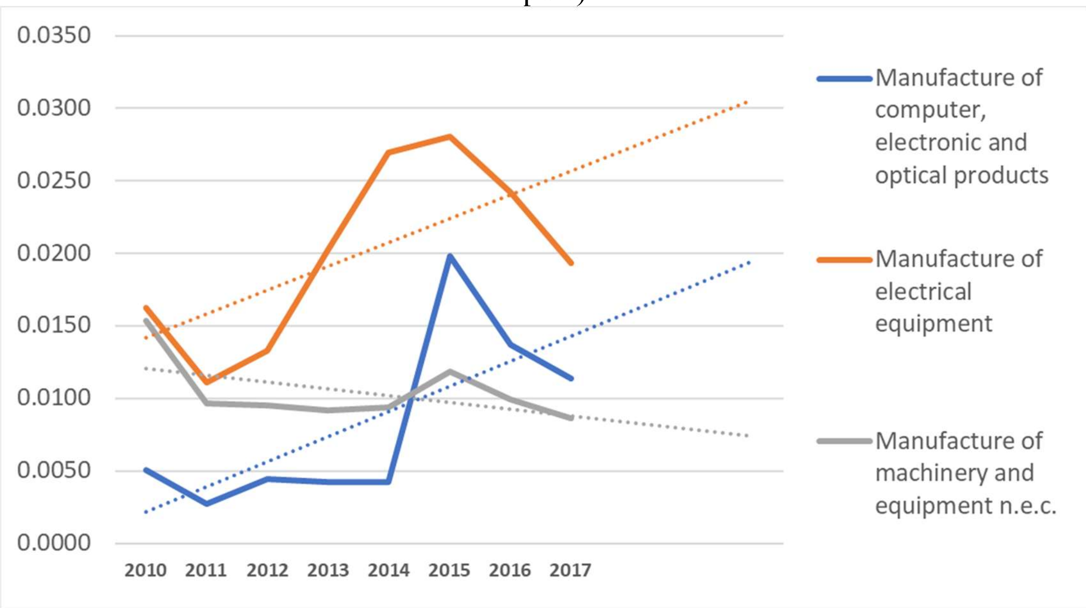
Source: EUROSTAT (2021) Figaro Tables, own calculations.

From the global value chain matrix, we can determine from where Slovakia imports the added value for the automotive industry and what kind of change happened between 2017 and 2010. From Chart 2.10 it is clear that the major portion of added value per unit of production is imported from the USA (6.4%), South Korea (6.2%) and from China (4.8%). The highest decline in the import of added value is observed from Hungary, Japan and the Czech Republic.

2.6.2 Trends in the development of input coefficients and production multipliers in the automotive industry through 2025

In the previous research within the UNIVNET project we were focusing, inter alia, on the general trends in the development of material inputs in car production. One of the main trends is the change in the ratio of inputs, that is, from ferrous and non-ferrous metals to plastics. The share of cast iron and steel in the modern cars likewise is decreasing and the value of plastic modules, rubber, electrical connections and lining materials is increasing. It is estimated that by 2030 the share of costs of electronic components with regard to the total value of the car will increase to 35 – 45%. This is also related to the increase of innovations with regard to electronics and software equipment or the Internet of things (Final report of UNIVNET, 2021, chapter by EUBA).

Chart 2.11 Development trends of inputs of computer and optical products, electrical devices, and machines in the automotive industry (domestic and imported inputs)



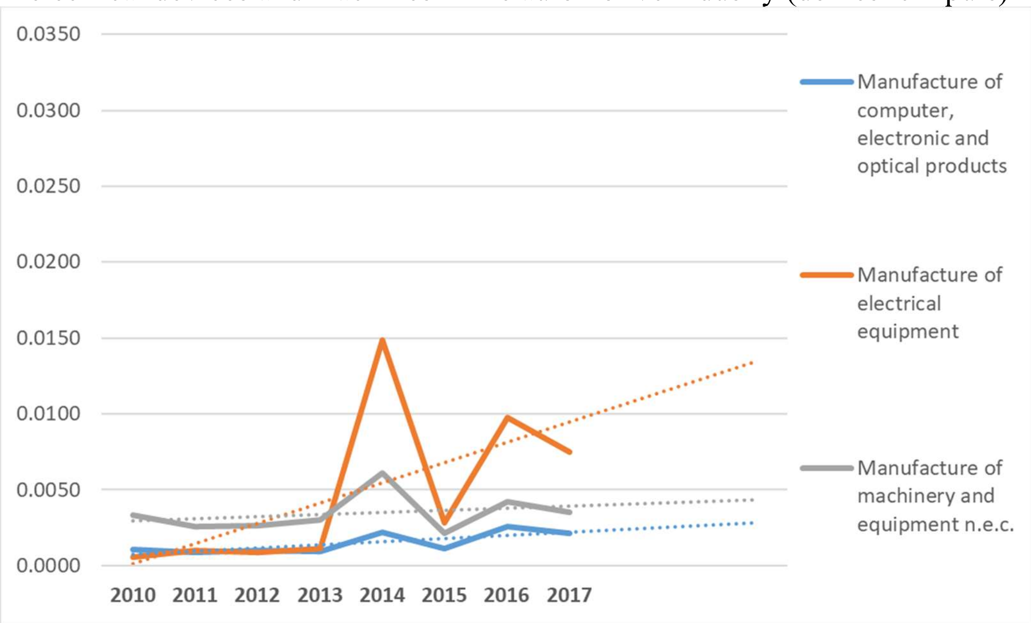
Source: EUROSTAT (2021) Figaro Tables, own calculations.

In this part of the paper, we analyze the trends in the development of the most important inputs of the automotive industry in Slovakia in terms of input-output tables. These trends form the basis for the estimation of broader economic effects of the automotive industry. One of the most important factors influencing the overall effects of the automotive industry on the domestic economy is the structure of inputs, and technical coefficients, per single production unit.

First, we will examine the trends in the development of the overall, and in particular, the domestic inputs of computer, electronic and optical devices, electrical devices and machinery.

In the period from 2010 to 2017, we observe an increase in the use of electric devices in the overall inputs per single production unit. While their share in 2010 was almost the same as that of the machines and devices, in 2017 it was significantly higher. This difference was caused by the stagnation or a slight decrease of inputs from the machines and machinery sector. A significant change was also observed in comparison with computer devices and electronics. The growing trend in this period resulted in the fact that electronic devices in 2017 represented a higher share than the machinery. The development trend of these inputs indicates that by 2025 we can expect a higher share of inputs of electronic and electrical devices in the overall inputs to the detriment of machines and machinery.
The following chart documents the development trend in the use of these components from the producers localized in Slovakia.

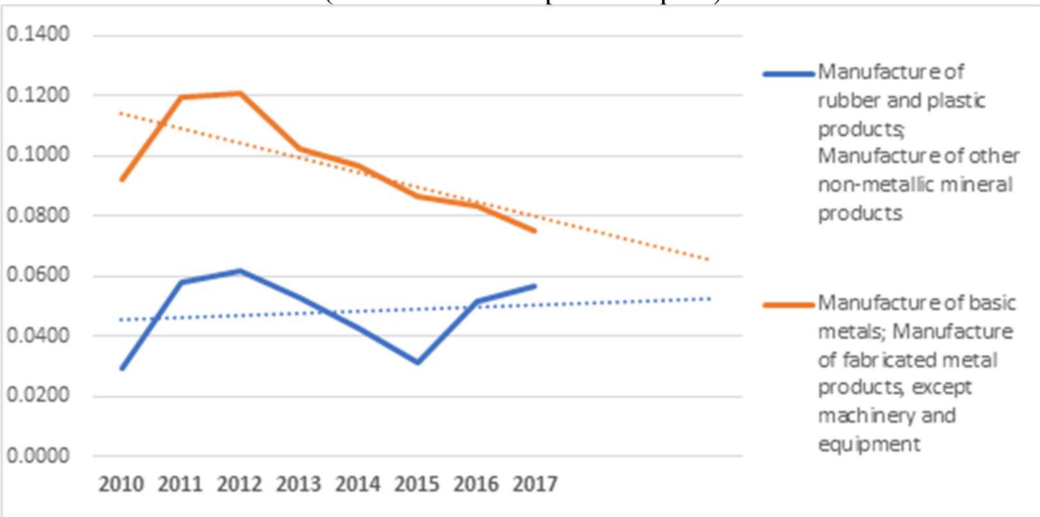
Chart 2.12 Development trends of inputs of computer and optical products, electrical devices and machines in the automotive industry (domestic inputs)



Source: EUROSTAT (2021) Figaro Tables, own calculations.

The highest increase of domestic inputs was observed in the production of electrical devices. In the production of electronic, computer and optical modules and components, as well as in the production of machines and equipment, we observe stagnation of their use per single production unit, or only very slow growth. To a certain extent this development is reasonable in the case of machines and equipment as such but does not correspond to the increased requirements for inputs of electronic and computer devices. In this sector, then, we observe a gap in the development of production trends and in the extent to which domestic producers participate in the increased requirements for inputs in this sector.

Chart 2.13 Development trends of plastic and other non-metallic inputs, basic metals, and metal products in the automotive industry
(domestic and imported inputs)

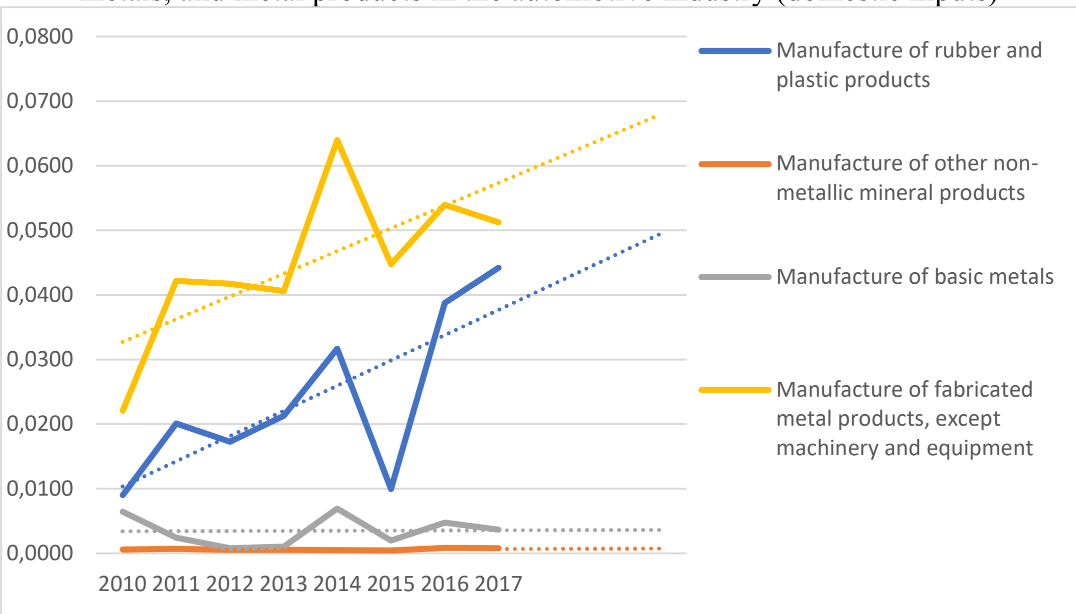


Source: EUROSTAT (2021) Figaro Tables, own calculations.

The general trend in the increase of inputs from the sectors Manufacture of rubber products, plastic products and other non-metallic products, and the trend in the decline of use of metal product inputs, is also observed in the automotive industry in Slovakia. In the period from 2010 to 2017, there was a rather significant decrease in the use of inputs from the sectors of Base metals, wrought metals and metal products (except for machines and equipment). Thus, by 2025 we can expect (on the basis of the development to date) the convergence of the share of inputs in these sectors. Inputs from the domestic sectors are important for the economic effects on the Slovak economy.

As results from the analysis of development trends of the domestic inputs in these sectors, the use of domestic inputs from the sector Manufacture of rubber products, plastic products, as well as wrought metals and metal products, except for machines and equipment, will be growing. On the contrary, with the use of base metals and other non-metallic mineral products, we observe their low and stagnant share in the overall inputs. In this context it is necessary to point out, in particular, the positive trend of growth in the use of domestic rubber and plastic products, which show faster overall growth than the growth of the overall domestic and imported inputs. This fact indicates significant competitive advantages in this sector since the growth in the use of inputs from this sector is increasingly covered by domestic inputs. We therefore expect that this growing trend of use of domestic inputs from the said sector will continue until 2025.

Chart 2.14 Development trends of plastic and other non-metallic inputs, basic metals, and metal products in the automotive industry (domestic inputs)

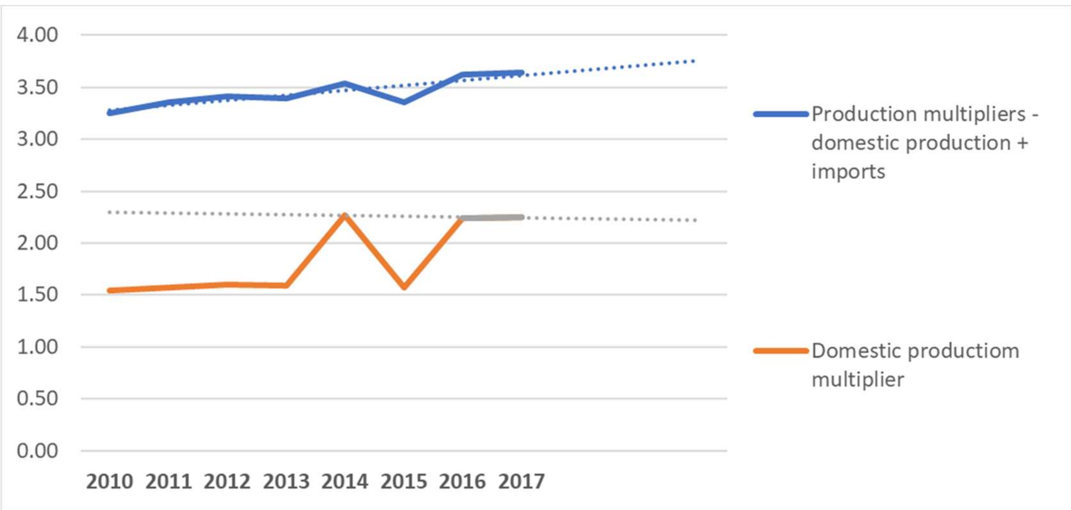


Source: EUROSTAT (2021) Figaro Tables, own calculations.

A similar increase of domestic inputs is also observed in the use of processed metal products. However, it is necessary to point out the general decline in the use of these inputs in the overall value of the vehicle, which is expected until 2030. Despite the increasing share of inputs of this sector in the period from 2010 to 2017, we expect that this increase will slow down by 2025, or it will stagnate.

Structural changes affecting the overall effects of the automotive industry on the economy. Chart 2.15 documents the trends in the development of overall automotive industry multipliers both for domestic and imported production, as well as separately for domestic production.

Chart 2.15 Development trends of automotive industry production multipliers



Source: EUROSTAT (2021) Figaro Tables, own calculations.

Structural changes in the production of cars in Slovakia, changes in the organization of global production chains, as well as the product mix of manufactured cars in the period from 2010 to 2017 resulted in a slight increase of the multipliers of domestic and imported production. While in 2010 the production multiplier was 3.25, in 2017 it was 3.64. With regard to the growing complexity of the production of cars and their components, we anticipate an increase of the overall production multiplier here, or in a slightly slower trend even through to 2025. Its value in the specified period is foreseen within the range 3.75 – 3.85.

Domestic production multipliers showed a different, rapid development. Up until 2015, they were within the value range of 1.54 – 1.6. The year 2014 was an exception. This has already indicated a ramp increase of domestic production multipliers in the following years, while in 2016 and 2017 they reached values of 2.24 or 2.25. These ramp changes do not result from the gradual structural changes in the production and, therefore, without any significant external changes, we do not expect their further growth. Based on the past development and provided that there is permanent ramp change in the recent period, the value of domestic multiplier **should range from 2.2 to 2.3 until 2025**.

In further research we consider it useful to estimate the development trends of the effects on added value and employment. In this context, the changes in the structure of inputs and labor intensity will be essential. However, the key factor will also be the extent to which we manage to provide supplies of components and modules made in Slovakia to the final producers.

2.7 Research and development as the source of innovation potential of the sub-contractors in the Slovak automotive industry

Several studies that were drawn up in the SR in the past (for example also for UNIVNET) reported low involvement of the domestic research and development potential in the creation of added value. This applies not only to the car production as such, which appears natural with regard to the transnational nature of car plants, but rather to the potential represented by supply chains and all entities operating within the circular economy in the automotive industry. **Certain topics are the subject of relevant parts of the study.**

2.7.1 Global value chains in the automotive industry

Conventional and, it is necessary to stress that in today's theoretical definition of the international trade, already insufficient, such is the view of the performance and competitiveness in the international trade through the ordinary export and import statistics on the basis of the value of imported goods and commercial services reported by delivery parities of FOB (value of import and export with the delivery of goods to the borders of the exporting country) and CIF (Cost, Insurance & Freight) (Zábojník et al., 2020). In the recent years, the experts from renowned institutions (WTO and OECD) point out the necessary consideration, or the overall orientation of international trade reporting through the global value chains and international trade statistics taking into account the level of added value (added value as the source of GDP creation). This need reflects the state in which only 30% of the global commerce is carried out between the producer and final consumer (customer). The remaining 70% is formed by the structure of international trade, in which the final product is generated in the system of activities of the transnationally operating companies on the basis of consumer-supplier relations crossing the borders (international offshoring and outsourcing) and is implemented by way of what is known as global value chains (GVCs). Commodities, raw materials and semi-finished products cross the borders of states several times until they are transformed into the final product and delivered to the customer in the international business environment (OECD, 2019). This phenomenon describing the frequency in which the semi-finished products (inputs) cross national borders for the purpose of product completion, is the subject of the concept known in the international trade as the TiVA (Trade in value-added) (Zábojník et al., 2020 and Folfas, 2019).

Global value chains (GVCs) represent a phenomenon in the period of economic research after the New Trade Theory, which indicates how the product completion is fragmented in countries, regions, and continents, and where the companies outsourcing and offshoring activities within the product completion profit from the comparative advantages in countries to which these activities were transferred. GVCs depend on the fragmentation of production and trade of intermediate products, in order to use the cost advantages of every site or stage in the chain up to the level of assembly. GVCs are typically used by transnational companies and become more and more important in the world (OECD, 2015) (despite the fact that these supply networks on the international market suffered disruptions caused by the global pandemic of COVID-19). The global value chain includes all activities which are pursued by enterprises either on the national market or on foreign markets from its concept up to its final use. The global trade in the entire world, production and direct foreign investments are increasingly organized by GVCs. These activities do not have to be performed only by one company, but can be shared by different companies (OECD, 2015). The development of GVC was from the beginning managed by large transnational companies which achieve competitive advantages and profits. The costs in several countries are minimized on the basis of economies of scale and specialization through the conduct of specific activities within the production process. According to UNCTAD (UN Conference on Trade and Development), 80% of gross export is currently connected with the international production networks of transnational companies.

According to OECD (2013), the levels of product production fragmentation depend on the technical preconditions and aspects of the products. The key role in the global value chains is played by the transnational corporations (TNCs, MNCs or MNEs) in the form of OEM (Original Equipment Manufacture, producers of such products that are assembled from the delivered parts from other producers). Competitiveness within the global value chains plays a critical role. Success on global markets currently depends on the ability to import high-quality products, but mainly on the export capacity. In order to increase the corporate, but in the long run even the national competitiveness, it is particularly important for the domestic companies to be involved in GVCs, in particular in the areas with the highest added value. In this context, the model of automotive industry is particularly fragmented on the international level, which was caused by active implementation of direct foreign investments from transnational corporations in the international automotive industry. There were several reasons for this natural breaking up of the value chain: from the effort to procure more affordable raw materials, components, labor, managerial decision to establish capital closer to the final customer (especially East Asia), up to the effort to gain strategic assets (especially technological) for the development of own company.

The European automotive industry faces many important challenges. In recent years, European producers (especially German and French car plants) have focused on the price competitiveness – cost reduction through optimization of costs and processes. Asian producers found the answer in the technological progress reflecting on the requirements and opportunities of Industry 4.0 and Industry 5.0. When we look at the involvement of Slovak sub-contractors in the global value chains, it is necessary to point out the complicated situation of car plants in the SR. Only 55.5% (OECD, 2021) of the Slovak gross export was produced in the SR (added value contributing to the creation of GDP). In the case of automotive industry, this indicator is only at the level of 40.1% (the remaining approx. 60% of the export of car plants in the SR is in the form of re-export – of previously imported semi-finished products).

The level of the specified indicator is one of the lowest in the entire EU which is caused by natural factors (market size, number of companies, openness of the economy), as well as the fact related to the shortcomings in the creation of added value in the SR (low level of innovations, significant focus on DFI (direct foreign investments), lack of their own sub-contractors in the automotive industry). In this context it is suitable to ask one fundamental question in relation to the economic policy of the SR – how to change the position of Slovak companies in the global value chains towards better creation of added value and increase their own production in the gross export of the country? The theoretical models and studies offer several alternatives through a so-called upgrade of the company or countries in the value chain in favor of involvement of domestic companies with higher level of added value.

The upgrade of a company or country in the value chain relates to the set of activities focusing on the improvement of production structure towards a higher share of added value. With this upgrade the companies and countries gain higher payroll and level of profits, but also "more secure" position within the chain, which results in higher economic stability. Specialized literature dealing with the upgrade in the value chain (Humphrey; Schmitz, 2002 and Gereffi, 2019) proposes strategies used by companies, clusters and states to improve their positions in the global and regional value chains.

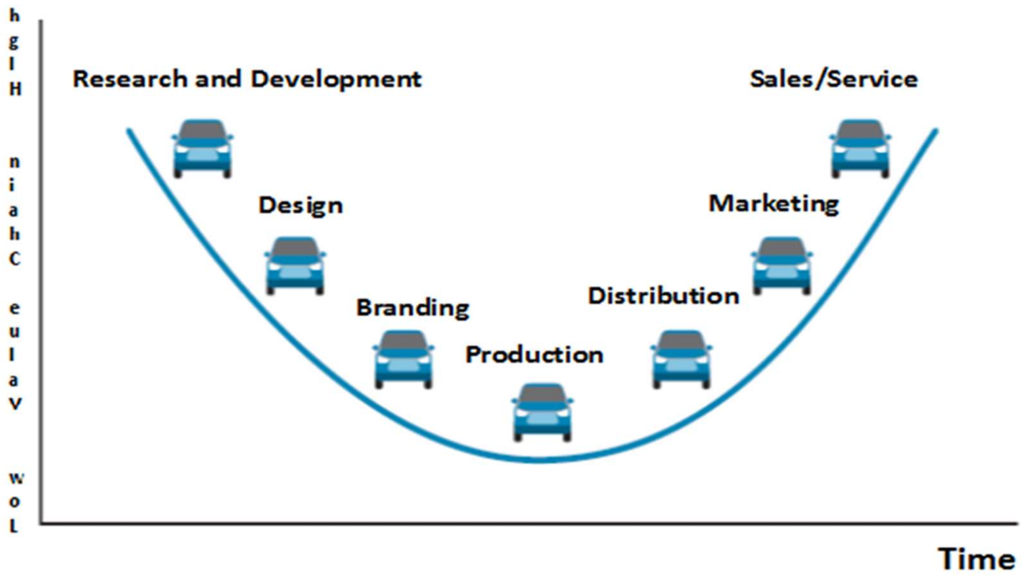
a) Process upgrading – focuses on process innovations, such as improvement of manufacturing technology or reorganization of the manufacturing process in order to achieve a more efficient ratio of inputs and outputs.
b) Product upgrading is the same as reorientation of the production portfolio towards more sophisticated products.
c) Functional upgrading focuses on the restructuring of functions within the production cycle. The company and/or country gains new competences (for

example, design, research, branding) and is able to move to a higher production phase within the production chain.

d) Inter-sectoral upgrading describes a situation in which the companies and/or countries reallocate their resources into the new (often related) sectors.

One of the most often used diagrams showing the relations between the value chain phases and the level of added value is the “smile curve” by Stan Shih. The curve (model) illustrates opportunities for the production of higher added value which are present mainly at the beginning and end of the value chain (Low, 2013).

Chart 2.16 Value chain in the automotive industry



Source: drawn up by the authors based on Gangnes – Assche (2011) and SIEA (2018).

The majority of processes with higher added value is usually implemented in RTE (Real Time Economy) with more innovative companies (better able to commercially apply R&D expenditures). Companies from the developing countries are concentrated within the GVCs especially in the activities with lower added value, in which the comparative advantage such as cheap labor force, unregulated environmental burden, etc. is applied. The activities in GVCs executed by RTE companies eventually result in spill-over effects into the developing countries and subsequently, the companies from developing countries, within the catching-up process, “domesticate” the innovations within production processes (baselines applicable from the Product Life Cycle Theory by R. Vernon). Naturally, the activities that include a higher added value within the pre-production phase are more demanding in terms of R&D (research and development) findings, and in the second part, the post-production phase, the relevant marketing knowledge is inevitable for their successful implementation.

In this regard, the network of sub-contractors in the automotive industry in the SR faces a key challenge – **through the transformation of the knowledge and skills of the labor force, or innovation activities at the level of enterprises** enable higher involvement in the sub-contracting structure of the automotive industry. It is envisioned that more intensive participation in the creation of the added value of cars exported from the SR will result in the increase of the added value for the SR and gross export of the Slovak automotive industry.

2.7.2 Research methodology

A questionnaire was drawn up **in order to identify the barriers and triggers of the innovation potential of the companies in the SR** in the area of the automotive industry (EUBA, 2019). The questionnaire was anonymous and sent to companies with registered offices in the SR. The survey, through questions included in the questionnaire and the resulting conclusions, is based on the assumption that the innovation activity of enterprises is contingent on the existence of innovation potential and its proper use. If we acknowledge innovation activity as the fundamental concept of competitiveness of enterprises, it is necessary to know and develop the elements of innovation potential. About one fifth of the enterprises participating in the value chain of car production in the SR perceives the **absence of innovation potential** as a barrier in the participation development of sub-contractors in the value chain in automotive industry. The following data about the nature of innovation activities and innovation potential of sub-contractors in the automotive GVCs in the SR is based on the survey executed in 2019 (EUBA, 2019), that is, in the conditions not affected by the crisis development associated with the pandemic of COVID-19.

The questionnaire survey was taken by about 100 companies from the area of automotive industry with different product portfolios. The questionnaire allowed for multiple answers. The structure of respondents corresponded to the suppliers in tier 1 or tier 2 with less than 1/3 for tier 3. The majority of respondents operate in the region of Žilina and Trnava.

The relevant enterprises carry out their R&D activities mainly within their own or corporate R&D technological center. One fifth of the companies carries out the relevant activities within its own R&D department responsible for innovations. These enterprises form the potential for the establishment of a technology center. Thus, the execution of individual R&D activities is declared by almost 2/3 of the enterprises. Non-formalized forms of cooperation within R&D activities are declared by almost half of the enterprises. Together, with the share of enterprises that do not perform R&D activities, they form **further potential for the creation or expansion of the existing technology center.**

Survey in the field of sources for financing of R&D activities of sub-contractors resulted in the following: **81%** of enterprises uses their own resources to finance the relevant activities, **19%** of enterprises uses outside capital in the form of bank loans. Only **9%** of enterprises carries out their R&D activities through project financing from foreign grant programmes and **5%** through project financing from domestic grant programmes. Risk capital and joint ventures are not used to finance the research and development among the sub-contractors in the automotive industry in the SR. The transfer of funding sources towards other forms, except for their own resources and bank loans, is the key element **in the support of the development of innovation potential of subcontractors and subsequently their R&D activities**.

Innovations fail due to the inability to implement innovative ideas. Only one third of companies operating in Slovakia apply innovations. These results are from the data of the European Statistical Office – Eurostat (2021). The implementation of innovations by sub-contracting businesses in the automotive industry is associated with many obstacles. The most often specified obstacles: low support/low R&D expenditures of the state, lack of self-financing, lack of qualified specialists for the implementation of R&D, insufficient government incentives, lack of qualified workers for the implementation of innovations, relatively low profit margin depressed by "strong" consumers, short innovation cycle of products/rapid introduction of new technologies.

The European Union is trying to openly encourage innovations by better regulation, digitization and access to scientific findings. **However, the respondents do not find the state's support sufficient for their innovation activities and none of them stated that the policy of the government with regard to the support of innovations is sufficient.** 68% of respondents think that the state support in the area of innovation activities is insufficient (26% answered No and 42% answered More likely no). 30% of respondents cannot determine whether the state policy is sufficient.

The results of the survey document that the financial incentives for the support of R&D and support and development of R&D infrastructure play the most important role in the development of innovativeness of businesses in the automotive industry in the SR. It is also necessary to focus on improving the quality of education of qualified researchers in universities and colleges, and on the increase of the number of graduates in technical and scientific disciplines in the SR. Entrepreneurs also put emphasis on the innovation friendly legislative and tax environment and on encouraging the young Slovak scientists to return from abroad.

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2.8 Bibliography

[1] Climate Change Performance Index. 2021. [online] Dostupné na internete ku dňu 12. 3. 2021: https://ccpi.org/

[2] Eurostat: Passenger cars in the EU. 15. 02. 2021. [online] Dostupné na internete ku dňu 12.3. 2021: https://ec.europa.eu/eurostat/statistics-explained/index.php/Passenger_cars_in_the_EU EUROSTAT DATABASE (2021). https://ec.europa.eu/eurostat/data/database?p_p_id=NavTreeportletprod_WAR_NavTreeportletprod_INSTANCE_nPqeVbPXRmWQ&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&p_p_col_id=column2&p_p_col_pos=1&p_p_col_count=2, http://appsso.eurostat.ec.europa.eu/nui/show.do

[3] IEA 2015. Automobilový priemysel na Slovensku a globálne hodnotové reťazce. [cit. 2019-04-18] Dostupné na: https://www.siea.sk/materials/files/inovacie/publikacie/studia_Automobilovy_priemysel_na_Slovensku_a_globalne_hodnotove_retazce_SIEA_web.pdf

[4] FOLFAS, P. – UDVARI, B. 2019. Chemical industry and value-added trade – A comparative study on Hungary and Poland. In Acta Oeconomica. 2019, Vol. 69, issue 1, pp. 81-89. https://doi.org/10.1556/032.2019.69.1.5

[5] GANGNES, B. – Van ASSCHE, A. 2011. Product Modularity and the Rise of Global Value Chains: Insights from the Electronics Industry (October 24, 2011). CIRANO – Scientific Publication No. 2011, p. 64, Available online: SSRN: https://ssrn.com/abstract=1948681 or http://dx.doi.org/10.2139/ssrn.1948681

[6] GEREFFI, G. (2019). Economic upgrading in global value chains. In Handbook on global value chains. Edward Elgar Publishing.

[7] HUMPHREY, J. – SCHMITZ, H. 2002. How Does Insertion in Global Value Chains Affect Upgrading Industrial Clusters? In Regional Studies. 2002, No. 36/9, p. 1017-1027. ISSN: 0034-3404.

[8] KOLEKTÍV AUTOROV EUBA. (2019). Analýza EUBA. Analýza zameraná na identifikáciu a inovačný potenciál subdodávateľských subjektov. 224 s. [27. 07. 2019], In: https://www.economy.gov.sk/uploads/files/L7RmyFHH.pdf

[9] Kruh sa uzatvára – Akčný plán EÚ pre obehové hospodárstvo V Bruseli 2. 12. 2015 COM (2015) 614 OZNÁMENIE KOMISIE EURÓPSKEMU PARLAMENTU, RADE, EURÓPSKEMU HOSPODÁRSKEMU A SOCIÁLNEMU VÝBORU A VÝBORU REGIÓNOV.

[10] MH SR, SIEA (2017). Produktové línie pre doménu Dopravné prostriedky pre 21. Storočie, Dostupné na: https://www.opvai.sk/media/99315/produktove-linie-pre-domenu-dopravne-prostriedky-pre-21-storocie_web.pdf

[11] Monti, N.: OECD, Reviewed by Katarina Svatikova, Peter Börkey and Shardul Agrawala: Technical support for the preparation of circular economy roadmap for the Slovak Republic. Draft Background Report (November 2020) OECD.

[12] National Geographic Staff: The environmental impacts of cars, explained. 4. 9. 2019. In National Geographic. [online] Dostupné na internete ku dňu 12. 3. 2021: https://www.nationalgeographic.com/environment/article/environmental-impact

[13] Nový akčný plán EÚ pre obehové hospodárstvo Za čistejšiu a konkurencieschopnejšiu Európu V Bruseli 11. 3. 2020 COM (2020) 98 OZNÁMENIE KOMISIE EURÓPSKEMU PARLAMENTU, RADE, EURÓPSKEMU HOSPODÁRSKEMU A SOCIÁLNEMU VÝBORU A VÝBORU REGIÓNOV.

[14] OECD (+WTO). 2019. TiVA – databáza Trade in Value Added. [online]. [cit. 2021-12-19] Dostupné na: https://stats.oecd.org/Index.aspx?DataSetCode=TIVA_2016_C4

[15] OECD (and WTO). 2021. TiVA – Database Trade in Value Added. [online].

[16] OECD. 2013. Knowledge-based capital and upgrading in global value chains. Supporting Investment in Knowledge Capital, Growth and Innovation. Paris: OECD Publishing, 2013, pp. 215-25.

[17] OECD. 2015. Trade in Value – Added: Concepts, methodologies and challenges. Available online: https://www.oecd.org/sti/ind/49894138.pdf online: https://stats.oecd.org/Index.aspx?DataSetCode=TIVA_2016_C4

[18] Ochotnický, P, Káčer, M and Alexy, M (2018) Sustainability of the ELV processing system in the Slovak Republic and forecasting of waste streams from the operation of passenger motor vehicles. Waste Forum (5). pp. 452-467. ISSN 1804-0195.

[19] Ochotnický, P, et all. 2021: "Trendy štrukturálnych vplyvov elektromobility na ekonomiku SR a potenciál odpadov pre obehové hospodárstvo". In Šooš, Ľ.: Správa o postupe riešenia výskumu platformy UNIVNET za rok 2021.

[20] Ochotnický, P, a kol. 2017 in: Scenáre vývoja prúdov odpadov najmä z automobilového priemyslu do r. 2020, optimalizácia rozmiestnenia uzlov pre skladovanie a spracovanie vybraných prúdov odpadov z automobilového priemyslu. Správa I etapy výskumu Ekonomickej univerzity v Bratislave za rok 2016. Bratislava jún 2017 projektu „ integrovaná výskumná platforma zhodnocovania jednotlivých prúdov odpadov najmä z automobilového priemyslu.

[21] Podpora Slovenskej republiky z hľadiska efektívnejších zdrojov hospodárstva. Štúdia OECD, dokument o environmentálne politike č. 7. december 20127 dostupné na : file:///C:/Users/EU/Desktop/policy-paper-making-slovak-republic-more-resource-efficient-economy.pdf

[22] SZALAI, Pavol: Nová plastová daň ako príjem európskeho rozpočtu? Slovensko súhlasí. 19. 7. 2019. In EURACTIV.sk. [online] Dostupné na internete ku dňu 12. 3. 2021: https://euractiv.sk/section/obehova-ekonomika/news/nova-plastova-dan-ako-prijem-europskeho-rozpoctu-slovensko-suhlasi/

[23] Technical support for the preparation of circular economy roadmap for the Slovak Republic. Draft Background Report OECD November 2020.

[24] Šooš, Ľ. (ed.) (2020). Stav a vízie zhodnocovania odpadov z automobilového priemyslu SR. Bratislava: Spektrum STU.

[25] WALSHAW, Tim: Deriving the Laffer Curve using the concept of the excess burden of taxation. [online] Dostupné na internete ku dňu 12. 3. 2021: https://rxiv.org/pdf/1808.0551v1.pdf,

[26] ZÁBOJNÍK, Stanislav, Denisa ČIDEROVÁ a Daniel KRAJČÍK. Competitiveness in International Business: Challenges for the EU Economies. Praha: Wolters Kluwer ČR, 2020, 272 s. ISBN 978-80-7676-006-6.
[27] https://www.minv.sk/
[28] https://univnet.sk/
[29] https://www.zapsr.sk/
[30] BADIDA, M. – ŠOOŠ, Ľ. et al.: Analysis of the state, forecasts and new technologies of waste recovery in the automotive industry. - Lüdenscheid (Nemecko): RAM-Verlag pp. 190, [print]. ISBN 978-3-96595-008-5.

SmartWaste III. – Integrated information and innovation platform of recycling technologies

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3 SmartWaste III. – Integrated information and innovation platform of recycling technologies

3.1 Introduction

Change in the EU's economic structure in terms of greening the economy is not feasible without the transition to cutting-edge technologies which use materials on the basis of critical strategic raw materials. It is therefore inevitable to mobilize and separate the waste containing the specific strategic raw materials, and their significant source in Slovakia are things such as electric waste, waste from the processing of end-of-life vehicles, etc. In order to achieve the globally set objectives it is necessary to more strictly promote and observe the binding hierarchy of the waste management to increase the rate of waste recycling.

The concept of the digital platform "SmartWaste" integrates the fundamental principles of two strategic documents in the field of waste management in Slovakia. The primary document is the Waste Management Plan of the Slovak Republic. However, if we perceive waste as a long-term significant source of secondary raw materials and energy, it is legitimate to also accentuate the innovation strategy of the SR "Through knowledge towards prosperity – Research and Innovation Strategy for Smart Specialization of the Slovak Republic (RIS3)" which, within the economic specialization of the economy, identified the automotive industry and engineering as one of the priorities and has defined these development tendencies:

- increasing the added value of domestic products, especially through an efficient transfer of technologies and results of the science and research into the production process,
- development of manufacturing procedures focusing on more effective use of available resources, higher rate of recycling and use of environmentally friendly materials through the use of scientific and technological development and innovations.

The philosophy of the SmartWaste platform is based on the fundamental principles applied in the modern waste management:

- The recycling society using waste as a source of raw materials, moving away from waste disposal especially through landfills.
- Life cycle thinking, taking into consideration the entire life cycle of materials and products and not just thinking about the waste phase. This approach is reflected most notably in the definition of waste hierarchy.
- Waste hierarchy defines the order of priorities of waste management according to what is best for the environment, taking into consideration the precautionary principle, sustainability, technical feasibility, economic viability and environmental protection.
- Expanded producer responsibility as a means to promote the development and production of products which take into account and facilitate the effective use

of resources during their entire life cycle, including repair, re-use, dismantling and recycling.

- Using waste as a resource, when the sorting of waste directly at its source and its subsequent separate collection will ensure the increase of economic value of the waste as a source of secondary raw materials.
- End-of-waste, which determines the conditions under which the waste is no longer waste and may be regarded as material freely tradable on the market.
- Circular economy, which preserves the value of products and materials as long as possible in order to minimize the quantity of waste and the use of new resources, and thus promotes the separation of economic growth from the need to extract the primary raw materials. In practice, this approach is implemented through savings on materials, re-use, change of the eco-design of products and development of new products and services with reduced material intensity, or re-use in the circular cycle.

3.2 The concept of "preparation for re-use" and re-use in the policy and legal acts of the EU

The efforts made to meet the objectives of the Thematic Strategy on the prevention and recycling of waste [1] have led to the adoption of the new framework Directive 2008/98/EC on waste and repealing certain Directives (hereinafter referred to as WFD). The new Waste Framework Directive has systematically defined the environment for waste management, defined the basic concepts for the area of waste management, the entities involved in the waste management chain and their mutual relations, conditions and measures for waste management which will ensure protection of the environment and human health against adverse effects of waste generation and waste management. The application of its provisions in real practice should lead to the decrease of overall effects of the use of primary resources and, at the same time, to the increase in the efficiency of their use. The directive consistently applies the "life cycle thinking" approach, which takes into consideration the entire life cycle of materials and products and not only the waste phase. This approach has been adequately reflected in the definition of the waste management hierarchy and the principle of extended producer responsibility.

The waste management hierarchy is the backbone of policies and laws in waste management of the European Union (EU). Its primary objective is to minimize the negative environmental impacts of waste and increase and optimize the efficiency in the use of resources contained therein. The new *waste management hierarchy* (art. 4 WFD) expresses the approach generally applied in the EU's legislation in terms of waste management and defines the order of priorities for the management of waste:

1) prevention,
2) preparing for re-use,
3) recycling,
4) other recovery, e.g. energy recovery, and
5) disposal.

The hierarchy sets out five possible ways of waste management, although, "prevention" is not among the waste management tools as it applies to the life cycle phases of materials and objects before they become waste, and ranks them according to priority in terms of what is best for the environment. The "preparing for re-use" was included into the hierarchy as a new concept of EU policies related to waste and protection of the environment.

Philosophy of the hierarchy taking into account the life cycle principles is documented in **Fig. 3.1** Waste management hierarchy according to Art. 4 of the Directive 2008/98/EC on waste, which shows that the level of waste prevention is implemented in the phase of design and production, that is, before the end of life, and also that the Community aims to become a recycling society which uses waste as a source of raw materials, diverting it from waste disposal, especially to landfills.

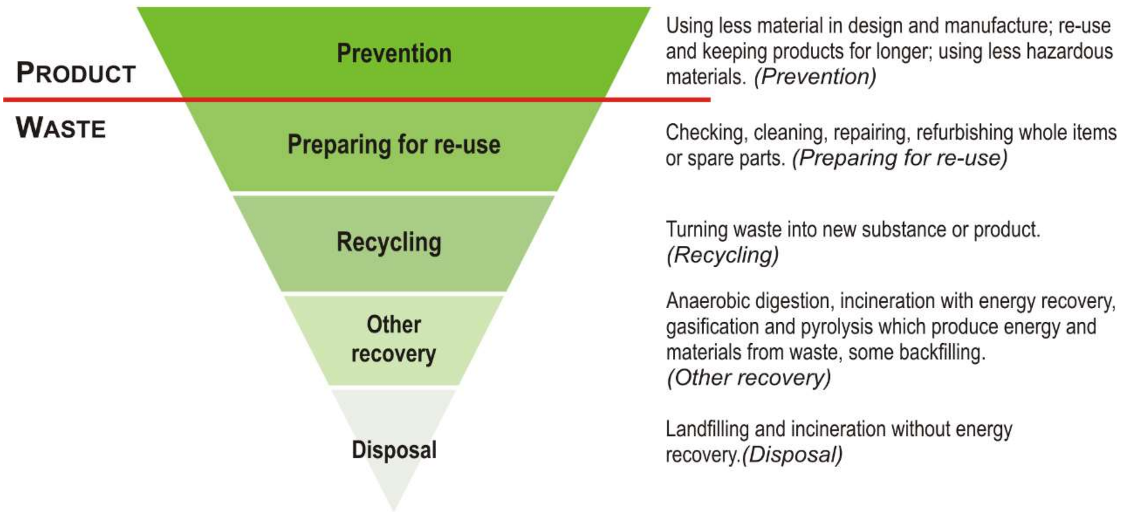

Fig. 3.1 Waste management hierarchy according to Art. 4 of the Directive 2008/98/EC on waste

The waste management hierarchy is built on fundamental concepts which are set out in Art. 3 of WFD [2]:

"*Waste*" is any substance or object which the holder discards or intends to discard or is required to discard. (Art. 3, par. 1 of WFD)

"*Re-use*" means any operation by which products or components that are not waste are used again for the same purpose for which they were conceived. (Art. 3, par. 13 of WFD)

In terms of the applied waste management hierarchy, re-use is an instrument for waste prevention. It is not a waste management operation, and it is exempt from the laws applicable in waste management. To illustrate this, when someone takes any material, for example, a functional part of a vehicle intended for disposing, directly from the current owner in order to re-use it (even if certain modifications of this part are necessary) for the same purpose, this demonstrates that this material is not waste [3].

"*Preparing for re-use*" means checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other preprocessing. (Art. 3, par. 16 of WFD)

The basic difference between the concepts of “re-use” and “preparing for re-use” is that in the first case the material or object is not waste; in case of “preparing for re-use” the material or object in question has become waste pursuant to the definition of “waste” (Art. 3, par. 1 of WFD). An example of preparing for re-use is the repair of motorcycles or electric and electronic devices that were already discarded by their owners, that is, they disposed them of at the site or in a facility designated for waste management [4].
“Recovery” is any operation, the principal result of which is waste serving a useful purpose by replacing other materials that would otherwise have been used to fulfil certain function or readiness of waste to fulfil this function in the plant or in the wider economy. (Art. 3, par. 15 of WFD)
“Recycling” is every recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations (Art. 3, par. 17 of WFD)
The term “recovery” represents the set of operations containing the sub-categories of preparation for re-use, recycling and other recovery.
“Disposal” means any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy (Art. 3, par. 19 of WFD)
The preparing for re-use is closely related to the concept of “end-of-waste status” which reflects the systematic approach applied in the EU’s legislation in the area of waste management. In other words, the specific obligations of waste producers and holders will continue to be valid until the recovery process is completed in compliance with the objectives of the WFD, that is, with the minimization of possible negative impacts of the waste on human health and environment. According to Art. 6 of WFD the specific waste is no longer waste if it undergoes recovery, including recycling, and meets special criteria which are in compliance with the conditions:

a) substance or object is commonly used for specific purposes,
b) there is a market or demand for this substance or object,
c) substance or object meets the technical requirements for specific purposes and complies with the existing laws and standards applicable to products, and
d) use of the substance or object does not lead to overall adverse effects on the environment or human health.

The compliance with the first two conditions will ensure that the object will most probably be used for a useful purpose, and it is less probable that it will be disposed of. These two conditions prevent the definition of the end-of-waste status to apply also to materials for which the market or demand is not yet created. Compliance with them indicates real trading of such substance with the normally verifiable market price paid for the substance or object, and in relation to the third condition it is the existence of standards or specifications applied in trading. The existence of recognized (accepted) standards and specifications for trading, as in the case of scrap metal, clearly indicates the end-of-waste status. The third condition lays down that the object ceases to be waste only if it is suitable for use. When a substance ceases to be waste, it should be governed by laws applicable to products, therefore, the end-of-waste status may only be applied if its use is in compliance with the law. Indicators of compliance with this condition include compliance with certain technical standards applicable to products used for the same purpose. The end-of-waste status is not to be applied if the substance or object under consideration requires special measures and processing, which would not be required for the same products placed on the market [5]. The fourth condition defines that the use of materials or objects does not require the application of waste legislation [6].

The end-of-waste criteria do not exclude materials from the recycling process. If the material does not meet the end-of-waste requirements, it does not automatically mean that it cannot be recycled and must be disposed of. Materials not compliant with the end-of-waste requirements may be recycled and further used in the treatment of waste.

A direct implementation of the concept of end-of-waste status is the adoption of the Council Regulation (EU) No. 333/2011, setting out the criteria for determining when the iron, steel and aluminum scrap, including aluminum alloy scrap, cease to be waste according to WFD. In order for the metal scrap holder to become a so-called "producer" pursuant to this Regulation, according to Art. 6, they must have a *certified quality management system in place*, by which they are able to prove the compliance with criteria for the relevant scrap metal. The quality management system will include a set of documented procedures related to:

a) inspection upon the receipt of waste to be used as input for recovery operations,
b) monitoring of processes and processing techniques,
c) monitoring of the resulting quality of recovery operations,
d) feedback from customers in relation to the quality maintenance of the metal scrap,
e) keeping records of the monitoring results,
f) revisions and improvements of the quality management system,
g) personnel training.

Verification of the quality management system in place should be carried out every three years by conformity assessment bodies defined in the Regulation (EC) No. 765/2008 of the European Parliament and of the Council, setting out the requirements for accreditation and market surveillance relating to the marketing of products, or by environmental verifiers accredited according to the Regulation (EC) No. 1221/2009 of the European Parliament and of the Council on the voluntary participation by organizations in a Community eco-management and audit schedule (EMAS).

One of the instruments to support the prevention of waste generation and strengthen re-use, recycling, and other recovery without compromising the free circulation of goods on the internal market, has been the introduction of the *extended producer responsibility* (Art. 8 of WFD), which applies to every natural or legal person, who, in the course of his or her professional activity, develops, produces, processes, treats or imports products.

The principal concepts and approaches concentrated in the framework directive, which relate to the prevention of waste generation by promoting the re-use and the reduction of the quantity of waste through preparation for re-use, are summarized in Article 11 of WFD. Although the directive leaves it up to the member states to decide which procedures and instruments they will use to promote re-use and preparation for re-use, it also sets out specific objectives because it foresees that "by 2020, preparation for re-use and recycling of household waste, such as paper, metal, plastics and glass, and, if possible, also from other sources, provided that these sources contain similar waste as household waste, will increase to a minimum of 50% by weight".

3.3 Preparing for re-use and re-use in the conditions of the Slovak Republic

Waste management in the Slovak Republic is governed by laws which incorporate the legal acts of the European Union and also the generally binding legal acts of the European Union – regulations with direct effect on the EU member states and require no transposition to the legal system of the member state. The principal and currently applicable law governing the waste management is the Act No. 79/2015 Coll. on Waste and on the amendment to certain acts (hereinafter referred to as the Act on Waste) which transposes the Directive No. 2008/98/EC of the European Parliament and of the Council on waste. Therefore, the analysis of establishing a system for the re-use and other methods promoting the circular economy in Slovak environment is based on the provisions of the applicable Act on Waste with emphasis on the changes it introduced.
The issue of re-use in Slovakia was only addressed formally rather than systematically and the reasons for this were and still are various. Within the considerations about further procedure in the support of re-use and preparation for re-use, or about the establishment of centers and networks with this mission, it is again necessary to point out the difference between these activities in terms of legislation. Schematic illustration of this difference is shown in Fig. 3.2.

As seen in the results from Fig. 3.2, in terms of the life cycle and in accordance with the definition according to the WFD, re-use belongs to the product management phase and is governed by the standards and laws for the production and placement of products on the market [7]. The system of re-use is suitable for used products either directly from their current owner or as reusable products, which, after the process of preparation for re-use, comply with the requirements for products, and therefore they are no longer governed by the laws regulating the waste management, but their circulation is governed by the relevant laws for placement of products on the market. Used products according to Fig. 3.2 can be defined as products which had already been used or operated, but ceased to be used later on, and were not identified as waste. For example, obsolete or surplus products and devices, demonstration items, products and devices that were the subject of complaints, second-hand used devices or reusable products put into circulation, etc.

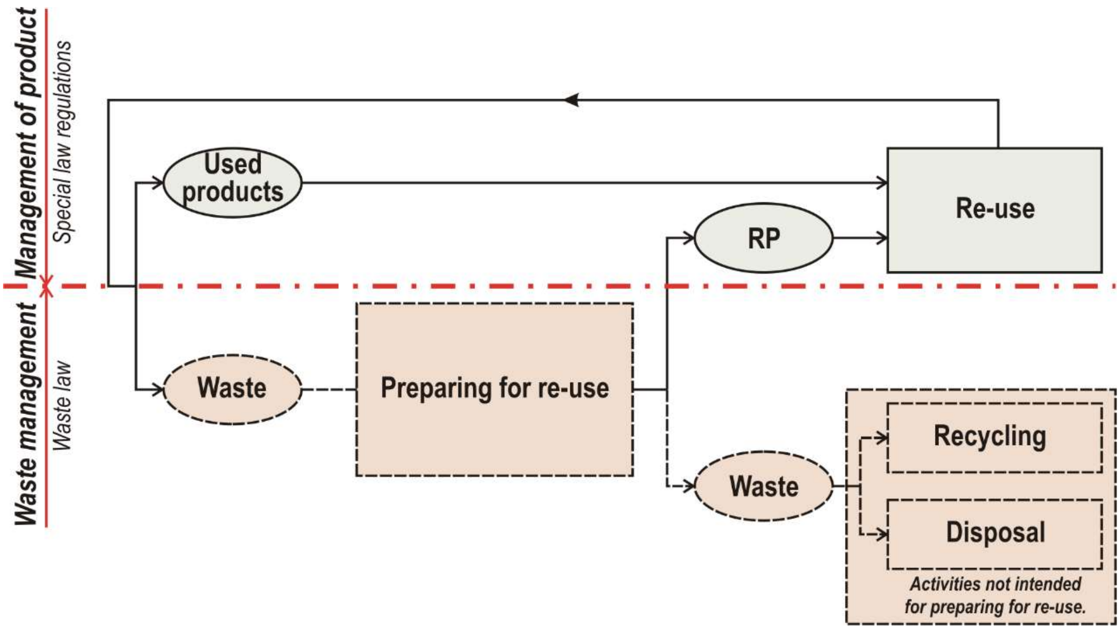

Fig. 3.2 Comparison of the preparing for re-use and re-use with regard to the legislation

Preparation for re-use, Fig. 3.2, is a process applied to the substance or object that are at the end of their life cycle and have become waste pursuant to the definition in WFD, as in their owner discarded them at the site or facility designated for waste management. The process of preparation for re-use is therefore suitable where it meets certain qualities so that, after the end of the process, it complies with the criteria specified for the transition from the waste phase to the product circulation phase. Where the substance or object do not meet the requirements defined for the end-of-waste status, they may be further recovered and used within the waste treatment regime. All operations carried out in relation to the preparation for re-use are subject to treatment governed by waste management laws.
Re-use on the basis of used products offered by their owners for further use, whether or not for remuneration, is currently also carried out by things such as donating or in the form of sales in "second-hand" type of shops or bazaars.
Another issue is the recovery of waste in the process of preparation for re-use which results in a reusable product meeting the criteria for its placement on the market. The theoretical possibility that an object transfers from the waste phase to the phase of what is called a usable object, but not usable in terms of its placement on the market, can now be available for businesses through the consent with waste supply to be used in households (Section 97 (1)(n) of the Act on Waste). However, this consent is mainly used for the supply of fuel wood for the heating of households. Fig. 3.3 provides an indicative overview of the sub-groups and quantities of waste which has been the subject of consent to transfer waste to be used in households.

Can this consent also be used by local governments? We will assume that the basic characteristics and conditions of operation of the waste collection facilities, would be preserved, according to the Act on Waste.

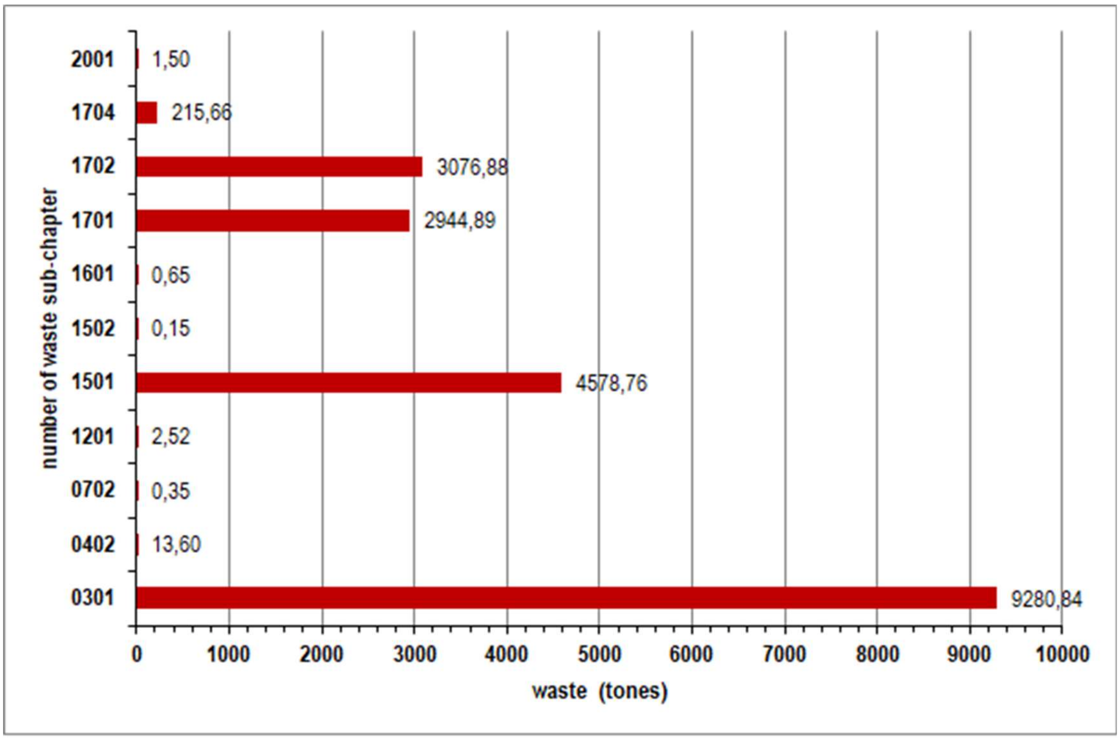

Fig. 3.3 Waste that was the subject of a consent with waste transfer for use in households. Source: Slovak Environment Agency, 2012

This means that the definition of municipal waste according to Section 2 (14) and also Section 39 (2) according to which "the municipality is responsible for the management of municipal waste generated within the territory of the municipality, and for the management of minor construction waste generated within the territory of the municipality". As results from the above, the waste collection facility can only take waste (Section 2 (1)) from the citizens residing in the given municipality. Collection of this waste is free of charge or for a fee paid by the citizen. Here, the waste is not purchased from the citizen (as in the case of secondary raw material collection facilities) because the municipality would already need consent for the collection according to Section 97 (1)(d).

The present Act on Waste directly states in its Section 2b (2) that "Certain specific waste ceases to be waste even when it undergoes the preparation for re-use or is supplied as waste suitable for use in households (Section 19 (8))".
In this context it is again noteworthy that as the instrument to demonstrate compliance with the end-of-waste criteria, the Commission chose the implementation of a quality management system which must be verified every three years by bodies that assess conformity as defined in Regulation (EC) No. 765/2008 of the European Parliament and of the Council, setting out the requirements for accreditation and market surveillance relating to the marketing of products, or by environmental verifiers accredited according to the Regulation (EC) No. 1221/2009 of the European Parliament and of the Council on the voluntary participation by organizations in a Community eco-management and audit scheme (EMAS).

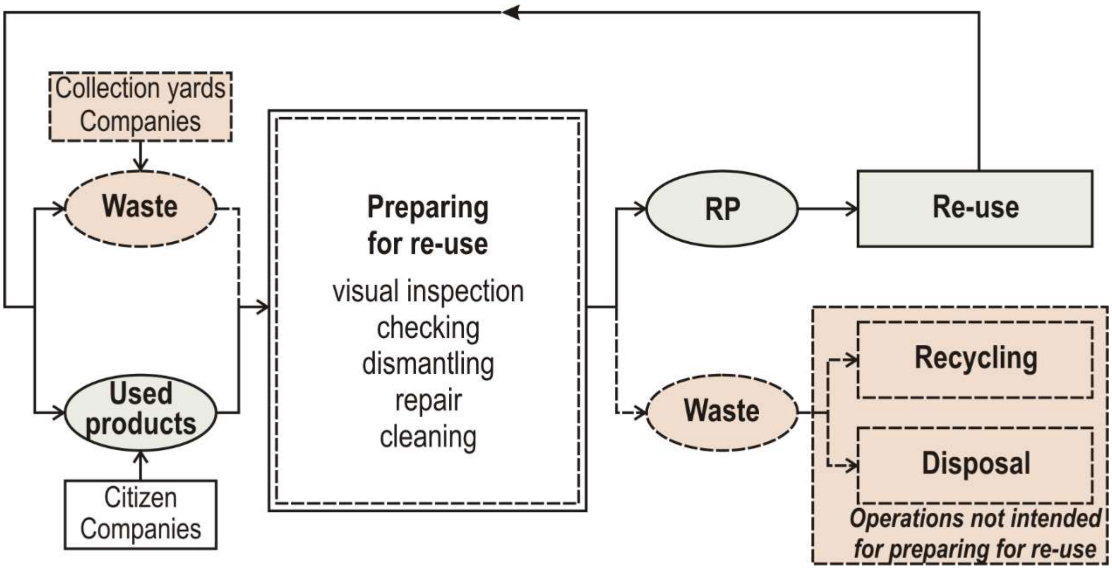

Fig. 3.4 Schematic illustration of the model of product re-use and preparation for re-use of products or their parts which became waste (RP – reusable products)

The issue of implementing quality management systems, whether standardized or documented (tailor-made), is also relevant, especially when there are centers for re-use, where the output of the re-use preparation operation is the product which will be placed on the market again. Ensuring managed and controlled conditions to achieve a permanent and reproducible level of required quality is therefore necessary. The quality management system should cover all phases of the process of preparation for re-use, from the inputs, applied processes and techniques, up to the quality of the final product, and the criteria should be set in such way that the waste which is only suitable for recycling or disposal, is excluded from the process. For inputs it is necessary to set criteria, for example, for the separate collection of specific waste, which should be the subject of preparation for re-use, in order to eliminate its contamination. Another set of criteria should apply to the management and control of the process of preparation for re-use, including the selected key operations, which are critical for achieving the specific result meeting the prescribed standards applicable to the given product. It is obvious that the process of preparation for re-use is carried out within the treatment of waste. Therefore, the set criteria should enable the management, monitoring and control of the entire process, as well as its individual steps, in order to be able to prove that the final result meets the relevant standards and ensures the prescribed level of protection of human health and environment when it is no longer handled as waste.
The quality management system itself does not guarantee the quality of the final product, but it can ensure the consistency of applied processes in the entire processing chain. Since it is impracticable to strictly prescribe the specific quality management system, it is necessary to require such a system which includes the critical steps of the process, and which will demonstrate compliance with all end-of-waste criteria. Finding the suitable methodology for proving the end-of-waste status also indirectly results from the essentials of consent to the preparation for re-use, in which it is required to state the description of operations related to the preparation for re-use and method of use of the

products or product components which have undergone the preparation for re-use. The introduction of quality management systems for this type of consent facilitates not only the activity of the authorizing authorities, in which case a uniform decision-making procedure is ensured, but also of the state supervision authorities within waste management, who should bear the burden of inspections, since the operations of preparation for re-use will be carried out within the treatment of waste. Many non-profit organizations in Germany and Austria, which actively operate within the area of re-use, are for instance, certified according to the standard ISO 9000 or ISO 14000 [8], [9].
One of the commodities suitable for re-use and the potential of which should be utilized, is the waste from electrical and electronic equipment (WEEE), which forms an important part of modern cars, but only so long as sufficient control of quality and safety of the reusable products placed on the market is ensured. The model of re-use and preparation for re-use within the electric and electronic equipment and waste from electrical and electronic equipment is presented in Fig. 3.5. The schematic contains the term, used electrical and electronic equipment (UEEE), which applies to electrical and electronic equipment that have already been used or operated, but stopped being used later on and, at the same time, was not marked as waste. These may be, for example, obsolete or surplus products and devices, demonstration items, products and devices that were the subject of complaints, second-hand devices, etc.

If we compare Fig. 3.4 and Fig. 3.5, it is obvious that the scope of operations within the process of preparation for re-use is extended, for example, by an electric safety test or deletion of data and software. As regards the initial source of waste, returns or complaints currently seem suitable, since the conditions of collection ensure that the initial quality of WEEE will guarantee at least a certain level of success in the process of preparation for the reusable product (REEE). The use of waste from electrical and electronic equipment in the process of preparation for re-use is a good example of the need for the application of quality management system as a control tool.

List of abbreviations

RP	reusable products
UEEE	used electrical and electronic equipment
REEE	reusable electrical and electronic equipment
WEEE	waste from electrical and electronic equipment
WFD	Directive 2008/98/EC of the European Parliament and of the Council on waste and repealing certain directives (OJ L312/3)

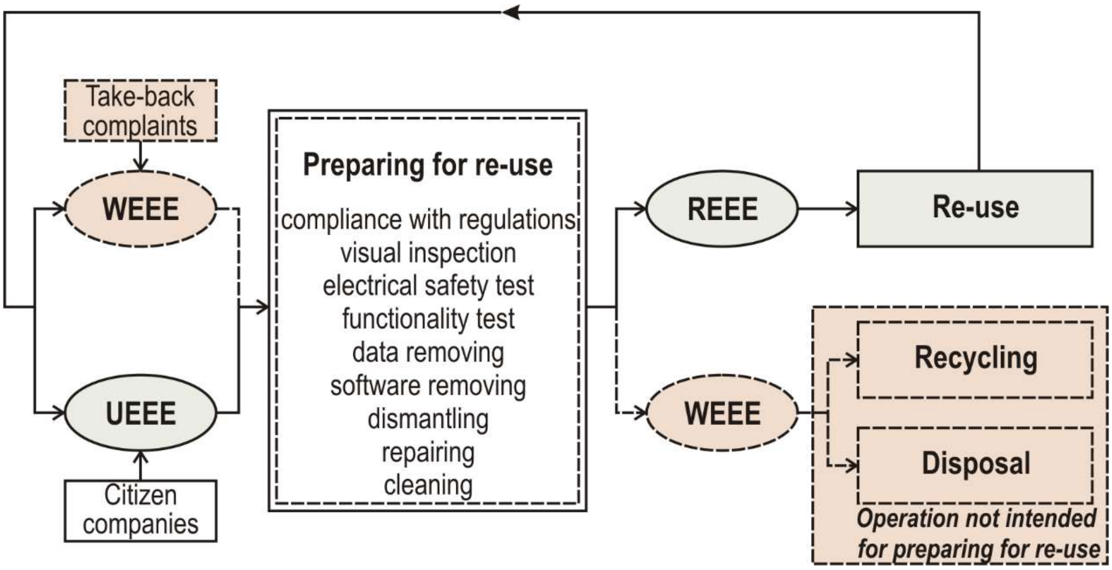

Fig. 3.5 Schematic illustration of the model of re-use and preparation for re-use of electric and electronic equipment and waste from electrical and electronic equipment

3.4 Conclusion

Waste management today is facing several significant trends which substantially affect the current business model. Global warming, pollution in the seas and oceans, circular economy and intensive development of digital technologies of Industry 4.0 redefine waste management. Implementation of the circular economy policy moves the waste management closer to the concepts of the management of resources and makes it an integral part of the global resource markets. The digital platform "SmartWaste" represents a tool which will promote the transformation of waste management into compliance with the objectives of the circular economy and opportunities brought by Industry 4.0.

Acknowledgements

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3.5 Bibliography

[1] Oznámenie Komisie Rade, Európskemu Parlamentu, Európskemu Hospodárskemu a Sociálnemu Výboru a Výboru Regiónov: Presadzovanie trvalo udržateľného využívania zdrojov - Tematická stratégia predchádzania vzniku odpadu a jeho recyklovania (KOM/2005/666).

[2] Directive 2008/98/EC of the European Parliament and of the Council on waste and repealing certain directives. [2008] OJ L312/3.

[3] Guidelines on the interpretation of key provisions of Directive 2008/98/EC on waste. European Commission, Directorate-General Environment, 2012, 74 s. (dostupné na: http://ec.europa.eu/environment/waste/framework/pdf/guidance_doc.pdf).

[4] Guidelines on the interpretation of key provisions of Directive 2008/98/EC on waste. European Commission, Directorate-General Environment, 2012, 74 s. (dostupné na: http://ec.europa.eu/environment/waste/framework/pdf/guidance_doc.pdf).

[5] Delgado, L. et al.: End of Waste Criteria: Final Report. Luxembourg: Office for Official Publications of the European Communities, 2008, 379 s. (dostupné na ftp://ftp.jrc.es/pub/EURdoc/JRC53238.pdf)

[6] Delgado, L. et al.: End of Waste Criteria: Final Report. Luxembourg: Office for Official Publications of the European Communities, 2008, 379 s. (dostupné na ftp://ftp.jrc.es/pub/EURdoc/JRC53238.pdf)

[7] Napr. zákon č. 264/1999 Z. z. o technických požiadavkách na výrobky a o posudzovaní zhody a o zmene a doplnení niektorých zákonov; zákon č. 90/1998 Z. z. o stavebných výrobkoch; zákon č. 250/2007 Z. z. o ochrane spotrebiteľa a o zmene zákona Slovenskej národnej rady č. 372/1990 Zb. o priestupkoch v znení neskorších predpisov; a pod.

[8] Arold, H. – Koring, C.: An Investigation and Analysis of the Second-Hand Sector in Europe. Bremen: ITB, 2006, 96 p. (dostupné na http://www.rreuse.org/t3/fileadmin/editor-mount/documents/Leonardo-SH-Sector/LSH004-European-Sector-Analysis-Report-english.pdf)

[9] Quality management in Reusing/ Recycling Social Enterprises. RREUSE, 2006, 108 p.

[10] BADIDA, M. – ŠOOŠ, Ľ. et al.: Analysis of the state, forecasts and new technologies of waste recovery in the automotive industry. - Lüdenscheid (Nemecko): RAM-Verlag pp. 190, [print]. ISBN 978-3-96595-008-5.

Recycling of laminated glass
Construction of line modules for the decomposition of multilayer laminated glass

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4 Recycling of laminated glass – Construction of line modules for the decomposition of multilayer laminated glass

4.1 Introduction

The content of the presented third report follows the report of 2019 and 2020. The **content of the report from 2019** [5] was the mapping of the quantities of waste from the multi-layer laminated sheets of glass and the analysis of available technologies for the decomposition of the specified glass, the possible uses of individual secondary raw materials from these wastes, as well as the economy of recycling and recovering of these wastes. The analysis of waste quantities from the multi-layer laminated sheets of glass has shown that based on estimates of ZAP SR, there are approx. 3 600 tonnes in Slovakia and the total annual available waste of flat glass from construction is approx. 13 200 tonnes, [1]. The analysis also pointed out the fact that the recovery of such sheets of glass is currently very problematic. Although approximately 40% of the total amount is recovered, the extractability with the use of current technologies is only 60 – 65%. This means that from the waste in a total amount of 16 800 tonnes, only approx. 6 700 tonnes are processed and only 4 000 – 4 400 tonnes of secondary raw materials are gained from this amount. This corresponds only to 26% of the total amount of waste. The rest, 12 400 tonnes of such waste, is deposited at landfills.

The second report from 2020 [6] focused on the verification of known analyzed principles from the report drawn up in 2019 and experimental verification tests. The aim of this part of the research was the comparison and SWOT analysis of the available technologies. There are a range of various types of technologies in the world. These technologies are mainly dry, wet, chemical combined thermal/chemical. Based on literature references, in order to achieve perfect separation and extraction of pure laminate phases, only the wet method of glass layer separation from the foil is suitable, as it uses a reverse effect of the bonding technology – the adhesion to the glass increases with the decreasing humidity of the foil. However, these technologies are very expensive. Moreover, their applicability on damaged windshields is significantly complicated.

The results of analysis have shown that the classic mechanical technology for the disintegration of glass and subsequent separation of individual commodities of the laminated glass is cheap, but the currently known technologies are very noisy, dusty, and not very effective. Even though there is demand for the foil and glass fragments, glass and chemical plants do not want secondary raw materials that are incompliant for the required purity criteria. The extractability of clean glass fragments and foil with the use of the specified technologies is only 50 – 60%. The remaining non-separated waste is deposited at landfills.

The second most important result of the report from 2020 was the experimental laboratory verification of the known technologies. Based on the results of laboratory tests, the conclusion of the paper includes an outline of the authors’ own affordable technology for small and medium-sized outputs with a yearly capacity of 1 000 – 2 000 kg. The working hypothesis of the decomposition of multiplayer sheets of glass in such way as to eliminate disintegration of the glass waste within the decomposition process, is crucial. Within this process the glass should be separated by its breaking and subsequent stripping and scraping off of the glass fragments in such way that the foil remains intact, if possible, [7].

The aim of the present third report from 2021 is the presentation of production documentation, production of individual modules and the overall variant concept of the line for the decomposition of waste laminated glass. The designed modules, as well as the variant solutions, are the result of laboratory tests. The proposed variant solutions are affordable and designed according to the exact requirements of the client for various types, layers, and dimensions of the processed waste glass.

4.2 Design of laminated glass recovery technology

For mechanical separation, the windshield is crushed with the use of an input line which is equipped with a crusher capable of crushing the glass from passenger cars and lorries, as well as from buses and trucks. Conveyors and separators then carry the material and ensure sorting out of metals and other impurities. Small parts of the glass are transported to a set of optical detectors where the impurities, parts of car foil and sealing rubber, etc. are removed from the crushed glass. This processing method includes the formation of glass dust which can be contaminated with foreign substances and no longer represents a pure raw material for the glass industry. The resulting PVB foil does not always have the required (100%) purity, its further use is therefore limited.

The dry method was developed by the company ZIPPE Industrieanlagen, [2] and it is based on mechanical stripping of the glass using a dry procedure. The result of this process is only pure glass; the PVB gained using this method contains a high amount (10 – 20%) of glass dust and other non-homogenous particles (dust, paper or plastics). For this reason, such foil is landfilled.

The nature of the proposed principle of high-efficiency decomposition of waste laminated glass, [7] is based on the fact that the sheets of waste laminated glass are not crushed into small fragments, foil is not broken, but remains intact in its original state and individual fractions of the broken glass are gradually separated from the foil. The processed waste glass is gradually broken in the transverse and longitudinal direction between two pairs of breaking profile cylinders, after that, in the next module, these broken undivided sheets of glass are shaken between the vibration tool with pyramid-shaped points in the shape of a strip and the smooth rolling cylindrical tool, and finally, in the next module, the remaining glass fragments stuck to the PVB foil are stripped by the stripping cylinders.

4.3 Structural design of individual modules

4.3.1 Receiving module

The first technological module, the so-called feeder module, consists of two cylinders between which there is an adjustable gap according to the thickness of the processed

glass (Fig. 4.1, Fig. 4.2). These cylinders are driven by an interlocking gear. This module has several basic functions: it provides smooth intake of the glass and its adjustable feeding to the next module; it ensures flattening of rounded car glass for further processing; thanks to the designed cylinder profile the module ensures primary uniform and very dense crushing or breaking of the glass without damaging the PVB foil by which it significantly reduces the glass strength before further processing and streamlines its separation from the PVB foil in the next operations thanks to the significant reduction of adhesion between the layers of glass and foil.
The arrangement of intake cylinders and their coupled drive with flexible pushing is shown in the drawing Fig. 4.1. Fig. 4.2 shows the axonometric view of the implemented structure design of the receiving module.

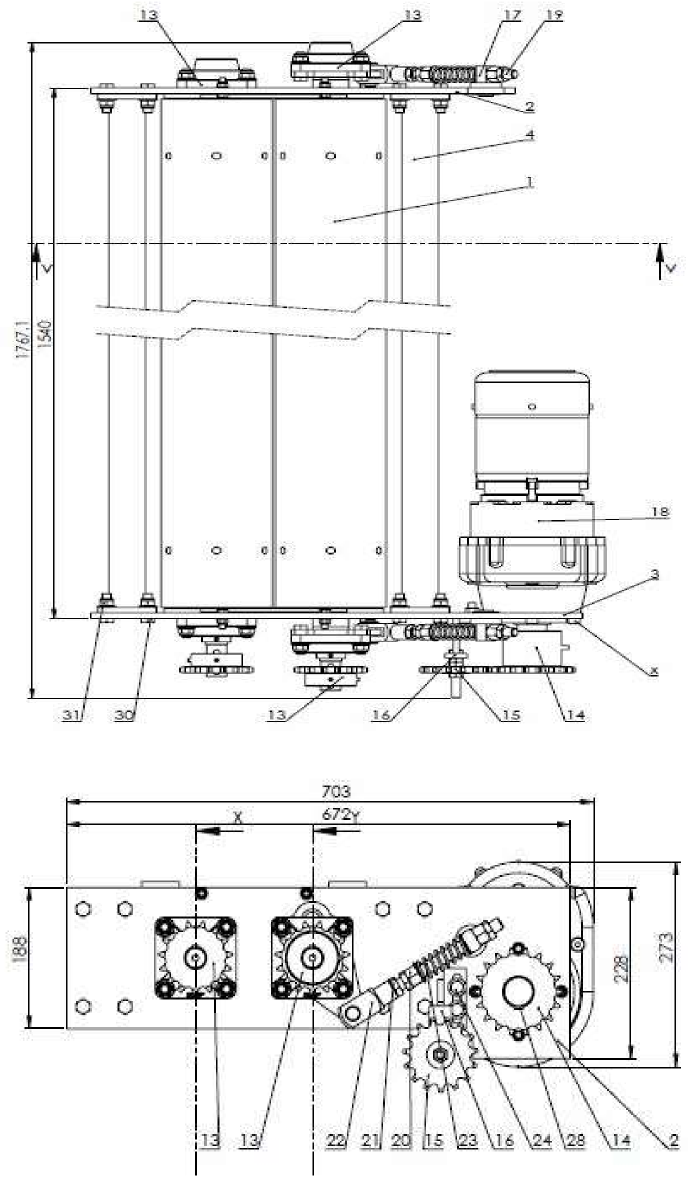


Fig. 4.1 Drawing of the receiving module assembly with the adjustable gap and flexible pushing of the intake cylinders, [5]

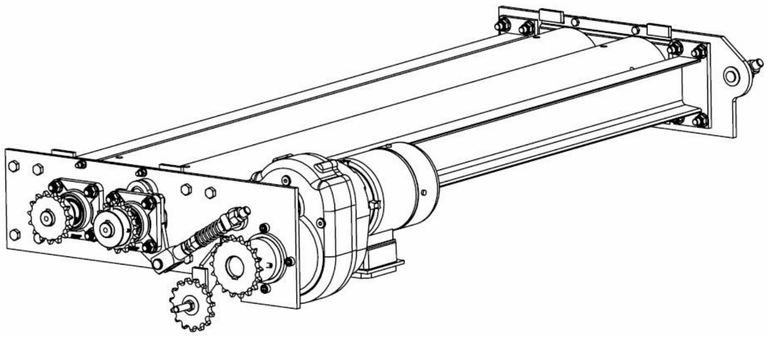


Fig. 4.2 Axonometric view of the receiving module, [5]

4.3.2 Breaking module

The developed secondary module, also called the breaking module, is the technological follow-up for the pre-treated glass as the output from the receiving module. The arrangement options of various types of breaking wheels are shown in Fig. 4.3. The profiling of breaking cylinders 1 (Fig. 4.3) is designed in such way that the wheels with larger convex diameter alternate with wheels with smaller concave diameter. The cover of one breaking cylinder 1 with smaller diameter fits into the cover of the second breaking cylinder 2 with larger diameter forming a gap between them comparable to the thickness of laminated glass. The shape of longitudinal profile and length of these cylinders can easily be changed by the exchange of these wheels which are fitted onto these cylinders. Breaking cylinders are driven by a coupled drive from a separate electric motor, (Fig. 4.4). One breaking cylinder of every pair of cylinders is coupled with an adjusting mechanism for adjusting the gap between the breaking cylinders of every pair, which is shown in Fig. 4.4.The specified implemented structural design of the primary breaking module.

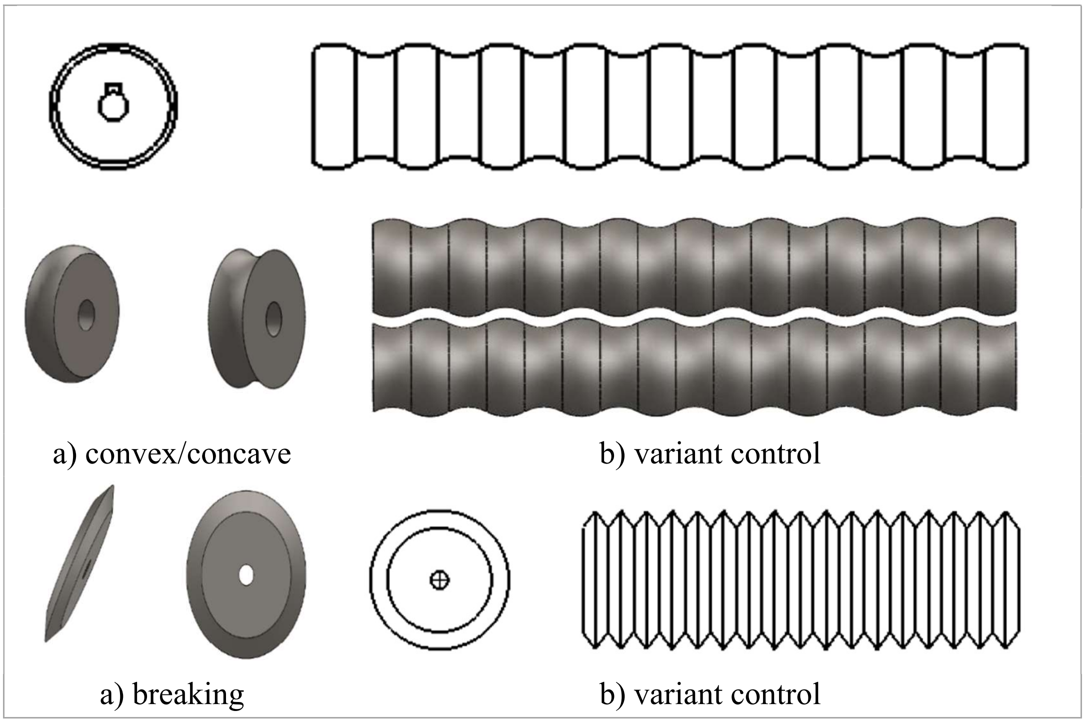


Fig. 4.3 Arrangement of cylinders in the breaking module

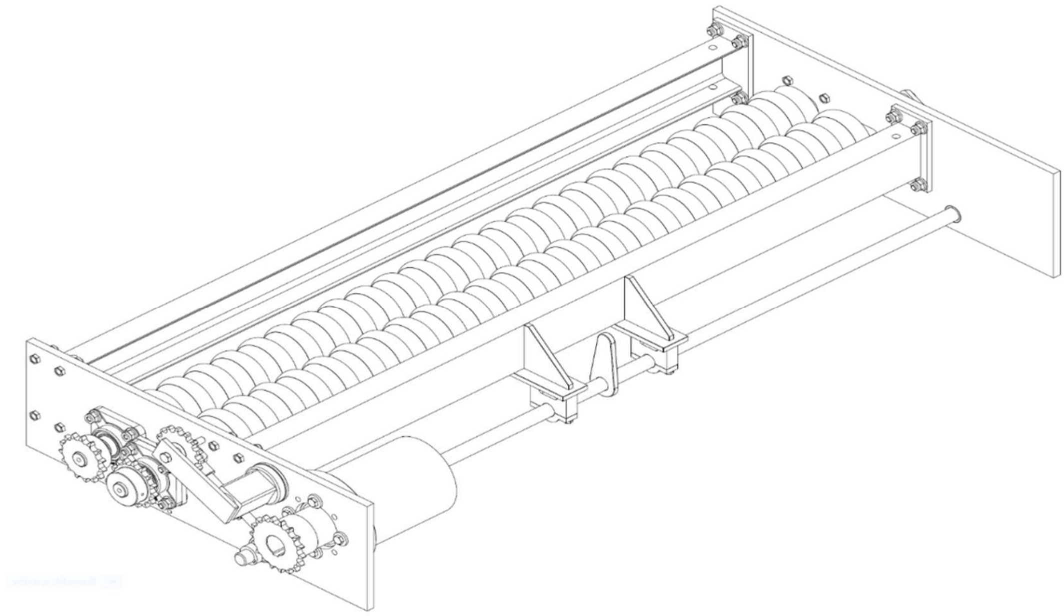


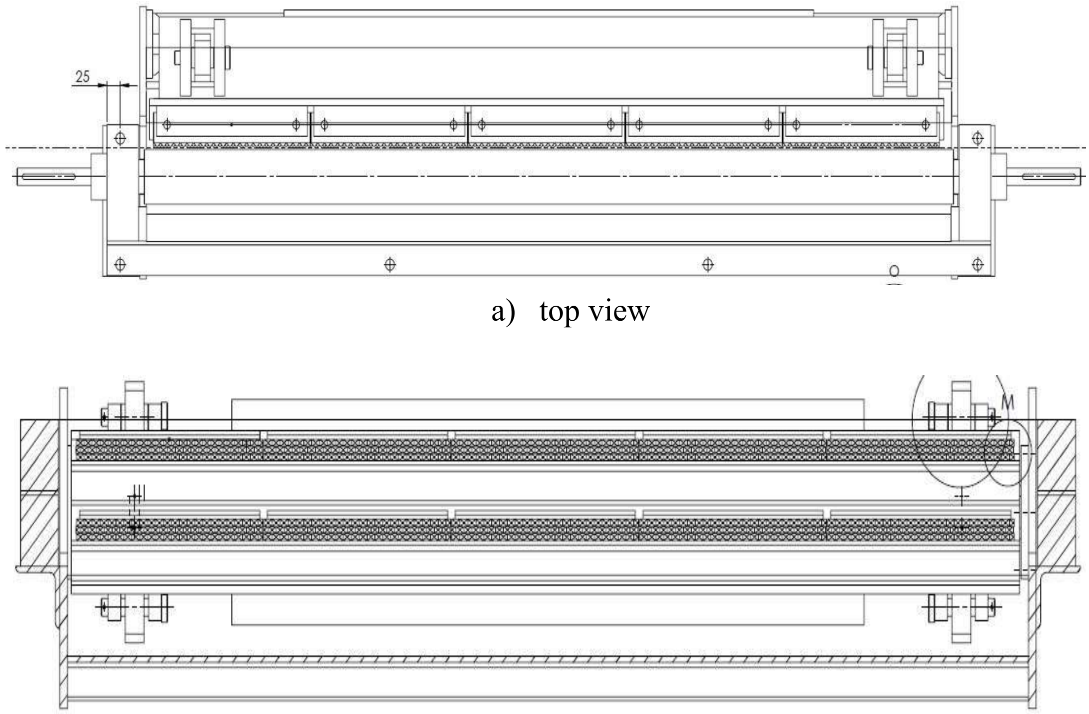
Fig. 4.4 Two cylinders in the breaking module, [6]

4.3.3 Vibration module

Based on the results of the first stage, we have designed a functional laboratory model of the "hammering-vibration" device. The second stage of experimental works continued with tests on the laboratory model of the vibration device which was constructed for this purpose at the research site. The functional part of the laboratory machine consists of two plates. One is firmly fixed to the base, while the second is flexibly connected and fitted with the vibrating electric motor. The contact edges of both plates are fitted with shape profiles from angle irons or rebars.

Based on the results of the laboratory tests, we have designed the third, or grinding module, a technological module that receives the pre-treated glass as the output from the breaking module. The principle of its operation is in the vibration hammering of glass between the pyramid-shaped tools and rolling smooth cylindrical tools, which ensure the continuous and uniform movement of the processed glass (Fig. 4.5 a). The module includes tools in two rows above each other (Fig. 4.5 b). Smooth cylinders are driven by frequency-controlled gears. The process of hammering the glass from foil is ensured by pyramid-shaped tools moving in a straight reverse direction induced by an industrial vibrator.

Fig. 4.6 shows the structural design of the vibration module in the form of a three-dimensional model. The developed and manufactured modules are able to work independently as well as together with the smooth follow-up of the technology. Their mutual movements and cooperation may be connected thanks to the frequency-controlled drives of individual cylinders as well as the frequency of the applied industrial vibrator.



a) top view

b) two rows above each other

Fig. 4.5 Vibration module, [7]

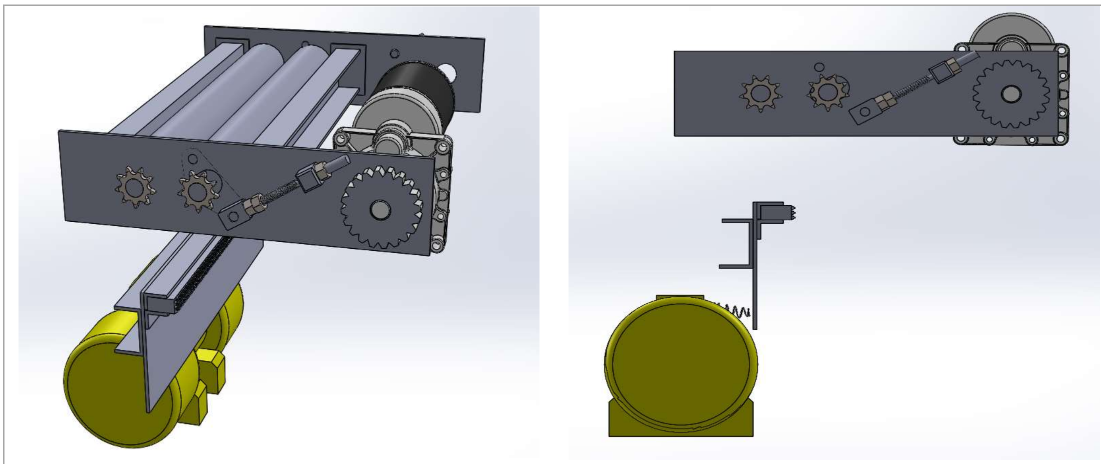


Fig. 4.6 Variant solution of the vibration module, [2]

4.3.4 Stripping module

The principle of operation of the stripping module is similar to the principle of operation of the feeding module. The only difference lies in the fact that the breaking or stripping wheels are not inserted onto the basic shafts, Fig. 4.7.

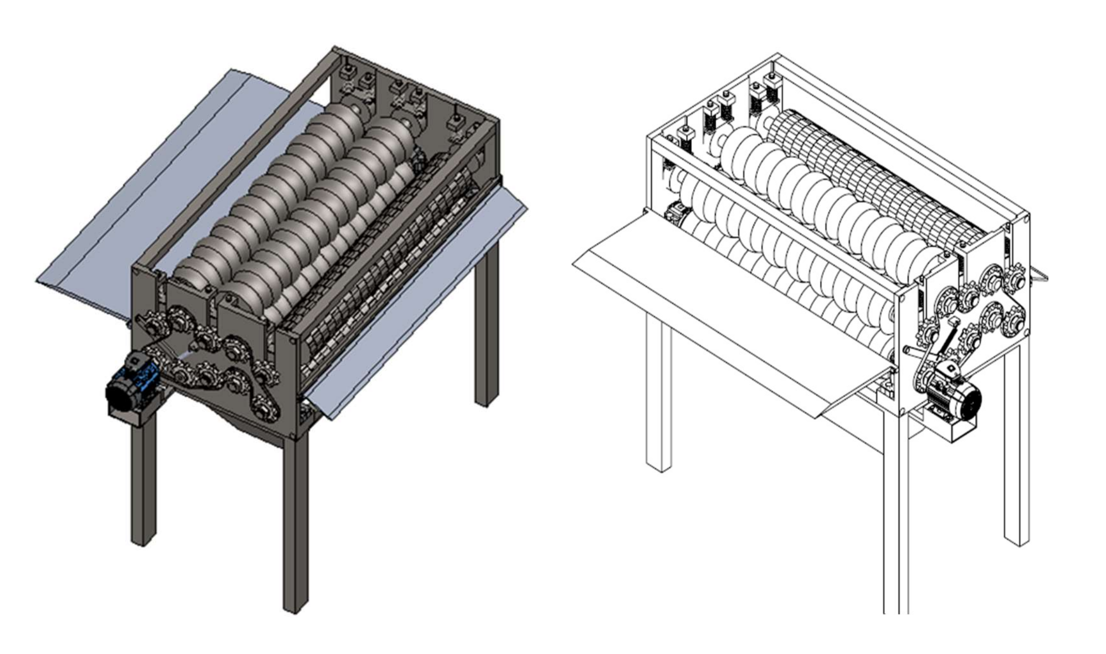


Fig. 4.7 3D multiple arrangement of the breaking pairs in combination with the pair of stripping wheels, [7]

4.4 Production of individual modules

4.4.1 Receiving module

Fig. 4.8 Receiving module prototype

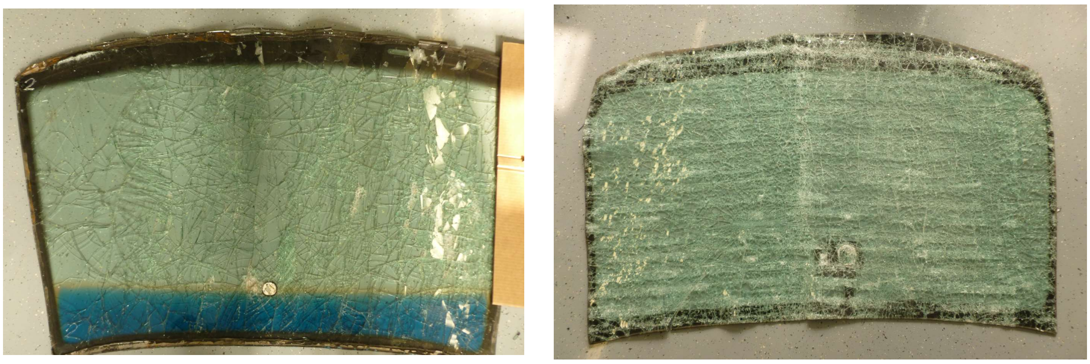
Fig. 4.8 shows the constructed receiving module. In order to ensure better intake of the waste glass, we have welded smooth strips onto the smooth cylinders. Tests have demonstrated that welding of the strips significantly improved the intake. The welded strips also partially assist in breaking of the glass.

4.4.2 Breaking module

Fig. 4.9 Breaking module prototype

Fig. 4.9 shows the breaking module. Frame of the machine is constructed from U-profiles. Rotation of the individual cylinders is ensured through a motor with transmission and chain gear. The horizontal and vertical spacing of the cylinders may be adjusted with adjusting screws.

The first tests of the breaking module have already demonstrated the correctness of the designed structure. Fig. 4.10 shows the windshield after first rolling; Figure 10b shows the windshield after third rolling. The efficiency of the rolling module is clear from individual samples.



a) after 1 rolling b) after 3 rollings

Fig. 4.10 Front windshield

4.4.3 Vibration module

The aim of the designed vibration module is to provide the best possible separation of the broken glass from the foil. The principle of operation in the vibration module is in the hammering of glass between the pyramid-shaped tools and rolling smooth cylindrical tools, which ensure the continuous and uniform movement of the processed glass. The vibration module includes tools in two rows above each other. Smooth cylinders are driven by frequency-controlled gears. The process of hammering the glass from foil is ensured by pyramid-shaped tools moving in a straight reverse direction induced by an industrial vibrator. Fig. 4.11 shows the structural design of the vibration module.

4.4.4 Stripping module

We plan to complete the system of modules with the stripping module, Fig. 4.12. Its manufacture is not yet completed. However, its structure will be very similar to the structure of the breaking module with the difference that the stripping wheels will be inserted onto the bearing cylinders, Fig. 4.13.

Fig. 4.11 Structural design of the vibration module

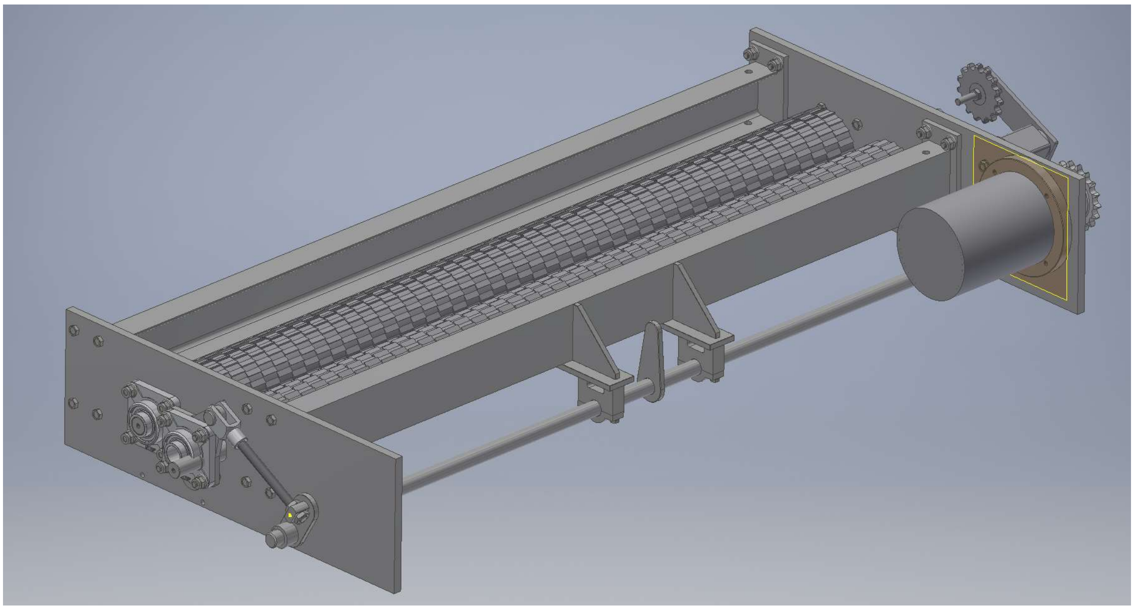
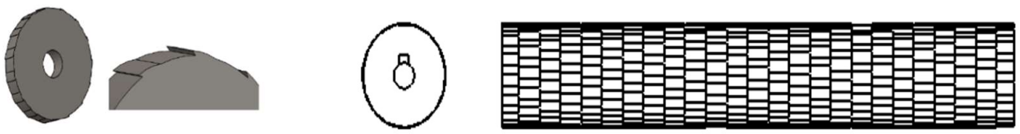


Fig. 4.12 Stripping module, [7]



a) convex/concave b) variant control

Fig. 4.13 Arrangement of cylinders in the stripping module

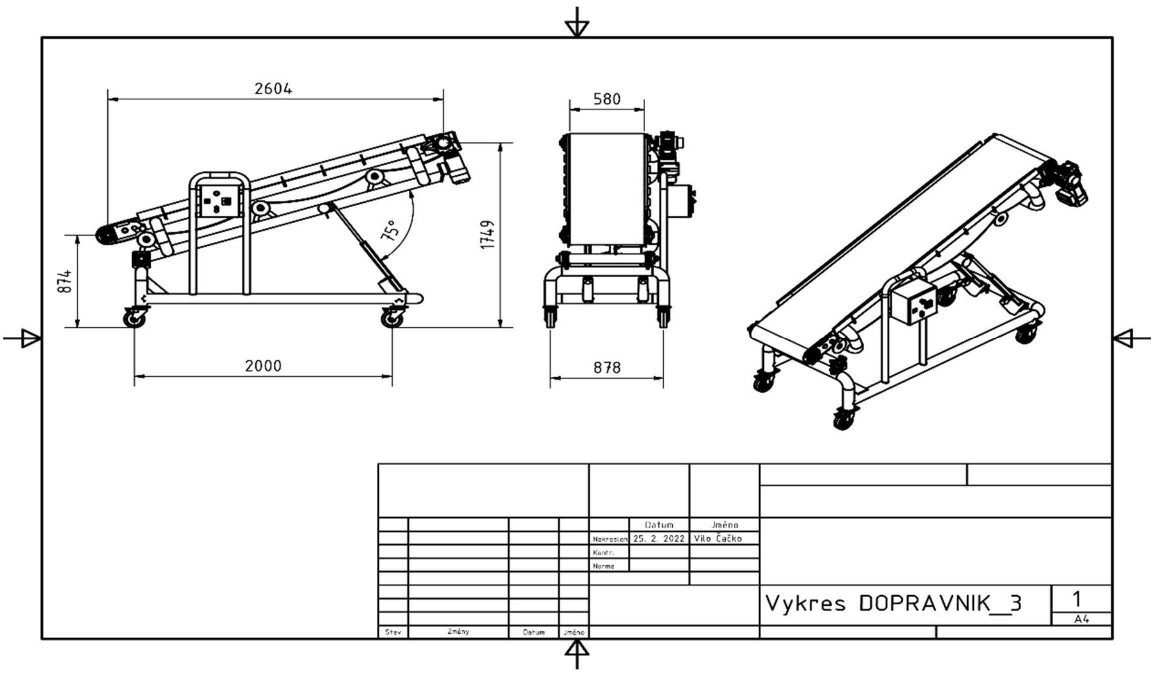


Fig. 4.14 Example of the designed conveyor

The line will also include conveyors (Fig. 4.14) and containers for crushed glass. Individual additional components will be manufactured according to specific requirements and available space of the future customer.

4.5 Variant solution of the line

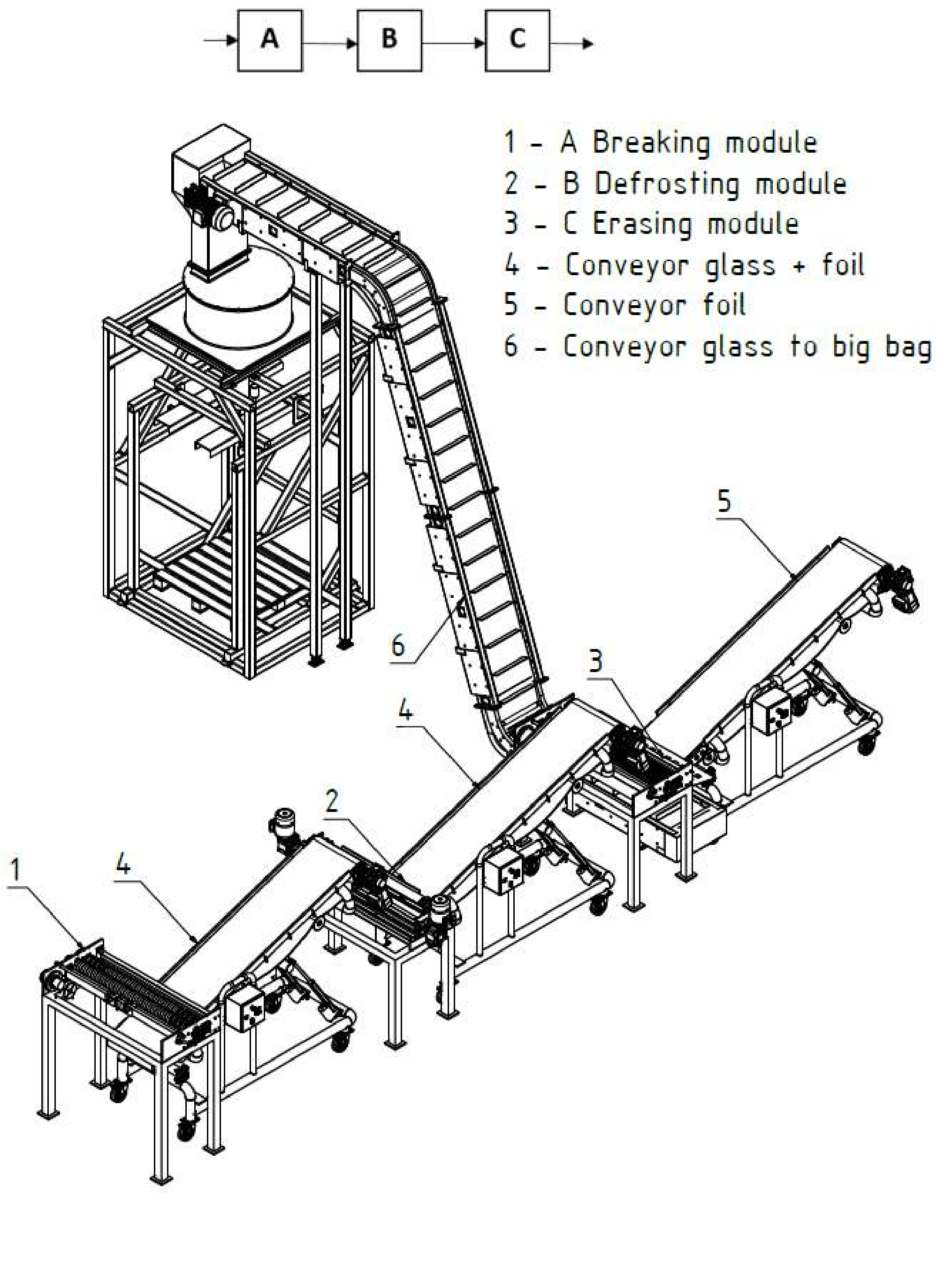
The structure of the designed technological equipment for the processing of waste laminated glass is based on the fact that it consists of a multi-stage set of variable modules. Thanks to this important feature, it is possible to process laminated sheets of glass of various thicknesses, dimensions, or even multilayer laminated glass using a single piece of equipment. This way it is possible to create new variable configurations for the specific requirements of individual customers. The described modules are able to work independently as well as together with the smooth flow of technology. Their mutual movements and cooperation may be connected thanks to the frequency-controlled drives of individual cylinders as well as the frequency of the applied industrial vibrator. On one hand, individual customers will get their machines made to measure, and on the other hand, the module design enables a wide application of these machines in the processing of waste laminated glass, especially in the construction and automotive industry [3, 4].

The structural design of the line is designed with a strong emphasis on modularity. Thanks to this important feature, it is possible to process laminated sheets of glass of various thicknesses, dimensions, or even multilayer laminated glass using a single piece of equipment. Individual modules can be arranged one after another, multiple times. Where there are thick and multilayer laminated sheets of glass, it is possible to use several breaking modules arranged one after another in order to achieve an even, dense, horizontal crushing of the glass and thus significantly reduce the strength and adhesion forces between the glass and foil. Similarly, according to the type of the laminated glass, it is possible to arrange several vibration modules one after another. In the operation, vibration modules should be arranged against each other in pairs in order to achieve the separation of glass from foil on both sides by just a single passage of glass through the machine. In case of thicker glass and glass from a higher number of layers, it will be more appropriate to arrange several pairs of vibration modules one after another in order to increase the efficiency of glass separation and achieve better cleanness of the PVB foil.

If necessary, this modular technology of processing waste laminated glass can be completed with other components. For example, this involves blowing the remaining glass dust particles from the PVB foil with air flow through a set of air jets located behind the stripping module.

4.5.1 Minimum configuration of the line

In the minimum configuration (Fig. 4.15), the line consists of one breaking module (A), where the glass is broken in a transverse and longitudinal direction between two pairs of breaking profile cylinders. The second module of the line is the shaking vibration module (B), where the broken and still undivided sheets of glass are shaken between the vibration tool with pyramid-shaped points. The last module of this minimum configuration is the stripping module (C) where the PVB foil is mechanically cleaned by the effect of various frequencies of stripping cylinder rotations.



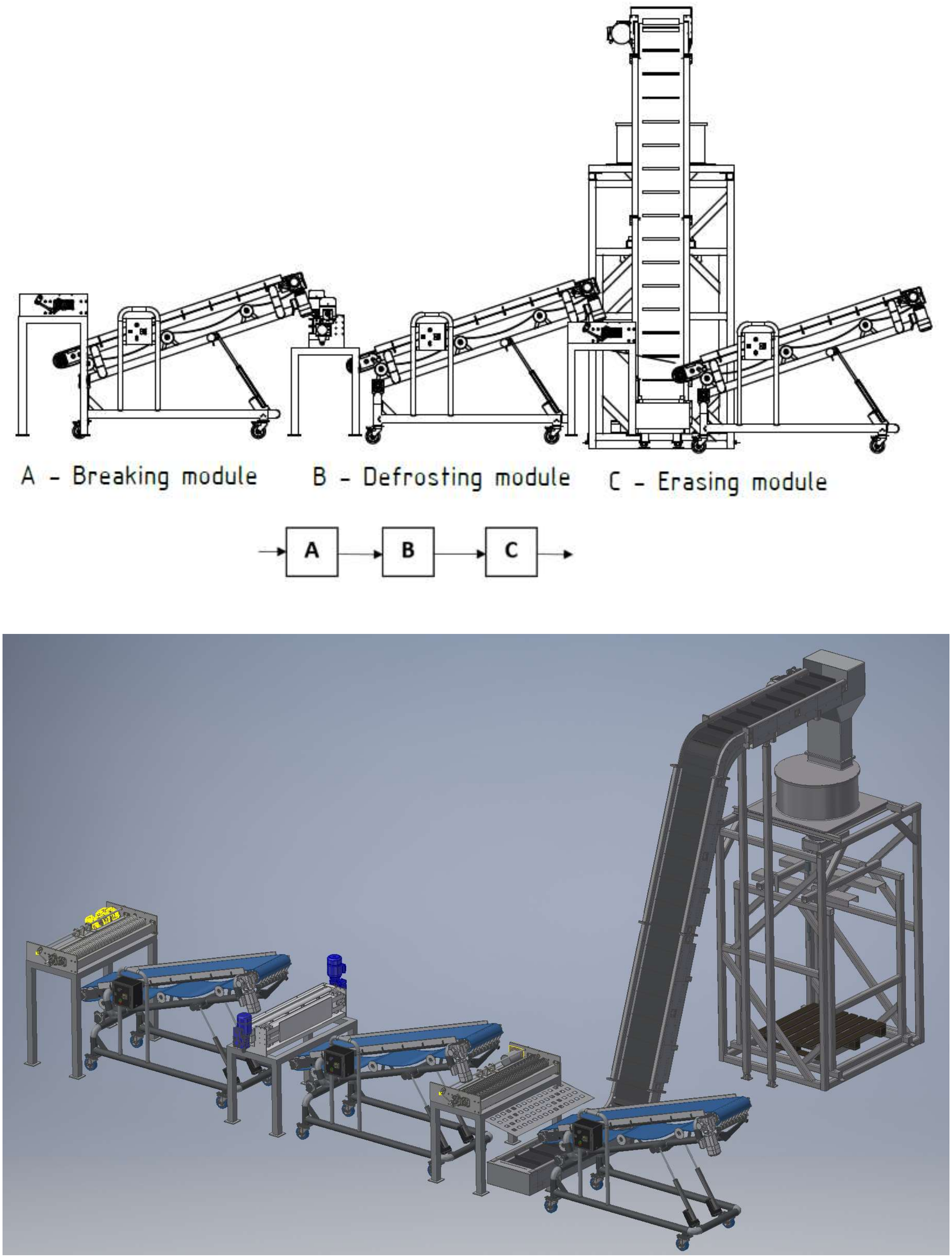
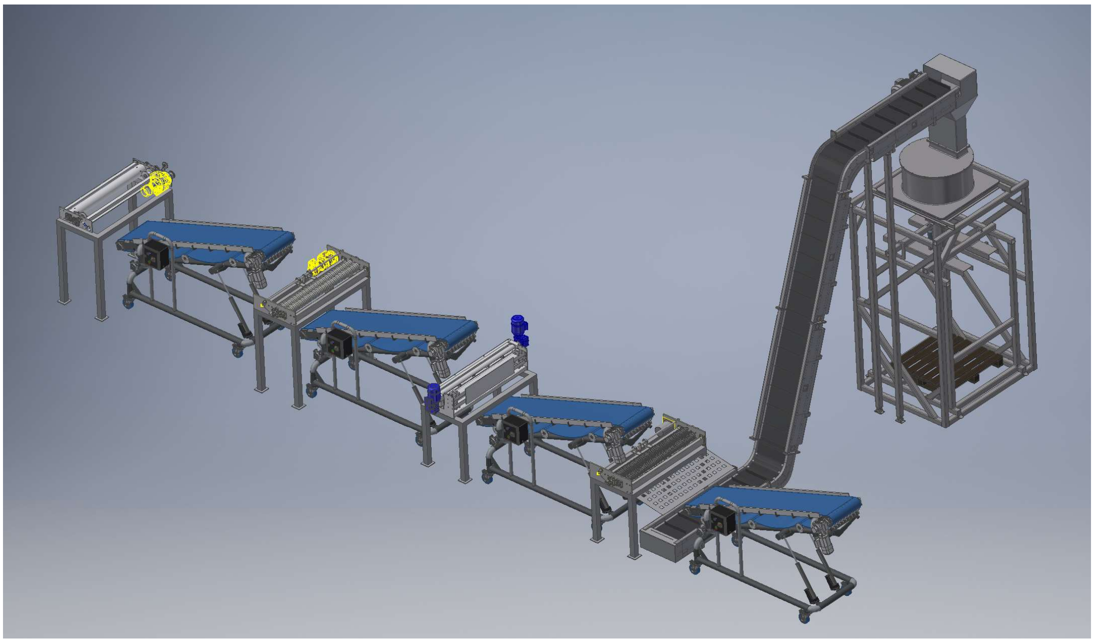
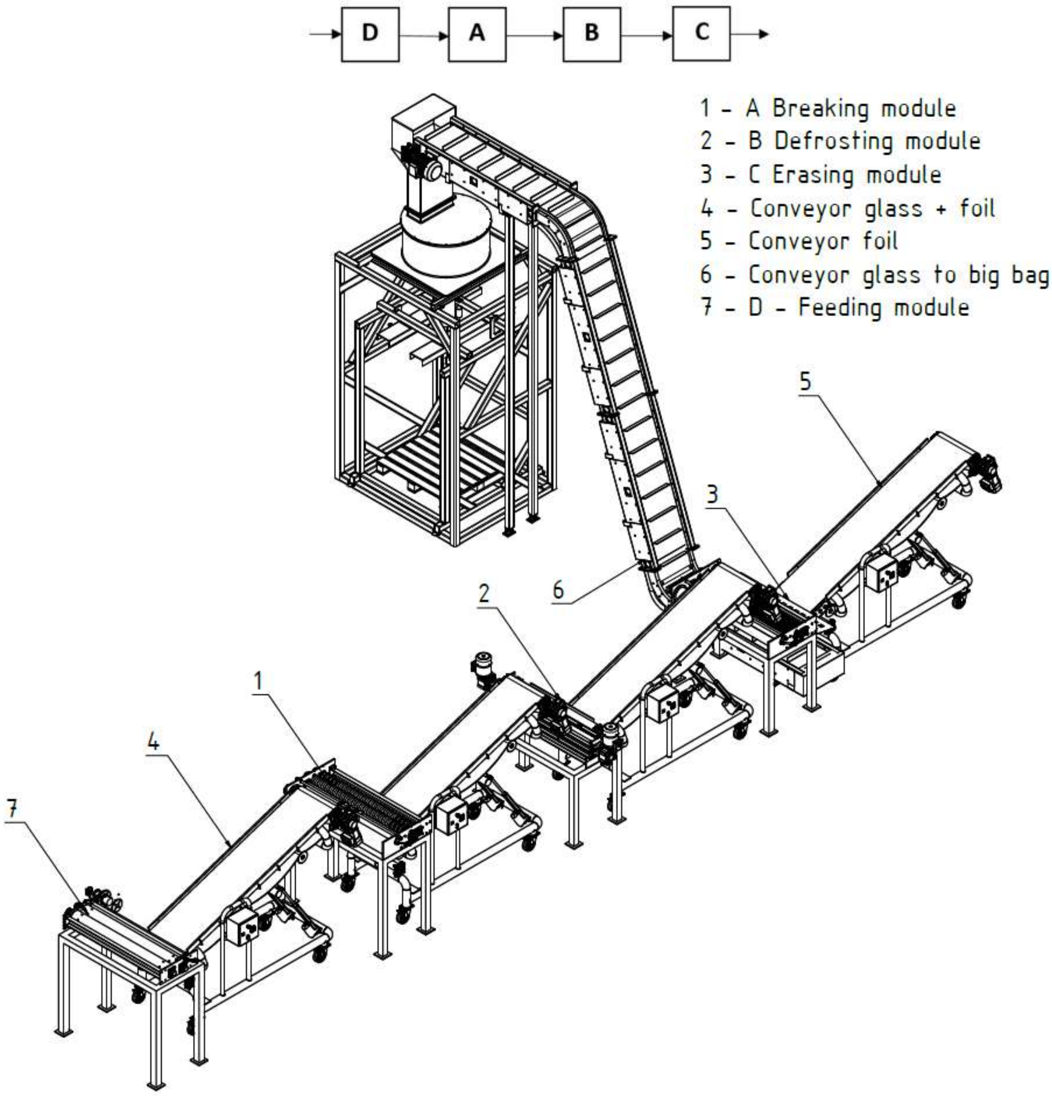


Fig. 4.15 Minimum configuration of the line

The advantage of the following horizontal arrangement of the line is the simple change or addition of individual modules. Another advantage is the fact that it is not necessary to build an overall load-bearing structure of the line. Higher requirements for the spatial arrangement may be a disadvantage.

4.5.2 Line configuration with feeder module





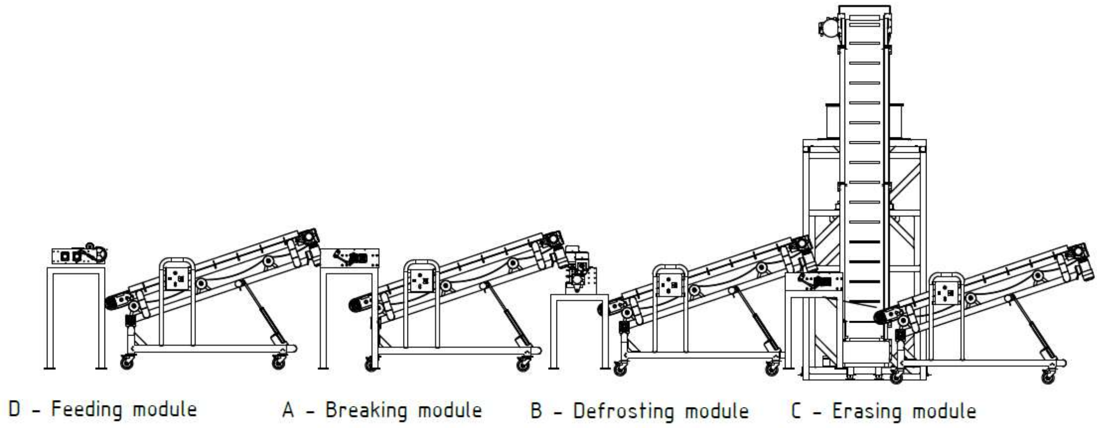
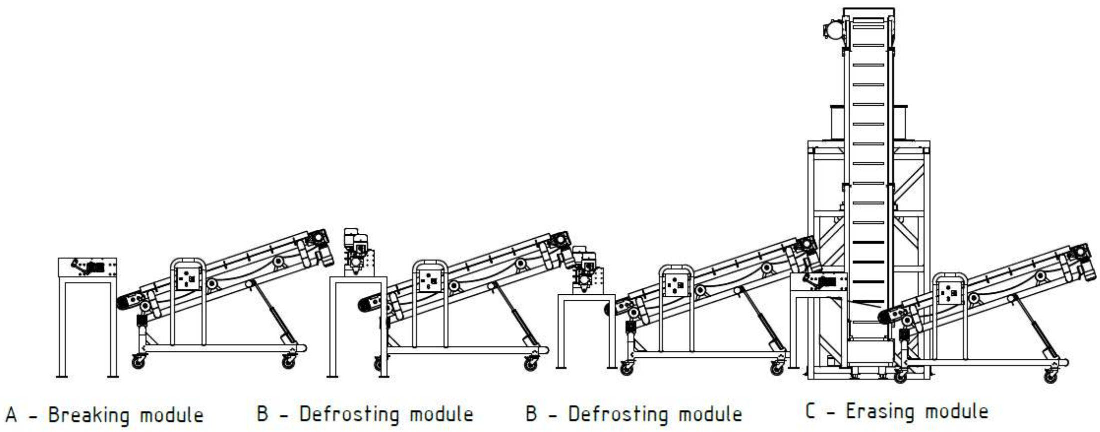


Fig. 4.16 Minimum configuration of the line

The benefit of completing the basic configuration with this module is the fact that the processed waste glass in this module is spatially oriented and even partially flattened. When a glass passes through this module, it is also broken to a certain extent.

4.5.3 Line configuration with two vibrations – shaking modules

This configuration includes two vibration modules, Fig. 4.17. The aim of this configuration is to increase the efficiency of cleaning the foil. Sufficient space is a prerequisite for achieving this level of cleanliness, as is, to a certain extent, the entire line's performance.



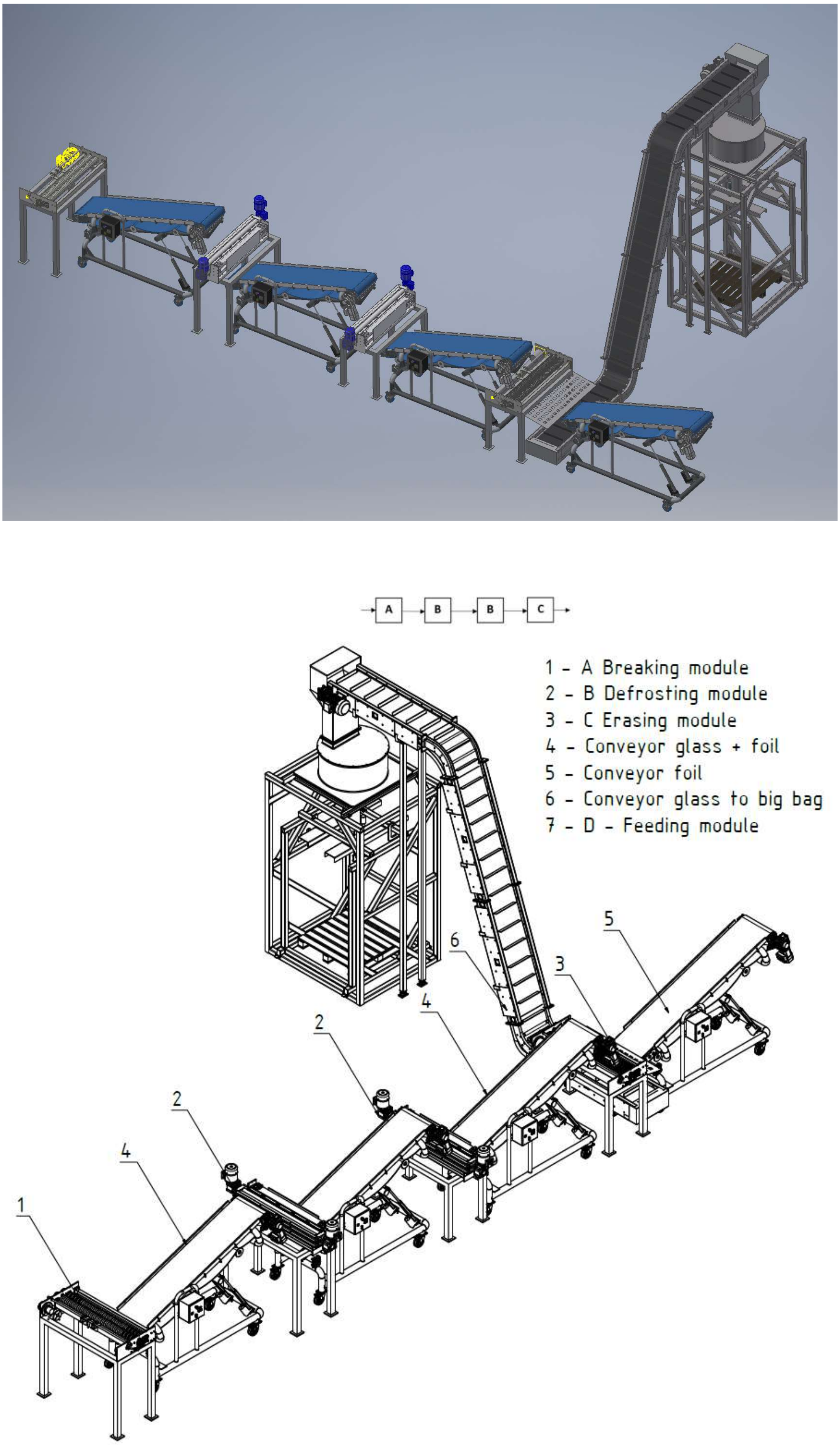


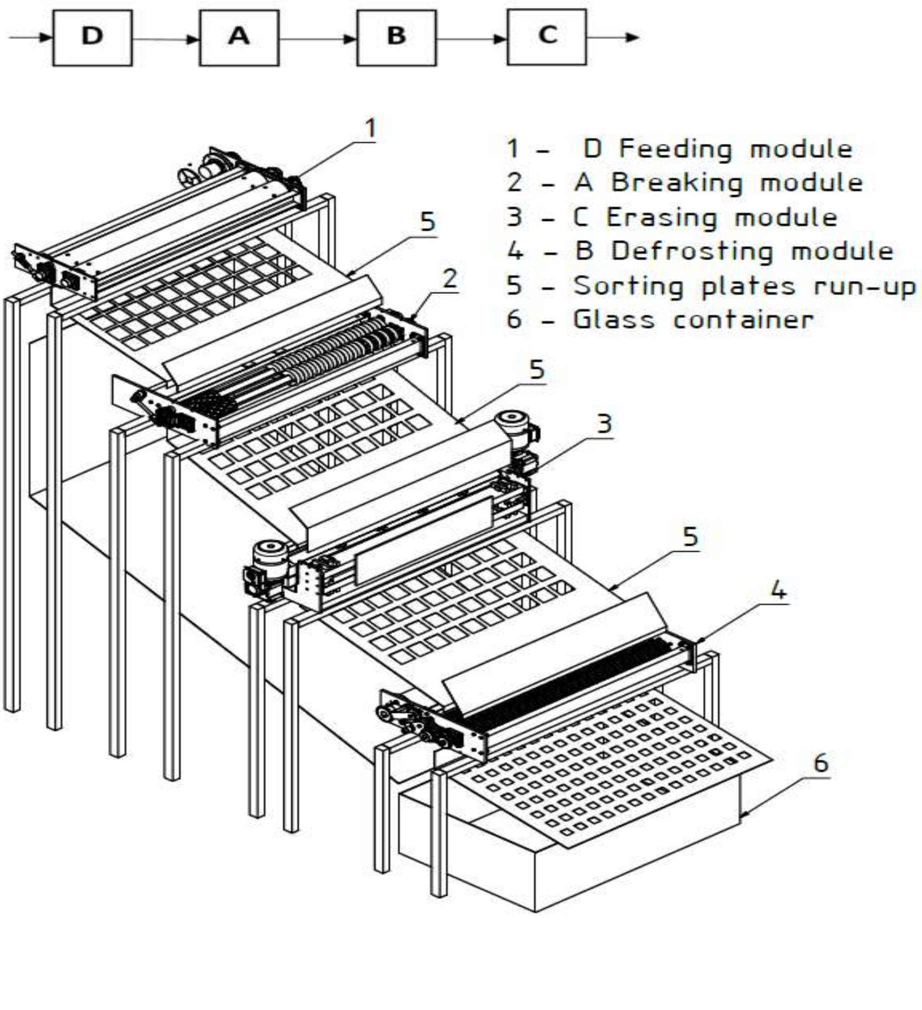
Fig. 4.17 Line configuration with two vibration – shaking modules

4.5.4 Vertical arrangement of the line

The specified line can also be arranged in vertical configuration. The advantage of vertical arrangement is:

- reduced spatial requirements (length and width of the shop) since individual modules are arranged partially one over the other,
- better removal of shards as they fall into the containers through sieves into the bins,
- lower energy intensity; movement of waste glass between the modules is ensured by gravity without any powered conveyors.
- Disadvantages of this configuration include:
- necessity of a higher shop height, as the shop must have sufficient height for the arrangement of the modules,
- necessity of constructing a bearing structure of the line given by the requirement for spatial arrangement of modules.

Fig. 4.18 shows the example of vertical arrangement of the line; Fig. 4.19 shows the example of vertical arrangement of the line with service platform.



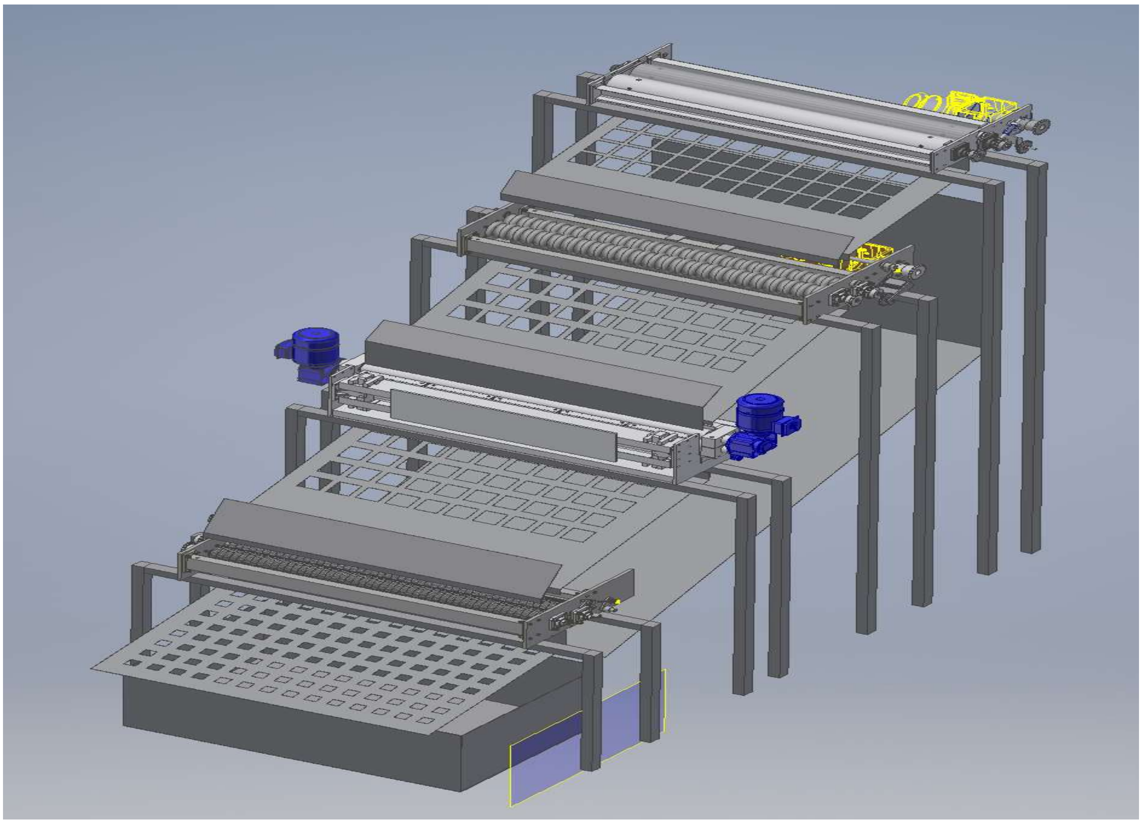
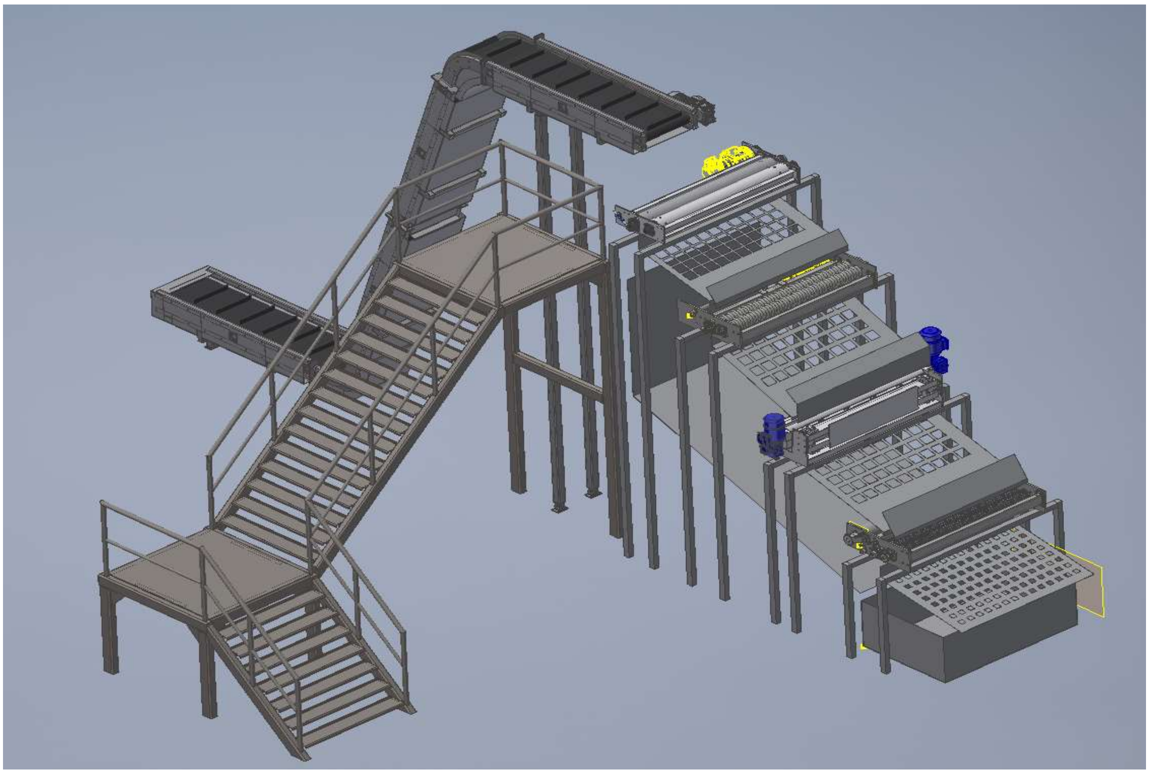


Fig. 4.18 Vertical arrangement of the line



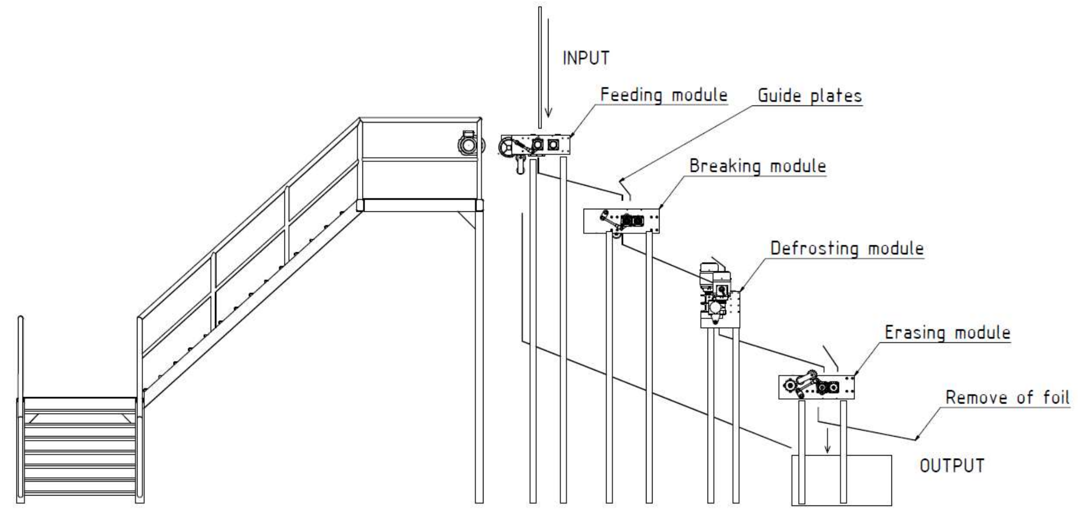


Fig. 4.19 Example of the vertical line arrangement with service platform

4.5.5 Extended arrangement of the line

As has been already mentioned, the line provides many possible configurations customized according to specific needs of the customer. This is true for the type of processed waste glass, spatial arrangement of the line, as well as for the required output of the line. For thick and multilayer laminated glass, multiple modules can be installed in a row Fig. 4.20, [3, 4]. In order to increase the processing capacity and the cleanliness of the procured foil, the line configuration is completed with the washing module where the PVB foil is washed in a warm water solution.

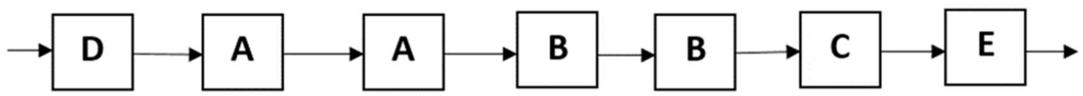


Fig. 4.20 Example of an extended line configuration
D – receiving module, A – breaking module, B – vibration module, C – stripping module, E – washing module

4.6 Conclusion

The aim of the present report is to document the yearly progress in the research of the technology for the recovery of waste glass. The results of analysis carried out in the first year of the project have shown that the classic mechanical technology for glass disintegration and the subsequent separation of individual commodities of the laminated glass is cheap, but the currently known technologies are very noisy, dusty, and not very effective.

The objective of the second year of research was the experimental laboratory verification of the known technologies. Based on the results of laboratory tests, we have designed our own affordable technology for small and medium-sized outputs with a yearly capacity of 1 000 – 2 000 kg. The basic idea of the designed technology was the working hypothesis of the decomposition of multiplayer sheets of glass in such a way as to eliminate disintegration of the glass waste during the decomposition process. According to the hypothesis, this process should be carried out in such a way that the glass would be separated by its breaking and subsequent stripping and scraping off of the glass fragments in such a way that the foil remains intact, if possible. For this concept, we have started to draw up the drawing documentation.

The aim of the present third report from the third year is the presentation of production documentation, production of individual modules and the overall variant concept of the decomposition line. The designed modules, as well as the variant solutions, are the result of laboratory tests. The proposed variant solutions are affordable and designed according to the exact requirements of the client for various types, layers and dimensions of the processed waste glass.

The overall concept of the modular design of the structure enables arranging variable changes to the structure, its management and regulation as well as the coupling of individual follow-up modules and their outputs depending on the type and kind of processed laminated glass being processed. The structure enables optimization of the output and technology of the processing of various types of glass. Because of these malleable features, it also makes possible very effective subsequent research in this field of glass recycling not only from old vehicles, but laminated glass from construction sites or multilayer safety glass as well.

The subject of the upcoming period of time will be the testing of and final adjustment of the functional models manufactured. These tests will be executed at the Faculty of Mechanical Engineering of STU in the prototype shop. Functional models will be tested separately as well as in combined in-line arrangement.

Acknowledgements

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4.7 Bibliography

[1] Kolektív ZvSP SR: Podkladový materiál ZvSP SR k projektu Slovenskej technickej univerzity v Bratislave. Etapová správa projektu „Vyhľadávanie a možnosti aplikácie nových technológií v procese spracovania odpadového skla nespracovateľného bežnými technológiami – stratégia výskumu a vývoja technológií a logistiky a spracovania jednotlivých prúdov odpadu“. Trenčín, október, 2019.

[2] Voláriková, S.: Experimentálne zariadenie na spracovanie lepených skiel, Diplomová práca, SjF STU Bratislava 2016, 67 s.

[3] ŠOOŠ, Ľubomír - POKUSOVÁ, Marcela - BLECHA, Petr - MATÚŠ, Miloš - ONDRUŠKA, Juraj - ČAČKO, Viliam - BÁBICS, Jozef.: PP 107-2019 Spôsob vysoko účinnej dekompozície vrstvených odpadových skiel a stavebnicová linka, 08.10.2019, Úrad priemyselného vlastníctva SR, 2019.

[4] ŠOOŠ, Ľubomír - POKUSOVÁ, Marcela - BLECHA, Petr - MATÚŠ, Miloš - ONDRUŠKA, Juraj - ČAČKO, Viliam - BÁBICS, Jozef: Spôsob efektívneho zhodnocovania odpadových lepených skiel a modulová konštrukcia zariadenia úžitkový vzor č. 8786. Banská Bystrica Úrad priemyselného vlastníctva SR 2020. 5 s.

[5] ŠOOŠ, Ľubomír - POKUSOVÁ, Marcela - MATÚŠ, Miloš - ONDEROVÁ, Iveta - ONDRUŠKA, Juraj - ČAČKO, Viliam - BABICS, Jozef. Recyklácia vrstveného skla: Návrh progresívnej technológie dekompozície viacvrstvových lepených skiel. In Progresívne technológie zhodnocovania odpadov v automobilovom priemysle. 1. vyd. Bratislava: Spektrum STU, 2021, S. 84 - 119. ISBN 978-80-553-3867-5.

[6] ŠOOŠ, Ľubomír - POKUSOVÁ, Marcela - MATÚŠ, Miloš - KRIŽAN, Peter - ČAČKO, Viliam. Design of a modular technological line for the recycling of laminated car glass. In Analysis of the state, forecasts and new technologies of waste recovery in the automotive industry. 1. vyd. Ludenscheid: RAM-Verlag, 2021, S. 68 - 91. ISBN 978-3-96595-008-5.

[7] ŠOOŠ, Ľubomír - POKUSOVÁ, Marcela - MATÚŠ, Miloš - BENIAK, Juraj - ONDEROVÁ, Iveta - BABICS, Jozef. SmartOdpady II.: Integrovaná informačná a inovačná platforma recyklačných technológií. In Progresívne technológie zhodnocovania odpadov v automobilovom priemysle. 1. vyd. Bratislava: Spektrum STU, 2021, S. 66 -83. ISBN 978-80-553-3867-5.

[8] ŠOOŠ, Ľubomír - MATÚŠ, Miloš - POKUSOVÁ, Marcela - ČAČKO, Viliam - BÁBICS, Jozef. The recycling of waste laminated glass through decomposition technologies. In Recycling. Vol. 6, iss. 2 (2021), s. 26. ISSN 2313-4321 (2020: 0.569 - SJR, Q2 - SJR Best Q). V databáze: SCOPUS: 2-s2.0-85105488852.

[9] BADIDA, M. – ŠOOŠ, Ľ. et al.: Analysis of the state, forecasts and new technologies of waste recovery in the automotive industry. - Lüdenscheid (Nemecko): RAM-Verlag pp. 190, [print]. ISBN 978-3-96595-008-5.

Extraction of valuable components from the discarded lithium accumulators from electric vehicles

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5 Extraction of valuable components from the discarded lithium accumulators from electric vehicles

5.1 Introduction

The activity of the UNIVNET association – University and Industrial Research and Education Platform of the Recycling Society, focuses on the condition and vision of the recovery of selected types of waste especially from the Slovak automotive industry. The main aim of the association consists of prognostic and research and development activities in the search for new technologies and methods for the maximum efficient recovery of waste, especially in the automotive industry, with the aim of minimizing negative impacts on the environment and to save the primary resources of energy and raw materials.

One of the most important challenges of the waste industry within the dynamically developing sector of electric vehicles is the management of discarded traction lithium accumulators (LiA). They represent a potentially very dangerous waste, but, on the other hand, they are the source of very important materials that must be recycled with regard to their price and scarcity. It is not negligible that some components, such as cobalt, graphite, and lithium, contained in LiA belong among the critical raw materials for the European Union. Recycling of LiA is an important way to gain these critical raw materials, but, on the other hand, it is a complicated and demanding process, since it is a complex composite material and its character as well as electrical and chemical properties pose a serious risk in terms of safety and the protection of health.

Within the activities of the UNIVNET association, the Institute of Recycling Technologies, Faculty of Materials, Metallurgy and Recycling, Technical University of Košice, deals with this issue and the results of their work in this field for 2021 are presented in this paper.

5.2 Work progress design

The following procedure of material recycling of the discarded car LiA accumulators was designed in order to address the possibilities of material recycling of the discarded LiA:

- Current status of the issue, analysis of published results,
- Material and structural analysis of LiA,
- Experimental verification of recovery,
- Discharge of residual voltage,
- Determination of the fundamental method of processing of the discarded LiA,
- Possibilities for the separation and extraction of metals in their elementary form such as Cu, Al, Fe,
- Possibilities for the separation and extraction of active material,
- Possibilities for the separation and extraction of plastic,

- Possibilities for the separation and extraction of metals from the solution, especially Li, Co, Ni, Mn, etc.,
- Management of the produced waste,
- Pilot operation experimenting.

Average material composition of LiA is shown in Fig. 5.1 Average material composition of LiA.

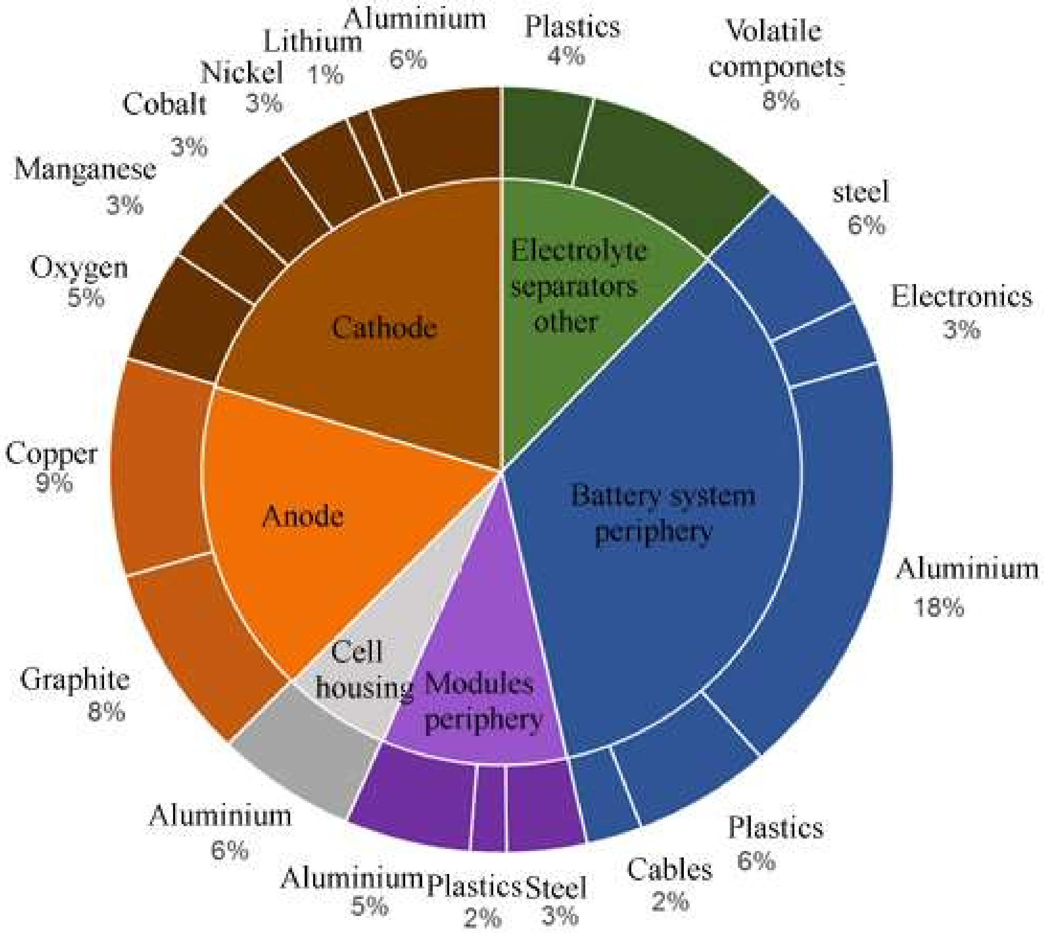


Fig. 5.1 Average material composition of LiA

From an economic point of view, the content of valuable components in the discarded LiA is interesting, as shown in Table 5.1
Material composition of LiA in terms of prices of individual components. Here it is necessary to point out that prices of metals have risen dramatically recently, on average by 100 or even more percent in comparison with 2020 [1].

The lithium-ion electrical cell, Fig. 5.2, consists of metal electrode holders, usually made of copper and aluminum, or only of aluminum, which are coated with electrode materials consisting of graphite or complex oxides of lithium with nickel, manganese, cobalt, titanium, etc. Electrode materials are generally known as active or black matter.

Individual electrodes are separated from each other by plastic separators. Electrolyte is made of organic liquids, for example Table 5.2.

The content of organic solvents in LiA ranges from 10% to 15% and in general they are very volatile, flammable and explosive. This significantly affects the entire processing operation, since shredding is inevitable. Since every discarded LiA contains some residual voltage, its destruction causes sparking and subsequent ignition and/or explosion. This leads to a mandatory discharging of residual voltage step in the material recycling of the discarded LiA.

Table 5.1

Material composition of LiA in terms of prices of individual components

COMPONENT	Representation of the component [%]	Component price/t [US$] 2020	Component price/t [US$] 2021	Component price in LiA [US$/t]
Lithium (Li_2CO_3)	1(5.32)	8 000	24 800	1 319
Cobalt	3	33 965	55 755	1 672
Copper	9	6 810	9 860	887
Aluminum	35	1 744	3 076	1 076
Nickel	3	14 554	19 825	594
Manganese	3	1 667	7 520	225
Graphite	8	500	970	78
Steel	9	295	445	40
Plastics	11			
Volatile components	8			
Electronics	3			
Wiring	2			

 # US$ 5 891/t LiA

Fig. 5.2 shows only a single electrical cell. In reality, the lithium accumulator for EV or HEV is rather complicated equipment structurally and, in addition to electrical cells, it also contains metal, often aluminum casing, copper contacts and conductors, electronic control unit, plastic parts, etc. Fig. 5.3.

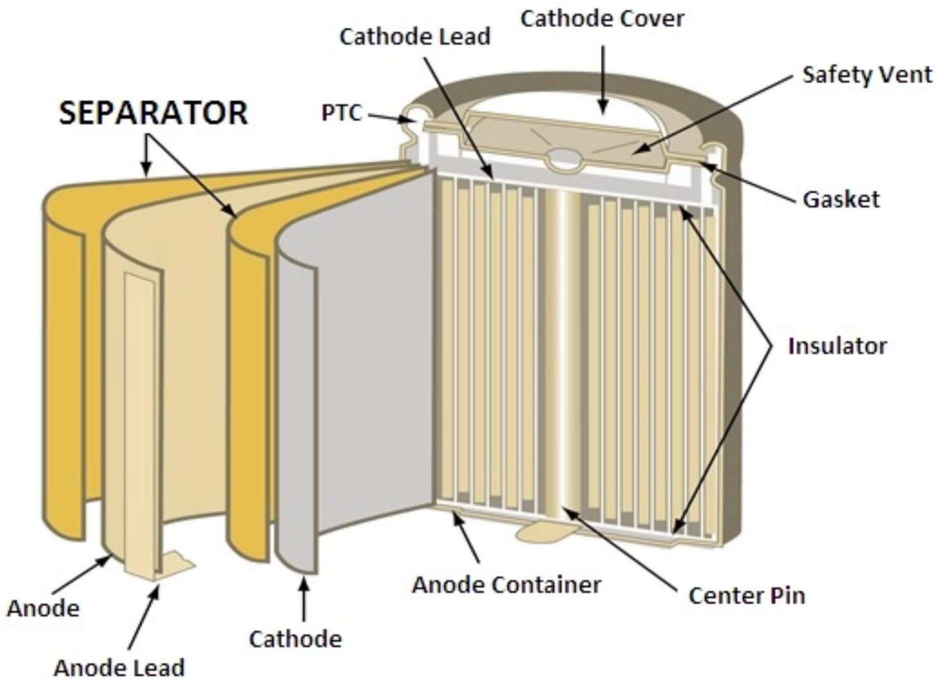


Fig. 5.2 Schematic of LiA

Table 5.2
Some published electrolytes for use in LiA [2]

ionic liquid	acronym	viscosity (mPa s)	conductivity (mS/cm)	electrochemical potential (V)
1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide	(EMIM)(TFSI)	34	10.8	4.0
1-ethyl-3-methylimidazolium tetrafluoroborate	(EMIM)(BF4)	32	16.01	4.0
1-ethyl-3-methylimidazolium bis(fluorosulfonyl)imide	(EMIM)(FSI)	19	17.74	3.5
1-ethyl-3-methylimidazolium trifluoromethanesulfonate	(EMIM)(TfO)	45.7	8.5	4.1
1-butyl-1-methylpyrrolidinium bis(trifluoromethylsulfonyl)imide	PYR14 TFSI	85	2.2	>4.8
N-propyl-N-methylpyrrolidinium bis(trifluoromethanesulfonyl)imide	PYR13 TFSI	58.7	4.92	5.0
1-ethyl-3-methylimidazolium chloride	(EMIM)(Cl)	-	1.85	2.8
N-methyl-N-propylpiperidinium bis(trifluoromethylsulfonyl)imide	Pip13 TFSI	-	10	4.35
N,N-diethyl-N-methyl-N-(2-methoxyethyl) ammonium tetrafluoroborate	DEME-BF4	-	4.8	6.0
1-ethyl-3-methylimidazolium hexafluorophosphate	(EMIM)(PF6)	-	1.93	3.2
1-butyl-3-methylimidazolium hexafluorophosphate	(BMIM)(PF6)	-	2.1	3.0

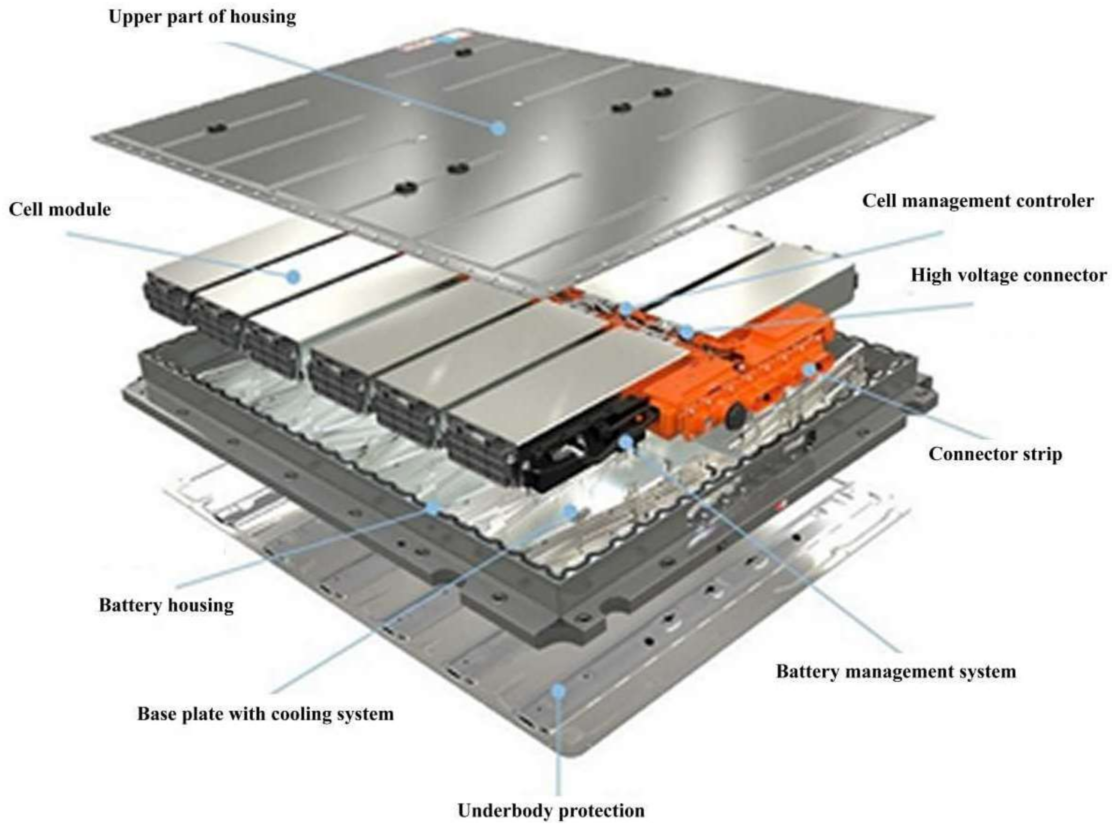


Fig. 5.3 Structure of the lithium accumulator

From the results above, the material recycling of the discarded LiA accumulators is a complex and relatively involved process. The multitude of components present in LiA will require individual approaches and specialized procedures and equipment. Not least, the selection of the procedure will also depend on the economic benefits of individual components and their application on the available market.

5.3 Experimental part

The experimental part of the work to date [3] dealt with solving the issue of discharging the residual voltage in the discarded LiA. We have tested and designed the method for discharging the residual voltage in the NaCl solution at a defined concentration. At the same time, the values of residual voltage in LiA were also noted. Depending on the structure, these values in the individual cells range from 2.2 to 3.5 V.The problem is that discarded LiA are not only in the form of individual cells, but often as modules; the overall residual voltage can reach values in the range 20 – 45 V, which presents a significant risk during processing.

The general schematic of material recycling of LiA considered for the experimental procedure is shown in Fig. 5.4.

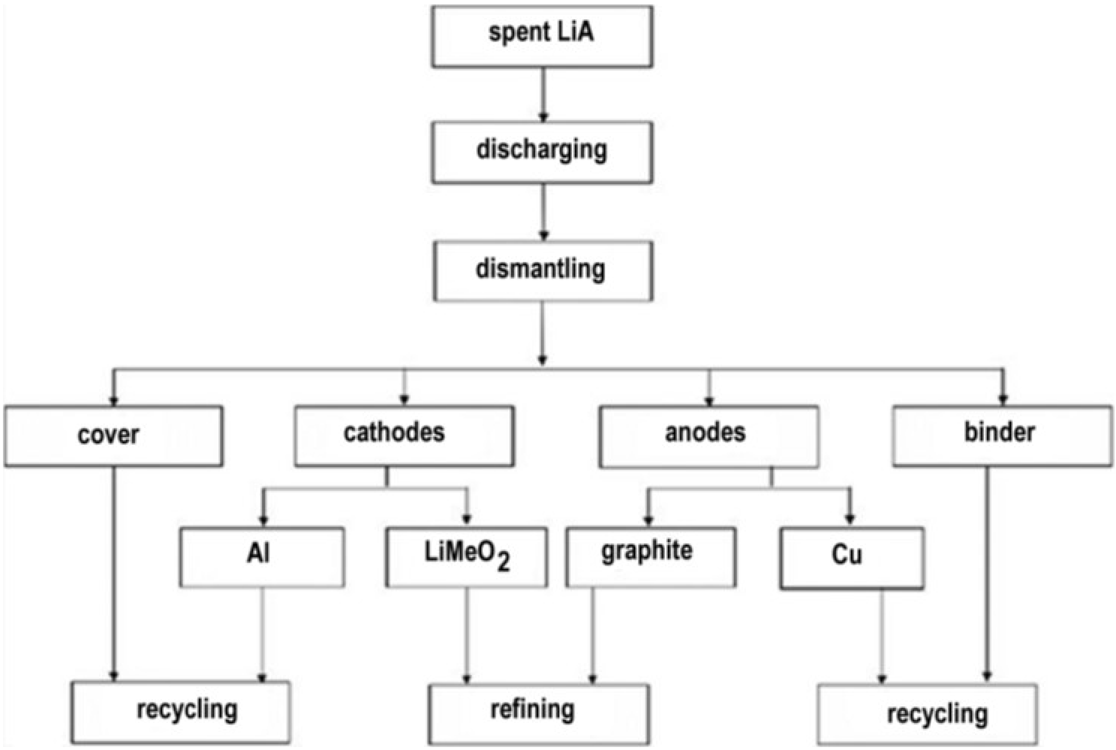


Fig. 5.4 General schematic of material recycling of LiA

After the discharge of the residual voltage [3], the discarded LiA were crushed, and the resulting mixture was put through a sieve. Fig. 5.5 shows the resultant mixture after crushing the discarded LiA. The presence of copper and aluminum particles, as well as plastic and black matter in the mixture, can also be observed by the naked eye.

Fig. 5.5 View of the crushed LiA

In order to determine the composition of particle size, we carried out the sieve analysis using a standard method according to STN ISO 44 1313. The experiment was performed with the use of 1000 g of previously quartered crushed LiA. The result is cumulative and distribution composition of the crushed LiA shown in Fig. 5.6.

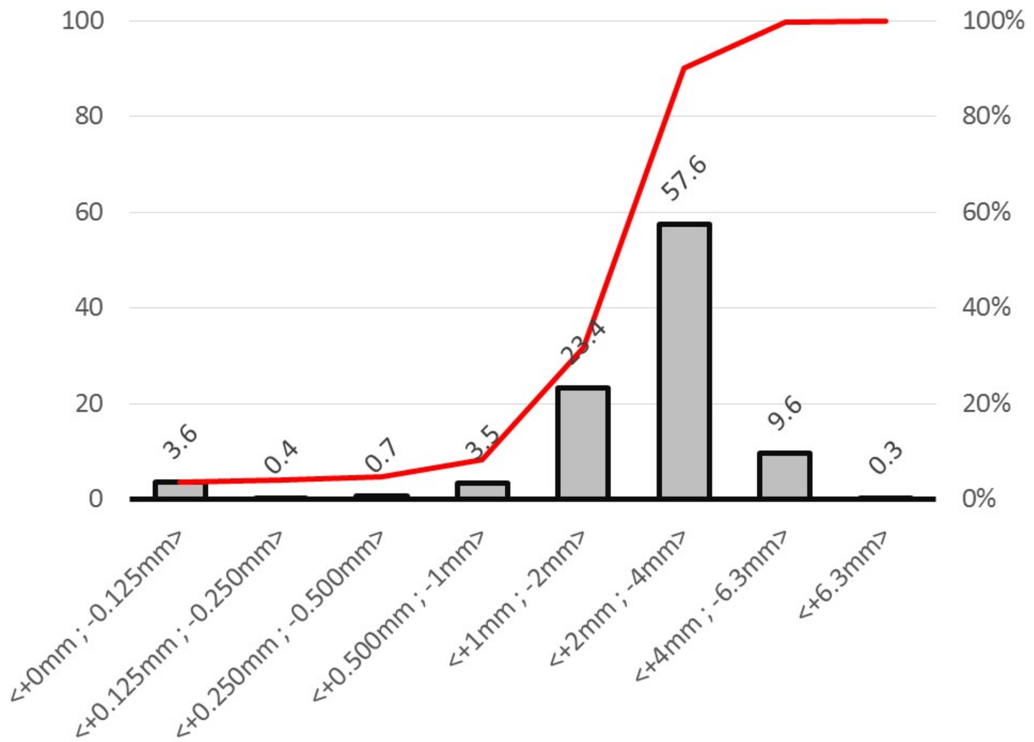
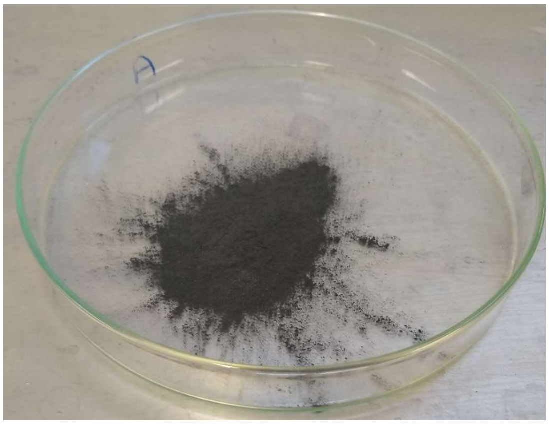
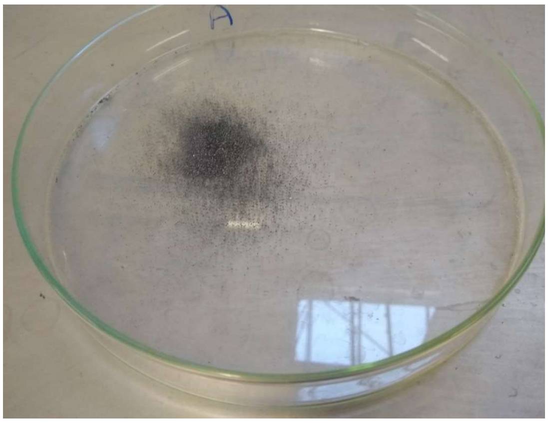


Fig. 5.6 Cumulative distribution of grain size (red dependency) and distribution of particles (bar chart)



+0 -0.125 mm



+0.125 -0.250 mm

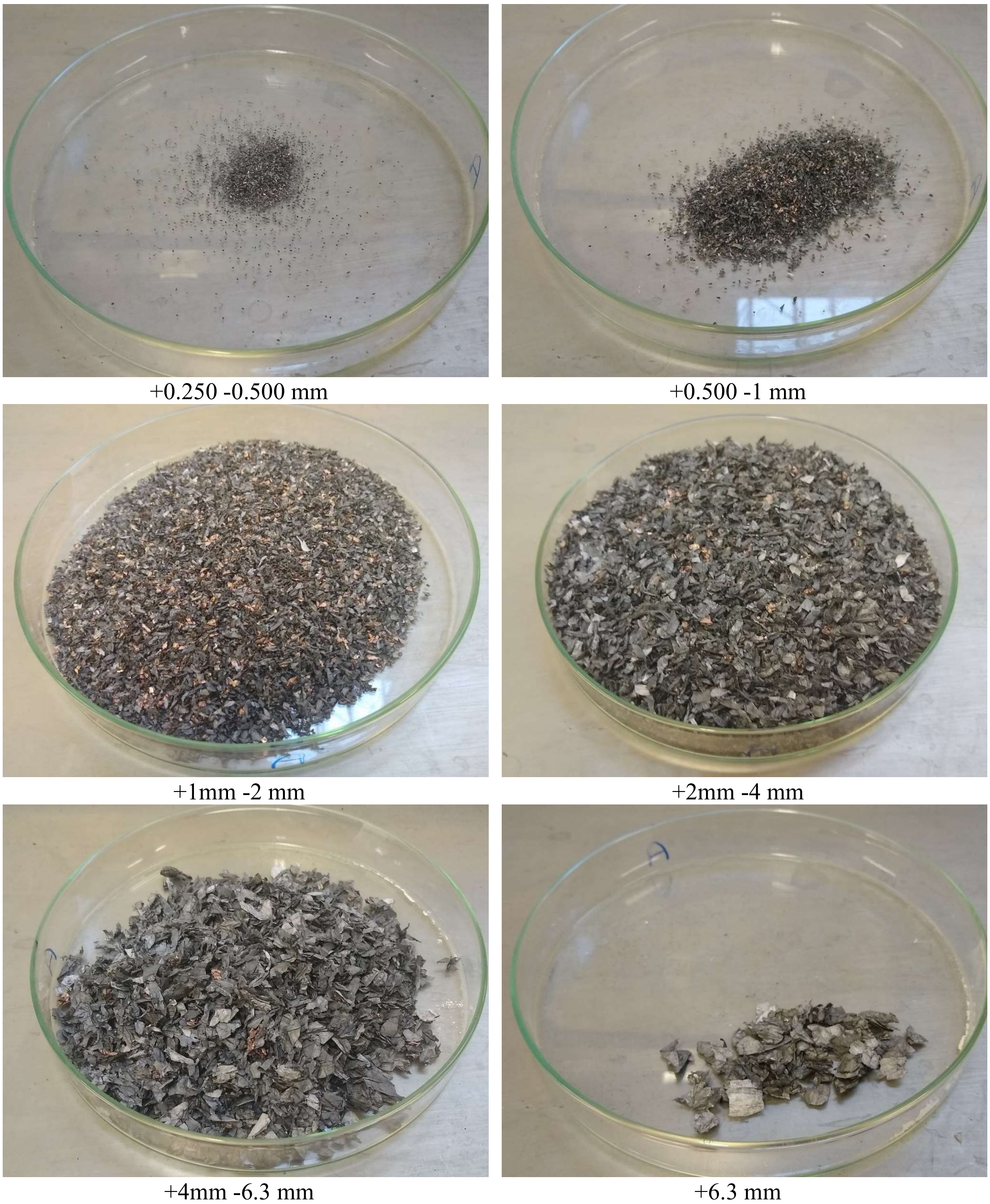


Fig. 5.7 Grain classes of the crushed LiA

The results indicate that around 60% of particles are in the range from 2 to 4 mm. Fig. 5.7 shows the individual grain classes. Fig. 5.8 shows detailed views of individual grain classes. Optical observation detects the presence of gold-red particles which are represented by copper, gray to black particles represented either by aluminum or the plastic from separators, with both contaminated by the black matter, and the black matter itself, which is concentrated into small grain sizes. Likewise, the distribution of these particles into individual grain classes can be seen. Copper was mainly concentrated in the grain class +1 -2 mm, aluminum in class +2 -4 mm and separators in class +4 mm. However, the aluminum and separators are probably mixed, and there are more separators in the mixture with larger particles.

The finest particles are formed by black matter, and it was not possible to determine their form. Therefore, they were subjected to diffraction phase analysis.

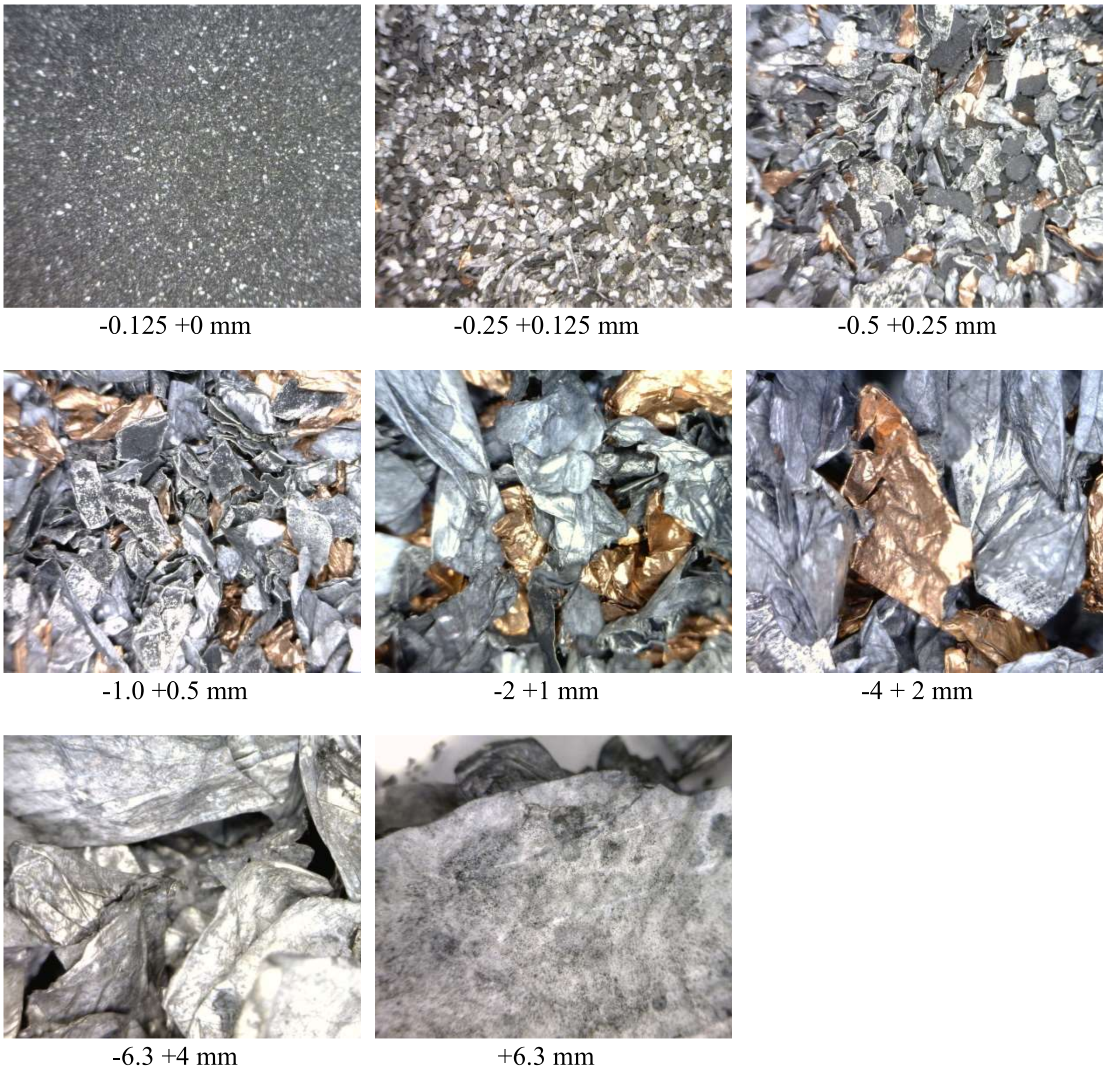
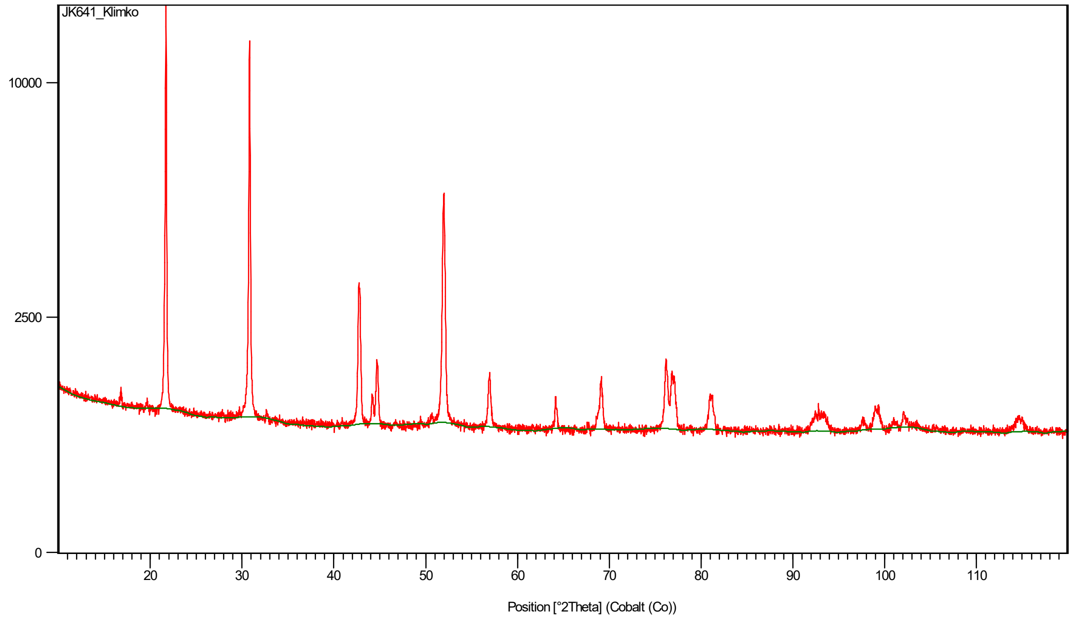


Fig. 5.8 Detailed view of the grain fractions at a magnification of 50x

Material analysis of the crushed LiA has demonstrated the presence of basic components: copper, aluminum, black matter and plastic separators. These components are significantly differentiated by their specific weight. Therefore, the experimental work was carried out with the use of gravitational sorting. The results have shown that the relatively light aluminum concentrates into a light fraction and the heavier copper into heavier fractions. The separation of aluminum from copper can be achieved with high efficiency. Separators are very light and were separated into the lightest fractions.

The x-ray diffraction phase analysis has shown the presence of graphite and $LiNiO_2$, which represent the anodic and cathodic black matter. It has been demonstrated that the "black matter" is not homogeneous material. Phase analysis has showed the presence of at least two phases, aluminum and $LiNiO_2$.



Ref. Code	Compound Name	Chemical Formula
01-088-1604	Lithium Nickel Oxide	Li.92 Ni1.08 O_2
00-041-1487	Carbon	C

Fig. 5.9 X-ray diffraction phase analysis of the black matter

There are two types of active black matter, anodic and cathodic. During the disintegration, it was shown that the anodic matter, represented by graphite, easily separates from the metal bearing material, but the cathodic matter, represented by complex lithium oxides, sticks to the aluminum cathode very firmly and is difficult or impossible to separate. The result was that the mixture of aluminum with active matter and copper was separated in the first phase, Fig. 5.10.

Therefore, it was necessary to look for methods having a more thorough separation of active matter from aluminum and also separating the rest of the copper from this intermediate product. There are several options to achieve this. One of them is the separation of individual components with the use of ultrasound in a water suspension of the crushed LiA [4]. Since the $LiMeO_2$ electrodes in LiA are not only composed of the lithium oxide, but also of the conductible aluminum, binder and, of course, the aluminum bearing material, the recycling using conventional methods, as was also demonstrated in this case, is not easy and requires more sophisticated methods [5,6] using a wet process [4,7]. In this case, the lithium and cobalt oxide particles were effectively separated from the aluminum bearing material.

Separation of the cathodic materials from the aluminum foil during the recycling of LiA is a very difficult process due to the very firm Polyvinylidene fluoride (PVDF) binder. The use of ultrasound can be effective for the separation of cathodic matter and aluminum foil with regard to its cavitation effect [8].

Fig. 5.10 Metal-bearing concentrate of Cu + Al + active material

It was demonstrated that the use of ultrasound removes only part of the cathodic material, but there is efficiency of the cathode matter separation with mechanical stirring of the mash. This way it is possible to separate almost the entire quantity of the active cathodic matter. This is due to the fact that the cavitation effect of the ultrasound purification can create higher pressure on the disruption of the insoluble materials and their following dispersion in the water. The effect of washing with the use of mechanical stirring significantly promotes the separation of cathodic material from the collector.

Examination of this procedure has brought optimum efficiency conditions of 99% separation of cathodic matters as follows: the solution used for the dissolution of PVDF was N-methyl pyrrolidone (NMP) at a temperature of 70 °C for 90 minutes and 240 W ultrasound output.

After the separation of the cathodic materials, the active cathodic matter was filtered off and used in the next leaching phase.

Ultrasound sorting was also carried out on an industrial scale at the firm of Hielscher Ultrasound Technology in Germany [9]. Within this process, the sorted mixture was placed into a 2 M solution of LiOH and stirred. The ultrasound radiation was switched on and the mixture was heated to 120 °C. The ultrasound was switched on for 6 hours and then the system was cooled down to the ambient temperature. After the filtration, the insoluble solution was rinsed with water and dried. The result was crystalline $LiCoO_2$.

Ultrasound leaching in organic acids, for example, in citric acid, is not only effective but also environmentally friendly. Experimental activity has shown that the extraction of cobalt and lithium is more effective in citric acid than in sulfuric acid or hydrochloric acid. More than 96% of Co and almost 100% of Li was extracted. The fact that the organic acids, such as the citric acid or acetic acid, are cheap and biodegradable, indicates further economic and environmental benefits of sonification.

The metal aluminum reacts in the alkaline conditions to produce soluble compounds. This forms preconditions for the extraction of cathodic materials from the aluminum electrodes by leaching in the alkaline solutions. This procedure was examined with the use of NaOH solution [11-14]. Experiments were carried out in 10% NaOH solution with the ratio of K:P = 10:1, reaction time of 5 hours at ambient temperature. 98% of the aluminum was extracted and dissolved under these conditions. Two substances react with the use of NaOH solution for the extraction of aluminum cathode: the protective surface oxide layer of the cathode, and the metal aluminum according to:

$$Al_2O_3 + 2NaOH + 3H_2O = 2Na[Al(OH)_4] \quad (1)$$

$$2Al + 2NaOH + 6H_2O = 2Na[Al(OH)_4] + 3H_2 \quad (2)$$

This method is beneficial in terms of simple operation and high efficiency of the process. On the other hand, the recovery of aluminum from the solution is a relative difficult process. Moreover, recycling of the NaOH solution is complicated and this solution is very dangerous for the environment.

Methods of thermal re-processing [15-17] employ high-temperature disintegration of the binder in order to reduce the bonding forces between the cathodic material particles. The cathodic material can then be easily separated by sieving or using a similar procedure. PVDF binder generally decomposes at the temperature higher than 350 °C, while other components (such as acetylene carbon, conductible carbon, etc.) generally degrade at temperatures higher than 600 °C [17]. Sun and Qiu have designed a new method for the separation of cathodic substances with the use of vacuum pyrolysis. In this process, the electrolyte and binder evaporate or decompose, which reduces the adhesion of cathodic active matter and the collector. At pyrolysis temperatures lower than 450 °C the cathodic material does not peel off the collector. At temperatures between 500 and 600 °C the efficiency increases with increasing temperature.

On the other hand, the aluminum foil brittles at temperatures higher than 600 °C, which causes problems in the separation of cathodic matter from the collector. Yang et al. [15] has designed a thermal reduction process in order to achieve separation of the cathodic material from the aluminum collector. It was shown that the control of reaction reduction temperature ensures easy separation of the cathodic materials from the metal collector. Moreover, this process changes the crystalline structure of the active cathodic material, which enables the extraction of metals during the leaching phase. Advantages of thermal processing lie in process simplification and increase of efficiency. However, a disadvantage is the formation of toxic and explosive gases from the decomposition of the binder and additives.

Based on the published information and after consideration of the real situation, the use of NaOH solution for the mutual separation of cathodic matters was tested in this instance. It was established that prolongation of the leaching time in a NaOH solution results in purer active matter, but, on the other hand, it causes higher loss of aluminum in the solution. If the metal aluminum is to be extracted as well, it is necessary to conduct extremely sensitive adjustments of the experiment with variables: concentration of NaOH in the solution, leaching time, temperature, ratio of K:P. These are experimental parameters which must be monitored.

It is probable that the price of the recycled active matter is higher than the price of aluminum, therefore, the work should focus mainly on its extraction. However, this does not mean that aluminum should be lost forever. There are known processes for the extraction of aluminum from alkaline solutions. It is a general procedure for the production of alumina in its primary production from bauxite. On the other hand, Al_2O_3 (corundum) does not have to be the only product of such a procedure. The process can be set in such way to obtain other aluminum oxides, such as corundum, or alums for example, or other substances based on aluminum with higher added value and/or high purity, or defined properties, which may be interesting for, perhaps, the electrical engineering industry. This would, of course, lead to further investments and operating costs which must be decided by a precise economic analysis.

The results achieved within this project indicate the attainability of all foreseen targets in the separation of cathodic materials. Fig. 5.11 shows the separated products: copper, aluminum and black active matter, in the sorting process within the phase of mutual separation of the cathodic matters.

Fig. 5.11 Separation of cathodic materials within the sorting process

The process carried out resulted in the extraction of pure aluminum concentrate, Fig. 5.12.

Fig. 5.12 Aluminum concentrate

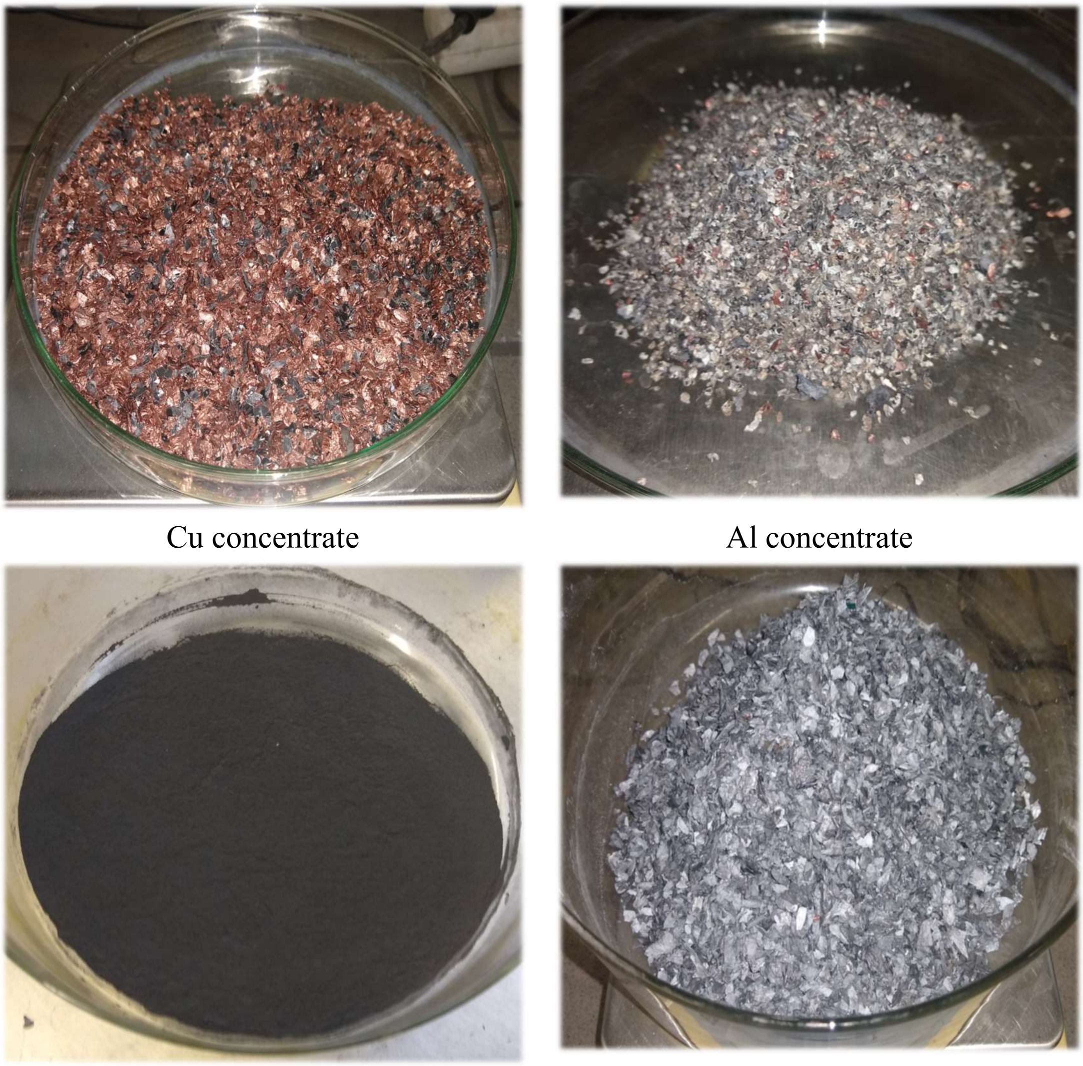
Overview of all products from sorting of crushed LiA through gravitational disintegration are shown in Fig. 5.13.

Material balance of the implemented procedure is shown in Table 5.3.

Table 5.3
Material balance of the implemented procedure

Component	Copper	Aluminum	Active substance	Separator	Returnable material
quantity [%]	36.47	10.12	14.87	19.05	19.8

Returnable material is the mixture of electrode collectors, active material and plastics. It is then returned to the process for repeated sorting.



Cu concentrate | Al concentrate

active black matter | separators

Fig. 5.13 Products of experimental sorting of the crushed LiA

5.4 Conclusion and proposal of further action

The results so far have shown the possibility of material recycling of discarded traction accumulators from electric vehicles. Through a suitably adjusted procedure and by compliance with the monitored parameters, we can get sorted materials, such as metal copper, metal aluminum, and black active matter, which consists of cathodic and anodic matter and plastic separators. Prior to processing, it is necessary to treat the discarded LiA in order to discharge the residual voltage.

The procedure was experimentally studied in laboratory conditions, where multiple methods were examined by which it is possible to get either maximum possible quantity of active black matter with the minimum amount of aluminum, or the metal aluminum in a mixture with active matter and possibly even with copper. The decision as to which procedure is acceptable with high benefit must be made upon a thorough economic analysis not only in terms of the price of final marketable products, but also in terms of investment and operating costs.

The extracted products are currently of particular interest for the recycling industry. However, the lithium accumulators also contain other components that are very interesting in terms of prices. These include organic components, such as PVDF, etc., other non-ferrous metals (based on the structure of LiA) such as nickel, cobalt, manganese, etc., but especially lithium.

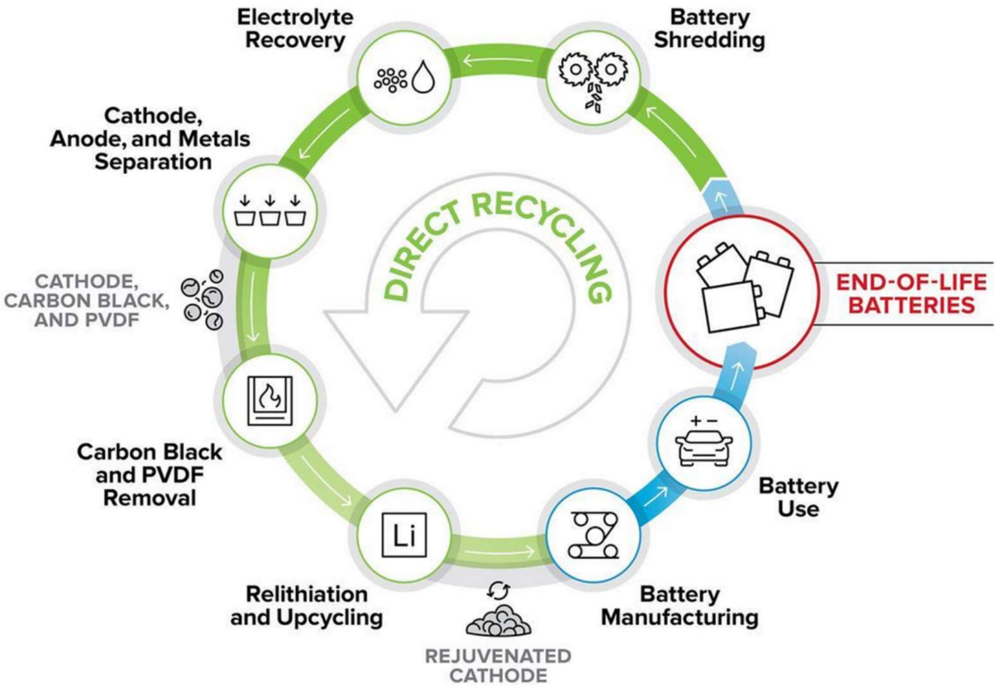


Fig. 5.14 Material recycling of LiA in terms of the circular economy

In the future, the attention within this research project will be given to the extraction of these components in the material recycling of the discarded LiA. We will also focus on the semi-industrial and operational verification of the proposed procedures. From this point of view, the cooperation with the company SAKER, s.r.o. in Horný Hričov, is invaluable.

Fig. 5.14 shows the proposed method of material recycling of discarded car accumulators in terms of the circular economy.

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5.5 Bibliography

[1] https://www.fastmarkets.com/commodities/exchange-data/lme-base-metal-prices-and-charts

[2] Ray, A.; Saruhan, B. Application of Ionic Liquids for Batteries and Supercapacitors. Materials 2021, 14, 2942. https://doi.org/10.3390/ma14112942

[3] Havlik, T.; Miškufová, A.; Oráč, D. Materiálová recyklácia lítiových trakčných akumulátorov, In: Progresívne technológie zhodnocovania odpadov v automobilovom priemysle, Badida, M. ed., Spektrum STU, ISBN 978-80-553-3867-5, 2021, s.121-144.

[4] Zhang, Z. et al. Ultrasound-assisted Hydrothermal Renovation of $LiCoO_2$ from the Cathode of Spent Lithium-ion Batteries, Int. J. Electrochem. Sci., 9 (2014) 3691 – 3700, dostupné na file:///D:/AKTUALNE%20RIESENE%20ULOHY/Konferencie/2021/Konferencia%20UNIVNET/Ultrasound%20assisted%20Hydrothermal%20Renovation%20of%20LiCoO2%20from%20the%20Cathode%20of%20Spent%20LiIon%20Batteries.pdf

[5] Sethuraman, V.A; Hardwick, L.J; Srinivasan V; Kostecki, R. Surface Structural Disordering in Graphite upon Lithium Intercalation Deintercalation, Journal of Power Sources, 195 (11), 3655-3660, 2010.

[6] Zhang, L. et al. Degradation mechanism of over-charged $LiCoO_2$ mesocarbon microbeads battery during shallow depth of discharge cycling, J Power Sources, 145 (2005) 97.

[7] Zhang, Z. et al. Recovery of Lithium Cobalt Oxide Material from the Cathode of Spent Lithium-Ion Batteries, ECS Electrochemistry Letters, 3, 6, A58-A61 (2014) 2162-8726.

[8] He, L.-P; Sun, S.-Y.; Song, X.-F.; Yu, X.-F. Recovery of cathode materials and Al from spent lithium-ion batteries by ultrasonic cleaning. Waste Management, 46, December 2015, 523-528 https://www.hielscher.com/ultrasonics-for-the-recycling-of-lithium-ion-batteries.htm

[9] Zheng, X. et al. A Mini-Review on Metal Recycling from Spent Lithium Ion Batteries. Engineering. 4, 3, June 2018, 361-370.

[10] Chen, L. et al. Process for the recovery of cobalt oxalate from spent lithium-ion batteries. Hydrometallurgy, 108, 1-2, June 2011, 80-86.

[11] Alvarenga, D. et al. Hydrometallurgical separation of aluminium, cobalt, copper and lithium from spent Li-ion batteries. Journal of Power Sources, 187, 1, February 2009, 238-246.

[12] Nan, J; Han, D; Yang, M; Cui M; Hou, X. Recovery of metal values from a mixture of spent lithium-ion batteries and nickel-metal hydride batteries, Hydrometallurgy, 84, 1-2, October 2006, 7580.

[13] Nan, J; Zuo, X. Recovery of metal values from spent lithium-ion batteries with chemical deposition and solvent extraction, Journal of Power Sources, 152, 1, December 2005, 378-284.

[14] Yang, Y; Huang, G; Xu, S; He, Y; Liu, X. Thermal treatment process for the recovery of valuable metals from spent lithium-ion batteries, Hydrometallurgy, 165, 2, October 2016, 390-396.

[15] Xincun, L.Ch.; Tang, X.; Zhang, Y, Li, L.; Zeng, Z.; Zhang, Y. Process for the recovery of cobalt oxalate from spent lithium-ion batteries. Hydrometallurgy, 108, 1-2, June 2011, 80-86.

[16] Hanisch, Ch. et al. Recycling of lithium-ion batteries: a novel method to separate coating and foil of electrodes. Journal of Cleaner Production, 108, part A, December 2015, 301-311.

[17] Sun, L.; Qiu, K. Vacuum pyrolysis and hydrometallurgical process for the recovery of valuable metals from spent lithium-ion batteries. Journal of Hazardous Materials, 194, October 2011, 378-384.

[18] BADIDA, M. – ŠOOŠ, Ľ. et al.: Analysis of the state, forecasts and new technologies of waste recovery in the automotive industry. - Lüdenscheid (Nemecko): RAM-Verlag pp. 190, [print]. ISBN 978-3-96595-008-5.

Development of materials and products with sound and thermal insulating and other properties on the basis of waste from the automotive industry

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6 Development of materials and products with sound and thermal insulating and other properties on the basis of waste from the automotive industry

6.1 Introduction

The study of the research team follows up the research executed in 2019 and 2020. The researchers have focused on the selection of suitable materials from the components in the end-of-life vehicles. For the further detailed research, the research of sound insulating materials, we have selected materials such as various fractions of recycled waste tires, various fractions of textile materials from the automotive industry and also glass fractions from car glass. The basic objective of the research is the idea to use bulk materials, that is, those specified fraction types of the selected materials for use as sound insulating products. The study was focused on the comparison of the same fractions of materials in compact form and in bulk form. For the purpose of the research of bulk materials, we have developed and produced special testing cartridges and special test cartridge filling equipment. Attention was given to a wide range of scientific experiments which were analyzed and evaluated. The researchers have also focused on the specific products characterized by good sound insulating properties.

6.2 The selection of components and their materials which would be suitable for our needs

Within the research of acoustic and heat insulating properties of materials from end-of-life vehicles, we have studied the issue of recycling of the selected types of materials from cars that are suitable and available for re-use in practice.

The selection of materials was conditional on the possibilities and the laboratory equipment available in the experimental workplace, as well as on its use in practice as the insulating and sound absorbing material.

Based on the material's physical and mechanical properties, we have selected the following materials for the experiments:

- tires and rubber from cars and the resulting recycled rubber granulate,
- textile material from cars – seat covers and textile from the interior of cars,
- Glass – crushed glass from cars.

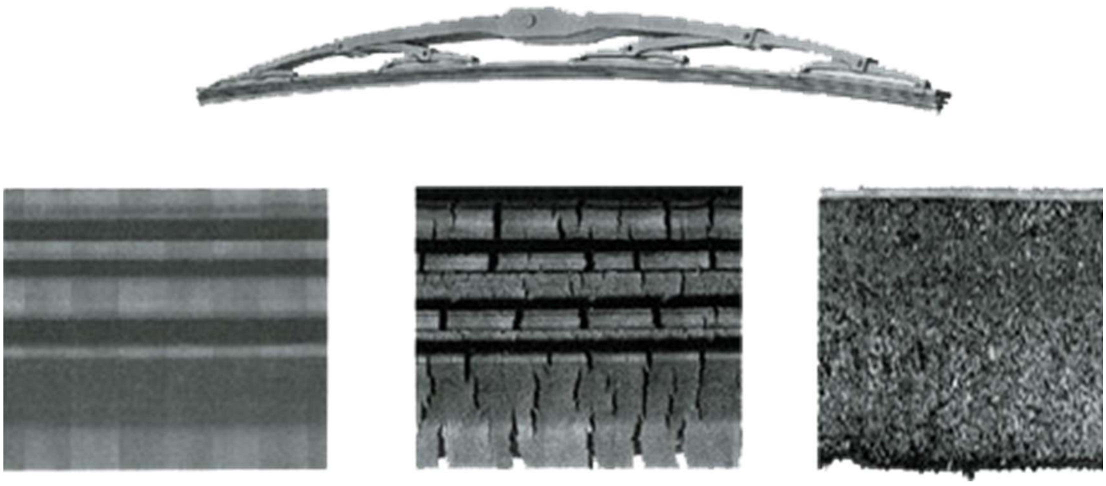
6.2.1 Tires and rubber and the resulting recycled rubber granulate

Tires belong among consumables within the operation and maintenance of vehicles. Their consumption grows each year together with the increasing number of vehicles at home and worldwide. In terms of safety and running characteristics of tires, this number grows even more since car owners are obliged to use special tires according to the seasons in our latitudes, which increases the number of used tires.

In addition to the initial material properties, as the given chemical composition of tires, the life of tires is affected by the maintenance, running characteristics of drivers, unexpected obstacles during the drive, ageing and physical factors of the environment.

Tire wear, mechanical damage, storage conditions and ageing belong among the most common factors under which the tire is discarded and becomes waste. Examples of damaged tires are specified in Fig. 6.1 and Fig. 6.2. aged rubber from wipers.

Fig. 6.1 Aged and worn tires [1, 2]



New Effect of ozone Effect of UV

Fig. 6.2 Rubber from car wipers: new, aged by the action of ozon and UV radiation [1]

From a physical perspective, the mechanical parameters such as mechanical strain and deformations, physical properties such as light, heat and UV radiation, negatively affect the ageing of tires.

From a chemical perspective, this concerns oxygen, ozone, and oil, which age tires, as well as other components, such as metal oxidation, radiation and biological factors [1]. By the recycling of tires, Fig. 6.3 we get fragments usable in practice, and thus from the environmental point of view, we can reduce waste and landfills of materials, and at the same time find new possibilities for practical use of the recycled material.

Fig. 6.4 shows the schematic of tire recycling process. Tires for lorries are characterized by much higher weight than tires for passenger vehicles. The weight of tire for a lorry can range from 30 kg up to 80 kg. It all depends on the diameter: 24-inch tires are usually the heaviest, while a 17-inch tire weighs about 35 kg. In the case of another popular dimension (22.5-inch), it will be 60 kg.

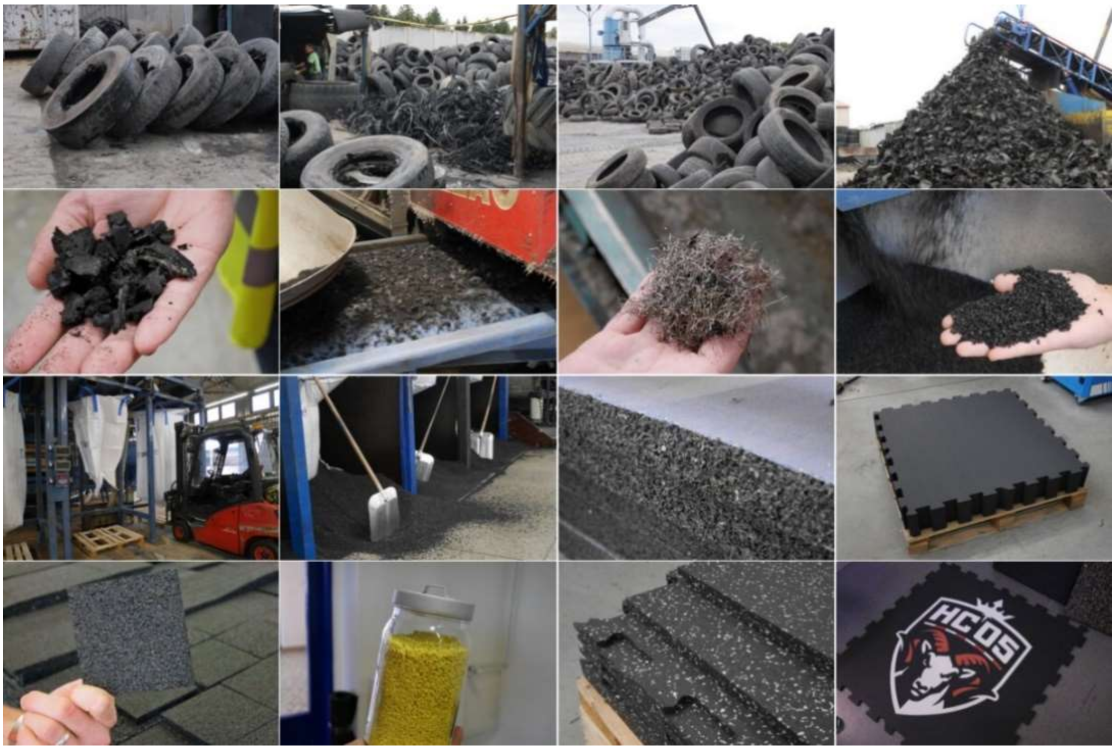


Fig. 6.3 Fragments from tire production [3]

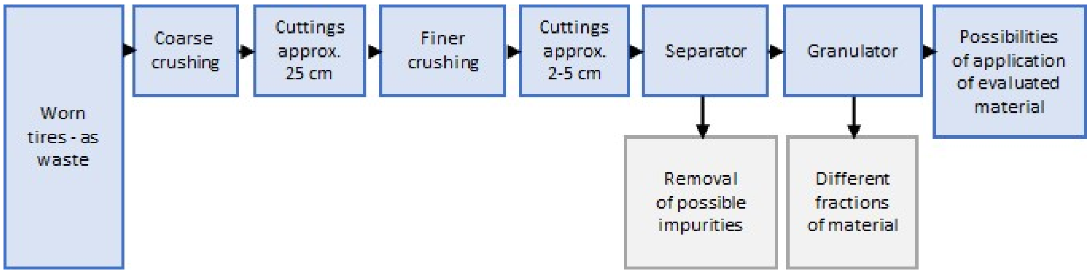


Fig. 6.4 Tires recycling and production of fractions

The input commodity for the production of recycled material are the end-of-life tires and the output product is a quality granulate from rubber with a fraction of 0 to 4 mm. The most frequently used fractions are:

- 0.0 – 0.5 mm, the finest fraction as the latest production suitable as an additive,
- 0.0 – 1.0 mm, the finest fraction as the latest production,
- 0.5 – 2.0 mm, backfill for artificial grass, products from recycled rubber, sport grounds,
- 1.0 – 3.0 mm, backfill for artificial grass, products from recycled rubber, sport grounds,
- 2.5 – 4.0 mm, products from recycled rubber, sport grounds.

6.2.1.1 Properties of the rubber granulate

An example of properties of the recycled, crushed rubber granulate Granubit 1000, which was produced by mechanical crushing of end-of-life tires mainly from passenger cars in the plant AVE SK odpadové hospodárstvo s.r.o. Table 6.1 lists the properties of the specified granulate.

Table 6.1
Basic properties of the rubber granulate Granubit 1000

GRANUBIT 1000	Test method	Recommended quality	Achieved values
Appearance	visually	black	black
Grain size [mm]	ASTMD-297	max. 2% > 1.0	0.9
Ash content [% weight]	ASTMD-297	max. 8.0	5.5 – 8.0
Humidity, volatile substances [%]	ASTMD-297	max. 0.95	0.65
Acetone extract [% weight]	ASTMD-297	max. 10.0	–
Note: Producer must provide a certificate of zero iron content in the product			

The amount of binder is inversely proportionate to the crushed fraction. The finer the crushed fraction, the more binder is necessary for its subsequent crosslinking. The average binder consumption for the production of various coatings ranges from 4 to 12%, depending on the presence/absence of coloring agent, density of materials, quality of binder and size of the used fraction. For example, for the production of colored coating Mat 500 * 500 * 16 mm (from fine fractions), it is necessary to use at least 6% of coloring agent and 5% of binder from the amount of rubber fractions.

The coatings and amount of binder classify as follows:

a) black coating (fraction 4 – 10 mm) 4% binder,
b) black coating (fraction 2 – 3 mm) 5% binder,
c) black coating (fraction 1.2 – 1.8 mm) 6% binder,
d) color coating (fraction size 1.2 – 1.8 mm) 7 – 9% binder.

The indicative average composition of tire rubber on our market is shown in Table 6.2.

Table 6.2
Average composition of tires on our market

Component	Content in [%] of weight
Natural rubber	10 to 15
Synthetic rubber	20 to 25
Regenerated rubber	1 to 1.5
Carbon black, SiO_2 etc.	35 to 40
Softening oils	approx. 3.0
Sulphur S	3.5 to 4.0
Reinforcement – wire, textiles	15 to 20
Other	4 to 6

6.2.1.2 Rubber materials used for experimental purposes

Materials from tires for the experiments were supplied by the plant AVE SK odpadové hospodárstvo s.r.o. – Industrial park Kechnec, in the form of different fractions in plastic packaging, Fig. 6.5.

Fig. 6.5 Supplied test materials – selected rubber fractions

The supplied fractions were of various dimensions and sizes, as follows:

- 0.0 – 1.0 mm, the finest fraction, Fig. 6.6 and it is shown in detail in Fig. 6.7.
- 2.5 – 4.0 mm, the largest fraction, products from recycled rubber, sport grounds, Fig. 6.10 and detail in Fig. 6.11.

Fig. 6.6 Size of rubber fraction 0.0 – 1.0 mm

Fig. 6.7 Details of rubber fraction size 0.0 – 1.0 mm

6.2.1.3 Textile material

Textile material used for experimental tests for the measurement of heat insulating properties and for the measurement of noise, was supplied by the company Stered, s.r.o. Krajné. [1]

In an average car the textiles form 2 – 2.5% of its total weight, which represents 23 – 26 kg; an increase up to 35 kg is foreseen by 2025. The production of a new car generates 2.5 – 4 kg of technological waste. Textiles from cars include the pull-on covers, textiles from child seats, airbags, etc.

Fig. 6.8 Size of rubber fraction 0.5 – 2.0 mm

Fig. 6.9 Details of rubber fractions, fraction size 0.5 – 2.0 mm

Fig. 6.10 Size of rubber fraction 2.5 – 4.0 mm

Fig. 6.11 Detail, size of fraction 2.5 – 4.0 mm

The aim of the experiment was to turn waste into a raw material for new products. Technical textiles in a car fulfil the intensive needs of the automotive industry and their life highly exceeds the period determined by the car itself. It is used in a car, on average, for 10 years. When we say technological waste, we mean the original, production textile waste.

Textile samples for experimental tests were supplied in the form of:

- a compact whole piece from car materials bonded and pressed with the dimension of 300 x 300 mm,
- Cut or torn individual textile fractions with approx. dimensions of 20 x 40 mm.

The properties of recycled textile declared by the company Stered Krajné, s.r.o. are specified as material parameters of KEAVS STERED® and have:

A cooling effect for the roof covered with vegetation or gravel, 40% savings in cooling with drip irrigation only through the transfer of heat through the structure, 20% savings in cooling without drip irrigation only through the transfer of heat through the structure:

- sound absorptivity and soundproofing,
- the retention ability of the board is 25 – 40 l/m^2 and water evaporation 1.5 – 4.5 l/m^2/day,
- at full retention, the STERED board still contains 30% air,
- favorable conditions for the establishment of vegetation directly on the panel,
- very good mechanical and physical properties,
- the product is made of recycled material and is recyclable again,
- resistance to recurring freezing and de-freezing in cases of full saturation with water,
- stable dimensions in dry, wet and frozen state,
- mechanical resistance to pressure – enabling full serviceability of devices located on the green roof without the need to use additional stepping surfaces in dry, wet or frozen state,

- surface sound absorption DLα, at least 13 dB,
- air soundproofing of the structure Rw, at least 11 dB,
- composition of the STERED green roof protects the roof deck from UV radiation and adverse weather, thus prolonging the life of waterproofing 2 to 3 times. [1]

Properties of the recycled textiles are specified in Table 6.3.

The environmental benefit of recycled textiles lies in the use of insulation based on recycled textiles, Fig. 6.12. With the same thermal resistance with regard to its high thermal capacity, it reduces the needs for heating and cooling of buildings, reduces the amount of textile waste and can partially replace the production of insulation from non-renewable resources. With regard to lower energy intensity in comparison with the classic mineral insulations, it also reduces the carbon footprint of insulation production.

Table 6.3
Selected properties of recycled textiles [1]

Measured technical parameters	Unit	Value
Thickness	mm	50
Format	mm	1200 x 600
Board surface	m^2	0.72
Board weight	kg	7.2
Bulk density of the material	Kg/m^3	200
Thermal conductivity λ	W/mK	0.054
Sound absorption coefficient αw	–	0.90
Tensile stress at 10% compression	kPa	20.3
Tensile strength perpendicular to the board plane	kPa	32.2
Short-term absorptivity at partial immersion Wlp, method A	Kg/m^2	11.8
Long-term absorptivity at partial immersion Wlp, method A	Kg/m^2	13.4
Compressibility	mm	3.68
Water vapor permeability μ	–	2.9
Reaction to fire	–	E
Health safety	–	in compliance with the relevant provisions

Fig. 6.12 Example of recycled textiles [2]

6.2.1.4 Materials used for experimental purposes

Samples of supplied material are in the form of:

- cut or torn fractions, specified in Fig. 6.13,
- compact textile board, Fig. 6.14.

Material fractions – textiles cut or torn into small pieces are from different parts of textiles, such as covers or carpets from cars.

Fig. 6.13 Supplied loose textile fractions

Compact boards from textiles can have various thicknesses. Samples used are shown in Fig. 6.14 to Fig. 6.17.

Fig. 6.14 Supplied compact test samples

Fig. 6.15 Test sample – top view, outline

Fig. 6.16 Examples of divided samples – outline

Fig. 6.17 Examples of divided samples – side view

6.2.2 Glass

Another component from cars was the crushed material from car glass. Front and rear car glass is multilayer and side glass is usually formed by single glass layer. Fig. 6.18 shows the example of multilayer glass composition.

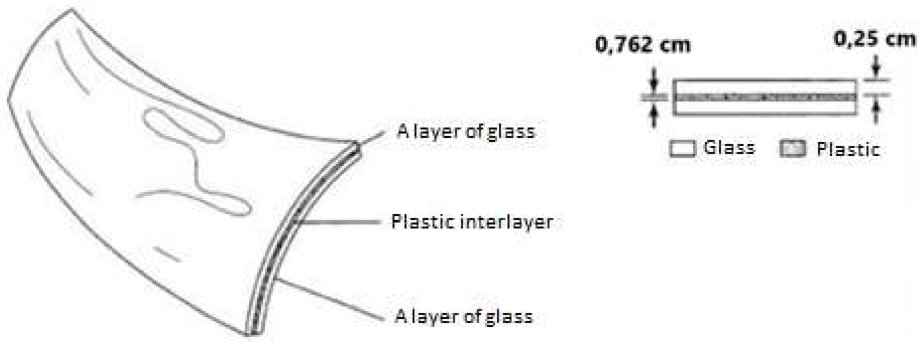


Fig. 6.18 Car glass and its parameters [1]

It includes damaged car glass from car services, car scrapyards and technological waste from car glass production, Fig. 6.19.

The complete windshield consists of two types of convex sheets of glass with a foil in between ensuring enhanced security of the glass. The foil prevents the glass fragments from getting inside the car during an accident and breaking the windshield, thus protecting the passengers [2].

The foil is from polyvinyl butyral, so-called PVB foil, and it is hot-fixed between two pieces of convex sheets of glass. The PVB foil is characterized by extreme strength. Even though such laminated glass is very thin, about 0.635 mm thick, it is very strong, and its breakage is less probable than in case of common safety glass [2].

The existing methods of car glass disposal in Slovakia has not includes the separation of PVB foil from the glass. Due to the absence of such processing line, there was practically no recycling of windshield glass.

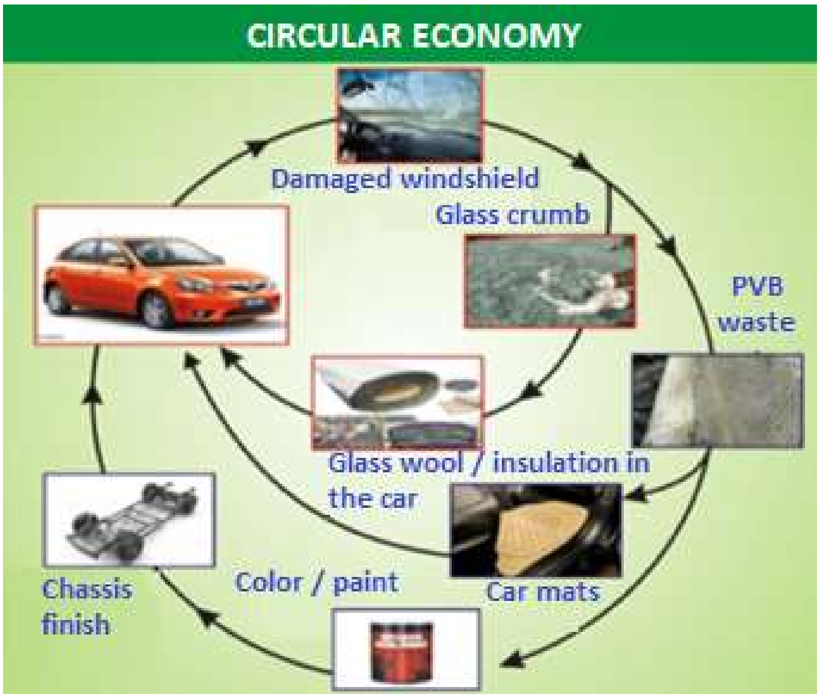


Fig. 6.19 Circular economy in the recycling of car glass [3]

From a technical point of view, the waste glass is fed to a processing line by feeder through the feeding section. The glass gets to devices by way of conveyor for the gradual treatment and removal of unwanted substances. The undesirable elements are gradually physically and mechanically removed from the fragments. This also removes the foil, thus allowing the fragments to be turned into glass granulate.
Windshield Recycling technology works within the size range of 2 to 30 mm and contains no contamination with stone, metal, plastic and rubber. [4]
Glass granulate as the output raw material of the glass material processing is used as the input raw material in the glass industry and replaces what is known as glass sand. It is an important part of input raw materials protecting the environment. It helps save energy in production, savings in primary raw materials and relieves the strain on the environment caused waste glass landfill.
The total weight of glass in end-of-life vehicles is approx. 40 kg which represents around 3% share on the total weight of old vehicle. The windshield from a passenger car weights around 13 kg and contributes to the increase of end-of-life vehicle recovery by approx. 1%. Glass is 100% recyclable. Examples of the use of recycled glass, its intermediate products, vary. It is used in the glass industry, in the construction industry for the insulation of buildings, or in the construction of roads.

Recycled glass for the products thereof can be in the form of:

- expanded glass beads,
- foam glass,

Expanded glass beads, Fig. 6.20 are used as a light fill into dry mortar, adhesives for tiles, light concrete, acoustic and light boards and mineral castings. Loose beads are used as bulk heat insulating material. Beads are added into paints in order to get a polished finish. [8]
Expanded glass beads are available in sizes from 0.04 mm to 4 mm. Bulk density ranges from 190 kg/m³ to 530 kg/m³ depending on the type. Two samples have a diameter of 2 – 4 mm and 0.25 – 0.5 mm. Selected properties are listed in
Spherical beads Fig. 6.21 are made of recycled glass. The beads have stable dimensions and are highly resistant to humidity, fire and chemicals. They have a fine closed cell structure of pores which results in excelled heat insulating and sound insulating properties. [9]

Table 6.4
Properties of the expanded glass beads [8]

d (mm)	Tensile strength	KS/KG	Contact surface
1.5 ± 0.2	600 N	226 354	15 992 cm^2
10 ± 0.5	6 200 N	764	2 399 cm^2
2 ± 0.2	900 N	95 493	11 994 cm^2
2.5 ± 0.2	1 100 N	48 492	9 595 cm^2
3 ± 0.2	1 600 N	28 294	7 995 cm^2
3.5 ± 0.3	1 800 N	17 818	6 854 cm^2
4 ± 0.3	2 300 N	11 937	5 997 cm^2
4.5 ± 0.3	2 400 N	8 388	5 334 cm^2
5 ± 0.3	2 600 N	6 112	4 798 cm^2
6 ± 0.3	3 600 N	3 537	3 998 cm^2
7 ± 0.3	3 800 N	2 227	3 426 cm^2
8 ± 0.4	5 200 N	1 492	2 999 cm^2
9 ± 0.4	5 700 N	1 047	2 665 cm^2

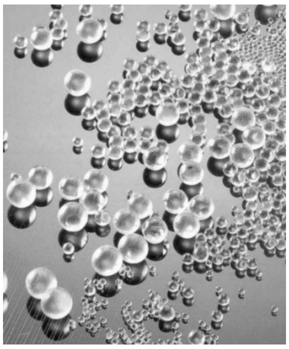


Fig. 6.20 Expanded beads [8]

Fig. 6.21 Spherical beads and crushed glass [9]

Glass foam has a thermal conductivity around 0.038 W/mK (temperature 24 °C). The foam can resist temperatures from -268 °C to 482 °C. Density of standard foam is 117 kg/m1 and it is available in the dimensions up to 450 mm x 600 mm x 180 mm. Pieces of glass foam can be bent using adhesive.
Foam glass, for example, REFAGLASS.
Foam glass is non-flammable, its softening point is above 700 °C, it is classified in the class of A1 construction materials according to EN 13501-1.
Bulk density of foam glass is in the range of 145 kg/m^3 – 165 kg/m^3, which represents 1/10 of the weight of stone gravel. It is supplied in bulk, in canvas or Big Bag packaging.

Crushed glass used for experimental purposes
Crushed glass used for the experiments is in Fig. 6.22 to Fig. 6.23, the size of crushed materials is approx. 1 mm. Crushed glass was supplied in a 1-kg package. Specific weight 1.4 – 1.5 kg/ dm^3, hardness 5.5 – 6 HV, grain size 10 – 400.

Fig. 6.22 Crushed glass – experimental material

Fig. 6.23 Detail of the crushed glass

6.3 The research of bulk materials of various fractions for the development of sound and heat insulating products

The measurements and evaluation of the acoustic properties were carried out using an impedance tube (Fig. 6.24). [17, 18, 19] The measurements were carried out using the BSWA TECH SW433 impedance tube with condenser microphones. 5 repeated measurements were carried out for each sample and the average values were evaluated. The evaluation of the acoustic properties of the samples was carried out using the sound absorption coefficient (α) and attenuation index (R). [18, 20, 21, 22, 23, 24] The measuring and evaluation were performed in the frequency range of 100 – 1600 Hz in compliance with ISO 10534-2.

Measurement of the sound absorption coefficient of the selected materials was carried out with the use of BSWA SW433 impedance tube in configuration with two microphones. The length of tube is 500 mm, and its inside diameter is 60 mm. One end of the tube is fitted with a loudspeaker having a diameter of 4 inches (101.6 mm) and output of 20 Watts. The operating frequency of the loudspeaker is from 20 Hz to 8000 Hz. The other end of the tube is fitted with a sample holder designed for samples with diameter of 60 mm and thickness from 0 – 100 mm. Within this configuration, there are three options of microphone position on the tube. Their positioning depends on the frequency range in which we want to carry out the measurement. Microphone positions 1 and 2 will be used for the measurement of sound absorption in the frequency range from 400 – 2500 Hz. Distance between positions 1 and 2 is 45 mm and distance of position 2 from the test sample is 35 mm. Positions 0 and 1 which are 170 mm apart will be used for the measurement of sound absorption in the frequency band from 100 – 800 Hz. In this form of tube configuration, it is possible to measure the sound absorption coefficient in the frequency band from 100 – 2500 Hz.

The measurement of the transmission attenuation coefficient of the examined materials was carried out with the use of BSWA SW433 impedance tube, as in the case of the sound absorption coefficient measurement, in the configuration of four microphones. There are three possible positions for microphone location on the wall of the tube. In this case the other end of the tube is not fitted with a sample holder, as is for the sound absorption measurement, but with an extension tube. The length of extension tube is

500 mm with an inside diameter of 60 mm. The wall of the extension tube also offers three possible positions of microphone placement.
Their positioning depends on the frequency range in which we want to carry out the measurement. Microphone positions 1 and 2 on the main tube will be used for the measurement of attenuation index R in the frequency range from 400 – 2500 Hz. Distance between positions 1 and 2 is 45 mm and distance of position 2 from the test sample is 35 mm. Positions 3 and 4 on the extension tube will be used. The distance between positions 3 and 4 is 45 mm and the distance of position 3 from the test sample is 100 mm. Microphone positions 0 and 2 on the main tube will be used for the measurement of attenuation index R in the frequency range from 100 – 800 Hz. The distance between positions 0 and 2 is 170 mm and distance of position 2 from the test sample is 35 mm. Positions 3 and 5 on the extension tube will be used. The distance between positions 3 and 5 is 170 mm and distance of position 3 from the test sample is 100 mm.
The measurement technology includes the MC32424-channel analyzer for data collection, the PA50 measurement power amplifier from the company BSWA TECH and the computer equipped with VA-Lab4 software for the information evaluation and tube control. This was followed by the preparation and connection of the measurement technology: the MC3242 data collection analyzer with 4 input ICP and 2 output channels (0~20 kHz), PA50 measurement power amplifier (50W) for the supply of the loudspeaker in the impedance tube, a PC with VA-Lab4 software, necessary wiring, SW433 impedance tube (100 Hz – 6.4 kHz) and their connection.

Fig. 6.24 View of the BSWA TECH impedance tube

The system for the measurement of sound absorption coefficient (α), (for frequency bands 100 Hz to 800 Hz and 400 Hz to 2500 Hz) is shown in Fig. 6.25, it consists of the following: the tube with an inside diameter of 60 mm and measurement sample holder with an inside diameter of 60 mm.

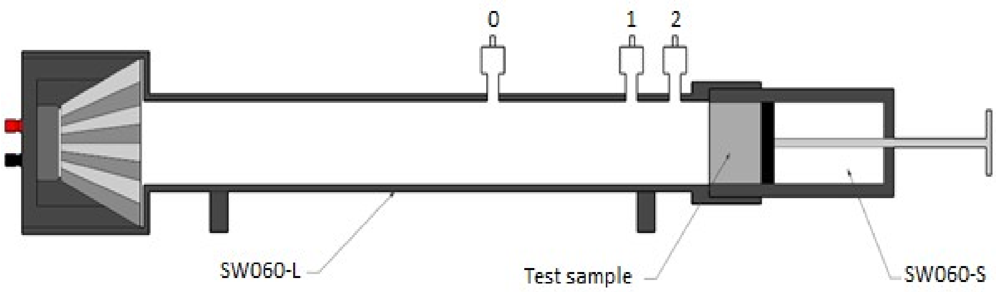


Fig. 6.25 The system for the measurement of sound absorption coefficient (100 Hz to 800 Hz, 400 Hz to 2500 Hz)

Measurement procedure

The measurement of acoustic properties of the bulk materials from the end-of-life vehicles was carried out with the use of aluminum test cartridges designed at our workplace. The measurements were carried out on 3 size fractions of the recycled rubber granulate and a mixture of textile material, the same as used for the production of Stered insulation board. In order to compare the acoustic properties of bulk materials, we have used the standard available products (a compact panel from recycled rubber from the company AVE and insulation board Stered made from recycled textiles). From these commonly available panels, we have made samples with the diameter of 60 mm applicable for the measurement of acoustic properties in the impedance tube. The list and characteristics of individual samples are specified in Table

.

Table 6.5
List of tested materials

Sample No.	Material	Test cartridge	Material thickness [mm]	Bulk density [kg.m^{-3}]
1	Compact rubber panel AVE	No	40	812
2	Recycled rubber granulate	Yes	55	464
3	Recycled rubber granulate	Yes	55	470
4	Recycled rubber granulate	Yes	55	377
5	Compact panel, Stered	No	50	276
6	Cut textile material, Stered	Yes	50	91

During the measurement, the cartridges were filled with bulk material (recycled rubber granulate and textiles), while the material was poured into the cartridges without any additional compression of the bulk material.

The following acoustic parameters were evaluated during the measurement:

- Sound absorption coefficient (α),
- Attenuation index (R).

Measurements of each sample were repeated five times and the results were then averaged. In order to evaluate the effect of the test cartridge on the measurement results, we have also carried out measurements of an empty test cartridge. Based on these measurements, it is possible to correct the results of measurements of bulk materials located in the test cartridge.

6.4 Development and production of test cartridges for the purpose of testing of the selected acoustic properties of bulk materials

This part of the report deals with the design of test cartridges for the measurement of acoustic properties of bulk as well as compact materials resulting from the recycling of end-of-life vehicles. The test cartridges are designed in such a way to be applicable for measuring the acoustic properties of bulk, granulate and compact materials in the BSWA SW433 impedance tube with the length of 500 mm and inside diameter of 60 mm. The design of the cartridges was important for several reasons. The fist reason is that the sample of bulk or granulated materials cannot be placed into the measuring device – impedance tube. Another one is that the resulting product (anti-noise barrier) will consist of multiple layers, a so-called sandwich (bulk and compact layers). It is equally important that the examined bulk material obtained by the recycling of end-of-life vehicles will be examined and tested with the use of the filling equipment at various pressures, and in this way we will change the porosity of the measured sample which is either glass, crushed rubber or textile components. In this case, the test cartridge will not only serve for the measurement itself, but also as auxiliary filling equipment.

We have developed 2 variants of the test cartridges:

- with the use of 3D printing,
- with the use of a CNC machining device.

6.4.1 Design and production of test cartridges for the extension of measurement possibilities of bulk materials from the end-of-life vehicles with the use of 3D printing and CNC technology

Production with 3D printing

The market currently offers many types or technologies of 3D printing. In general, 3D printing is an additive production method which uses the gradual application and joining of material in layers to create the resulting object according to the original in the computer. With the use of 3D printing, we can quickly and easily make models of various sizes and shapes with suitable mechanical properties.

Since this research is focused on the measurement and design of new materials from the recycled parts of end-of-life vehicles, in particular the used tires (crushed rubber), glass

(fraction ≥ 1mm), textiles (fibrous materials), etc., it was necessary to design and produce a suitable auxiliary device which would fit our needs.
This type of test cartridge was made with the use of a PRUSA i3 MK3 3D printer. Printing was carried out with the use of PLA and PETG filament. PLA is one of the most universal materials. It is fully biodegradable and used more frequently in industrial production. PETG is more durable, stronger and withstands greater impacts. PLA was used for the production of internal sieves and external edging. PETG was used for the remaining parts of the test cartridge.
With the use of 3D printing, we have designed a centering ring for the test cartridges (Fig. 6.26) which will serve to secure the exact positioning of the test cartridge on the place in the filling device, preventing its movement outside the required position.

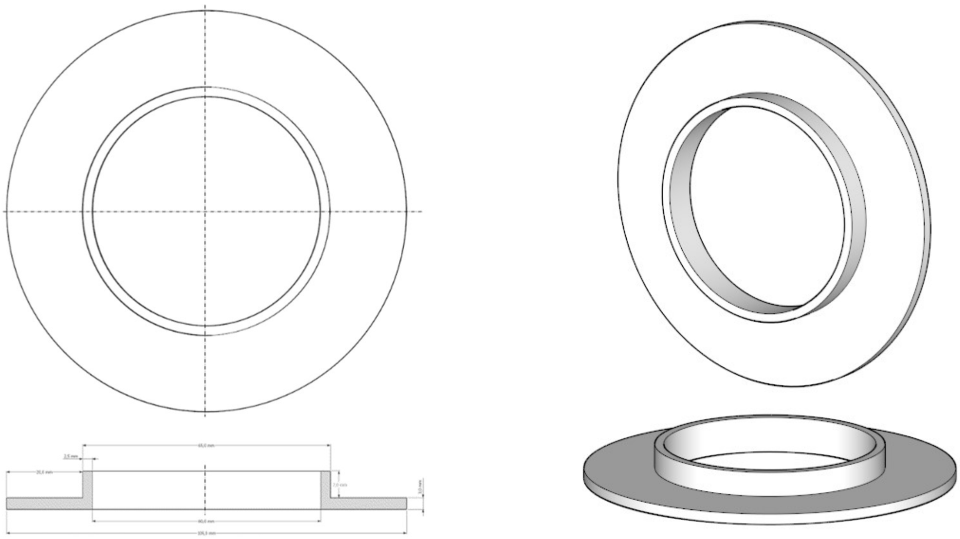


Fig. 6.26 Model of the centering ring for the capsule – 3D printing

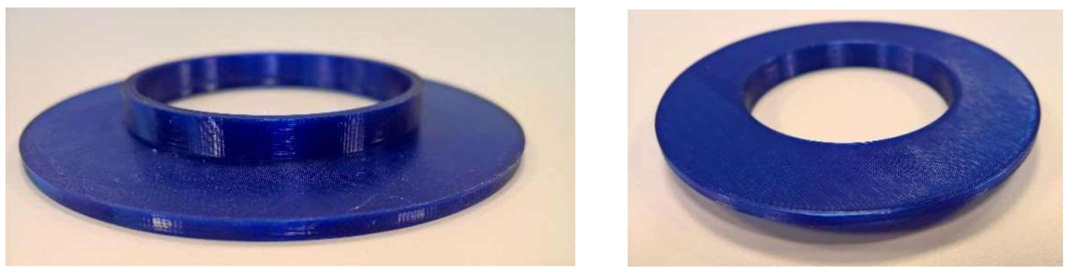


Fig. 6.27 Real view of the centering ring for the capsule after 3D printing

Production with the use of a CNC machine
Aluminum was selected as the material for the production of the test cartridges. The test cartridges were produced on CNC machines with the subsequent surface finish by anodic oxidation.

Designs of test cartridges for the extension of measuring possibilities in the impedance tube

Test cartridges were designed and produced on the CNC in five lengths, 25, 50, 75, 100 and 125 mm, with external thread on one end and internal thread on the other end. In the case of 3D printing, we have decided to produce 25- and 50-mm-long cylinders modifiable for various resulting lengths. Individual cylinders end with an external thread. An important part of the test cartridges are the perforated lids (sieves). For production on a CNC machine, these serve for closing the test cartridge and prevent the bulk materials from pouring out. Where a cartridge is printed on the 3D printer, we also produced internal sieves with a thickness of 1 mm which serve for partitioning the individual cylinders, thus enabling one cartridge to be filled with different types of bulk materials and, if necessary, separate them with an air pocket, or compact material. Fig. 6.28 shows the model of the test cartridge.

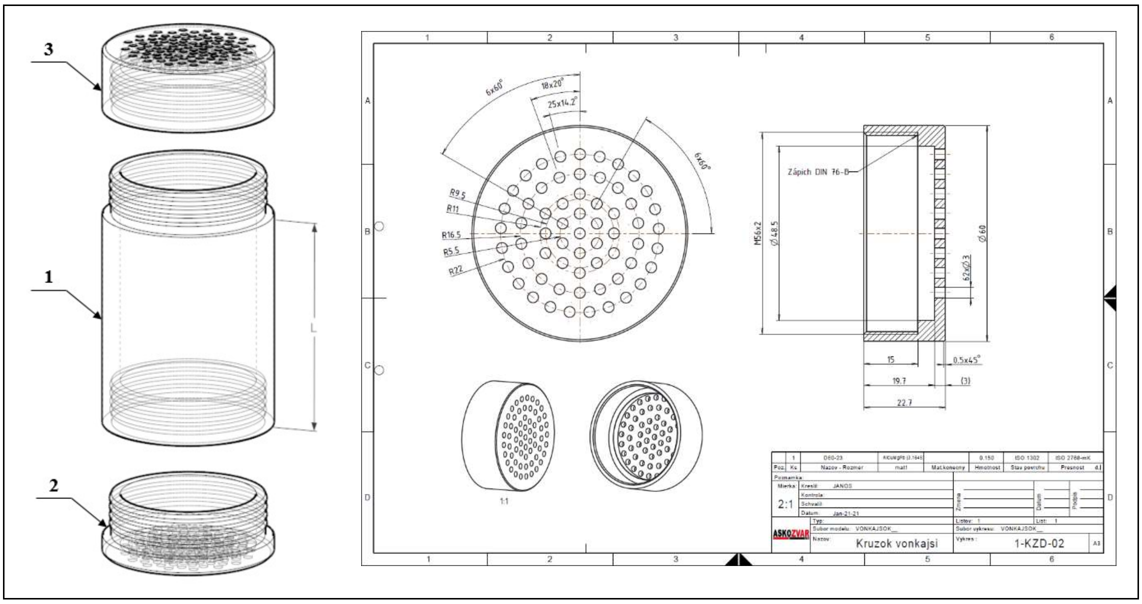


Fig. 6.28 Test cartridge models – CNC machining
Legend: 1 – body of the cartridge, 2 – lower perforated bottom (sieve), 3 – upper perforated lid (sieve)

The following Fig. 6.29 shows the real view of the individual types of test cartridges.

Fig. 6.29 Test cartridges – CNC machining

Fig. 6.30 shows the model of the test cartridge.

Fig. 6.30 Models of the test cartridges – 3D printing

The following Fig. 6.31 Real view of the test cartridges – 3D printing shows the real views of the test cartridges made by 3D printing.

Fig. 6.31 Real view of the test cartridges – 3D printing

6.4.2 Practical application of the cartridges

The test cartridges were designed and produced for the extension of possibilities of laboratory measurements of the selected acoustic descriptors, in other words, the sound absorption coefficient (α) and attenuation index (R). They were developed for the measurement of mainly bulk acoustic materials, in particular the crushed waste from end-of-life vehicles. Besides other things, they serve for the filling (compression) of the required bulk material, such as rubber granulate, glass, textile fractions, etc., in order to get a compact block for the measurement of sound and heat insulation with verified properties. Their production enabled us to conduct measurements in the impedance tube which is structurally limited for solid materials.

6.5 Development and production of the device for the filling of test cartridges

The device for filling of test cartridges with bulk and compact materials was developed at the Department of environmental engineering of the Faculty of Mechanical Engineering of the Technical University of Košice. An application for the utility model, as well as a patent application, which are granted by the Industrial Property Office of the Slovak Republic in Banská Bystrica, have been currently filed for the device. The following Fig. 6.32 shows the model of the designed filling device.

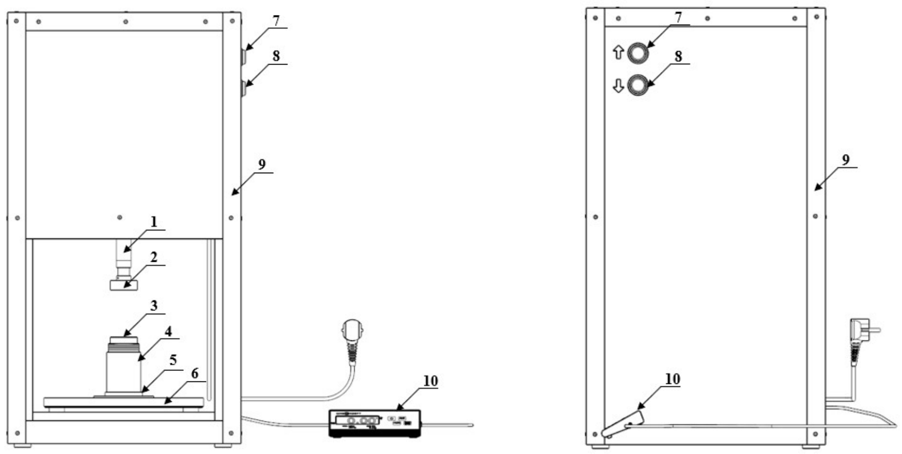


Fig. 6.32 Model of the designed filling device
Legend: 1 – electric linear piston, 2 – pressure ring, 3 – bulk material, 4 – cartridge, 5 – centering ring, 6 – scales base, 7 – button switch – upwards, 8 – button switch – downwards, 9 – frame, 10 – control element of the scales

The following Fig. 6.33 shows the 3D view of the filling device for the test cartridges.

Fig. 6.33 3D view of the filling device for test cartridges

Principle of the device

After the removal of the upper perforated lid from the cartridge, the bulk material is poured into the cartridge and the cartridge with material is then placed into the centering ring which is located at the scales base. By pressing the button switch “downward” the electric linear piston starts to extend and when the pressure ring touches the bulk material, the material is compacted or compressed inside the cartridge. After the completion of material compression, the resulting value is displayed in kilograms on the display of the control element of the scales. After reading the measured value and pressing the “upward” switch, the electric linear piston starts to retract into its original position. After that, the test cartridge with the compressed material is removed from the centering ring, the upper perforated lid is screwed on, and the sample is prepared for further measurements in the impedance tube.

The real view of the designed device, the cartridge as well as the centering ring is shown in the following Fig. 6.34.

Fig. 6.34 Real view of the designed device

Detailed view of the electric linear piston, cartridge and also the centering ring is shown in Fig. 6.35.

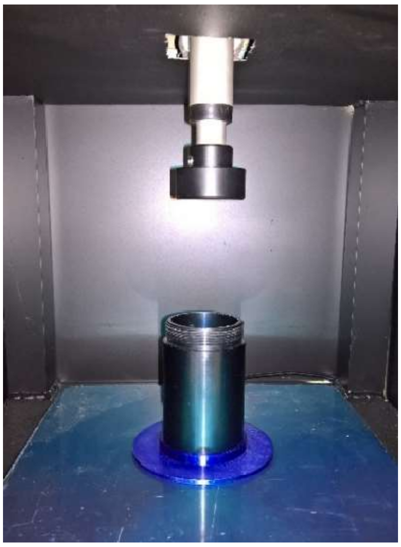


Fig. 6.35 Detailed view

The following Table 6.6 lists the technical parameters of the designed device for filling of test cartridges with bulk material.

Table 6.6
Technical parameters of the designed device

Device	
Material of the frame:	Aluminum
Cover:	steel sheet
Dimensions of the device (W x H x D):	410 x 754 x 414 mm
Total weight of the device:	15 kg
Electric linear piston	
Dimensions (W x H x D):	35 x 370 x 40 mm
Material:	aluminum alloy
Rated output:	20 W, maximum 30 W
Drive:	direct current
Motor:	with permanent magnet
Recommended operating cycle:	15 min./hour
Diameter of the piston rod:	20 mm
Piston rod extension:	250 mm
Operating temperature:	-20 +65 °C
Resistance:	3 A
Level of protection:	IP65
Noise level:	50 dB (measured at a distance up to 30 cm)
Power supply:	12 V
Scales	
Dimensions of scales base (W x H x D):	270 x 25 x 270 mm
Material:	premium steel

Dimensions of the control element of the scales (W x H x D):	180 x 40 x 90 mm
Power supply of the scales:	alternating current adapter 220 – 240 V or 9 V battery
Weight reading:	in kilograms and English pounds
Weighing range:	up to 200 kg, readable from 100 g
Weight of the scales:	2 kg

6.6 Results of the acoustic properties measurements of bulk materials and comparison with the same material composition

This part of the report deals with the measurement results of acoustic properties of bulk materials and their comparison with compact materials of the same material composition. Individual results of the specific measured samples are described in the following sub-chapters.

6.6.1 Results of the measurement of reference samples

Based on the measurements of acoustic properties of the reference samples of absorptive and reflective material and their comparison with the measurements of an empty cartridge, we can state that the contribution of the cartridge in the measurement results is minimal. Since the cartridge is made of an acoustically perfectly reflective material, the measurement results of the attenuation index with the use of this cartridge are slightly improved. On the contrary, it degrades the results of sound absorptivity measurements since it is made of material with minimum sound absorption.

Table 6.7

Measurement results of sound absorption coefficient – reference samples and empty test cartridge.

Material	Standard		
Parameter	Sound absorption coefficient		
Weight	–		
Freq.	Empty capsule	Absorptive material	Concrete
100	0.04	0.20	0.03
125	0.04	0.27	0.03
160	0.06	0.37	0.04
200	0.06	0.48	0.04
250	0.07	0.60	0.05
315	0.08	0.70	0.05
400	0.12	0.82	0.09
500	0.16	0.87	0.08
630	0.19	0.84	0.10
800	0.19	0.81	0.06
1 000	0.16	0.80	0.06
1 250	0.15	0.80	0.12
1 600	0.16	0.79	0.19
2 000	0.17	0.78	0.15
2 500	0.10	0.79	0.08

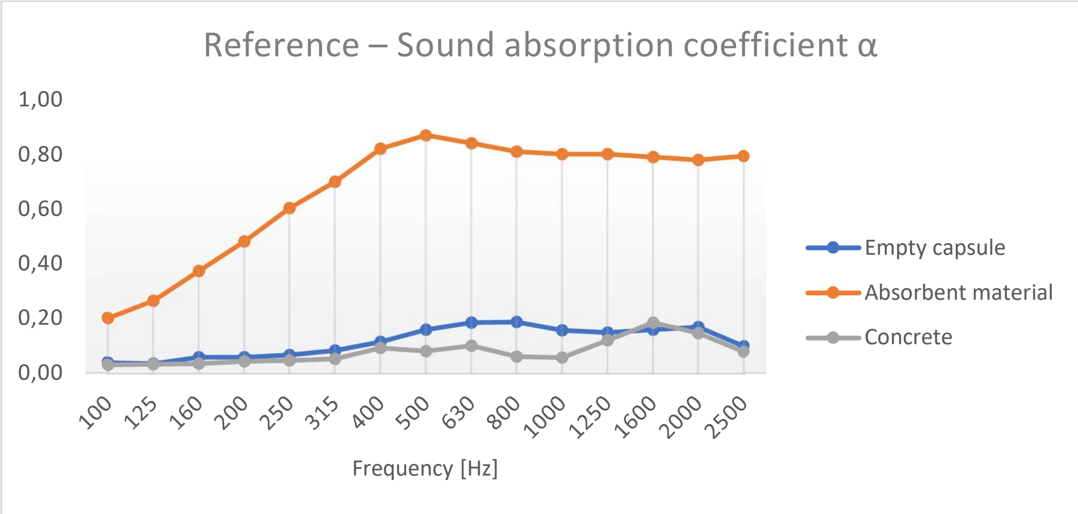


Fig. 6.36 Reference – Sound absorption coefficient α

In acoustic applications, the bulk material will still be used in combination with the external layer since, with regard to its character, the bulk material cannot be used without an outer case. In the measurement of acoustic properties, the measuring cartridge forms the outer case of the material. Based on these facts, we can regard the measurement results of acoustic properties of the bulk materials with the use of the measuring box as objective since the contribution of the measuring cartridge is minimal and in practical applications the bulk material will still be enclosed in some form of outer case with similar properties to the measuring cartridge.

Table 6.8
Results of attenuation index measurements – reference samples and empty test box

Material	**Standard**		
Parameter	**Attenuation index R**		
Weight	–		
Freq.	Empty capsule	Absorptive material	Concrete
100	0.53	10.72	40.42
125	0.53	10.84	41.59
160	0.57	11.09	41.48
200	0.64	11.39	40.99
250	0.76	11.88	40.29
315	0.93	11.49	40.71
400	1.15	10.71	41.62
500	1.41	11.32	37.31
630	1.79	12.71	39.71
800	2.55	15.30	39.14
1 000	4.58	17.80	39.50
1 250	4.95	16.88	42.47
1 600	4.23	17.06	50.39
2 000	3.43	18.00	50.52
2 500	1.41	19.13	55.92

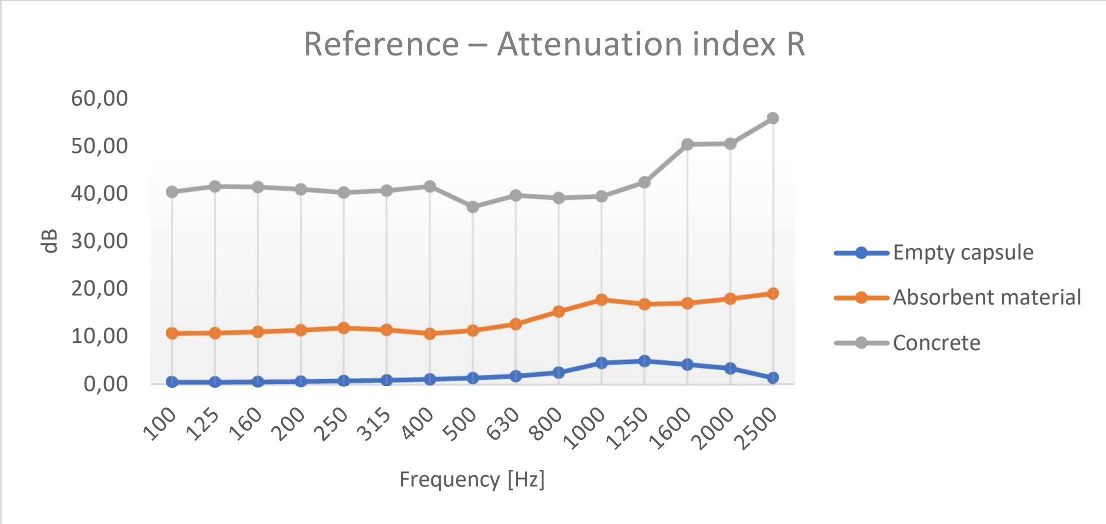


Fig. 6.37 Reference – Attenuation index R

6.6.2 Measurement results of materials on the basis of recycled rubber granulates

Measurement of acoustic properties was carried out on 4 samples on the basis of rubber granulate. One sample was made of a compact panel from recycled rubber material. Another 3 samples were made from bulk recycled rubber of various fraction sizes.

Rubber material is generally characterized by its good absorptivity and lower attenuation. This is also confirmed by the executed measurements. The main aim of the measurements was to compare the properties of bulk rubber recycled materials with a compact rubber panel, which is normally commercially manufactured. Based on the measurements conducted, we can state that the sound absorption coefficient of bulk materials reaches higher values than that of the compact rubber sample. This is caused mainly by the fact that the sound in bulk materials is absorbed not only by the material itself, but also by the air gaps between individual rubber particles.

As expected, the best values in measuring the attenuation index are achieved with the compact rubber sample. Almost equal values are reached with the bulk rubber granulate having the lowest fraction size. The bulk materials with bigger fractions reach lower attenuation index values than the compact rubber and bulk rubber with the smallest fraction. In this case, the lower attenuation index values are caused mainly by the compactness of bulk rubber granulates with larger fractions.

Table 6.9

Results of sound absorption coefficient measurements – compact rubber

Material	Recycled rubber – compact					
Parameter	Sound absorption coefficient					
Weight	88.8 g					
Freq.	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	Average
100	0.01	0.04	0.06	0.05	0.08	**0.05**
125	0.03	0.04	0.06	0.05	0.04	**0.04**
160	0.06	0.07	0.07	0.07	0.06	**0.07**
200	0.08	0.07	0.08	0.08	0.08	**0.08**
250	0.1	0.11	0.1	0.1	0.11	**0.10**
315	0.14	0.14	0.14	0.14	0.14	**0.14**
400	0.2	0.2	0.2	0.2	0.2	**0.20**
500	0.32	0.31	0.31	0.32	0.32	**0.32**
630	0.46	0.47	0.47	0.47	0.46	**0.47**
800	0.7	0.7	0.7	0.7	0.7	**0.70**
1 000	0.74	0.74	0.74	0.74	0.74	**0.74**
1 250	0.57	0.57	0.57	0.57	0.57	**0.57**
1 600	0.4	0.4	0.4	0.4	0.4	**0.40**
2 000	0.35	0.35	0.35	0.35	0.35	**0.35**
2 500	0.38	0.38	0.39	0.39	0.39	**0.39**

Fig. 6.38 shows the sample of compact rubber material.

Fig. 6.38 Compact rubber material

Table 6.10
Results of sound absorption coefficient measurements – recycled bulk rubber – fraction 1

Material	Recycled rubber – bulk (Fraction 1)					
Parameter	Sound absorption coefficient					
Weight	42.7 g					
Freq.	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	Average
100	0.05	0.05	0.04	0.04	0.06	0.05
125	0.06	0.05	0.07	0.07	0.05	0.06
160	0.08	0.07	0.07	0.07	0.06	0.07
200	0.08	0.08	0.08	0.09	0.09	0.08
250	0.1	0.1	0.09	0.1	0.1	0.10
315	0.13	0.13	0.12	0.14	0.13	0.13
400	0.26	0.26	0.26	0.26	0.26	0.26
500	0.33	0.32	0.33	0.31	0.33	0.32
630	0.41	0.41	0.41	0.37	0.41	0.40
800	0.66	0.66	0.67	0.55	0.66	0.64
1 000	0.94	0.94	0.94	0.78	0.94	0.91
1 250	0.81	0.81	0.81	0.68	0.82	0.79
1 600	0.5	0.5	0.5	0.42	0.5	0.48
2 000	0.37	0.37	0.38	0.31	0.38	0.36
2 500	0.4	0.4	0.4	0.33	0.4	0.39

The following Fig. 6.39 shows the recycled rubber granulate with fraction size 2.5 – 4 mm.

Fig. 6.39 Recycled rubber granulate – fraction size 2.5 – 4 mm

Table 6.11
Results of sound absorption coefficient measurements – recycled bulk rubber – fraction 2

Material	Recycled rubber – bulk (Fraction 2)					
Parameter	Sound absorption coefficient					
Weight	43.3 g					
Freq.	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	Average
100	0.06	0.03	0.03	0.03	0.04	**0.04**
125	0.07	0.06	0.05	0.05	0.05	**0.06**
160	0.07	0.07	0.07	0.07	0.06	**0.07**
200	0.08	0.07	0.08	0.08	0.08	**0.08**
250	0.1	0.1	0.09	0.09	0.1	**0.10**
315	0.13	0.14	0.13	0.13	0.13	**0.13**
400	0.27	0.26	0.26	0.26	0.26	**0.26**
500	0.32	0.33	0.33	0.33	0.33	**0.33**
630	0.37	0.41	0.42	0.42	0.41	**0.41**
800	0.54	0.66	0.66	0.66	0.66	**0.64**
1 000	0.78	0.94	0.94	0.94	0.94	**0.91**
1 250	0.69	0.84	0.84	0.84	0.84	**0.81**
1 600	0.44	0.54	0.53	0.53	0.54	**0.52**
2 000	0.34	0.41	0.41	0.41	0.41	**0.40**
2 500	0.36	0.42	0.43	0.43	0.42	**0.41**

Fig. 6.40 shows the recycled rubber granulate with fraction size 0.5 – 2 mm.

Fig. 6.40 Recycled rubber granulate – fraction size 0.5 – 2 mm

Fig. 6.41 shows the recycled rubber granulate with fraction size 0 – 0.5 mm.

Fig. 6.41 Recycled rubber granulate – fraction size 0 – 0.5 mm

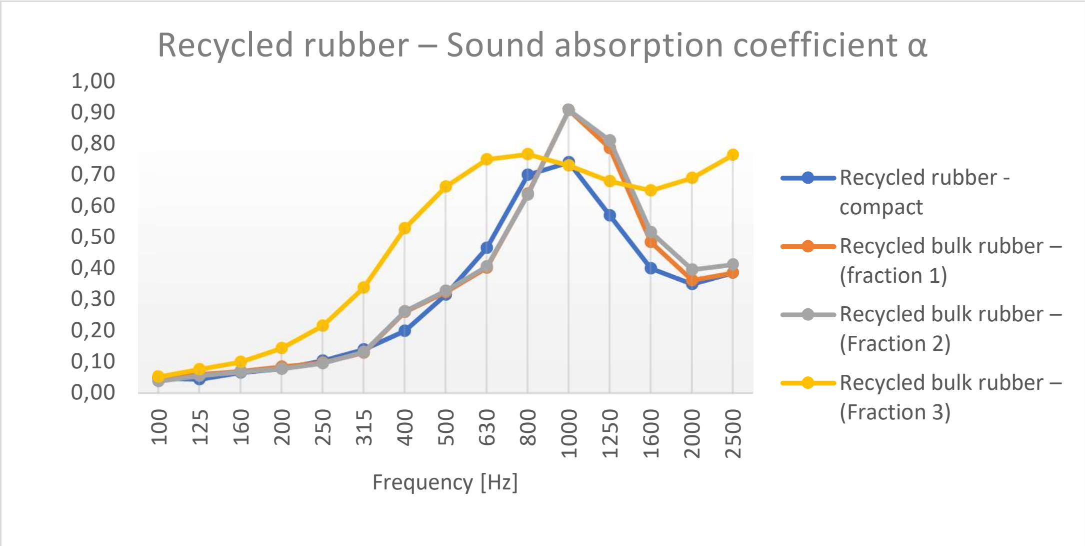


Fig. 6.42 Sound absorption coefficient – rubber materials

Table 6.12

Results of sound absorption coefficient measurements – recycled bulk rubber – fraction 3

Material	Recycled rubber – bulk (Fraction 3)					
Parameter	Sound absorption coefficient					
Weight	34.7 g					
Freq.	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	Average
100	0.06	0.06	0.03	0.05	0.06	**0.05**
125	0.07	0.09	0.07	0.07	0.08	**0.08**
160	0.1	0.09	0.1	0.11	0.1	**0.10**
200	0.14	0.14	0.14	0.15	0.15	**0.14**
250	0.21	0.22	0.22	0.21	0.22	**0.22**
315	0.33	0.34	0.34	0.34	0.34	**0.34**

400	0.52	0.53	0.53	0.53	0.53	**0.53**
500	0.66	0.67	0.66	0.66	0.66	**0.66**
630	0.75	0.75	0.75	0.75	0.75	**0.75**
800	0.76	0.77	0.77	0.77	0.76	**0.77**
1 000	0.73	0.73	0.73	0.73	0.73	**0.73**
1 250	0.68	0.68	0.68	0.68	0.68	**0.68**
1 600	0.65	0.65	0.65	0.65	0.65	**0.65**
2 000	0.69	0.69	0.69	0.69	0.69	**0.69**
2 500	0.76	0.77	0.76	0.77	0.76	**0.76**

Table 6.13

Results of attenuation index measurements – compact rubber

Material	**Recycled rubber – compact**					
Parameter	**Attenuation index R**					
Weight	**88.8 g**					
Freq.	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	**Average**
100	8.96	9.21	9.27	9.3	9.38	**9.22**
125	9.09	9.34	9.39	9.45	9.46	**9.35**
160	9.38	9.56	9.61	9.67	9.68	**9.58**
200	9.72	9.8	9.86	9.9	9.95	**9.85**
250	10.16	10.19	10.23	10.29	10.32	**10.24**
315	10.66	10.7	10.75	10.81	10.84	**10.75**
400	11.21	11.37	11.41	11.46	11.47	**11.38**
500	11.44	11.7	11.73	11.77	11.8	**11.69**
630	12.23	12.13	12.14	12.15	12.21	**12.17**
800	12.21	12.39	12.44	12.46	12.44	**12.39**
1 000	12.4	12.5	12.54	12.56	12.65	**12.53**
1 250	12.06	12.2	12.24	12.26	12.3	**12.21**
1 600	11.53	11.65	11.69	11.71	11.76	**11.67**
2 000	11.85	11.85	11.91	11.91	12.14	**11.93**
2 500	12.81	13.01	13.01	13.04	13.08	**12.99**

Table 6.14

Results of attenuation index measurements – recycled bulk rubber – frac. 1

	Recycled rubber – bulk (Fraction 1)					
Parameter	**Attenuation index R**					
Weight	**42.7 g**					
Freq.	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	**Average**
100	5.24	2.31	2.39	2.37	2.4	**2.94**
125	5.49	2.42	2.45	2.46	2.49	**3.06**
160	5.83	2.66	2.69	2.7	2.72	**3.32**
200	6.1	2.95	2.98	3	3.02	**3.61**
250	6.25	3.35	3.39	3.42	3.44	**3.97**

315	5.52	3.8	3.83	3.87	3.88	**4.18**
400	5.04	4.36	4.38	4.42	4.43	**4.53**
500	5.9	4.93	4.97	4.99	5	**5.16**
630	5.79	5.51	5.54	5.58	5.59	**5.60**
800	6.01	6.01	6.03	6.04	6.06	**6.03**
1 000	6.18	6.25	6.26	6.27	6.29	**6.25**
1 250	5.89	5.96	5.97	5.99	6.01	**5.96**
1 600	4.64	4.7	4.71	4.73	4.75	**4.71**
2 000	3.76	3.8	3.82	3.84	3.86	**3.82**
2 500	4.7	4.75	4.79	4.78	4.81	**4.77**

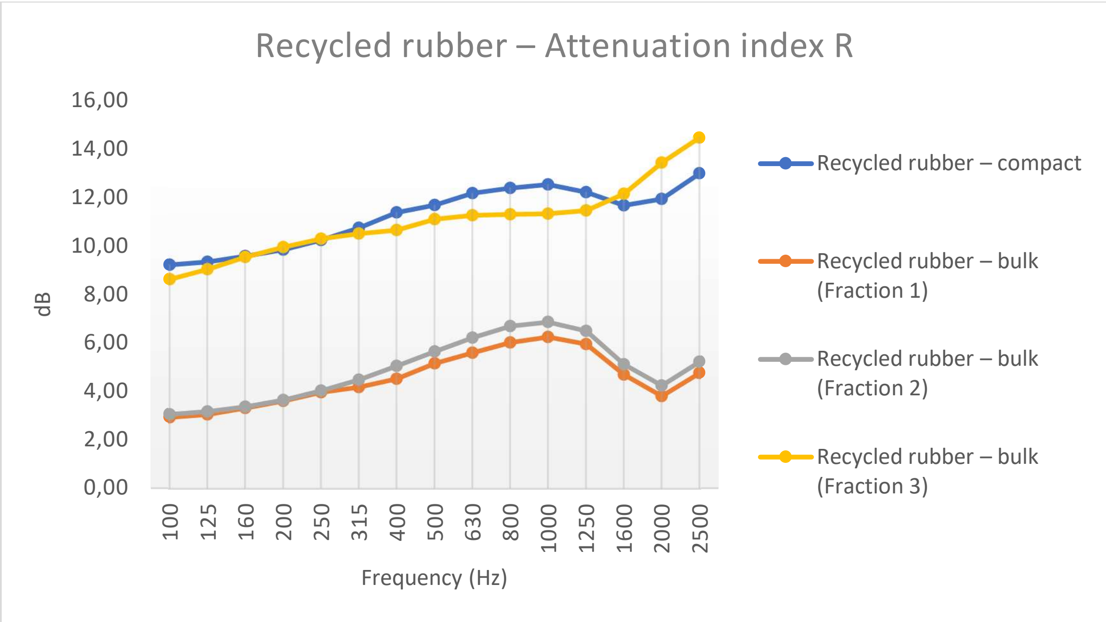


Fig. 6.43 Attenuation index – rubber materials

Table 6.15

Results of attenuation index measurements – recycled bulk rubber – frac. 2

Material	**Recycled rubber – bulk (Fraction 2)**						
Parameter	**Attenuation index R**						
Weight	**43.3 g**						
Freq.	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	**Average**	
100	3.01	3.08	3.1	3.11	3.03	**3.07**	
125	3.14	3.18	3.21	3.21	3.16	**3.18**	
160	3.35	3.39	3.42	3.42	3.34	**3.38**	
200	3.62	3.66	3.67	3.68	3.65	**3.66**	
250	3.99	4.02	4.04	4.04	4.08	**4.03**	
315	4.43	4.48	4.49	4.51	4.56	**4.49**	
400	4.98	5.07	5.08	5.08	5.08	**5.06**	
500	5.62	5.67	5.68	5.67	5.66	**5.66**	

630	6.2	6.21	6.21	6.22	6.26	**6.22**	
800	6.68	6.68	6.69	6.71	6.7	**6.69**	
1 000	6.84	6.84	6.85	6.85	6.94	**6.86**	
1 250	6.5	6.5	6.5	6.5	6.51	**6.50**	
1 600	5.11	5.11	5.13	5.12	5.14	**5.12**	
2 000	4.25	4.24	4.25	4.23	4.27	**4.25**	
2 500	5.23	5.21	5.24	5.22	5.22	**5.22**	

Table 6.16

Results of attenuation index measurements – recycled bulk rubber – frac. 3

Material	**Recycled rubber – bulk (Fraction 3)**					
Parameter	**Attenuation index R**					
Weight	**34.7 g**					
Freq.	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	**Average**
100	8.38	8.88	8.88	8.53	8.47	**8.63**
125	8.92	9.26	9.23	8.91	8.88	**9.04**
160	9.55	9.64	9.64	9.44	9.44	**9.54**
200	9.99	9.94	9.95	9.93	9.93	**9.95**
250	10.21	10.25	10.26	10.37	10.4	**10.30**
315	9.92	10.58	10.6	10.71	10.73	**10.51**
400	9.63	10.9	10.91	10.89	10.91	**10.65**
500	10.91	11.17	11.17	11.11	11.13	**11.10**
630	11.18	11.25	11.27	11.3	11.32	**11.26**
800	11.26	11.32	11.32	11.31	11.32	**11.31**
1 000	11.33	11.33	11.35	11.31	11.34	**11.33**
1 250	11.47	11.46	11.46	11.47	11.48	**11.47**
1 600	12.14	12.13	12.14	12.15	12.16	**12.14**
2 000	13.41	13.4	13.41	13.46	13.48	**13.43**
2 500	14.43	14.46	14.47	14.48	14.51	**14.47**

6.6.3 Measurement results of recycled textile materials

Measurement of acoustic properties of recycled textile materials was carried out on two samples. One sample was made of compact recycled textile material STERED. The second sample was prepared from the same recycled bulk textile material which was not compacted.

On the basis of the conducted measurements of sound absorption coefficient, we can state that the compact textile material reaches better parameters in the frequency band 100 – 500 Hz and 1600 – 2500 Hz. The bulk textile material reaches better absorptivity parameters within the frequency band 500 – 1250 Hz.

Based on the results of attenuation index measurements, it is clear that the compact textile material has better properties in the entire frequency band. This result was expected since the bulk density of the compact material is 4 times higher than the bulk density of the bulk textile material.

Fig. 6.44 Compact textile material – Stered

Fig. 6.45 Recycled bulk textile material

Table 6.17
Results of sound absorption coefficient measurements – Stered compact

Material	Stered – compact					
Parameter	Sound absorption coefficient					
Weight	37.0 g					
Freq.	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	**Average**
100	0.1	0.1	0.09	0.11	0.13	**0.11**
125	0.14	0.13	0.14	0.14	0.13	**0.14**
160	0.2	0.19	0.2	0.2	0.19	**0.20**
200	0.27	0.27	0.27	0.27	0.27	**0.27**
250	0.37	0.37	0.37	0.37	0.37	**0.37**
315	0.49	0.49	0.49	0.49	0.48	**0.49**
400	0.59	0.59	0.59	0.58	0.59	**0.59**
500	0.66	0.66	0.66	0.66	0.65	**0.66**
630	0.68	0.68	0.68	0.68	0.67	**0.68**
800	0.71	0.71	0.71	0.71	0.71	**0.71**
1 000	0.75	0.75	0.75	0.75	0.75	**0.75**
1 250	0.75	0.75	0.75	0.75	0.75	**0.75**
1 600	0.8	0.8	0.8	0.8	0.8	**0.80**
2 000	0.82	0.82	0.82	0.82	0.82	**0.82**
2 500	0.82	0.82	0.82	0.82	0.82	**0.82**

Table 6.18
Results of sound absorption coefficient measurements – Stered bulk

Material	Stered – bulk					
Parameter	Sound absorption coefficient					
Weight	8.4 g					
Freq.	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	**Average**
100	0.07	0.07	0.04	0.07	0.07	**0.06**
125	0.09	0.07	0.07	0.08	0.08	**0.08**
160	0.11	0.1	0.11	0.1	0.1	**0.10**
200	0.14	0.14	0.14	0.14	0.14	**0.14**
250	0.21	0.2	0.2	0.2	0.21	**0.20**
315	0.29	0.3	0.3	0.29	0.3	**0.30**
400	0.46	0.46	0.46	0.46	0.46	**0.46**
500	0.66	0.66	0.66	0.66	0.66	**0.66**
630	0.87	0.87	0.87	0.87	0.87	**0.87**
800	0.97	0.97	0.97	0.97	0.97	**0.97**
1 000	0.91	0.91	0.91	0.91	0.91	**0.91**
1 250	0.79	0.79	0.79	0.79	0.79	**0.79**
1 600	0.69	0.69	0.69	0.68	0.69	**0.69**
2 000	0.68	0.68	0.68	0.68	0.68	**0.68**
2 500	0.75	0.75	0.75	0.76	0.75	**0.75**

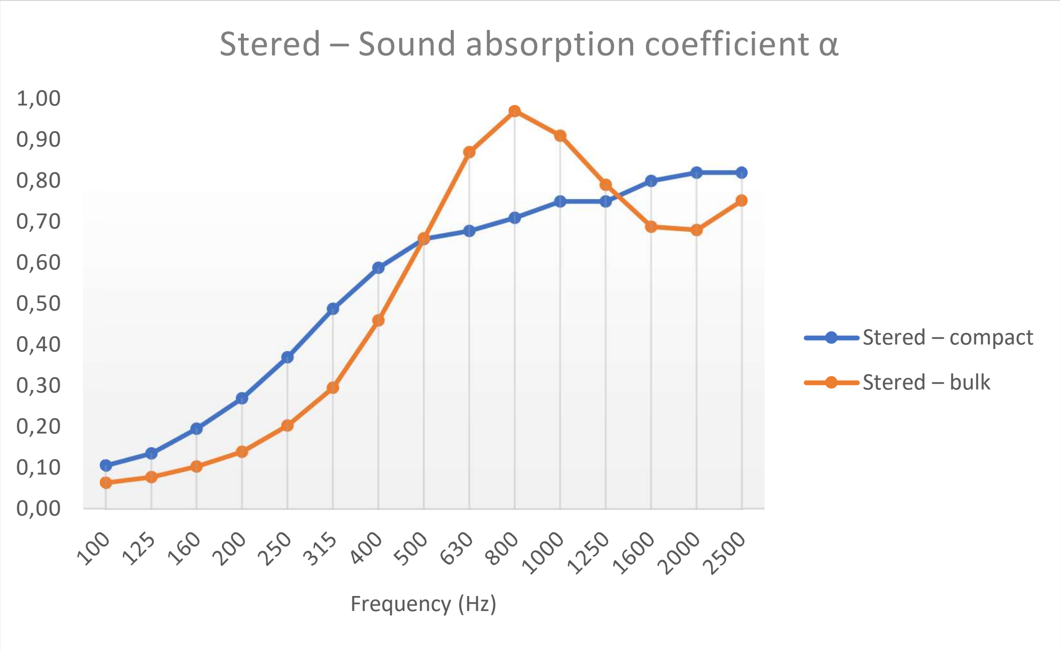


Fig. 6.46 Sound absorption coefficient – textile materials

Table 6.19

Results of attenuation index measurements – Stered compact

Material	Stered – compact					
Parameter	**Attenuation index R**					
Weight	**37.0 g**					
Freq.	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	**Average**
100	11.49	11.85	11.85	11.6	11.59	**11.68**
125	11.66	11.9	11.92	11.74	11.73	**11.79**
160	11.91	12	12.03	11.96	11.97	**11.97**
200	12.08	12.17	12.18	12.2	12.21	**12.17**
250	12.09	12.4	12.42	12.52	12.52	**12.39**
315	11.79	12.75	12.76	12.82	12.81	**12.59**
400	12.27	13.23	13.24	13.23	13.21	**13.04**
500	13.36	13.56	13.59	13.56	13.55	**13.52**
630	14.45	14.64	14.66	14.68	14.66	**14.62**
800	15.13	15.23	15.26	15.24	15.21	**15.21**
1 000	15.29	15.32	15.34	15.31	15.27	**15.31**
1 250	15.87	15.9	15.91	15.91	15.87	**15.89**
1 600	18.44	18.46	18.49	18.49	18.46	**18.47**
2 000	20.44	20.44	20.45	20.47	20.46	**20.45**

Table 6.20
Results of attenuation index measurements – Stered bulk

Material	**Stered – bulk**					
Parameter	**Attenuation index R**					
Weight	**8.4 g**					
Freq.	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	**Average**
100	4.27	4.37	4.27	4.41	4.4	**4.34**
125	4.5	4.56	4.47	4.6	4.62	**4.55**
160	4.82	4.9	4.82	4.91	4.93	**4.88**
200	5.17	5.2	5.17	5.23	5.24	**5.20**
250	5.61	5.6	5.63	5.62	5.63	**5.62**
315	5.68	5.67	5.71	5.69	5.7	**5.69**
400	6.18	6.2	6.18	6.22	6.22	**6.20**
500	6.31	6.33	6.31	6.34	6.34	**6.33**
630	6.62	6.62	6.63	6.61	6.62	**6.62**
800	6.75	6.76	6.77	6.79	6.79	**6.77**
1 000	6.81	6.82	6.82	6.84	6.84	**6.83**
1 250	6.92	6.92	6.92	6.91	6.91	**6.92**
1 600	7.82	7.83	7.83	7.83	7.83	**7.83**
2 000	9.64	9.65	9.65	9.6	9.6	**9.63**
2 500	11.18	11.19	11.2	11.21	11.22	**11.20**

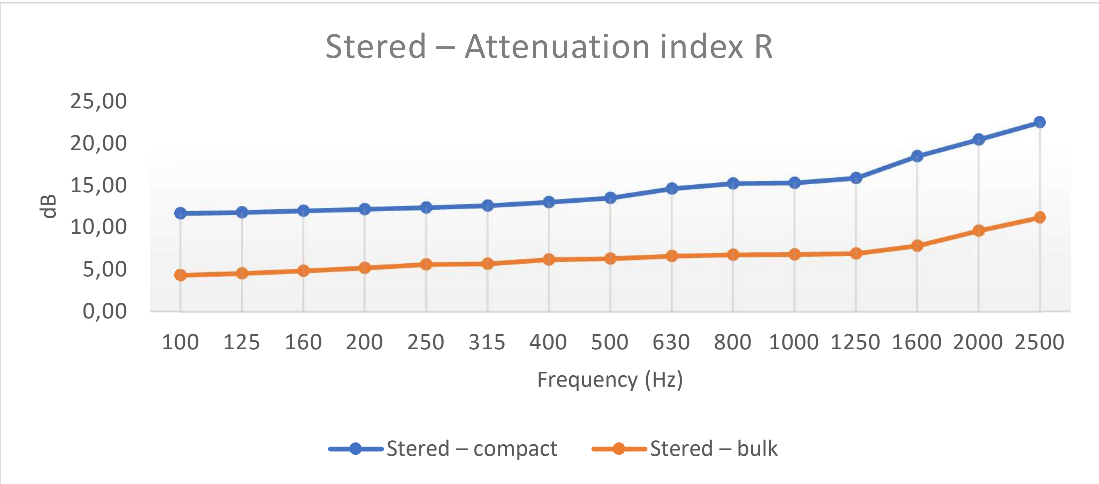


Fig. 6.47 Attenuation index – textile materials

6.7 Development and manufacture of the product based on bulk materials

The objective of the authors was to search for application possibilities of the recycled bulk materials from the components of end-of-life cars. They have specifically selected the recycled rubber, recycled textile material and crushed glass from cars. The application of the specified materials is foreseen in the implementation of noise barrier structures, or other sound and heat insulating products. Noise barriers are currently used to reduce traffic and industrial noise directly in the production process. The structures of noise barriers can be very varied.

Many materials included in the end-of-life vehicles which are problematic in terms of their further recovery (textiles, airbags, glass, tires, etc.) could be suitable for the production of sound-absorbing elements. The production of compact materials from these recycled materials requires the application of a certain amount of binder. The addition of binders will eventually make the production of these materials more expensive, and they are often harmful to the environment. One of the possible solutions for the use of recycled granulated (but also chopped, cut, torn and crushed) materials in acoustic applications without the use of binders is the application of these materials in noise barriers in the form of bulk material.

In the development of these noise barriers, the authors have cooperated with the firm FORSTER archívna dopravná technika s.r.o., Bratislava. The activities of the authors in 2021 will focus, in particular, on researching the acoustic properties of products made on the basis of such materials. The advantages to using these so-called "green" materials in acoustic (and also thermal) applications, such as noise barriers, in comparison with the commercial material, are the combination of a very light substance, high physical and chemical stability, low costs and high sound absorption values.

Fig. 6.48 shows the product (noise barrier panel) designed by the research team, which is completed with individual structural parts.

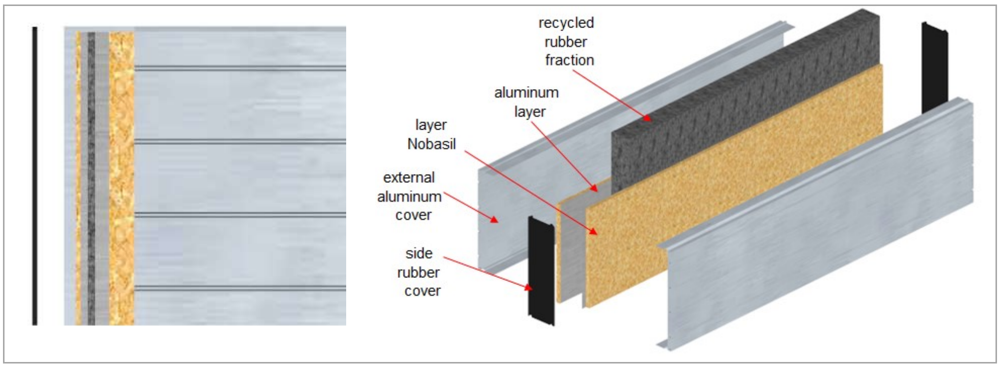


Fig. 6.48 Individual parts of the noise barrier panel (recycled rubber fraction)

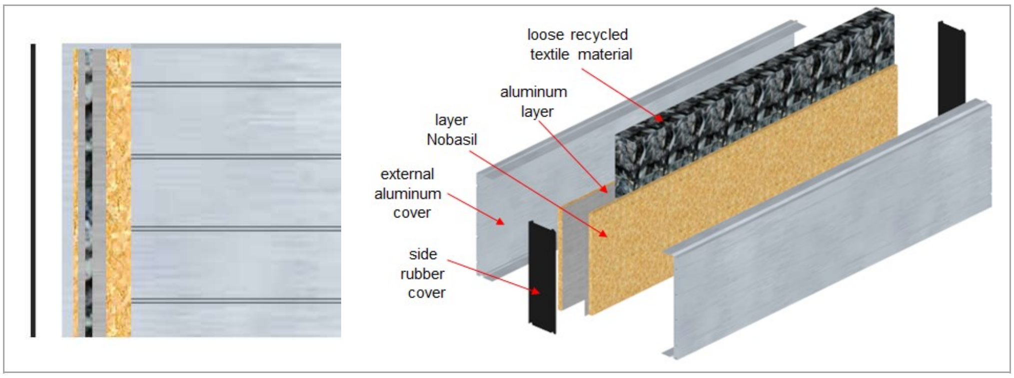


Fig. 6.49 Individual parts of the noise barrier panel (recycled bulk textile material)

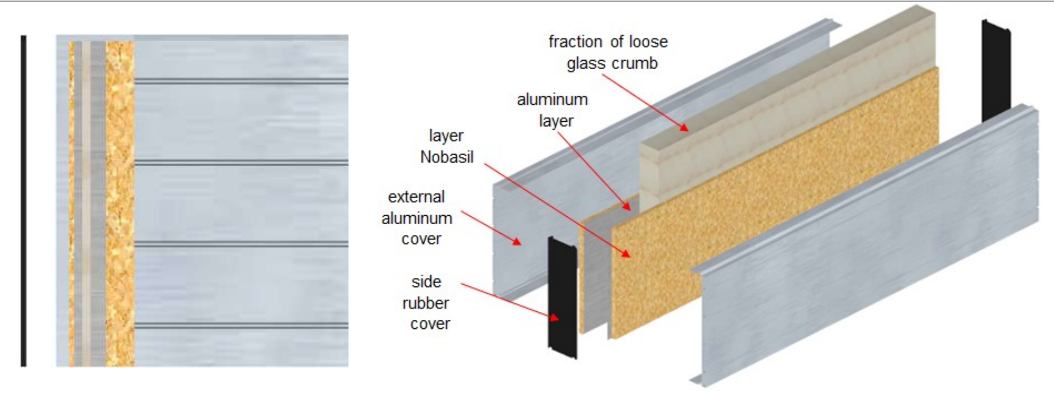


Fig. 6.50 Individual parts of the noise barrier panel (bulk crushed glass fraction)

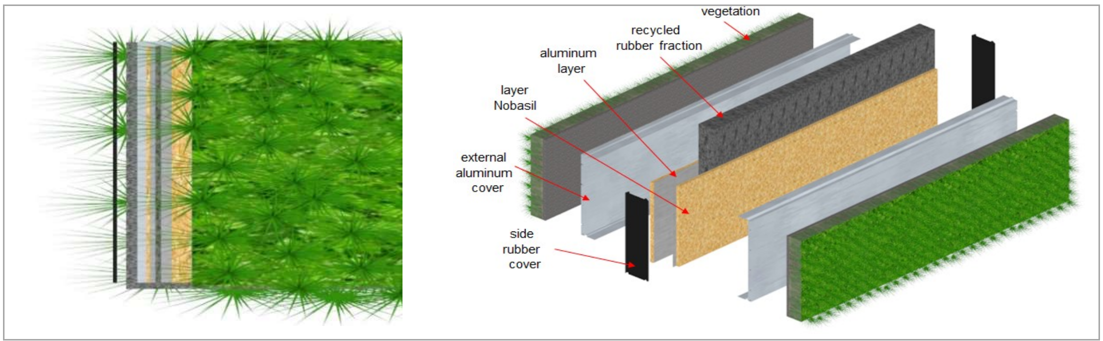


Fig. 6.51 Noise barrier panel with green wall

Fig. 6.52 Active green roof panel from recycled textiles with sound and heat insulating properties

6.8 Research activities of the authors

Activities for 2022:

- Selection and preparation of samples for further research and measurements.
- Measurement of the thermal conductivity coefficient of the samples.
- Comparison of the sound insulating and heat insulating properties of the examined materials on the basis of the achieved measurement results.
- Application possibilities of the examined materials in construction, industry and other areas – enhancement of the insulation of buildings and structures.
- Ecological insulations – green roofs and vertical barriers.
- The future use of recycled materials in terms of their sound and heat insulating properties.

6.9 Conclusion

In conclusion, it can be stated that the objectives set by the project developers were fully met. They have selected suitable materials from the components in the end-of-life vehicles. Suitable fractions of these materials for further research were also selected. They have developed and produced unique test cartridges for the measurements of bulk materials in the impedance tube and also a unique device designed for filling of these test cartridges. The test cartridges and the device for filling of these cartridges are the subject of the utility model and patent application. The same procedure will be used to protect the intellectual property with regard to the noise barrier panel.

Acknowledgements

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6.10 Bibliography

[1] Factors that Cause the Aging of Rubber. Katalógová literatúra. [online]. Dostupné na internete: https://tirerecyclingmachines.com/application/Factors-that-Cause-the-Aging-of-Rubber.html#post/0

[2] Reasons for the aging of rubber products and how to deal with them. [online]. Dostupné na internete: https://www.everflex-rubber-hose.com/reasons-for-the-aging-of-rubber-products-and-how-to-deal-with-them/

[3] Recyklácia starých pneumatík. Katalógová literatúra [online]. Dostupné na internete: https://auto.sme.sk/g/140776/recyklacia-starych-pneumatik?list=1

[4] Technológia Windshield Recycling [online]. Dostupné na internete: https://www.waterloohonda.com

[5] Vlastnosti gumovej dlažby (výrobkov z recyklovanej gumy) a návod na použitie. [online]. Dostupné na internete: https://www.avesk.sk/file/edee/2015/04/gumova-dlazba_vlastnosti-a-navod_2015.pdf

[6] Recyklácia textilu. Objav svet STEREDU – svet akustických a tepelných izolácií a terenčných riešení. Katalógová literatúra [online]. Dostupné na internete: http://www.stered.sk/

[7] Recyklácia textilu. Dávame textilu druhý život. [online]. Dostupné na internete: https://sk-tex.com/

[8] Automobile Windshield. [online]. Dostupné na internete: http://www.madehow.com/ Volume-1/Automobile-Windshield.html

[9] Automobile Windshield. The manufacturing process. [online]. Dostupné na internete: http://www.madehow.com/Volume-1/Automobile-Windshield.html#ixzz7CVnGxu7r

[10] Automobile Windshield. The future. [online]. Dostupné na internete: https://www.windshield-pvb-recycling.com/history-and-future/

[11] Windshield Recycling. Supplier for glass cullet. [online]. Dostupné na internete: https://www.windshield-pvb-recycling.com/supplier-for-glass-cullet/

[12] NATUR-PACK. Sklo sa dá recyklovať donekonečna. Boli sme sa pozrieť, ako sa to robí. 2018, [online]. Dostupné na internete: https://ciernalabut.sk/5568/sklo-je-jediny-material-ktory-sa-da-recyklovat-donekonecna-boli-sme-sa-pozriet-ako-sa-to-robi/

[13] Recyklácia a likvidácia skla. Katalógová literatúra [online]. Dostupné na internete: http://ekosmart.sk/sk/nase-sluzby-pri-recyklacii-skla

[14] Odvoz recyklácia a likvidácia autoskla. Eko-Smart, s.r.o. [online]. Dostupné na internete: http://ekosmart.sk/sk/recyklacia-autoskla

[15] Guličky technické. Katalógová literatúra LABO – SK, s.r.o. [online]. Dostupné na internete: https://www.labo.sk/produkt/sk/e-shop/sklo-a-porcelan/ostatny-sklenenny-material/gulicka-technicka-sklenena.html

[16] Recyklácia skla. Katalógová literatúra REFAGLASS. [online]. Dostupné na internete: https://www.refaglass.sk/recyklacia-skla/

[17] Aly, O.A.A.- Doumiati, S.- Moselhy, M.: Testing of Non-Traditional Acoustical Materials. In: 17th IEEE Mediterranean Electrotechnical Conference. Vol.1 (2014), s. 64-67. ISBN: 978-1-4799-2337-3. [cit. 2020-1-18]. Dostupné na internete: <https://www.researchgate.net/publication/265842651_Testing_of_Non-Traditional_Acoustical_Materials >

[18] Deepak, A.- Shashi, M.- Venkatesham, B.- Suryakumar, S.: Acoustic characterization of additive manufactured layered porous materials. In: The 48th International Congress and Exhibition on Noise Control Engineering (2019). [cit. 2020-1-23]. Dostupné na internete: <https://www.researchgate.net/publication/336604025_Acoustic_characterization_of_additive_manufactured_layered_porous_materials >

[19] Suhanek, M.- Jambrosic, K.- Domitrovic, H.: Student project of building an impedance tube. In: The Journal of the Acoustical Society of America. Vol. 123, No. 3 (2008). ISSN 1520-8524. [cit. 2019-11-29]. Dostupné na internete: <https://www.researchgate.net/publication/5325257_Student_project_of_building_an_impedance_tube >

[20] Vigran, T. E.: Normal incidence sound transmission loss in impedance tube – Measurement and prediction methods using perforated plates. In: Applied Acoustics. Vol.73, No. 4 (2012), s. 454-459. ISSN 0003-682X. [cit. 2019-11-22]. Dostupné na internete: <https://www.sciencedirect.com/science/article/abs/pii/S0003682X11003057 >

[21] Koruk, H.: An assessment of the performance of impedance tube method. In: Noise Control Engineering Journal. Vol. 62, No. 4 (2014), s. 264-274.ISSN 0736-2501. [cit. 2020-1-19]. Dostupné na internete: <https://www.researchgate.net/publication/265606083_An_assessment_of_the_performance_of_impedance_tube_method >

[22] Neto, B.G.- Pereira, I.- Futatsugi, S.: Experimental analysis of the dispersion in the measurement of the absorption coefficient with the impedance tube. In: 47th International Congress and Exposition on Noise Control Engineering – Internoise. Vol. IN18-2318 (2018). ISBN: 978-1-5108-7303-2. [cit. 2019-11-29]. Dostupné na internete: <https://www.researchgate.net/publication/331097879_Experimental_Analysis_of_the_Dispersion_in_the_Measurement_of_the_Absorption_Coefficient_with_the_Impedance_Tube >

[23] Palisa, V.: Návrh a konstrukce sendvičové vrstvy na bázitextilního recyklovaného materiálu: Bakalárska práca (2015). Zlín: Univerzita Tomáše Bati ve Zlíně: Fakulta technologická. [cit. 2020-4-29]. Dostupné na internete: <http://195.178.95.140:8080/bitstream/handle/10563/37849/palisa_2016_dp.pdf?sequence=1&isAllowed=y >

[24] Labašová, E.- Ďuriš, R.: Measurement of the acoustic absorption coefficient by impedance tube. In: Research Papers Faculty of Materials Science and Technology Slovak University of Technology. Vol. 27, No. 45 (2019), s. 94-101. ISSN 1338-0532. [cit. 2020-1-19]. Dostupné na internete: https://www.

researchgate.net/publication/338031592_Measurement_of_the_Acoustic_Absorption_Coefficient_by_Impedance_Tube
[25] BADIDA, M. – ŠOOŠ, Ľ. et al.: Analysis of the state, forecasts and new technologies of waste recovery in the automotive industry. - Lüdenscheid (Nemecko): RAM-Verlag pp. 190, [print]. ISBN 978-3-96595-008-5.

Research of new wooden composites containing waste polymers from cars

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7 Research of the properties or new wooden composites containing waste polymers from cars

7.1 Introduction

The constant industrial development as well as the consumption lifestyle result in the growth of produced waste including the plastic waste. Plastic products currently form an indispensable part of people's daily lives and are applied in various industry sectors, such as construction, agriculture, automotive industry, etc. By 2015, a total of about 6,300 Mt of plastic waste was produced, out of which around 9% was recycled, 12% was incinerated and 79% was accumulated at landfills or in the nature. It is estimated that by 2050 there will be about 12,000 Mt of plastic waste at landfills or in the environment if current trends of production and waste management are to continue (Geyer et al. 2017). Plastics increasingly become the first choice in the automotive sector leading to the enhancement of safety, output and fuel efficiency (Pradeep et al. 2017). Plastics, such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS), polyurethane (PUR) or thermosetting composites, such as plastics reinforced with carbon fibres (CFRP), or plastics reinforced with glass fibres (GFRP), are most often used in cars (Tranchard 2015). Like plastic waste, waste rubber (insulation, carpets, etc.) and used tires are still a global problem, and their volume is still much higher than the amount of waste which can be reasonably recovered. About 1,000 million of waste tires are disposed of in the world every year and according to Formel et al. (2019), this amount will reach 1,200 million per year in 2030. Tires are made from synthetic polymers (46 – 48%), such as polyamide, butyl rubber, butadiene rubber and styrene-butadiene rubber (Carmo-Calado et al. 2020, Bulei 2018). Carbon black is added to rubber during vulcanization in order to improve its abrasion resistance (Larsen et al. 2006). Together with silicone dioxide and following the rubber polymer, carbon black is the second major component in tires (Bockstal et al. 2019). Based on the paper of Danon and Gorgens (2015), the most common components of tires are natural rubber (14 – 27%), synthetic rubber (14 – 27 %), fillers such as carbon and silicon dioxide (26 – 28 %), extender oils and resins (5 – 6 %), sulphur (5 – 6%), and metals for reinforcement (16.5 – 25%). There is no recovery process that could recover the original rubber or other rubber raw materials from the rubber waste. Tires as the secondary material are only used in two ways: material conversion (floors, noise barriers, etc.) (Bulei 2018), and energy recovery (Bulei 2018, Demirbas et al. 2016). The thermochemical conversion processes, such as pyrolysis, gasification and liquefaction, offer alternative solutions for the reduction of the high level of global dependence on oil. These processes can be used for the provision of energy, fuel and products with high added value (Nkosi et al. 2021, Čabalová et al. 2021). Demirbas et al. (2016) have carried out the catalytic pyrolysis of the waste tire. The liquid product was produced at high temperature (up to 600 °C) with the use of sodium carbonate (Na_2CO_3) as the catalyst. The thermophysical properties of the liquid samples produced have shown that up to 85% of the produced oil can be used in the combustion engines. Wang et al. (2019) have achieved direct conversion of waste tires

to 3D graphene by an alkaline single-stage pyrolysis process without the use of expensive chemical agents and complex equipment. Experimental work of Buss et al. (2019) indicates that there are possible practical applications of rubber waste from end-of-life tires, resulting in a new product which is harder and contains 60% share of rubber particles, as indicated by the tests, with a smooth surface that requires no polishing.
In addition to the production of energy or graphene, another way of re-use of the waste rubber is material recycling. The main course for the recovery of used plastic and rubber waste is: re-use in the same quality as the original products; for the production of other products; recycling, as material re-used in regenerated elastomeric compositions; and as specified above: a source of different chemicals (carbon black, pyrolysis oils), a source of heat and as forms of different materials; as construction material (Fazli, Rodrigue 2020, Bulei 2018, Baričević et al. 2013); powder from the waste tire/polypropylene composite (Ong et al. 2021); wood-rubber composites from waste tires (Zhao et al. 2010, Ayrilmis et al. 2009); wood-plastic composites (Rajan et al. 2021). Shalbafan et al. (2016) in their study have compared the effect of different quantities of expanded polystyrene filler (5, 10, and 15%) on the properties of particle boards. The results have shown that the use of polystyrene fillers has a significant impact on bending properties, internal bonds, edge screw withdrawal resistance, swelling in thickness, and water absorption. Xu et al. (2020) have prepared fiberboard composites with powder from waste tires as functional fillers. This research has shown that it is possible to produce fiberboard composites with rubber filler resulting in added value and satisfactory properties. Test results of the research by Zhao et al. (2010) have shown that the sound insulating properties of a composite wood-rubber panel from waste tire is better than the properties of the commercial composite wooden flooring and particle board. Moreover, the acoustic insulation of these composites is significantly affected by the amount of crushed rubber and binder used in the composite. Increased usage of recycled crushed rubber and dosage of binder significantly improve the sound insulating properties of the composite.

There is information about the material recycling of waste tires, but the information about the use of rubber materials from cars is lacking. Therefore, the objective of this research task is:

- to reduce the volume of tires, other rubber materials and plastics as waste from the automotive industry,
- to reduce the consumption of raw materials, especially those that come from non-renewable resources and use waste rubber and plastics as secondary raw material,
- to reduce the enormous environmental burden represented by waste rubber and plastics,
- to prepare new composite materials containing the waste rubber (tires, carpets, insulation),
- to evaluate the properties of composites and possibility of their use as construction material in the exterior and/or interior,

- to create a concept of business investment plan for the production of new composites,
- to produce composites on a commercial basis.

7.2 Evaluation of the waste tire eco-toxicity

The toxicity of tire particles is probably caused, in addition to the organic substances, by the presence of heavy metals, especially zinc. The zinc comes from zinc oxide added to rubber mixtures as the vulcanizing activator. Degradation of the waste tire particles is slow, therefore it is assumed that these particles will accumulate and disperse further by run-off or wind. One of the possible ways how to eliminate the organic share from waste tires is by degradation using microorganisms – biodegradation (Nawong et. al. 2018). However, synthetic rubbers, unlike natural rubber which is sensitive, are resistant to biodegradation. The presence or absence of admixtures, such as fillers, vulcanizing agents, antioxidants, expanding agents and softening agents, also affect biodegradability (Shah et al. 2011).

Evaluation of biodegradability of polymeric materials is usually carried out with the use of OECD tests, for example:

OECD 301 B: CO_2 Evolution test (Modified Sturm Test)

OECD 302 B: Inherent biodegradability test (Zahn-Wellens method)

OECD 301 F: Manometric Respirometry Test with the use of OxiTop® Control measuring system

OECD 311: Anaerobic Biodegradability of Organic Compounds in Digested Sludge

OECD 301 D: Biodegradability test in closed bottles

The objective of our research is to evaluate the behavior of abraded material from tires in the environment during their active use in terms of biodegradability.

The assessment of biodegradability was carried out on the rubber fraction from waste tires (Cat. No. 16 01 03 – End-of-life tires). Waste sludge from the anaerobic stage of sewage sludge treatment at the same sewage treatment plant was used as the inoculum for anaerobic decomposition.

Biodegradability was assessed with the use of manometric respirometry test according to standard OECD 301F (1992) and test according to standard OECD 301 D (2006).

Biodegradability of rubber from waste tires was evaluated in aerobic and anaerobic conditions. Aerobic decomposition of the waste tire extract (301 D test) had reached the decomposition phase after 21 days with average degradation value of 61% (Fig. 7.1). The average biogas production reached a level of 0.0154 $dm^3/g_{sž}$ (sž – loss on ignition). The specified biogas production was much lower in comparison to biogas production during the decomposition of common organic wastes from food sector or agriculture.

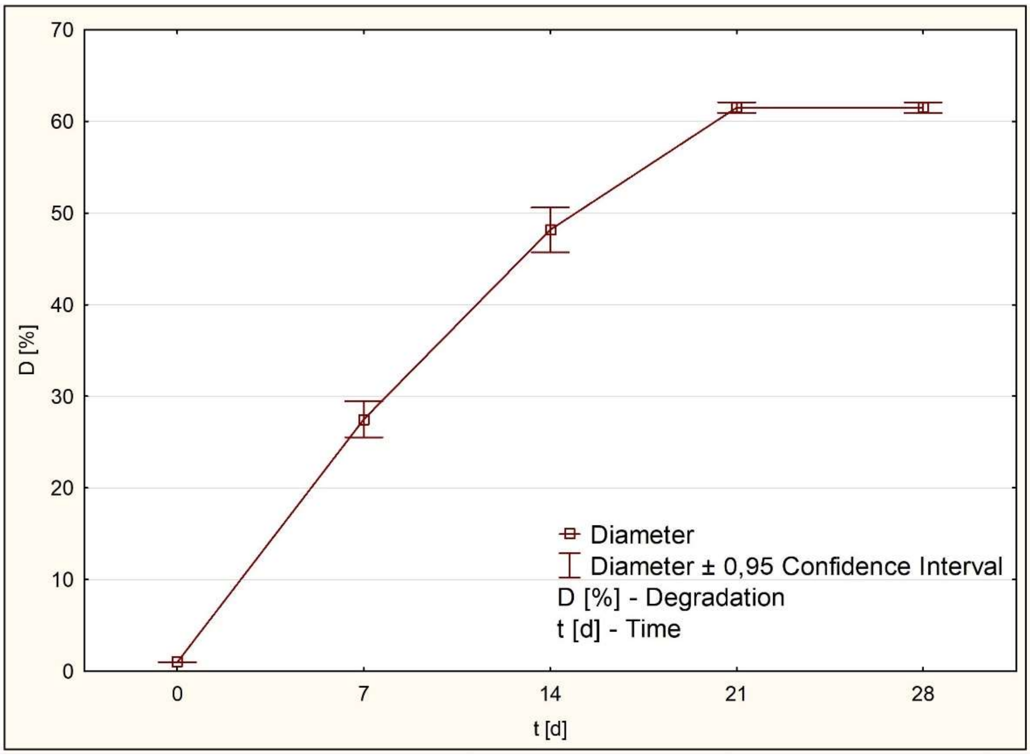

Fig. 7.1 The course of aerobic biodegradation of rubber from waste tires (OECD 301 D test)

7.3 Evaluation of the safety of waste polymers in terms of the effect on water and soil with the use of biotests

The evaluation of the health safety of materials used in the production of composites, which could release harmful and undesirable substances into contact media (water), has become a current problem especially in non-traditional products with incorporated waste. The substances released serve for the evaluation of health safety of these products in terms of their impact on the environment, in particular on water, soil and on human health. The release of harmful substances to the environment can adversely affect human health through all chains. The prepared evaluation of health safety of such products containing waste materials and products containing waste substances can be used as a baseline for the statement of the authorized body within the certification of such material or product.

Today's tires consist of approx. 19% of natural rubber and 24% of synthetic rubber, which is a plastic polymer. The production of tires still has large adverse effects on the environment, beginning from the ongoing deforestation, up to fossil fuels damaging the climate, which are used for the production of synthetic rubber. Even during their useful life, tires adversely affect the environment since they are mechanically abraded which results in the formation of microplastics that subsequently contaminate the environment. During their life, which is on average 6.33 years, tires from passenger vehicles lose almost 2.5 kg of rubber, and up to 28% of microplastics in the ocean comes from tires.

We have experimentally examined the properties of aqueous extract (24 hrs.) prepared from waste rubber granulate (fraction of 1 – 3 mm) gained from end-of-life tires. The aqueous extract was prepared from 100 g of dry granulate (gravimetrically determined by drying the sample to constant weight at 105 °C) in 1L of demineralized water. The sample was placed into a Selecta Rotabit laboratory shaker and was shaken for 6 hrs. at a speed of 180 revolutions per second. After shaking, the sample was left to freely sediment for 18 hrs. and then the solid part of the sample was separated from the liquid part by filtration.

Then the selected physical and chemical indicators were determined: pH, specific conductivity and COD-Cr. With the use of ecotoxicological tests: growth inhibition test on *Lemna minor* and *Sinapis alba*, and the acute toxicity test on *Daphnia magna*, their preliminary results, we have determined the toxic effect on aquatic environment. We found that the pH of the aqueous extract after 24 hrs. was alkaline – 9.18, the content of organic substances (COD-Cr) was: 47.2 mg/l (which exceeded the limit of 35 mg/l specified in Regulation of the National Council of the Slovak Republic No. 269/2010) and low concentrations of dissolved substances in the form of ions were measured (specific conductivity). Based on the biotest results, the extract was toxic only for the test organisms – *Daphnia magna*.

We started to evaluate the health safety of the manufactured wood composites with a different share of waste rubber and waste plastics from the automotive industry.

The health safety evaluation timetable consists of the following activities:

1. Preparation of the aqueous extract from the individual composites (monoblocks) with the following maceration times: 24 hrs., 48 hrs., 7, and 10 days, where the following condition is met for the volume of leaching agent used (demineralized water): 1000 ml of the leaching agent is used per 200 cm^2 of the monoblock surface.
2. Evaluation of the changes in pH and specific conductivity.
3. The chemical consumption of oxygen was determined to be the indicator of the amount of organic substances released into the aquatic environment.
4. Carrying out ecotoxicological tests in aqueous extracts with the use of biotests: growth inhibition (stimulation) test on *Lemna minor* and *Sinapis alba,* acute toxicity test on *Daphnia magna* and inhibition test on *Vibrio fischeri* (Hybská et al. 2021).

7.4 Preparation of composites

The composite wood materials, particle boards (PB), in combination with the recycled rubber were produced in the following manner:

a) surface layer from fine chips,
b) intermediate layer consisting of more coarse chips and crushed recycled rubber in various shares (Table 7.1),
c) surface layer from fine chips.

Table 7.1
Designation and characterization of the composites

Designation	Characterization of the composite
PB	Particle board
R10	Particle board – containing 10% rubber*
R15	Particle board – containing 15% rubber*
R20	Particle board – containing 20% rubber*
T10	Particle board – containing 10% waste tires**
T15	Particle board – containing 15% waste tires**
T20	Particle board – containing 20% waste tires**

Note:
*Granulated waste rubber – "GWR" (carpets, insulation) – fraction size from 1.0 to 3.0 mm.
**Granulated waste tires – "GWT" – fraction size from 1.0 to 3.0 mm.

The waste rubber and waste tire granulate from cars was supplied by the company AVE SK-Kechnec plant Slovakia.

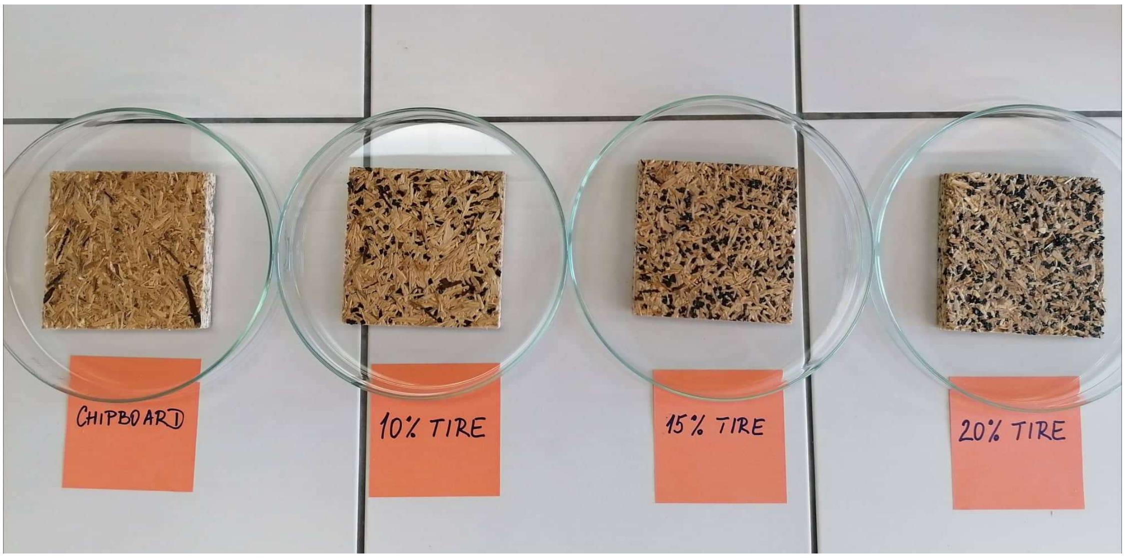

Fig. 7.2 Prepared composites, from the left: PB, T10, T15, T20

7.5 Properties of the composites – fire performance

The main shortcoming of the composites on the basis of wood is their high flammability, because wood is a naturally growing material which consists mainly of flammable organic compounds (Pedieu et al. 2012). The most important properties of flammable material are time to ignition, heat release rate, extinction flammability index and thermal stability index, surface spread of flame and fire resistance, smoke toxicity, mass loss, limiting oxygen index (Lee et al. 2011, Mouritz and Gibson 2006). Several researchers were evaluating the flammability of composite materials on the basis of wood (Pedieu et al. 2012, Harada et al. 2006). Several researchers were evaluating the flammability of composite materials on the basis of wood (Pedieu et al. 2012, Harada et al. 2006).

According to Harada et al. (2006) the following properties are required for the fire safety of the boards on the basis of wood to be used as the construction material:

- the structure must not deform, melt or disintegrate,
- the temperature of the non-exposed side must not exceed the burning temperature of the combustible material,
- the structure does not crack nor is otherwise damaged by the effect of fire outside the building.

The flammability of wood-rubber composites was analyzed by the determination of spontaneous ignition temperatures, mass burning rate, and calorific value.

Spontaneous ignition temperature

For the highest fire resistance, it is necessary to record the highest temperature and the longest time-to-ignition of the measured sample. In comparison with particle board (PB), the composites containing waste tires (T10, T15, T20) achieved very similar results in terms of temperatures and time-to-ignition. Composites containing rubber (R10, R15, R20) showed higher values of time-to-ignition than PB and T10, T15, T20 samples, but the average temperature was lower depending on the proportion of rubber in the composite. We can state that the fire resistance (in terms of SIT) of composites containing 10 – 20% rubber filler is comparable with the properties of common particle boards.

Mass burning rate

At a thermal load with heat flux of 30 $kW \cdot m^{-2}$ applied to PB samples, the average time-to-ignition was 34 sec, time to reach the maximum burning rate was 68 sec and the maximum burning rate was 0.414 $\% \cdot s^{-1}$. The relevant achieved values demonstrate the highest thermal resistance of the compared samples. Similar values were recorded with T10 samples, where the average time-to-ignition was 34 sec, time to reach maximum burning rate was 66 sec and the maximal burning rate was 0.756 $\% \cdot s^{-1}$. Based on the determined average time-to-ignition of 32 sec and the maximum burning rate, we can state that R10 samples reached the maximum burning of 84 sec and the maximum burning rate was 0.558 $\% \cdot s^{-1}$. It may be concluded that with the growing quantity of tire and sealing rubber admixtures, we recorded a shorter time-to-ignition as well as time to reach maximum burning rate.

Heat of combustion

It can be stated that the specified calorific values of composites ranged from 18.358 $MJ \cdot kg^{-1}$ (PB) to 21.497 $MJ \cdot kg^{-1}$ (R20), depending on the content of the rubber filler. With the higher content of rubber/recycled tire filler in the particle boards, we have recorded increased calorific values. The highest values were recorded for the R20 sample. Higher ash content was recorded in the composites containing recycled tires as compared to both composites containing rubber and plain particle boards. Increased ash content means a reduced calorific value of the materials, which was also confirmed in this research. In terms of the comparison of the calorific value of particle boards and composites containing both rubber fillers, it may be concluded that the composites with filler generated more heat. Separate samples of both granulates: rubber (insulation, carpet) and tires showed higher calorific value 29.894 $MJ \cdot kg^{-1}$ (GWR) and 36.441 $MJ \cdot kg^{-1}$ (GWT).

7.6 Properties of the composites – heat insulation

Thermophysical properties of the materials are among the basic material characteristics. These properties characterize heat transfer through the volume and accumulation of heat within the body. These parameters must be known, especially in cases where the material is exposed to heat. Higher heat transfer properties (thermal conductivity and thermal diffusivity) are often useful for the enhancement of the cooling capacity of the material.

In the study of the thermophysical properties of composites, it is important to know the values of these parameters of the entire composite part, or the matrix, which, in our case, is made of particle board and the filler part made from rubber waste. Based on the known values of these properties, it is possible to perform qualitative physical modelling of the final composite. It is known from the theory of composites that the resulting composite reaches higher values of thermal conductivity if more conductive materials are used for its production.

The rubber mixture, which is the basic component of a tire, used as one type of filler, is produced by the vulcanization process in which the filler is composed of rubber, carbon black and silicon dioxide, anti-degradants, sulfur, softening agents, activators, as well as other components. Materials with significant impact on the thermophysical properties are rubber and fillers and their concentrations. Higher filler concentration improves thermal conductivity and thermal diffusion of the rubber mixture, because the fillers have higher heat transport properties than rubber.

Thermal conductivity of rubber largely depends on its type. Thermal conductivity of rubber ranges from 0.09 $W.m^{-1} \cdot K^{-1}$ for butyl rubbers and 0.24 $W \cdot m^{-1} \cdot K^{-1}$ for nitrile rubber. While the thermal conductivity of rubber mixtures largely depends on the rubber type used, it is clear that rubber has at least the same thermal conductivity as particle boards, which according to Czajkowski et al. (2016) equals 0.1081 $Wm^{-1} \cdot K^{-1}$ for 8.8% EMC value, that is, it can be used as a filler for improving the thermal conductivity of the final composite.

In their article Koštial et al. (2010) the authors describe the method based on Newton's law of cooling for the measurement of all 3 thermophysical properties of materials. They have measured the thermophysical properties of a rubber mixture based on styrene-butadiene rubber (SBR) filled with carbon black and achieved a thermal conductivity of the mixture of 0.262 $Wm^{-1} \cdot K^{-1}$, which is a much higher value than for the styrene-butadiene rubber, the thermal conductivity of which ranges from 0.10 to 0.137 $Wm^{-1} \cdot K^{-1}$. Based on the results, the increase of thermal conductivity of the rubber mixture in comparison with the thermal conductivity of the rubber is by at least 91%.

There are very few studies dealing with the wood composites containing rubber. In the article by Xin et al. (2011) the waste rubber was added to the particle board. The authors have dealt with the characterization of the heat pressing process parameters with regard to the mechanical properties of the mixture. The achieved optimum technological parameters of the heat pressing technology were as follows: board density of 800 kg·m^{-3}, resin content of 3%, temperature of 160 °C, pressing period of 7 minutes, and the waste rubber content of 30%. With these parameters, the mixture with rubber reaches the same mechanical properties as the particle boards.

The rubber particles were mixed with different concentrations of LDPE resin in the particle board in order to improve the mechanical properties of the composite. The results have shown that the composite improves the properties, such as water absorption and thickness swelling. However, these composites have worse mechanical properties, such as modulus of elasticity and surface hardness, which are very important. The parameter which remained unchanged by the addition of rubber and LDPE resin was the internal bond. The best mechanical properties of the composite were achieved with 5% addition of LDPE resin.

Based on the results of our experiments for the determination of heat insulating properties, it can be stated that the thermal diffusivity and thermal conductivity increase with the increasing amount of fillers, which is in concordance with the higher thermal conductivity and diffusivity of fillers in comparison to the matrix material. This is a typical trend for the composite, in which the thermal conductivity increases together with the thermal diffusivity due to higher rate of heat spreading through the volume of the sample, which also results in higher thermal conductivity. The rubber fillers act mainly in the volume of the sample, and therefore have higher impact on the thermal diffusivity. The reduction of specific thermal capacity is typical for composites as well, in cases where the thermal diffusivity and thermal conductivity increase because the higher value of thermal diffusivity is related to a small temperature difference, which increases the specific thermal capacity.

Based on literature, the thermophysical properties of the fillers on the basis of rubber depend on:

- Thermophysical properties of the rubber used,
- Type and weight percentage of the fillers,
- The amount of water plays an important role in case of tires.

The level of crosslinking between the fillers and PB matrix.

It is well known that the thermal conductivity of the rubber mixture is higher than the thermal conductivity of rubber. In our samples, we have used the combination of EPDM and SBR rubber. Thermal conductivity of EPDM rubber ranges from (0.245 – 0.280) W·m^{-1}·K^{-1} and thermal conductivity of SBR rubber ranges from 0.103 W·m^{-1}·K^{-1} for 0% of butadiene weight and can increase up to 0.137 W·m^{-1}·K^{-1} for 100% butadiene weight. It is clear that the SBR rubber has significantly lower value of thermal conductivity in comparison with EPDM rubber. It is also good to know that the thermal conductivity of such a rubber mixture is higher than in the case of SBR rubber. From this we can conclude that the thermal conductivity of the rubber mixture should be higher than that of mixtures based on SBR rubber, which has been measured in the article by Koštial et al. (2010). The experimental value of thermal conductivity of the rubber mixture used should be at least 0.262 $W \cdot m^{-1} \cdot K^{-1}$.

The following can be stated based on the above specified facts:

- Thermal conductivity of PB + R mixtures is higher than of plain PB,
- Thermal conductivity of PB + R mixtures increases with % of R weight,
- Thermal conductivity of PB + R mixtures is lower than of plain R mixture.

Based on the publications, it is well known that the thermal conductivity of a tire increases with the bulk density and is at least equal to the rubber mixture used in tires. It is also well known that the thermal conductivity of the composite should be higher than that of the plain PB and higher than of PB+R composite since with the use of the same rubber mixture the level of crosslinking is also the same, hence the higher thermal conductivity value of the composite should also be higher.
Both types of composites reach approximately the same maximum value of thermal conductivity. Therefore, we can state that the PB+T composites do not have significantly different thermal conductivity values. The higher value of weight % for T composites means that in order to reach the same thermal conductivity value, it is necessary to add higher % of weight of crushed rubber into the PB matrix.

7.7 Business plan concept for the production of wood-plastic boards in the context of circular economy

This part of the report deals with the economic aspect of the research of the new wooden composites containing waste polymers from cars. The business plan presented represents the economic calculation of the potential for expanding production capacity of the sawmill plant for a secondary product using its own wood waste and recycled plastics. Specifically, it is the following product: large-dimensional construction wood-plastic board that does not absorb water, whose production is in accordance with the principles of circular economy. The following section presents the shortened composition of the investment plan in the form of a concept which can be modified if the input parameters change.

Circular economy

In March 2020, the European Commission adopted a new EU Action Plan for circular economy titled “For a cleaner and more competitive Europe”. The governments firmly stand by their commitments with regard to circular economy despite the economic challenges caused by the continuous pandemic. The current socio-economic system is based on the linear economy. The flow of material is perceived as the conceptual logic of value creation, whereas the beginning of the value chain is represented only by the plain material. This linear production model causes unnecessary losses of the resources in several ways: through the production chain and waste after the end of life, excessive use of energy and erosion of the ecosystems (Michelini et al. 2017). For this reason and with regard to the current situation and public interest in the protection of the environment, the vision of circular economy is increasingly coming to the fore. It represents careful use of resources and the effort towards continuous recycling of the used inputs. This principle inspires not only the environmental protection groups, or states, but also individual enterprises (www.nationalgeographic.com). EU defines the circular economy as a model of production and consumption, within which the things are not thrown away, but shared, leased, reused, repaired and recycled as long as possible. This way it is possible to reduce the amount of waste and increase the life of products. An end-of-life product creates potential for the use of materials in the production of new products (www.europarl.europa.eu).

Fig. 7.3 Comparison of linear and circular economy (www.europarl.europa.eu)

Specification of the reasons for investment, technology and final product

The presented business plan concepts were prepared for the real conditions of a specific wood production company (first-stage sawmill processing) in the region of central Slovakia. The reason for the investment is the intention to extend the existing capacities with the additional production of secondary product in order to ensure the recovery of part of the waste from the input raw material (wood waste). The investment is based on drawing on the current call for projects co-financed from the EU's structural funds within the period of 2021 – 2022 in combination with the use of partial financing by a foreign investor. The launch of operations within the extension of the company's product portfolio with the products based on the principles of circular economy, that is, the use of their own wood waste and recycled waste plastics, is planned to start in 2023. Since the company executives regard their plan as a certain know-how and competitive advantage, they do not want to present it publicly under their own name, so the given presentation will include all available pieces of information under the fictitious name of a company called PlastWood s.r.o.

The plan to extend production requires the procurement of a new technological line, which is also the main reason for the investment activity mentioned, since the company already has the necessary premises for operation.

Fig. 7.4 Line for the production of wood-plastic boards (www.res.cloudinary.com)

The technological line (Fig. 7.4) consists of a double-screw extruder, mold, stereotypes, traction, cutting machine as well as loading and cooling table, including conveyors. Its output should be a final product in the form of a large-dimensional wood-plastic board. The list of individual components of the technology together with the costs for their procurement is presented in Table 7.2. Values specified in the table are valid at the time of the elaboration of the investment plan. The summary value of the investment necessary for the procurement of the technology amounts to €1 032 000.

The final product should be a large-dimensional wood-plastic board (Fig. 7.5) made from a mixture of sawdust (Fig. 7.6) and plastic waste (the preferred ratio between the input commodities in the final product is considered as 40:60 (wood waste: recycled plastics).

Table 7.2

The list of procured assets

Name of the technology component		Purchase price of the component (EUR excl. VAT)
1	purifier	€300 000
2	homogenizer	€48 000
3	conveyors (4 pcs)	€34 000
4	dryer	€30 000
5	press	€620 000
IN TOTAL		**€1 032 000**

Fig. 7.5 Sample of the large-dimensional construction wood-plastic board that does not absorb water

Fig. 7.6 Sawdust generated in the company as a waste from the processing of lumber + crushed HDPE (www.static.wixstatic.com)

The basic surface dimensions of the large-dimensional wood-plastic board as the baseline for the calculation are as follows: H 2.5 m – W 1.25 m – T 0.02 m and weight of 48.5 kg. The preferred form of recycled plastic is HDPE – high-density polyethylene. It is a thermoplastic polymer made from ethylene monomer. It is a particularly universal plastic with many advantages. It is one of the most commonly used plastics. It is included in cars, but also in protective helmets, shopping trolleys, etc. HDPE is a material resistant to molds, rot and insects, which makes is a perfect material for industrial purposes (www.trenchlesspedia.com). Fig. 7.6 shows the crushed HDPE which should be procured from an external supplier.

Quantification of direct and overhead cost items for calculation purposes

The following Table 7.3 shows the calculation of the planned yearly amount of the input raw material (sawdust and HDPE + additives) in tonnes, together with the quantification of purchase prices. The calculation is based on the assumed maximum level of installed capacity of the procured technology amounting to 11.2 t/day in a single-shift operation. The yearly time fund is calculated at the level of 250 days/year, which means that the production capacity of the wood-plastic composite at 100%, use of the technology is expected to be 2 800 t/year. Thus, the calculated costs for the input raw material represent the total amount of €1 103 200. The sawdust is the waste from the company's own production, however, its price is determined at the level of factory price of € 55/t equal to the price of the external supply, which the company can purchase in case of material shortage. The HDPE item also includes the price for UV stabilizers and coloring agent. In order to protect the formula, the ratios of raw materials within the HDPE item are not published but calculated as a single item amounting to €620/tonne.

Table 7.3
Overview of the consumption and purchase prices of the material inputs per year

Raw material	Yearly consumption plan (t)	Purchase price (€/t excl. VAT)	Costs (€/year excl. VAT)
sawdust	1 120	55	€61 600
HDPE	1 680	620	€1 041 600
Σ Material inputs			€1 103 200

Quantification of the consumption of energy costs (Table 7.4) is calculated on the basis of a technical description from the manufacturers of the relevant technologies the company plans to purchase, with the application of the yearly fund of operating hours of the machine amounting to 2 000 hrs. The time fund includes 250 working days per year at 8-hour operation per day. Estimation of the price for water and sewage in the calculation will be included in the overhead costs, which are not directly caused by extended capacity, but will, within the calculation principle be taken into account by the relevant surcharge (55.8%) at the scheduled base for wage costs.

Table 7.4
Overview of the estimated consumption and energy prices per year

Energy	Yearly consumption plan	unit price (€ excl. VAT)	annual costs
Energy technology (input 105 kWh, efficiency 90%)	189 000 kWh	€0.18/kWh	€34 020
Water and sewage (m^3)	485 m^3	€2.38/m^3	€1 154.3
Σ Energy inputs			€ 35 174.30

Based on the prediction of the necessary jobs (in obtaining engineering and technological equipment, as well as based on the planned scope and production shifts), another 9 employees will be required. The remuneration of employees within the extension of the company's operation is planned in the gross amount of €912/month for operation personnel and €1 256/month for sales managers. The total quantification of the wage costs is shown in Table 7.5 and its estimated amount in relation to the investment plan is approximately €150 000/year.

Table 7.5
Salary costs of the investment

Type of job	No of employees	Gross salary / month	Gross salary / year	Employer's contributions / year (35.2%)	Total cost of labor/year
operation	6	€912	€65 664	€23 113.73	€88 777.73
sales manager	3	€1 256	€45 216	€15 916.03	€61 132.03
Σ Salary costs					**€149 909.76**

In order to quantify the amount of depreciations, we have selected the even depreciation method, applicable pursuant to Act 595/2003 Coll. on Income Tax, as amended. Individual components of the initial investment were assigned in the second depreciation group having a maturity of 6 years. The yearly depreciation amount was specified at the level of €172 000 (Table 7.6).

Table 7.6
The amount of annual depreciation of the investment

Calculation item	**Note to calculation**	**Calculation unit** (2.5m / 1.25m / 0.02m)	**Calculation unit** (1 tonne of mixture)
Material costs for sawdust	- internal overheads	1.07	22.00
+ Material costs for HDPE	€620/tonne	18.04	372.00
+ Other induced production costs (energy, salaries, depreciation)		4.50	92.61
= Total costs of production		23.60	**486.61**
+ Company overhead costs	Surcharge of wages N 55.8%	1.11	22.87
= Total costs of the product		24.71	**509.49**
+ Profit margin	80%	20.26	417.80
= Offer price excl. VAT		**€44.97**	**€927.28**

In order to quantify the gross calculation of costs for the final product, we acknowledge the anticipated ratio of input raw materials per single tonne of the mixture and 1 large-dimensional board of specific dimensions (mixture ratio 40:60, dimensions H 2.5 m – W 1.25m – T 0.02m with a weight of 48.5 kg), where 40% represent the share of sawdust and 60% HDPE (together with the unspecified ratio of UV stabilizers and coloring agents). It is a product with high added value, therefore, the calculation includes a high profit margin (80%) which includes a certain additional reserve for the coverage of unforeseen overhead costs and also a decreased level of capacity utilization in the initial stage of production. The offer price of the large-dimensional board with the probable dimensions determined by the preliminary surcharge calculation amounts to about €50 excl. VAT.

Financial and economic analysis
In this given section, we present the basic framework of the financial and economic analysis of the project evaluation. The investment plan was evaluated with the use of net present value, profitability index, internal rate of return and discount maturity. These are generally known methodologies which are presented in the papers (Balaram, 2015; Cuthbert et al. 2016; Mørch et al. 2017; Scholleová, 2009; Polách et al. 2012). Dynamic methods based on discounting were elaborated in the papers of Brealey (1992) and Fotr and Souček (2005).
The following **Table 7.7** shows the overview of the foreseen investment necessary for the relevant investment plan of the company.

Table 7.7
Total estimated amount of investment

	Investment capital required	**€1 032 000.00**
+	Working capital required	€130 000.00
=	**Total capital required (investment)**	**€1 162 000.00**
-	Available equity	€130 000.00
-	Non-repayable subsidy (EU's structural fund)	€516 000.00
=	**Required outside capital**	**€516 000.00**
-	Long-term outside capital	€516 000.00

The total capital required for the investment plan depends on the amount of the investment necessary for the machines and equipment and on the amount of the required working capital. The amount necessary to cover the costs of machines and equipment is calculated as €1 032 000. The calculation is based on the offer from the suppliers of the given equipment. The required yearly working capital (€127 769) was determined as the product of average daily costs and the average period of capital commitment. Therefore, the investment plan requires a total investment of €1 159 769. The planned amount of the coverage of investment going into the purchase of machines is €516 000 from the resources of the current call for projects within co-financing through the EU's structural funds. Another €516 000 is the planned investment of the foreign investor for the purchase of technology, and the company itself plans to use an instalment credit of €130 000 for the coverage of working capital needs (interest of 3.9%) with the possibility of non-identifiable intangible securities and proving the purpose of use. In the first year, the repayment of principal amounts to €21 667 and interest of €5 070.
The long-term capital provided by foreign investors amounts to €516 000 and covers 50% of the investment for machines and equipment. The company will repay this capital as a loan for the period of 6 years with the interest of 3% p.a. At the same time, there is preliminary agreed remuneration for the investor in the amount of 40% from the profit. The machines and equipment procured by the company in the form of subsidy programme from the EU's structural funds, will be pledged to the SIEA agency during the entire minimum life of the project, for two years, based on the standard conditions of the subsidy plans.

The development of the planned revenues for the period of six calendar years resulting from implementation of the investment plan is based on the plan for the annual production, which depends on the lower than maximum use of the capacity (2 800 t/year). The production plan in the first year is based on the capacity utilization at the level of 25% (700 t/yearly), in the second year it is 45%, in the third year 55%, and in the sixth year the installed capacity utilization is at a level of 75%, which represents 2 100 t/yearly. The development of planned revenues will therefore model the % growth of capacity, but also takes into consideration the increase of sale price. Just as with the cost items such as material, wages, energy and overheads, we will take into consideration a 3% variation in individual years. The following
Table **7.8** presents the Cash Flow calculation for the period of the investment lifetime (6 years). In order to calculate the current Cash Flow value, we have determined the assumed discount or revenue of the opportunity at the level of 5%. The income tax for legal persons in the amount of 21% and creation of funds (reserve fund) at the level of 5% were determined based on applicable legislation.

The analysis of critical production capacity depending on the specified initial conditions reached a level of approx. 32%. The critical production volume (break-even point) expressed in kind represents the production volume of 862 tonnes of the wood-plastic board under consideration or calculated per single board with the given surface dimensions (and weight of 48.5 kg) – 17 773 pieces. Within the analyzed cost structure, the break-even point expressed in value is calculated at the level of revenues exceeding €833 000/year.

Finally, it is necessary to state that all analyses and calculations were calculated with the currently applicable values of the initial data (May – September 2021). These values can change and in case such situation occurs, it will be necessary to re-calculate the submitted business plan concept with the modified values. Despite the fact that the project seems economically viable (of course, after thorough marketing support of the sales), the major basic risks of the project include the possible change in form and share of investment financing, but as well the growth of prices of the inputs (energy, material, wages, etc.).

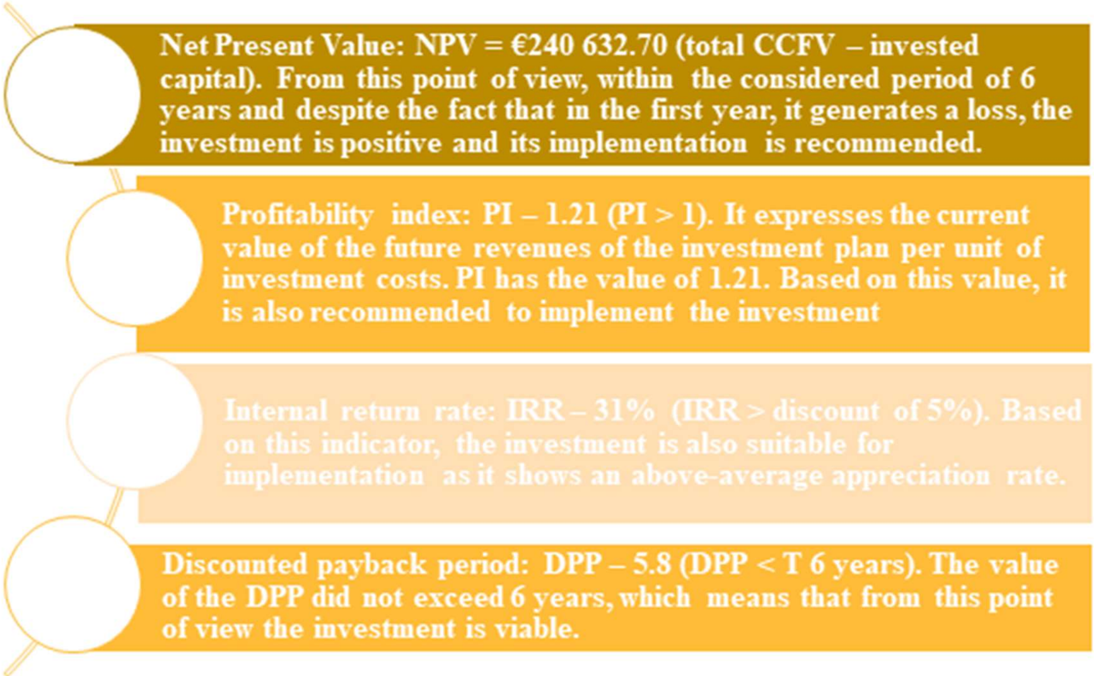

Fig. 7.7 Results of the dynamic methods of the investment plan effectiveness assessment

The activity plan for the next year also includes the preparation of possible modifications of calculations which will be based on the general principle of the system of total costs with the use of allocation of induced costs through the specific rates of machine hours (energy, wages, depreciations, interest), but also on the principle of incomplete calculations with the determination of the amount of covering contributions.

Table 7.8
Analysis of the expected CASH FLOW of the investment (in €)

			2023	2024	2025	2026	2027	2028
1		Revenues	658 030.49	1 219 988.53	1 535 830.01	1 869 523.98	2 073 733.53	2 288 513.07
2	-	Costs	517 869.06	752 779.25	874 381.77	996 404.92	1 061 790.09	1 127 507.01
3	-	Depreciations	172 000.00	172 000.00	172 000.00	172 000.00	172 000.00	172 000.00
4	-	Interest	20 550.00	12 900.00	10 320.00	7 740.00	5 160.00	2 580.00
5	=	Profit before taxes	-52 388.57	269 212.14	466 031.10	680 281.92	821 686.30	986 426.06
6	-	Corporate income tax (21%)	0.00	56 534.55	97 866.53	142 859.20	172 554.12	207 149.47
7	=	Net profit	-52 388.57	212 677.59	368 164.57	537 422.71	649 132.17	779 276.59
8	-	Reserve fund 5%	0.00	10 633.88	18 408.23	26 871.14	32 456.61	38 963.83
9	=	Disposable profit	-52 388.57	202 043.71	349 756.34	510 551.58	616 675.57	740 312.76

10	-	Investor share of profit (40%)	0.00	85 071.04	147 265.83	214 969.09	259 652.87	311 710.64
11	+	Depreciations	172 000.00	172 000.00	172 000.00	172 000.00	172 000.00	172 000.00
12	**=**	**Cash Flow**	**119 611.43**	**374 043.71**	**521 756.34**	**682 551.58**	**788 675.57**	**912 312.76**
13	-	Loan instalment	107 666.67	107 666.67	107 666.67	107 666.67	107 666.67	107 666.67
14	**=**	**NET CF FLOW**	**11 944.76**	**181 306.01**	**266 823.85**	**359 915.83**	**421 356.03**	**492 935.46**
15		Discount (5%)	1.0500	1.1025	1.1576	1.2155	1.2763	1.3401
16	**=**	**Current Cash Flow Value (SHCF)**	11 375.97	164 449.89	230 492.47	296 103.64	330 143.48	367 836.03
17		**Current Cash Flow Value (SHCF) in total**			**1 400 401.48**			

Based on different variants of the final product production (modification of thickness,surface dimensions, ratio of input components), the aim will be to model the calculations of the offer price. After the change of initial conditions, the business plan concept as well as the alternatives of the proposed calculations can also be used for alternatively assessed products within the project of UNIVNET carried out by TUZVO. This issue will be addressed in the dissertation thesis titled Economic Intensity and Calculations in the Manufacture of Products from Recycled Raw Materials, Wood-Plastic, in the Context of Circular Economy Principles, in the study program “Economy and Management of the Forestry-Wood processing Complex”.

7.8 Bibliography

[1] Geyer, R.; Jambeck, J.R.; Lavender, K. Production, use, and fate of all plastics ever made. Science Advances 2017, 3, e1700782, DOI: 10.1126/sciadv.1700782.

[2] Pradeep, S.A.; Iyer, R.K.; Kazan, H.; Pilla, S. Automotive Applications of Plastics: Past, Present, and Future, Editor(s): Myer Kutz, In Plastics Design Library, Applied Plastics Engineering Handbook (Second Edition), William Andrew Publishing, 2017, pp. 651-673. DOI:10.1016/B978-0-323-39040-8.00031-6.

[3] Tranchard, S. ISO 19095. Plastic-metal assemblies enjoy an enduring bond with ISO standards, 2015.

[4] Formela, K.; Hejna, A.; Zedler, L.; Colom, X.; Canavate, J. Microwave Treatment in Waste Rubber Recycling - Recent Advances and Limitations. Express Polym. Lett. 2019, 13, 565–588. DOI:10.3144/expresspolymlett.2019.48.

[5] Carmo-Calado, L.; Hermoso-Orzáez, M.J.; Mota-Panizio, R.; Guilherme-Garcia, B.; Brito, P. Co-Combustion of Waste Tires and Plastic-Rubber Wastes with Biomass Technical and Environmental Analysis. Sustainability 2020, 12, 1036. DOI: 10.3390/su12031036.

[6] Bulei, C.; Todor, M.P.; Heput, T; Kiss, I. Direction for material recovery of used tires and their use in the production of new products intended for the industry of civil construction and pavements. IOP Conference Series Materials Science and Engineering 2018, 294, 012064. DOI: 10.1088/1757-899X/294/1/012064.

[7] Larsen, M.; Schultz, L.; Glarborg, P.; Skaarupjensen, L.; Damjohansen, K.; Frandsen, F., et al. Devolatilization Characteristics of Large Particles of Tyre Rubber under Combustion Conditions. Fuel 2006, 85, 1335–1345. DOI: 10.1016/j.fuel.2005.12.014.

[8] Bockstal, L.; Berchem, T.; Schmetz, Q.; Richel, A. Devulcanisation and Reclaiming of Tires and Rubber by Physical and Chemical Processes: A Review. J. Clean. Prod. 2019, 236, 117574. DOI: 10.1016/j.jclepro.2019.07.049.

[9] Danon, B.; Gorgens, J. Determining rubber composition of waste tyres using devolatilisation kinetics. Thermochim. Acta 2015, 621, 56–60.

[10] Demirbas, A.; Al-Sasi, B.O.; Nizami, A.S. Conversion of waste tires to liquid products via sodium carbonate catalytic pyrolysis, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 2016, 38, 2487-2493. DOI: 10.1080/15567036.2015.1052598.

[11] Nkosi, N.; Muzenda, E.; Gorimbo, J.; Belaida, M. Developments in waste tyre thermochemical conversion processes: gasification, pyrolysis and liquefaction. RSC Adv. 2021, 11, 11844-11871. DOI: 10.1039/D0RA08966D.

[12] Čabalová, I.; Ház, A.; Krilek, J.; Bubeníková, T.; Melicherčík, J.; Kuvik, T. Recycling of wastes plastics and tires from automotive industry. Polymers 2021, 13, 2210. DOI: 10.3390/polym13132210.

[13] Wang, Ch.; Li, D.; Zhai, T.; Wang, H.; Sun, Q.; Li, H. Direct conversion of waste tires into three-dimensional graphene. Energy Storage Materials 2019, 23, 499-507. DOI: 10.1016/j.ensm.2019.04.014.

[14] Buss, A.H.; Kovaleski, J.L.; Pagani, R.N.; da Silva, V.L.; Silva, J.D.M. Proposal to reuse rubber waste from end-of-life tires using thermosetting resin. Sustainability 2019, 11, 6997. DOI: 10.3390/su11246997.

[15] Fazli, A.; Rodrigue, D. Recycling waste tires into ground tire rubber (GTR)/rubber compounds: A Review. J. Compos. Sci. 2020, 4, 103. DOI: 10.3390/jcs4030103.

[16] Baričević, A.; Lakušić, S.; Bjegović, D.; Serdar, M. Special purpose concrete products from waste tyre recyclates. Građevinar 2013, 65, 793-801. DOI: 10.14256/JCE.821.2013.

[17] Ong, H.R.; Iskandar, W.M.E.; Masiren, E.E.; Khan, M.M.R.; Ramli, R.; Halim, R.M.; Mohamed, M.K.A. The influence of waste tire powder on the properties of waste tire powder/polypropylene plastic composite. IOP Conf. Ser.: Mater. Sci. Eng. 2021, 1092, 012003.

[18] Zhao, J.; Wang, X.M.; Chang, J.M.; Yao, Y.; Cui, Q. Sound insulation property of wood–waste tire rubber composite, Compos. Sci. Technol. 2010, 70, 2033-2038.

[19] Nawong, C., Umsakul, K., & Sermwittayawong, N. (2018). Rubber gloves biodegradation by a consortium, mixed culture and pure culture isolated from soil samples. Brazilian Journal of Microbiology, 49(3), 481–488. doi:10.1016/j.bjm.2017.07.006.

[20] Shah, A. A., Hasan, F., Shah, Z., Mutiullah, & Hameed, A. (2011). Degradation of polyisoprene rubber by newly isolated bacillus sp. AF-666 from soil. Applied Biochemistry and Microbiology, 48(1), 37–42. doi:10.1134/s00036838120101.

[21] OECD 301 F: 1992, Manometric respiration tests with OxiTop® Control measuring system under GLP conditions. OECD Guidelines for the Testing of Chemicals, Section 3.

[22] OECD 311: 2006, Anaerobic Biodegradability of Organic Compounds in Digested Sludge: by Measurement of Gas Production, OECD Guidelines for the Testing of Chemicals, Section 3.Ayrilmis, N.; Buyuksari, U.; Avci, E. Utilization of waste tire rubber in the manufacturing of particleboard. Materials and Manufacturing Processes 2009, 24, 688-692. DOI: 10.1080/10426910902769376.

[23] Hybská, H.; Samešová, D.; Lobotková, M. 2021. Ecotoxicological effects of the leachate from the waste tires on the environment. Waste forum, 2021, 3 166-175.

[24] Rajan, R.; Näkki, J.; Layek, R. et al. Wood plastic composites with improved electrical and thermal conductivity. Wood Sci. Technol. 2021, 55: 719–739. DOI: 10.1007/s00226- 021-01275-9.

[25] Shalbafan, A.; Tackmann, O.; Welling, J. Using of expandable fillers to produce low density particleboard. Eur. J. Wood Prod. 2016, 74, 15–22. DOI: 10.1007/s00107-015-0963-4.

[26] Xu, X.; Tian, F.; Li, X. Regenerated waste tire powders as fillers for wood fiber composites. BioRes. 2020, 15, 3029-3040.

[27] Pedieu, R., Koubaa, A., Riedl, B. et al. Fire-retardant properties of wood particleboards treated with boric acid. Eur. J. Wood Prod. 70, 191–197 (2012). https://doi.org/10.1007/s00107-011-0538-y

[28] Lee, B-H., Kim, H-S., Kim, S., Kim, H-J., Lee, B., Deng, Y., Feng, Q., Luo, J. Evaluating the flammability of wood-based panels and gypsum particleboard using a cone calorimeter. Construction and Building Materials, 2011, 25, 3044-3050, DOI: 10.1016/j.conbuildmat.2011.01.004.

[29] Mouritz, A.P.; Gibson, A.G. Fire properties of polymer composite material. Springer, Berlin, Chap 3, 2006, pp 59–101.

[30] Harada, T.; Uesugi, S.; Masuda, H. Fire resistance of thick wood-based boards. J. Wood Sci. 2006, 52, 544 – 551.

[31] Czajkowski, L; Olek, W.; Weres, J.; Guzenda, R. Thermal properties of wood-based panels: specific heat determination. Wood Sci. Technol., 2016, 50, 537–545.

[32] Koštial, P; Ružiak, I.; Jonšta, Z.; et al. Experimental Method for Complex Thermo-mechanical Material Analysis. Int. J. Thermophys., 2010, 31, 630 –636.

[33] Xin, S.Y.; Cui, Y.; Xu, M.; Li, J. Technological Properties of Poplar Particle/Waste Rubber Powder Composites. Advanced Materials Research, 2011, 194-196, 602-605.

[34] https://www.europarl.europa.eu/news/sk/headlines/economy/20151201STO05603/eu-a-obehove-hospodarstvo [cit.22.10.2021].

[35] Michelini, G., Moraes, R. N., Cunha, R. N., Costa, J.N.H., Aldo, R. Ometto. A. R. From Linear to Circular Economy: PSS Conducting the Transition, Procedia CIRP,, 2017, 64, 2-6.

[36] https://res.cloudinary.com/plast/image/upload/c_limit,f_auto,q_auto,w_1000/v1/plastech/images/b2b/84023/technologiczne-wytlaczania-profili.jpg [cit. 20.10. 2021].

[37] https://static.wixstatic.com/media/d69a42f3d72e4806a3c7aeb3c5095aa9.jpg/v1/fill/w_838,h_875,fp_0.50_0.50,q_85,usm_0.66_1.00_0.01/d69a42f3d72e4806a3c7aeb3c5095aa9.webp [cit. 20.10.2021].

[38] Balaram, B. Comparison between net present value and internal rate of return. International Journal of Research in Finance and Marketing, 2015, 5, pp. 61-71.

[39] Cuthbert, J. R., Magni, C. A. Measuring the inadequacy of IRR in PFI schemes using profitability index and AIRR. International Journal of Production Economics, 2016, 179, 130-140, DOI:10.1016/j.ijpe.2016.05.024.

[40] Mørch, O., Fagerholt, K., Pantuso, G., Rakke, J. Maximizing the rate of return on the capital employed in shipping capacity renewal. Omega, 2017, 67, 42-53, DOI:10.1016/j.omega.2016.03.007.

[41] Scholleová, H. Investiční controlling: jak hodnotit investiční záměry a řídit podnikové investice: investiční proces jako základ budoucí prosperity, nástroje a metody investičního controllingu, volba financování a technologie, monitoring průběhu investice a postaudit. 1. vyd. Praha: Grada, 2009. 285 s. ISBN 9788024729527.

[42] Polách, J., Drábek, J., Merková, M., Polách, J. jr. Reálne a finančné investice. Praha: C. H. Beck, 2012. 280 s. ISBN 978-80-7400-436-0.

[43] Brealey, R.A., Myers, S.C. Teorie a praxe firemních financí, 1th ed., Victoria Publishing, Prague, Czech republik, 1992. ISBN 80-85605-24-4.

[44] Fotr, J., Souček, I. Podnikatelský záměr a investiční rozhodování, Grada Publishing, Prague, Czech republic, 2005. ISBN 80-247-0939-2.

[45] Zákon č. 595/2003 Z. z. Zákon o dani z príjmov Available at: https://www.zakonypreludi.sk/zz/2003-595 [Accessed: 4.9.2020].

[46] BADIDA, M. – ŠOOŠ, Ľ. et al.: Analysis of the state, forecasts and new technologies of waste recovery in the automotive industry. - Lüdenscheid (Nemecko): RAM-Verlag pp. 190, [print]. ISBN 978-3-96595-008-5.

Implementation of the pyrolysis reactor for energy recovery of waste from the automotive industry

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8 Implementation of the pyrolysis reactor for energy recovery of waste from the automotive industry

8.1 Introduction

The current objective of modern society is to implement the circular economy, which is based on maximum possible long-term utilization of objects and on their disassembly into individual components after the end of their life cycle. These components will be afterwards sorted to re-usable ones, either as individual parts or as a secondary raw material, and to parts that cannot be used further. The aim is to minimize the unusable waste. Since the automotive industry generates large quantities of waste, either from the production or after the end-of-life cycle of the cars, this issue is highly topical.

However, not all materials can be re-used in production. A large part of the waste cannot be used for other than energy purposes. The most common method of energy recovery is incineration, for example, in incineration and cement plants. This method is the simplest and is widely applicable. It results in the generation of energy, reduction of the waste volume, chemical stability of residues after incineration, and their safety with regard to the environment.

However, our aim is to gain another quality fuel with much broader use from these energy efficient raw materials. The recovery of such waste with the use of pyrolysis seems the most suitable. The result is pyrolysis gas and pyrolysis oil. Pyrolysis gas can be used directly at the site as fuel for the pyrolysis reactor, and pyrolysis oil can be used as liquid fuel in other various processes, as a fuel for combustion engines to take one example.

Therefore, at the Department of Energy, Machines and Equipment, Faculty of Mechanical Engineering at the University of Žilina, we have started to deal with the development of a small pyrolysis reactor the use of which we could verify the suitability of individual input materials and the quality of the resulting product.

In the first phase, we have designed a small pyrolysis reactor with discontinuous operation. Within the second phase, based on the dimensions of the proposed equipment, we have prepared space for this installation – an extended platform with a shelter in the exterior of a building adjacent to the laboratory of the Department of Energy Machines and Equipment. Later on, due to the unexpected growth of prices, we had to modify and simplify the structure of the reactor in order to achieve the objectives of the research. The designed pyrolysis reactor is constructed and ready for use in a trial operation.

8.2 Pyrolysis

The use of pyrolysis for the energy recovery of plastic waste is one of the most advantageous methods. Pyrolysis involves the thermal processing of waste substances in a pyrolysis furnace or reactor at a temperature of 250 to 1 650 °C without access to air or with limited access to air and at a reduced atmospheric pressure. The results of pyrolysis decomposition are liquid substances (pyrolysis oil) and gaseous substances (pyrolysis gas). Input materials consist of waste plastics which cannot be further recycled for any reason. The resulting product is a fuel, the final quality of which is specified by the quality of the batch added to the pyrolysis reactor. Technologies for processing plastic wastes into fuel oils have the potential to resolve two major problems of the present – the lack of fossil fuels and the production of further non-processable plastic waste. The process of processing plastics through pyrolysis lies in liquefaction, the pyrolytic and catalytic splitting of plastics during which the waste plastics turn into liquid hydrocarbons suitable as fuel (plastics are transformed into the original material). This way it is possible to process almost every plastic that would otherwise end up at landfills without any further use. Gases generated during pyrolysis condense in a specially designed condensation system under the occurrence of aliphatic and cycloaliphatic and aromatic hydrocarbons. The resulting mixture essentially corresponds to petroleum distillate. The density as well as other properties of this fuel are similar to diesel fuel and the resulting fuel has absolutely the same energy potential with considerably lower emissions in terms of ecology. The extracted fuel oil can be used as fuel for combustion engines, generators, boilers, and industrial burners, or it can be used as a secondary raw material for the production of benzene, toluene, etc. From 1 kg of plastics, it is possible to extract approx. 0.9 liter of fuel if the polyolefins such as polyethylene (PE) and polypropylene (PP) or polystyrene (PS) are processed.

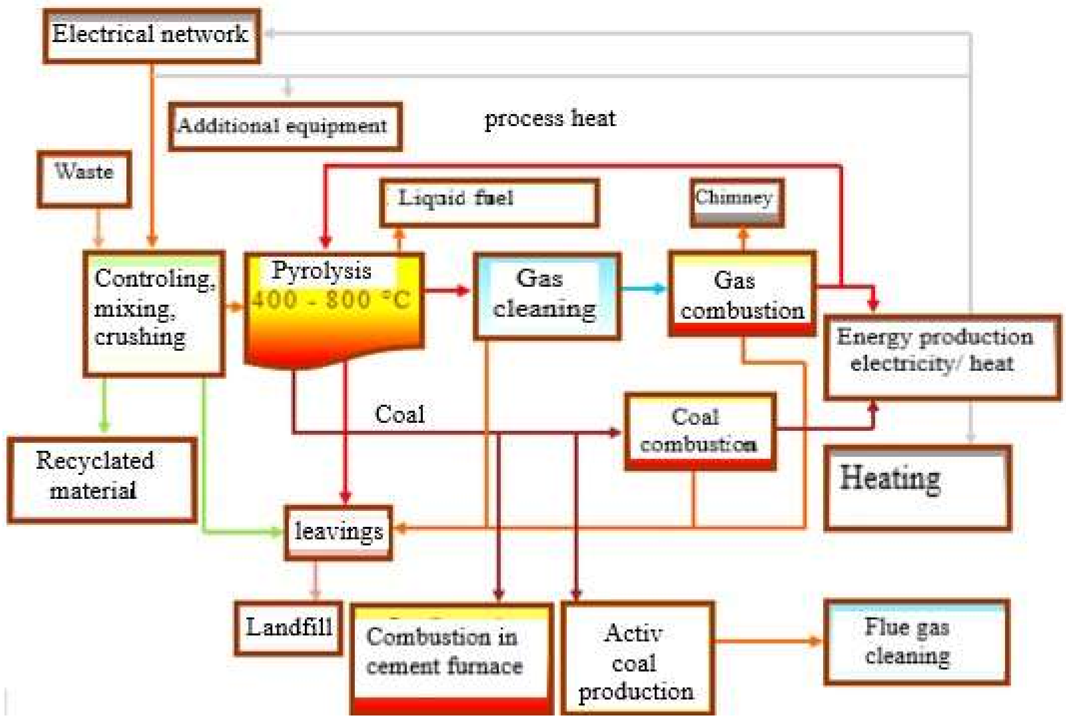

Fig. 8.1 General schematic of possible pyrolysis in the energy recovery of waste [11]

Pyrolysis is a promising technology. The advantage of this energy recovery technology is the fact that it can process a wide range of waste, even contaminated, because, for example, the majority of heavy metals are transferred into solid pyrolysis residues and not into the pyrolysis oil or gas, that is, not into the gaseous emissions from incineration. The solid residue from the pyrolysis reactor represented approx. 1/3 of the original weight of the dry waste if municipal waste is used and 1/10 of the original weight of dry waste if plastic waste is used. After the carbonization, this solid residue falls into the cooling chute where it is indirectly cooled with process water. Afterwards, it is transported for sieve sorting where the metal residue (ferrous and non-ferrous metals) and mineral parts (glass, etc.) are separated. The undersize portion containing carbon is milled to powder and transported to the post-incineration chamber. From the bottom part of the post-incineration chamber, where the temperature reaches 1 300 °C, the liquid slag flows into the water granulation bath [11]. Pyrolysis is carried out in pyrolysis chambers or fluid and rotary furnaces. The furnaces can be heated from the outside through the casing of the furnace or from the inside by an inert gas (nitrogen...). In order to accelerate pyrolysis, the combustion products from the boiler or gasification equipment are supplied to the pyrolysis machine. In fact, the implemented pyrolysis units are two-stage waste incinerators in which the first stage is pyrolysis and the second oxidation.

Implementation examples from around the world: BABCOCK-Kraus-Maffei (Germany), KWU-SIEMENS, small pyrolysis units are currently being developed in Hungary, Poland and in the Czech Republic.

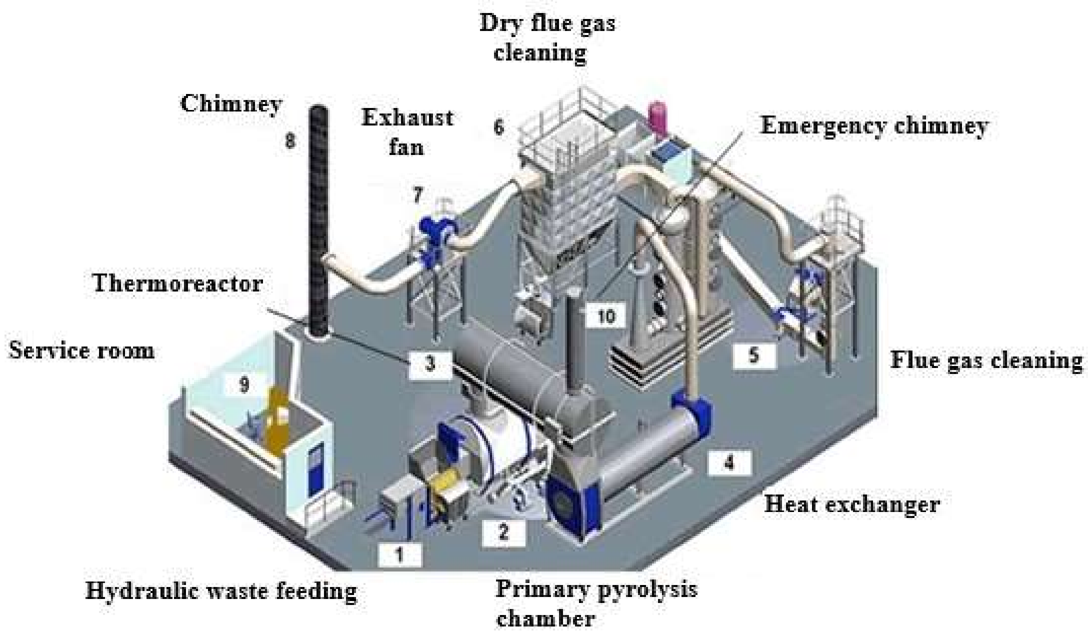

Fig. 8.2 Chamber pyrolysis incinerator [11]

The chamber pyrolysis incinerator and the course of waste processing: from the collection container (300 – 1000 l) the waste is poured into the filling chamber of the combustion plant with the use of a hydraulic equipment and from there it is pressed into the primary combustion chamber with a hydraulic piston. The waste is ignited with the use of initiating burners and burns at the temperature of max. 750 °C.

Flammable gases then continue to the pre-heated thermal reactor where they burn at the temperature of 1 200 °C for about 2 seconds, which ensures perfect combustion of all toxic substances. The hot flue gases continue through the heat exchanger into the flue gas cleaning device where the remaining impurities contained in the flue gases are chemically separated. Purified flue gases flow into the stack. After completion of the pyrolysis cycle (about 8 – 12 hours) and cooling of the primary chamber, the ash is poured into the collection container [11].

8.3 Conceptual design of a device for energy recovery of waste from the automotive industry

Not all industrial and municipal waste is suitable for recycling and subsequent utilization (either in terms of inability of its sorting by type, or due to its contamination with other substances, etc.). Another possible solution is its incineration or co-incineration with other fuel in order to produce heat for power generation, heating or technological process. Incineration or co-incineration of plastic waste and its energy recovery is a solution. Unfortunately, there are very few facilities within the territory of Slovakia, and they are unevenly distributed. A more favourable solution in terms of ecology and energy is the utilization of new technologies for the processing of plastic waste, such as gasification or pyrolysis, which also turn this waste into the initial raw material – gaseous or liquid phase, usable directly as a fuel or as a raw material for the petrochemical and chemical industry. Building of such facilities within the territory of Slovakia is not very common due to the financial burden, but also due to the almost non-existent market on which the plastic waste degradation products could be applied. The existing facilities for the gasification and pyrolysis processing of plastic waste for example, represent only pilot projects in Slovakia and their capacity is limited. Moreover, they are unevenly distributed which is associated with the need to transport the suitable waste over long distances from the broad surrounding area. A long-distance transportation of the waste can hardly be called economic or environmentally friendly. The global market offers large gasification and pyrolysis processing facilities which are investment-intensive and unsuitable for Slovak conditions. This situation could be resolved by the establishment of smaller gasification and pyrolysis processing facilities with their capacity sized according to the quantity of waste from the vicinity, evenly distributed along the entire territory of the Slovak Republic. Their establishment should be supported by state, with suitable legislation, subsidies, etc., and also by the creation of a market for the gasification or pyrolysis products – synthesis gas, oil, etc. Such smaller processing facilities for the non-recyclable industrial and municipal waste could be located in the vicinity of large sources of industrial waste, such as in the vicinity of facilities processing discarded cars, or they could be suitable for municipality associations or in municipal waste sorting areas. This facility could be in the form of modular system, being located in containers, and adapted to specific requirements, types and quantities of the processed waste.

The gasification or pyrolysis processing of single-type sorted plastic waste (for example, PET bottles, HDPE, LDPE, PP) is manageable in terms of technology. The technology from the processing of unsorted plastic waste remains problematic, which can be contaminated with various admixtures such as waste from the automotive industry. The heterogeneity of this input material for energy recovery increases the technological intensity of the entire process. This waste is specific especially due to its state (solid and liquid), type structure, and various fractions (depending on the method of previous processing). The waste from the automotive industry and car recycling that can be utilized in terms of energy recovery can be thought of as plastics, rubber, operating fluids (fuels, motor and transmission oils, coolants and brake fluids...), leather, synthetic textiles and seat covers, etc. The highest percentage of usable waste from discarded cars in terms of energy is formed by plastics. The biggest problems in the energy recovery of plastics lie with PVC, since its presence in the fuel is limited due to the generated emissions (if PVC is present in the fuel over 1%, it is necessary to increase the temperature in the combustion chamber and prolong the residence time). The composition of input fuel for the energy recovery process for plastics is given by the processing technology for wrecked cars. It is very difficult to separate the crushed plastic portion after shredding, and this plastic portion is primarily intended for energy recovery. The input fuel has non-specified properties and composition. The most precise chemical and physical properties as well as composition of the input fuel are reached by the complete disassembly of the wrecked car.

Both methods already specified for the energy recovery of wastes (especially plastics) are based on polymer degradation which can happen in the presence of a catalyst. The reaction happens in a closed reaction under the effect of heat. The reaction happens either in the presence of a small amount of air or without any oxidation agent, which is most often replaced with inert gas, usually nitrogen and usually at the normal atmospheric pressure. The supplied mixture of plastic waste is depolymerized in the reactor. It then splits into lower hydrocarbon chains (decomposition of long chains of plastic materials into a liquid mixture of saturated hydrocarbons). Waste plastic material is transformed into a gas and by its subsequent cooling, it transforms into petroleum fractions, back into the raw material that went into producing the material originally, and into synthesis gas which contains the non-condensable molecules. The process of fractional distillation starts by cooling the resulting fluid mixture of the saturated hydrocarbons, that is, separating individual petroleum fractions, when the plastic wastes transform back into the basic raw material. The final product of the process, called catalytic cracking, is a mixture of petroleum fractions containing diesel, petrol, and oil components, as well as paraffin, wax, and other components.

Depolymerisation usually takes place in the presence of a catalyst. The plastic waste gains elasticity during the addition of a catalyst even at low temperatures (around 200 °C). One advantage of the catalytic process of depolymerisation at lower working temperatures is the lower consumption of fuels necessary to heat the reactor. The catalyst is continually added into the reactor, thus ensuring its continuous and stable activity and also its balanced operation that is, maintaining temperature conditions with a favourable impact on the uniform quality of the product.

With the use of the described technologies, it is possible to process various types of municipal and industrial waste, biomass, plastics, old tires, etc. The given technologies are usually used to process plastic waste – waste polyolefins (polyalkenes) such as HDPE, LDPE, and LLDPE, that is, polyethylenes of various special weights, and PP (polypropylene). The suitability of these polymers is based on the fact that they are entirely composed of carbon and hydrogen and their basic construction units are ethylene $CH_2 = CH_2$ and propylene $CH_3–CH=CH_2$. The methods described above of depolymerisation result in the transformation of the input materials into a synthesis gas, which can be divided by cooling into condensable and non-condensable molecules (an example of synthesis gas composition depending on the input raw material is shown in Table 8.1). Depending on the raw material input, in the case of plastics, after cooling it mainly contains the liquid depolymerisation products, crackates which, depending on the conditions of the decomposition process and especially depending on the height of the decomposition temperature, have an oily, waxy, or diesel character. These generated products have a similar fractional composition as those which are primarily produced from petroleum. The remaining part after depolymerisation is waste and solid residue in the form of foreign remains from the original waste plastic raw material in the form of metal residues, glass, rocks, soil, and other mechanical impurities. The resulting liquid and gaseous portions do not contain any significant amounts of halogens, sulfur, nitrogen, or metals since they are not contained in the original raw material either. Therefore, in terms of the chemical composition in the gaseous portion, there are virtually only hydrocarbons C1 to C5 and the output product of the entire technology is a mixture of liquid compounds of carbon and hydrogen, in a weight ratio of 86: 14%, which are in structural terms mainly unsaturated hydrocarbons without any significant content of aromatic compounds. The output product corresponds to the fractional composition of light heating oil, diesel fuel, and wax, which are raw materials that can be further processed in the petrochemical industry as a valuable raw material or directly used for the production of heat and electric energy.

The use of given technologies for other types of plastic waste, such as from the automotive industry, is problematic especially due to the diversity of the input material, which has a considerable impact on the selection of the depolymerisation temperature, duration of depolymerisation, use of catalysts, final product, and residue after depolymerisation.

Table 8.1

Example of synthesis gas composition depending on the type
of input raw material

	H_2 [%]	CH_4 [%]	C_2-C_4 [%]	CO [%]	CO_2 [%]	N_2 [%]	Density [$kg.Nm^{-3}$]	Calorific value [$MJ.Nm^{-3}$]	Calorific value per tonne of input raw material [$kW.t^{-1}$]
biomass	15	26	3	35	17	4	1.10	17.10	2 591
plastics	25	38	18	9	5	5	0.80	28.00	7 778
tires	19	40	28	3.5	6.5	3	0.90	36.00	3 333

8.3.1 Technologies necessary for gasification and pyrolysis

In general, the technological equipment used for gasification and pyrolysis can be divided into three basic technological components:

a) crushing, transportation, and dosing equipment,
b) gasification or pyrolysis equipment, and
c) devices for the treatment and use of the synthesis gas.

8.3.2 Crushing, transportation, and dosing equipment

Depending on the type and technology of plastic waste depolymerization, it is necessary to crush the waste into smaller fractions prior to processing, and in the case of multiple-type waste even to mix it. Several literature sources state that the optimum particle fraction size of the crushed plastic waste is approx. 20 mm. A hammer, worm, or rotary mills (with direct or inclined blades) are used for this purpose. In general, crushers are divided into low-speed and high-speed. Examples of the structures of some crusher types are shown in Fig. 8.3. The size of the output raw material is given by the size of the mesh of the sieve placed near the crushing head.

Fig. 8.3 Overview of different types of shredding equipment (www.profing.sk)

Waste from the automotive industry should be processed with the use of a low-speed crusher followed by the use of a high-speed crusher. As specified above, the variable size of the waste from the automotive industry is problematic during its crushing. The low-speed pre-crusher with large hopper and conveyor crushes all the input raw material into a particle fraction size of approx. 50 mm, and is then processed in the high-speed crusher with blade head and sieve with a mesh diameter of 20 mm. The output raw material after crushing is suitable in terms of its size for further processing in the gasification or pyrolysis reactor.

The input raw material is crushed and fed into the reactor at the specified time and in the specified quantity. The feed device contains safety elements against the penetration of synthesis gas into the workspace of the mill and the entry of an inappropriate amount of oxidizing agent into the workspace of the reactor most often filled with inert gas (such as nitrogen).

8.3.3 Gasification and pyrolysis equipment

Gasification and pyrolysis are usually carried out in reactors of a cylindrical shape; depending on the amount of processed waste, they are constructed either as continuous or discontinuous. Both technological processes require the supply of a certain amount of heat; its amount depends on the operating temperature, quantity, and type of the processed waste. Heat is supplied to the process either by the combustion of gaseous and liquid fuels or by electric heating. Heating by electric energy is carried out directly through an electric coil, which can be situated in the feeding screw. For safety reasons, heating by combusting liquid or gaseous fuels in burners is usually carried out by transferring heat from the flue gases through the reactor wall. In order to ensure the economy of operation, the reactor is fitted with thermal insulation. The capacities of the reactors range from several hundreds of kilograms up to several tonnes of processed waste per hour. The dwell time of the batch in the reactor, and the parameters of the operation depend on the structure of the reactor and type of processed waste. An example of operational parameters is shown in Table 8.2. The solid residue after the technological process is removed through the bottom of the reactor by a cooled screw conveyor. The amount of solid residue depends on the type of processed waste, the technology used and on the operational parameters. Reactors for gasification or pyrolysis are industrially produced in small series, with type lines individually adjusted to the specific requirements.

Table 8.2

Examples of the operational parameters of the pyrolysis reactors

	Biomass[1]	**Polymer plastics[2]**	**Old tires**
Operating temperature	250 – 700 °C	650 – 800 °C	650 – 800 °C
Batch dwell time	5 – 15 min	15 – 25 min	15 – 25 min
Amount of synthesis gas	15 – 80%	60 – 95%	30 – 60%
Amount of synthesis oil (after cooling)	5 – 40%	5 – 30%	20 – 40%
Solid residue	15 – 90%	2 – 30%	35 – 45%

[1] chips from woody plants, agricultural woody biomass, sawdust...

[2] plastics, energy-related components of municipal and industrial waste

[3] changes depending on the operating conditions (torefication/pyrolysis/high-temperature pyrolysis)

8.3.4 Devices for the treatment and use of the synthesis gas

After leaving the reactor, the temperature of the synthesis gas depends on the operating temperature in the reactor and ranges from 350 to 700 °C. The majority of the hot synthesis gas consists of a mixture of hydrocarbons, partially of gaseous and solid admixtures. It can be used directly in the hot state or cooled in the condensation heat-exchangers and purified from undesirable admixtures, dividing it into synthesis gas (non-condensable molecules under normal pressure and temperature) and synthesis oil. Condensation heat-exchangers are cooled with process water. Condensation and fractional distillation from the hot synthesis gas are additional functions of the overall complex equipment.

The hot synthesis gas can also be directly used for:

1) heat production for drying and industrial use,
2) production of technological steam,
3) cooling in order to get fuel oil,

4) as a substitute for conventional fuels in existing boilers,
5) generation of power by ORC,
6) generation of power by steam turbine, ...

The cooling of the hot synthesis gas to the ambient temperature causes the separation of the liquid phase, for example, pyrolysis oil; it is a mixture of petroleum fractions containing diesel, petrol, and oil components, as well as paraffin, wax, and other substances. These are subsequently separated by filtration. They are used either directly as a fuel or as input raw materials for the chemical industry. The synthesis gas at ambient temperature is easier to transport and provides wider possibilities of application, processing, separation of molecules, and utilization. It can be used for:

- power production by combustion engine,
- power production by combustion turbine,
- heat production for technological processes,
- supply to gas network,
- hydrogen production,
- use in fuel cells,
- storage in tanks for later use,
- other special applications.

8.3.5 Conceptual design of a small complex device for the energy recovery of plastic waste

Using market research, we have discovered that there is currently no device on the market which would meet the above-specified requirements, especially the compactness and complexity of the entire device and lower hourly amount of the processed plastic waste. Therefore, our conceptual design deals with the design of such a device, which will be largely constructed from components available on the market. The entire set will be compact, container type, and will comprehensively resolve all the technological steps of plastic waste processing, from its transportation, preparation, from its depolymerisation processing up to its treatment and use of the resulting products.

The conceptual design is based on the technological schematic in Fig. 8.4. The container type device intended for continuous operation can be produced in various performance lines according to the type and required hourly amount of the processed waste. In the initial phase, prior to the construction of the prototype, it is necessary to build an experimental device sized for an hourly amount of 50 kg of plastic waste. The individual structural and operational parameters of the entire device will be verified within the pilot phase of the project. After the verification and optimization phase, the hourly capacity will be increased followed by the creation of a calculation algorithm for the construction and production of type lines of devices for specific applications.

The first part of the device (as shown in Fig. 8.4) will consist of the initial low-speed crusher, hopper with high-speed rotary crusher, and sieving and mixing devices. It will be possible to change the size of mesh and the resulting size of the particles entering the pyrolysis device, resulting in the optimization of the entire fuel preparation process. The pyrolysis device itself will be comprised of a cylindrical reactor with a screw mixer; its heating will be ensured by two dual-fuel burners enabling the combustion of gaseous and liquid fuel. This heating concept was selected due to the fact that the output from the pyrolysis device is synthesis gas and oil that can be directly used as fuel.

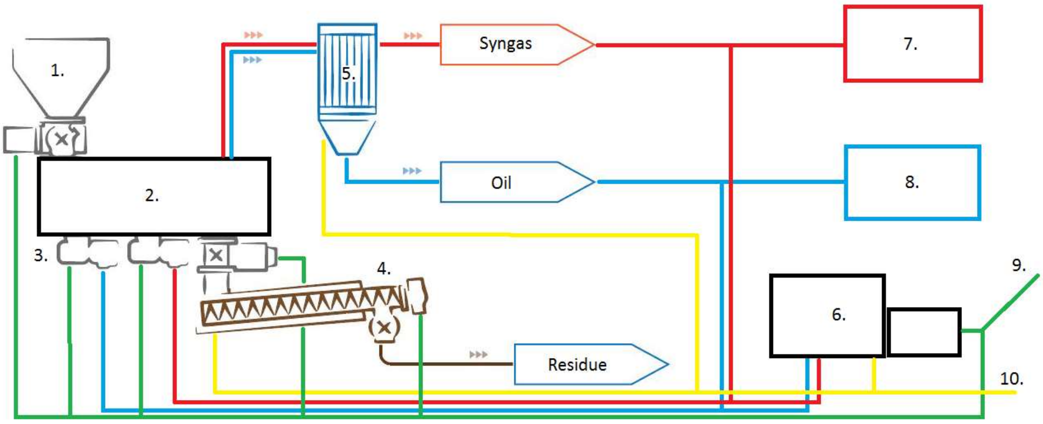

Fig. 8.4 Technological schematic of the device for plastic waste processing
Legend: Red line – synthetic gas circuit, blue line – synthetic oil circuit, yellow line – heating circuit, green line – power circuit, brown line – residue circuit. 1 – dosing device, crusher, 2 – pyrolysis reactor, 3 – double-fuel burners, 4 – conveyor for unusable residues, 5 – filtering and condensation device, 6 – cogeneration unit, 7 – synthetic gas container, 8 – synthetic oil container, 9 – outlet into external power network, 10 – outlet into the external heating circuit.

Direct electric heating by an electric coil was excluded from the conceptual design due to the problems specified in many literature sources, in particular due to the formation of sinters on the surface by the effect of the high surface temperature. At the maximum expected duration of fuel for 20 minutes and an estimated hourly capacity, the active volume of the reactor will be sized for 70 kilograms. For safety reasons, the plastic waste will be located in an inert nitrogen atmosphere inside the reactor. The generated hot synthesis gas will be discharged to the next technological step, purification and condensation, through safety fittings. The solid unused residue will be removed through the lowest part of the reactor. It will be transferred to a cooled conveyor with the subsequent removal of any metals, while the rest will be deposited at a landfill (in case a pure biomass is used as fuel, the residue is pure carbon which can be further used in the chemical industry, agriculture, etc.). The cooled synthesis gas and oil will be used for the repeated heating of the pyrolysis reactor and in the cogeneration unit located at the end of the entire technological chain. The cogeneration unit will be constructed with either a combustion engine or with a combustion turbine, able to incinerate liquid and gaseous fuel. The power produced will be used to cover the consumption of the entire device or the operating area, and the surplus will be sold to the public distribution network. Heat absorbed from the fly ash in the condensation heat-exchanger and cogeneration unit will be used in the heating system of the plant or for drying the input industrial and municipal waste. The unused synthesis gas and oil will be stored in the gas container and tanks for later use or sold for further processing.

8.4 Laboratory experimental device

The presented conceptual design of the compact device for energy recovery of waste, especially plastics, serves as a baseline for the construction of the experimental device, which will be used to verify the individual operational parameters; the impact of the processed waste type will be examined through the process of gasification or pyrolysis, through to the properties of the resulting products and their use in the energy industry or in transport or the chemical industry.

8.4.1 Location of the experimental device

For safety reasons, the experimental reactor will be located outside on an external platform.

Fig. 8.5 Views of the location and extension of the external platform

All the outputs from the installed measurement devices will lead into the adjacent laboratory where the operator will be located. In order to ensure the positioning of an experimental device, it was decided to extend the existing external platform (Fig. 8.5) which can be accessed from the interior through doors directly from the laboratory. The gas distribution system is also located in the adjacent laboratory together with the measurement of consumption, which can be recorded in the metering center. The same applies to the connection to the power network. Flue gases will flow through the stack pipe with an outlet above the roof level.

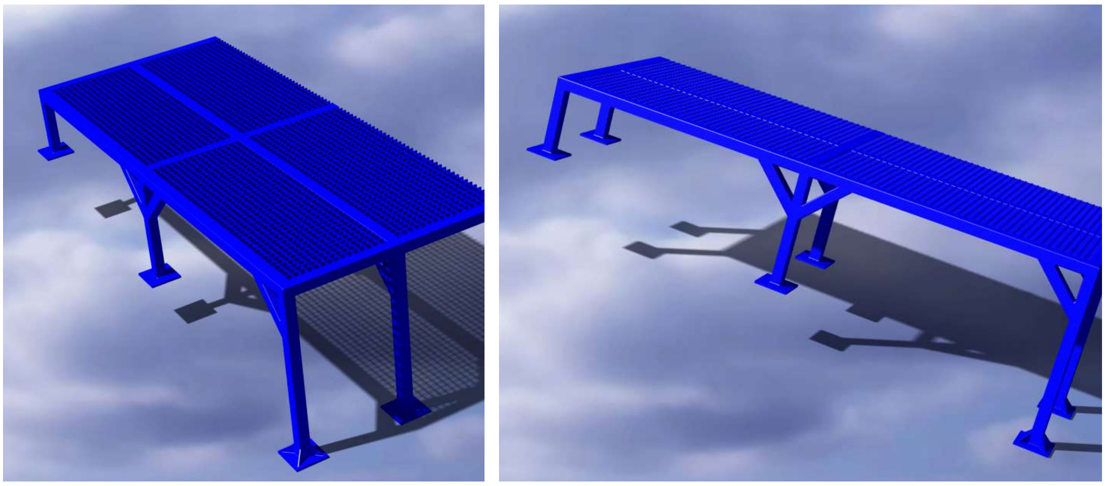

Fig. 8.6 Platform for the experimental reactor for the energy recovery of waste from the automotive industry

Fig. 8.7 The implemented platform with a shelter prepared for the installation of a small pyrolysis reactor.

The platform (Fig. 8.6, 8.7, 8.8) will be located in a sloping terrain and consists of a welded steel structure made of 100 x 100 x 5 sections with six posts in concrete foundations. The floor is made of welded steel floor grate SP 40 x 3. For safety reasons, the platform will be completed with a railing and for technological reasons, it will be completed with a roofing in order to protect the measurement devices and reactor parts from the adverse weather. We have carried out a structural analysis and dimensioning for the load of the experimental reactor with condensation exchangers and accessories according to the applicable standards.

Fig. 8.8 The implemented platform with a shelter prepared for the installation of a small pyrolysis reactor, view of the platform location in the terrain near the laboratory of the Department of Energy Machines and Equipment

8.4.2 Experimental reactor - original design

This year, we have performed the calculations and created the construction documentation for the following public procurement for the construction of the experimental reactor. The structure of the experimental reactor is based on the structure of reactors for the thermal recovery of waste available on the market. As was already specified, the market does not offer any small laboratory reactors suitable for our research, it was therefore necessary to optimize the entire structure for the given use.

The experimental reactor is constructed as discontinuous; the calculated amount of the input material is 10 kg per one cycle. Optimization was based on the unit quantity of the work filling and on the results of the experimental evaluation of the physical and chemical properties of waste from the automotive industry. By assessing the results, we have created a simplified algorithm of batch heating (plasticizing and evaporating temperatures at atmospheric pressure, degree of pressure growth, etc. The operating temperature of the reactor and thermal output of the heating were determined based on these assumptions.), and determined the required dimensions of the reactor, among other things.

In principle, the structure of the reactor consists of two closed pipes (Fig. 8.9); the space of the internal pipe is the workspace of the reactor; the space between external and internal pipe is the space for the flow of combustion products from the gas burner. The reactor is constructed from refractory stainless steel for the chemical and oil industry – DIN 17249. The external pipe is thermally insulated using Sibral Fiberfrax in the thickness of 100 mm for high temperatures with aluminium foil on the surface; the thermal insulation is then covered with sheet metal. The entire reactor is inclined at the angle of 10° (for easier discharge and cleaning).

The heating of the reactor batch is executed by the transfer of heat through the internal wall from the combustion products of the Weishaupt flange block gas burner working on natural gas. The maximum thermal output of the burner is 50 kW with the continuous modulation of the output from 12.5 to 50 kW. The heat transfer from combustion products is intensified by tangential movement – the location of the block burner and partition in the space between the internal and external pipe. After the heat transfer, the combustion products are discharged through the duct system into the surrounding environment. The modulation of the required output depends on the required operating temperature (an operating temperature ranging from 250 to 800 °C is considered).

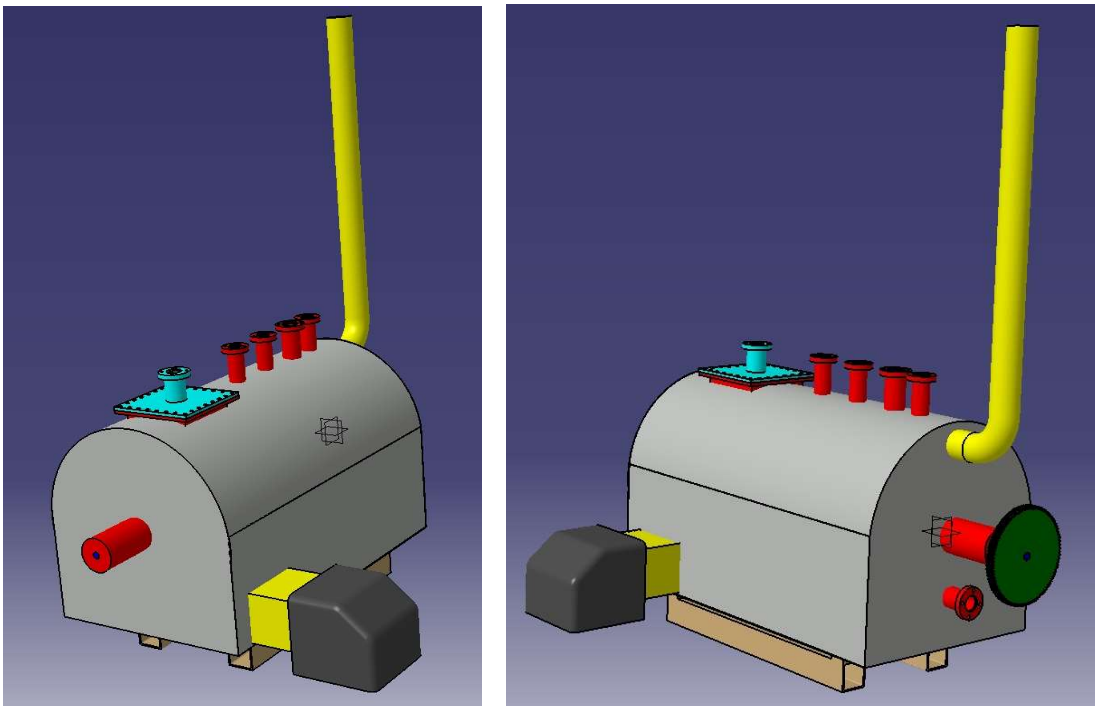

Fig. 8.9 Pyrolysis reactor – assembly

The workspace of the pyrolysis reactor consists of a pipe with two faces; the front face is removable (for cleaning of the inside and maintenance of the mixer), and for safety reasons, all other inlets and outlets lead outside the heating area. The filling inlet for the input of raw material (waste from the automotive industry together with depolymerisation catalysts) is located on the top – the sealed lid with screw joints and a flange joint draw off the pyrolysis gas. Other flange joints serve for the placement of safety elements (an overpressure safety valve with emergency ventilation of the workspace into the emergency stack), measuring the operating temperature and pressure, and filling the workspace with inert atmosphere. The rear face includes a flange joint to draw off the pyrolysis oil and remove residues after the work cycle.

The internal space includes a mixer which will prevent the sintering of the input material at high temperatures. The mixer is bedded in cooled sliding bearings with a ceramic coating; its placement is located outside the reactor. The mixer is driven by a gearwheel on the back side and the single-phase electric motor with a pinion; the electric motor is connected through a frequency converter enabling the current mixing speed to be changed depending on the working conditions in the reactor.

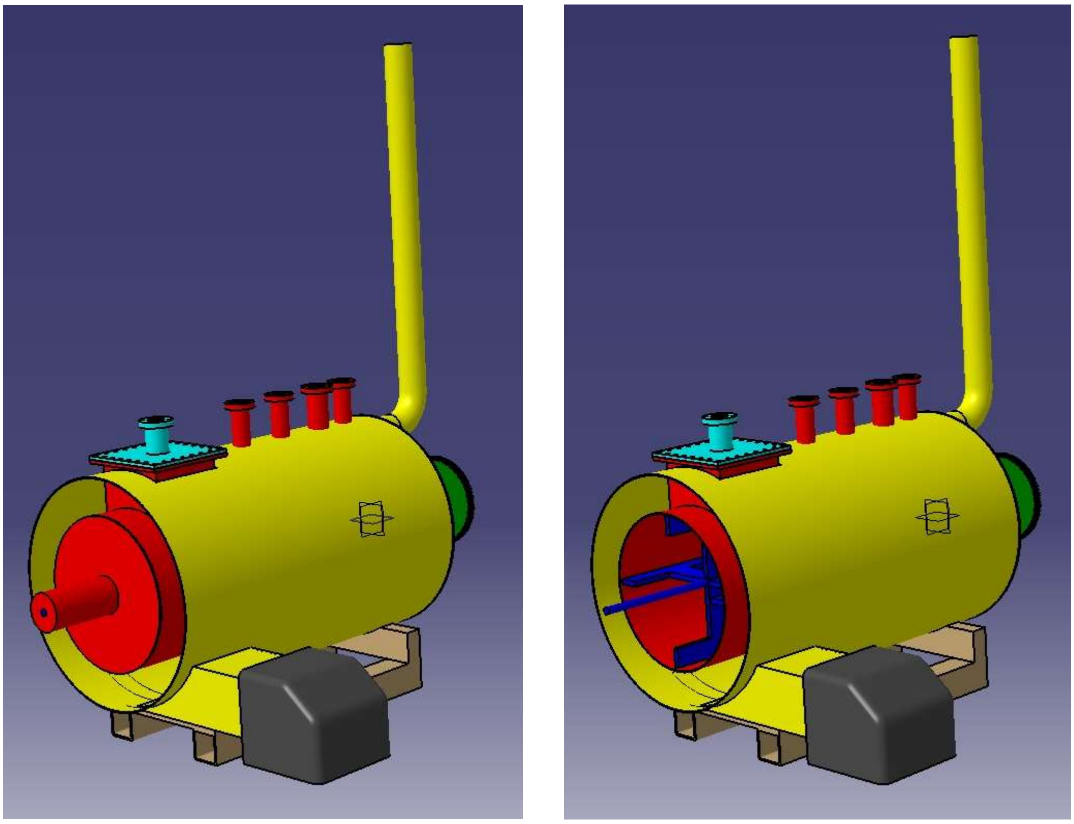

Fig. 8.10 Pyrolysis reactor – assembly without thermal insulation, open front faces

The external pipe has partitions welded on the inside, which ensure the spiral movement of the combustion products in order to intensify the heat transfer and evenly distribute the temperature in the workspace of the pyrolysis reactor. It also has a dismountable front face; it includes transitions for individual inlets and outlets; the input neck with flange for the block burner is sufficiently long to prevent the flames from reaching and point-overheating the workspace of the reactor. The back face includes the discharge of combustion products from the natural gas block burner.

The reactor is located at a 10° inclination and the change of its inclination with the use of an auxiliary frame is also considered. Several literature sources refer to the inclination as an important parameter for the proper functioning of the depolymerization device.

The synthetic gas and pyrolysis oil obtained will be purified and cooled in the condensation heat-exchangers. The cooling of the heat-exchangers is provided with cooling water; the cooling capacity is modulated by its flow rate and temperature. Non-condensable components of the gas will be stored in the gas container and the condensate in the collecting tank.

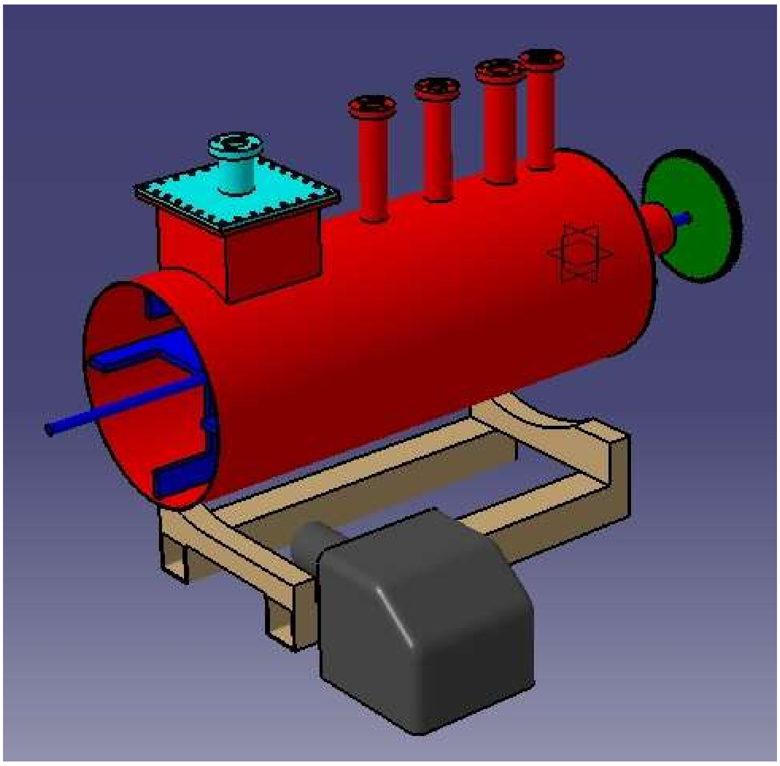

Fig. 8.11 Workspace of the pyrolysis reactor with mixer

8.4.3 Condensation exchanger

The output product of the pyrolysis reactor is the pyrolysis gas which contains various concentrations of hydrocarbons in gaseous phase. In order to obtain the pyrolysis oil, it is necessary to cool the pyrolysis gas below the condensation temperature by removing its latent heat. Since a diverse input material is expected, it is very difficult to determine the representation of individual hydrocarbons in the pyrolysis gas. In order to perform the calculation and design of the condensation heat exchanger, from available publications and physical and chemical laboratory analyses, we have determined the principal properties of individual hydrocarbons expected in the pyrolysis gas (Table 8.3 to Table 8.8).

The following limit conditions were selected for the calculation of the condensation exchanger:

[1] pyrolysis gas inlet temperature: max. 600 °C,
[2] required outlet temperature of the pyrolysis oil: at least 150 °C,
[3] coolant: water or glycol
[4] cooling with the use of Julabo circulating thermostat (cooling power of 50 kW), the maximum permissible inlet temperature of 70 °C, max. $\Delta t = 50$ °C.

The objective of the calculation was to determine the size of the heat exchange surface and the concomitant dimensions of the heat exchanger in order to achieve the required outlet temperature of the pyrolysis products while preserving the cooling power delivered from the circulating cooling thermostat.

Based on their structure, the heat exchangers are classified into main groups:

1) Plate fin heat exchangers,
2) Pipe heat exchangers:
   1. Single,
   2. Double and multiple.

According to the arrangement of the liquid flow direction we divide the heat exchangers into:

1.1 Concurrent flow,
1.2 Counter-flow,
1.3 Cross flow,
1.4 Complex flow.

In terms of the structure, we have decided for a pipe heat exchanger. Although the plate fin heat exchangers have a large heat exchanging surface with compact dimensions, they have a high hydraulic resistance and small channel cross-section, which could cause congestion problems due to waxy deposits from the pyrolysis oil. At the beginning, we considered using a multiple-pipe arrangement but for ease of maintenance, we decided for a single-operation heat exchanger with one pipe for the condensing medium. For safety reasons the pipe has a large enough diameter in order to prevent its congestion with waxy deposits.

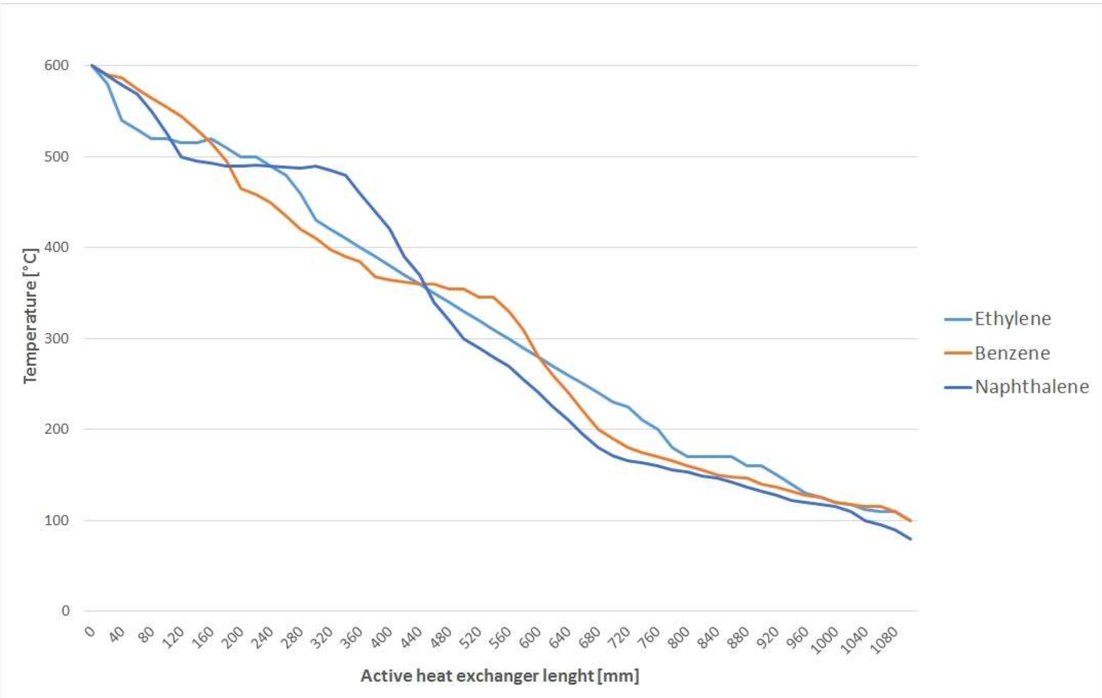

Fig. 8.12 Active length of heat exchanger

The aim of the calculation was to specify the size of the heat exchange surface and the resulting diameter and length of the internal pipe. The calculation was carried out in the Cairo computing environment. The calculation determined the dimensions of the heat exchange surface:

[1] Internal pipe – diameter: DN 100 mm,
[2] Internal pipe – active length: 1 000 mm,

[3] Internal pipe – connection: flange DN100 PN10,
[4] External pipe – diameter: DN 219.1 mm,
[5] External pipe – active length: 1 000 mm,
[6] External pipe – connection: 1´´ external thread.

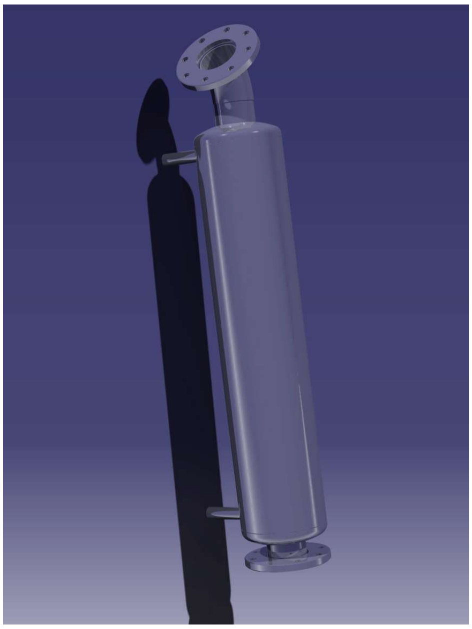

Fig. 8.13 Condenser, front view

Fig. 8.14 Condenser, back view

Using simulation calculations, we verified the state of each component at the end of the heat exchanger, that is, if condensing occurred. The calculation of temperatures of certain selected condensing components of the pyrolysis gas is shown in the following figure. It is generally applicable for every component that the gaseous phase cools down after entering the heat exchanger and condensation appears somewhere within the length of the heat exchanger by stabilization of temperature at more or less a constant value (change of state which is demonstrated by constant temperature), then the liquid phase undergoes cooling. The calculation took into consideration the fact that only one component flows through the heat exchanger at a time, not a mixture of gases as in the case of actual pyrolysis gas. The possible thermal decomposition of the condensing substance by the effect of high temperatures was not taken into consideration.

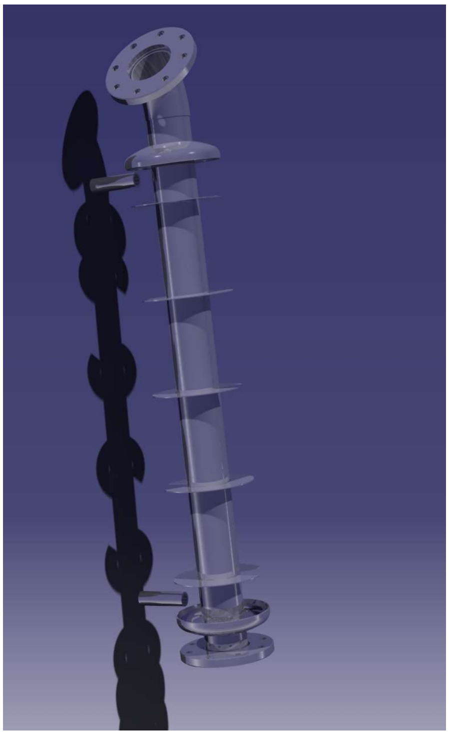

Fig. 8.15 Screens in the coolant circuit in the condenser, front view

Fig. 8.16 Screens in the coolant circuit in the condenser, back view

Fig. 8.17 View of the welded screens in the coolant circuit in the condenser

Fig. 8.18 View of the condenser prior to welding of the cooling circuit bottoms

Table 8.3
Main characteristics of light hydrocarbons

	Boiling point [K]	Triple point [K]	Molecular weight [kg.mol^{-1}]	Critical temperature [K]	Critical pressure [bar]	Fusion heat [kJ.kg^{-1}]	Heat of vaporization [kJ.kg^{-1}]	Thermal conductivity T_1 [W.m^{-1}.K^{-1}]	Thermal conductivity T_2 [W.m^{-1}.K^{-1}]	Temperature T_1 [K]	Temperature T_2 [K]
Methane	111.63	90.68	16.043	190.56	45.96	58.68	510.22	0.2240	0.1876	90.67	111.66
Ethylene	169.44	104.00	28.054	282.36	50.33	119.45	479.74	0.2681	0.1874	104.00	169.41
Ethane	184.54	90.35	30.070	305.33	48.72	95.08	490.90	0.2570	0.1617	90.35	184.55
Acetylene	189.15	192.35	26.038	308.32	61.41	144.62	640.44	-	-	-	-
Propylene	225.45	87.90	42.080	364.72	46.14	71.36	439.24	0.1872	0.1304	87.89	225.46
Propane	231.07	85.52	44.097	369.85	42.48	79.91	425.50	0.2165	0.1314	85.44	231.11
Propyne	249.93	170.45	40.065	402.39	56.29	-	555.05	0.1729	0.1384	170.45	249.94
Propadiene	238.65	136.85	40.065	393.15	54.71	-	513.92	0.1767	0.1347	136.87	238.65
iso-Butane	261.36	113.55	58.123	407.85	36.41	78.11	365.56	0.1635	0.1086	113.54	261.43
n-Butane	272.64	134.79	58.123	425.16	37.97	80.19	385.79	0.1845	0.1180	134.86	272.65
1 Butene	266.89	87.86	56.107	419.59	40.21	68.58	399.85	0.1828	0.1201	87.80	266.90
iso-Butene	266.25	132.80	56.107	417.90	40.00	105.71	395.74	0.1873	0.1171	132.81	266.25
Vinylacetylene	278.25	-	52.076	454.00	48.61	-	456.68	0.1278	-	278.25	-

Table 8.4
Main characteristics of n-paraffins

	Boiling point [K]	Triple point bod [K]	Molecular weight [kg.mol^{-1}]	Critical temperature [K]	Critical pressure [bar]	Fusion heat [kJ.kg^{-1}]	Heat of vaporization [kJ.kg^{-1}]	Thermal conductivity T_1 [W.m^{-1}.K^{-1}]	Thermal conductivity T_2 [W.m^{-1}.K^{-1}]	Temperature T_1 [K]	Temperature T_2 [K]
n-Pentane	309.20	143.40	72.151	469.70	33.70	116.44	357.10	0.1782	0.1085	143.40	309.20
n-Hexane	341.90	177.80	86.178	507.50	30.13	151.78	334.70	0.1621	0.1041	171.80	341.90
n-Heptane	371.60	182.60	100.205	540.20	27.37	140.22	316.20	0.1597	0.1024	182.60	371.60
n-Octane	398.80	216.40	114.232	568.80	24.88	181.56	301.10	0.1518	0.0980	216.40	398.80
n-Nonan	424.00	219.70	128.259	594.70	22.88	120.56	289.10	0.1510	0.0971	219.70	424.00
n-Decane	447.30	243.50	142.286	617.60	21.05	201.77	278.20	0.1454	0.0945	243.50	447.30
n-Undecane	469.00	247.60	156.313	638.80	19.66	141.90	271.90	0.1454	0.0940	247.60	469.10
n-Dodecane	489.50	263.60	170.340	658.20	18.24	216.27	261.00	0.1434	0.0908	263.60	489.50
n-Tridecane	508.60	267.80	184.367	675.80	17.23	154.59	251.00	0.1433	0.0940	267.80	508.60
n-Tetradecane	526.70	279.00	198.394	692.40	16.21	227.18	239.10	0.1401	0.0907	279.00	526.70
n-Pentadecane	543.80	283.10	212.421	706.80	15.20	162.85	233.40	0.1435	0.0878	283.10	543.80
n-Hexadacane	560.00	291.30	226.448	720.60	14.19	235.63	226.60	0.1423	0.0809	291.30	560.00
n-Heptadecane	575.20	295.10	240.475	733.40	13.17	168.25	217.50	0.1439	0.0818	295.10	575.30
n-Octadecane	589.50	301.30	254.502	745.30	12.14	243.48	217.00	0.1458	0.0809	301.30	589.90
n-Nonadecane	603.10	305.00	268.529	755.90	11.17	170.61	208.70	0.1451	0.0796	305.30	603.10
n-Eicosane	617.00	309.60	282.556	767.00	10.40	274.29	208.80	0.1487	0.0800	309.60	616.90

Table 8.5
Main characteristics of iso-paraffins

	Boiling point [K]	Triple point bod [K]	Molecular weight [kg.mol-1]	Critical temperature [K]	Critical pressure [bar]	Fusion heat [kJ.kg-1]	Heat of vaporization [kJ.kg-1]	Thermal conductivity T_1 [W.m-1.K-1]	Thermal conductivity T_2 [W.m-1.K-1]	Temperature T_1 [K]	Temperature T_2 [K]
iso-pentane	301.00	113.30	72.150	460.40	33.82	71.39	342.10	0.1685	0.1087	113.30	301.00
2 Methylpentane	333.40	119.50	86.177	497.50	30.11	72.73	324.10	0.1598	0.0999	119.60	333.40
3 Methylprentane	336.40	110.30	86.177	504.40	31.25	61.54	334.30	0.1644	0.1009	110.30	336.40
2 2 Dimethylbutane	322.90	173.30	86.177	488.80	30.81	6.72	306.40	0.1344	0.0949	174.30	322.90
2 3 Dimethylbutane	331.10	144.60	86.177	500.00	31.28	9.27	318.80	0.1420	0.0967	145.20	331.10
2 Methylhexane	363.20	154.90	100.200	530.40	27.34	91.66	310.90	0.1552	0.0991	154.90	363.20
3 Methylhexane	365.00	153.80	100.200	535.30	28.15	94.41	311.10	0.1566	0.1000	153.80	365.00
2 2 Dimethylpentane	352.30	149.30	100.200	520.50	27.74	58.12	291.90	0.1371	0.0903	149.30	352.30
2 3 Dimethylpentane	362.90	255.40	100.200	537.40	29.09	-	307.20	0.1403	0.0904	160.00	362.90
2 4 Dimethylpentane	353.70	153.90	100.200	519.80	27.38	68.31	297.20	0.1350	0.0897	153.90	353.60
3 3 Dimethylpentane	359.20	138.70	100.200	536.40	29.46	70.53	296.60	0.1402	0.0913	138.70	359.20
2 Methylheptane	390.80	164.10	114.230	559.60	24.85	103.98	292.60	0.1571	0.0985	164.20	390.80
2 Methyloctane	416.40	192.80	128.260	586.80	22.91	140.34	283.90	0.1533	0.0979	192.80	416.40

Table 8.6
Main characteristics of naphthenes

	Boiling point [K]	Triple point bod [K]	Molecular weight [kg.mol-1]	Critical temperature [K]	Critical pressure [bar]	Fusion heat [kJ.kg-1]	Heat of vaporization [kJ.kg-1]	Thermal conductivity T_1 [W.m-1.K-1]	Thermal conductivity T_2 [W.m-1.K-1]	Temperature T_1 [K]	Temperature T_2 [K]
Cyclopentane	322.40	179.30	70.130	511.80	45.03	8.68	388.50	0.1583	0.1197	179.30	322.40
Methylcyclopentane	345.00	130.70	84.160	532.80	37.86	82.33	348.40	0.1603	0.1069	130.70	344.90
Cyclohexane	353.90	279.70	84.160	553.50	40.76	32.56	355.00	0.1281	0.1095	279.70	353.90
Methylcyclohexane	374.10	146.60	98.190	572.20	34.72	68.75	324.00	0.1455	0.0934	146.60	374.10
Ethylcyclopentane	376.60	134.70	98.190	569.50	33.99	69.96	328.30	0.1533	0.0994	134.70	376.60
Ethylcyclohexane	404.90	161.80	112.210	609.20	30.41	74.27	304.30	0.1440	0.0951	161.80	405.00
n-Propylcyclopentane	404.10	155.80	112.210	603.00	30.01	89.41	308.20	0.1435	0.0936	155.80	404.10
n-Propylcyclohexane	429.90	178.30	126.240	639.20	28.07	82.16	289.00	0.1367	0.0900	178.30	429.90
n-Butylcyclopentane	429.80	165.20	126.240	621.30	27.24	-	409.50	-	-	-	-

Table 8.7
Main characteristics of olefins

	Boiling point [K]	Triple point bod [K]	Molecular weight [kg.mol^{-1}]	Critical temperature [K]	Critical pressure [bar]	Fusion heat [kJ.kg^{-1}]	Heat of vaporization [kJ.kg^{-1}]	Thermal conductivity T_1 [W.m^{-1}.K^{-1}]	Thermal conductivity T_2 [W.m^{-1}.K^{-1}]	Temperature T_1 [K]	Temperature T_2 [K]
1 Pentene	303.10	107.90	70.13	464.80	35.27	82.80	365.70	0.1744	0.1143	107.90	303.10
cis 2 Pentene	310.10	121.80	70.13	475.90	36.55	101.40	378.20	0.1723	0.1141	121.80	310.10
trans 2 Pentene	309.50	132.90	70.13	475.40	36.55	119.10	374.10	0.1665	0.1135	132.90	309.50
2 Methyl 1 Butene	304.30	135.60	70.13	465.40	34.00	112.80	364.60	0.1551	0.1062	135.60	304.30
2 Methyl 2 Butene	311.70	139.40	70.13	470.90	34.00	108.30	377.40	0.1558	0.1057	139.40	311.70
Cyclopentene	317.40	138.10	68.12	507.00	47.91	49.40	405.10	0.1754	0.1230	138.10	317.40
2 Methyl 1 3 Butadiene	307.20	127.20	68.12	484.00	38.51	72.30	376.00	0.1835	0.1179	127.30	307.20
Cyclopentadiene	314.70	188.20	66.10	507.00	51.51	-	389.50	0.1683	0.1284	188.20	314.70
1 Hexene	336.60	133.30	84.16	503.80	31.42	111.10	340.20	0.1856	0.1070	133.40	336.60
Cyclohexene	356.10	169.70	82.15	560.40	43.51	40.10	378.50	0.1615	0.1162	169.70	356.10
1 Heptene	366.80	154.30	98.19	537.50	28.31	126.30	323.10	0.1730	0.1030	154.30	366.80
1 Octene	394.40	171.40	112.21	567.10	25.61	136.40	306.30	0.1671	0.0999	171.50	394.40
1 Nonen	420.00	191.80	126.24	593.30	23.31	142.50	293.20	0.1446	0.0898	191.80	420.00

Table 8.8
Main characteristics of aromatics

	Boiling point [K]	Triple point bod [K]	Molecular weight [kg.mol^{-1}]	Critical temperature [K]	Critical pressure [bar]	Fusion heat [kJ.kg^{-1}]	Heat of vaporization [kJ.kg^{-1}]	Thermal conductivity T_1 [W.m^{-1}.K^{-1}]	Thermal conductivity T_2 [W.m^{-1}.K^{-1}]	Temperature T_1 [K]	Temperature T_2 [K]
Benzene	353.30	278.70	78.11	562.20	48.99	126.30	393.40	0.1503	0.1266	278.68	353.24
Toluene	383.80	178.20	92.14	591.80	41.10	72.00	364.40	0.1617	0.1126	178.18	383.78
Ethylbenzene	409.30	178.20	106.17	617.20	36.10	86.50	338.10	0.1588	0.1033	178.15	409.35
o-Xylene	417.60	248.00	106.17	630.40	37.65	128.10	348.40	0.1429	0.1039	274.98	417.58
m-Xylene	412.30	225.30	106.17	617.10	35.42	109.00	342.10	0.1474	0.1034	225.30	412.27
p-Xylene	411.50	286.40	106.17	616.30	35.12	161.20	337.30	0.1325	0.1030	286.41	411.51
Styrene	418.30	242.50	104.15	636.00	38.40	105.10	351.50	0.1488	0.1101	242.54	418.31
Isopropylbenzene	425.60	177.10	120.19	631.20	32.10	61.00	316.6	0.1494	0.0964	177.14	425.56
n-Propylbenzene	432.40	173.60	120.19	638.40	32.00	77.10	319.00	0.1525	0.0993	173.55	432.39
1 2 4 Trimethylbenzene	442.50	229.30	120.19	649.10	32.33	109.80	325.10	0.1439	0.0990	229.38	442.53
1 3 5 Trimethylbenzene	437.90	228.50	120.19	637.40	31.28	79.20	325.70	0.1513	0.1037	228.46	437.89
n-Butylbenzene	456.40	185.20	134.22	660.60	28.88	83.60	300.70	0.1510	0.0922	185.30	456.45
Naphthalene	491.10	353.40	128.17	748.40	40.52	148.10	338.70	0.1332	0.1278	353.43	491.14

8.4.4 Experimental reactor – implementation

Since the pandemic, prices have grown exponentially, the original budget was insufficient for the implementation of the originally designed reactor. After market research, we have concluded that we need to simplify the pyrolysis reactor in such way as to maintain the quality of the final pyrolysis products and to meet the expected objectives of this research.

The first thing we removed was the rotary stirrer from the conceptual design because it was mounted in bearings that had to be able to withstand the high temperatures of the reactor. With regard to the total investment, bearings of this type were not affordable. The formation of sinters will be prevented by a higher degree of temperature control of the flue gases heating the reactor pyrolysis chamber with a load on the basis of better regulation. For this reason, it was not necessary to place the pyrolysis chamber horizontally, but it will now be vertical, easily removable and the solid residues will be easily cleanable. The flue gases will flow in a spiral around the pyrolysis chamber, as in the original design, but the spiral for the flue gases will lead from the bottom upwards in the direction of the flue gases flowing up from the heating source to the stack. The spiral extraction of flue gases is designed in order to prevent point heating of the reactor chamber on the one hand, and on the other hand to increase the retention time in the combustion chamber, and thus increase the efficiency of the energy utilization of fuel used for reactor chamber heating.

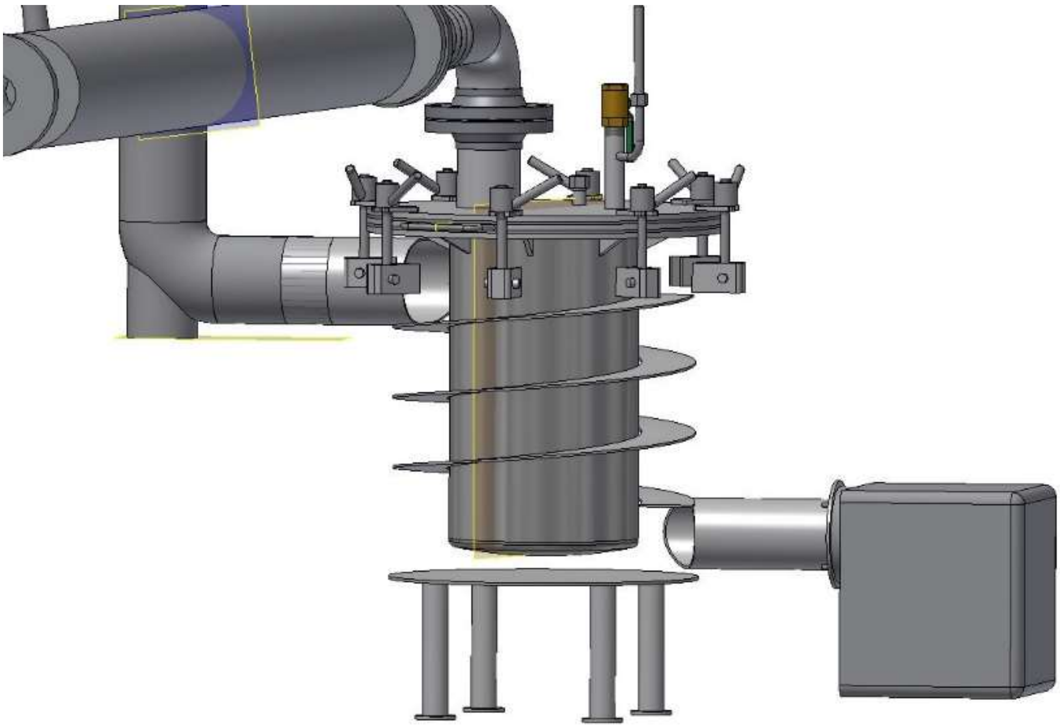

Fig. 8.19 Pyrolysis reactor without cover with a detail for the spiral flow of flue gases from the burner

The hopper is easily removable after disconnecting the chimney flange. Since the operation of this reactor is discontinuous, this method does not limit the practical use of the designed pyrolysis reactor.

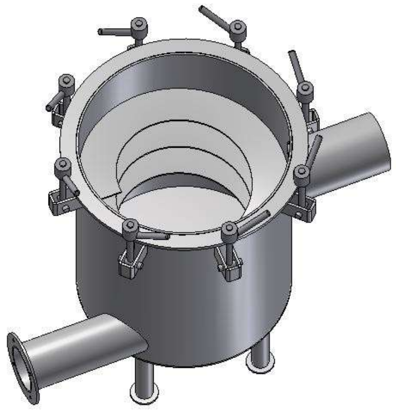

Fig. 8.20 Detail of the helix for spiral flow of pyrolysis reactor flue gases, inside view

Fig. 8.21 Detail of the helix for spiral flow of flue gases from the constructed pyrolysis reactor

Fig. 8.22 View of the pyrolysis chamber of the reactor

Fig. 8.23 Pyrolysis chamber pulled out of the reactor

The condenser is designed as a twin-shell, while the internal pipe is intended for the extraction of vapours from the pyrolysis reactor which are subsequently liquefied. Non-liquefied vapours will be returned to the burner, which will reduce the energy intensity of the pyrolysis process. The condensate will be extracted into the retention accumulator – collector. The coolant will flow between the condensing pipe and external pipe. In order to ensure even cooling of the condenser, the condensing pipe was designed with screens which prevent the coolant from direct flow through the cooler – described in section 4.3 Condensation exchanger. The temperature of the coolant will be regulated in the flow thermostat Julabo located on the premises of the laboratory.

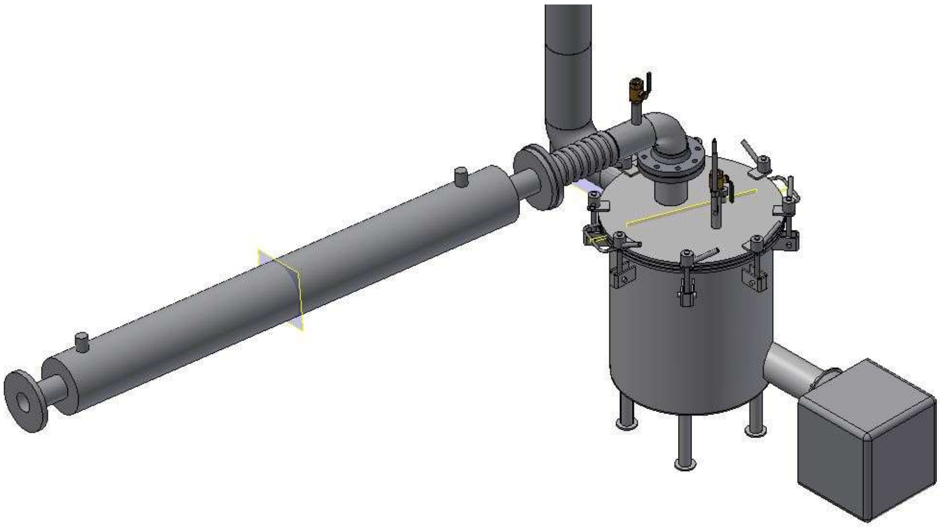

Fig. 8.24 Structural design of the pyrolysis reactor – overview

Fig. 8.25 Detail of the removable reactor cover

Fig. 8.26 Completed pyrolysis reactor without condenser

8.4.5 Material preparation for pyrolysis – shredding device

The shredding device will be in the form of a specially adjusted crusher with modified blades and adjustable blade movement. The movement of blades must be adjusted according to the kind and type of shredded material.

Fig. 8.27 Adjustable blades of the crusher

Fig. 8.28 Disassembled crusher after blade adjustment

Fig. 8.29 Hopper for input material

Fig. 8.30 Hopper for crushed material from the crusher

We have intentionally opted for a crusher which is independent from the power network and driven by a petrol combustion engine. It can be attached to a motor vehicle in order to be able to prepare input material – crushed material – outside the laboratory of the Department of Energy Machines and Equipment and directly at the site, either in the waste collection facilities or at the scrapyard, and from there transport the prepared material in compact bags. Tests of the crusher were performed in the environmental technology laboratory at the Department of Energy Machines and Equipment. They involved many materials (ABS, PS, PP, LDPE, HDPE, PET) with various thickness of the crushed material. The tests were satisfactory.

Fig. 8.31 Complete crusher

Fig. 8.32 Sample of crushed material

8.5 Conclusion

Within the energy recovery of waste, the pyrolysis technology is not among the simplest, not the most popular since it is associated with several problems. Despite that, it results in a quality and valuable fuel which can be further used, in combustion engines, for example. It is therefore meaningful to keep improving this technology, since in addition to the production of quality fuels, it also contributes to the elimination of a large portion of the environmental burden. The design and implementation of the small pyrolysis reactor was therefore carried out carefully, bearing in mind the major importance of this technology which will play an important role in the future.

Acknowledgements

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8.6 Bibliography

[1] BEUKENS, A. 2013. Incineration Technologies, Springer 2013. 90 s. ISBN 978-1-4614-5751-0.

[2] ČARNOGURSKÁ, M. – LAZÁR, M. 2013. Plazmové spracovanie a zhodnocovanie odpadu. Košice: Strojnícka fakulta Technickej univerzity v Košiciach. 2013. 164 s. ISBN 978-80-553-1541-0.

[3] ČERMÁK, O. a kol. 2008. Životné prostredie. Bratislava: Slovenská technická univerzita v Bratislave, 2008. 390 s. ISBN 978-80-227-2958-1.

[4] DAVIS, G. – KINCAID, L. 1994. Car recycling and environmental improvement in Western Europe. [online]. 1994, p.1 [cit.2010-02-16]. Dostupné na: <http://www.p2pays.org/ref/24/23758.pdf >.

[5] HESTER, R.E. – HARRISON, R.M. 1994. Waste Incineration and the Envirinment, Royal Society of Chemistry 1994. 158 s. ISBN 0-85404-205-9.

[6] HŘEBÍČEK, J. a kol. 2009. Integrovaný systém nakládání s odpady na regionální úrovni. Brno 2009. s. 202, ISBN 978-80-85763-54-6.

[7] HUDEC, I. 2008. Použitie plastov pri konštrukcii a výrobe automobilov. In: ai magazine, roč. 1, 2008, č. 1, s. 48, ISSN 1337–7612.

[8] CHMIELEWSKÁ, E. 1997. Odpady, Bratislava: Prírodovedecká fakulta Univerzity Komenského, 149 s.

[9] CHMIELEWSKÁ, E. – KURUC, J. 2008. Odpady, Nakladanie s tuhým neaktívným a rádioaktívným odpadom, Bratislava: Univerzita Komenského, 336 s.

[10] CHRISTIANOVÁ, A. 2000. Uplatnění preventivního přístupu k problematice autovraku (smernice EU k autovrakům, minimalizace odpadů). In: Halousková, O.: Recyklace jako součást životního cyklu automobilu. Seč: Juniorcentrum Seč, 2000, s. 26, ISBN 80-7080-410-6.

[11] JANDAČKA, J. a kol. 2014. Energetické využitie komunálneho odpadu. Žilina: UNIZA – edis, 2014. 170 s. ISBN 978-80-554-0923-8.

[12] JANDAČKA, J. a kol. 2014. Produkcia komunálneho odpadu. Žilina: UNIZA – edis, 2014. 113 s. ISBN 978-80-554-0897-2.

[13] KANARI, N. – PINEAU, J.L. – SHALLARI, S. 2003. End-Of-Life Vehicle Recycling in European union. In: JOM the member juornal of The Minerals, Metals & materials Society [online]. 2003, vol. 55, no. 8 [cit.2020-01-28] s.15. Dostupné na: <http://www.tms.org/pubs/journals/JOM/JOMbyIssue.asp?issue=JOM\2003\August >.

[14] KARAGIANNIDIS, A. 2012. Waste to Energy, Opportunities and Challengers for Developing and Transition Economies, Springer 2012. 370 s. ISBN 978-1-4471-2305-7.

[15] KNAPČÍKOVÁ, L. – ORAVEC, P. 2009. Vyuţitie pyrolýzy pri zhodnocovaní odpadových plastov. In: Najnovšie trendy, v strojárstve a odpadovom hospodárstve [zborník na CD ROM]. Nitra: Slovenská poľnohospodárska univerzita, 2009, s. 190-194. ISBN 978-80-552-0208-2.

[16] KOSCELNÍK, B. 2008. Spracovanie starých vozidiel. In: Automotive Engineering Journal, roč.1, 2008, č. 2, s. 88-89, ISSN 1337-7671.

[17] KOSCELNÍK, B. 2008. Vraky ako biznis. In: Automotive Engineering Journal, roč.1, 2008, č. 2, s. 91, ISSN 1337-7671.

[18] KOVÁČ, B. – MATĚJKA, R. 2009. Ekologické spracovanie osobných automobilov po dobe životnosti. In: Doprava a spoje [online elektronický časopis]. 2009, č. 1, s.36-41 [cit.2020-02-25]. Dostupné na: <http://fpedas.uniza.sk/dopravaaspoje/2009/1/kovac.pdf >. ISSN 1336-7676.

[19] KOVÁČ, B. 2007. Implementácia európskeho práva pri recyklácii cestných motorových vozidiel po dobe životnosti. In: Doprava a spoje [online elektronický časopis]. 2007, č. 1, s.38-42 [cit.2020-02-25]. Dostupné na: <http://fpedas.uniza.sk/dopravaaspoje/rok.php?rok=2007&c=1>. ISSN 1336-7676.

[20] LIPTAI, P. – PAVLÍKOVÁ, A. 2008. Recyklácia plášťov pneumatík a gumy. In: Automotive Engineering Journal, roč.1, 2008, č. november-december, s. 80, ISSN 1337-7671.

[21] LYSÝ, J. 2010. Technologické zariadenia prevádzky na spracovanie vrakov automobilov, SPU Nitra.

[22] MÁTEL, F. 2000. Možnosti recyklácie plastového odpadu z autovrakov. In: Halousková, O.: Recyklace jako součást životního cyklu automobilu. Seč: Juniorcentrum Seč, 2000, s. 65-66, ISBN 80-7080-410-6.

[23] MÁTEL, F. 2008. Recyklácia plastov z ojazdených vozidiel. In: ai magazine, roč. 1, 2008, č. 1, s. 50, ISSN 1337–7612.

[24] Materiálové zloženie automobilu – Dostupné na internete: https://www.engineering.sk/index.php/clanky2/automobilovy-priemysel/301-recyklacnetechnologievap

[25] NESVADBA, J. – VELEK, K. 1983. Tuhé dopady. Praha: SNTL - Nakladatelství technické literatury. 1983, 312 s.

[26] ORLOVSKÝ, I. – HATAL, M. – JADINÁKOVÁ, J. A. 2009. Ako zhodnotiť opotrebované pneumatiky. In: Automotive Engineering Journal, roč.2, 2009, č. máj-jún, s. 44, ISSN 1337-7671.

[27] PADO, R. 2007. Autovraky. [online]. 2007, [cit.2010-02-23] Dostupné na: < http://www.biospotrebitel.sk/clanok/1288-autovraky.htm>. Parfer Siti S.p.A. [online]. [cit.2010-03-01] Dostupné na: <http://www.parfersiti.com/index.php?action=main&locale=en_US>.

[28] PAVLÍKOVÁ, A. – VYSOCKÝ, M. 2009. Recyklačne orientované konštruovanie. In: ai magazine, roč. 2, 2009, č. 4, s. 60, ISSN 1337–7612.

[29] PATSCH, M. 2011. Horák pre spaľovanie glycerínu vo vybraných energetických zariadeniach. Doktorandská dizertačná správa, Žilinská univerzita v Žiline, 2011.

[30] PÍCHA, J. 2000. Zneškodňování a recyklace provozních kapalin automobilu. In: Halousková, O.: Recyklace jako součást životního cyklu automobilu. Seč: Juniorcentrum Seč, 2000, s. 72-73, ISBN 80-7080-410-6.

[31] PUIGJANER, L. 2011. Syngas from Waste, Emerging Technologies, Springer 2011. 327 s. ISBN 978-0-85729-539-2.

[32] Plasty používané na výrobu automobilu – Dostupné na internete: http://www.plasticportal.sk/sk/progresivne-vyvijane-polymerne-kompozity-v-automotive.html/c/1945

[33] Smernica Európskeho parlamentu a rady č. 2000/53/ES.

[34] https://ec.europa.eu/eurostat

[35] www.enviroportal.sk

[36] www.odpady-portal.sk

[37] BADIDA, M. – ŠOOŠ, Ľ. et al.: Analysis of the state, forecasts and new technologies of waste recovery in the automotive industry. - Lüdenscheid (Nemecko): RAM-Verlag pp. 190, [print]. ISBN 978-3-96595-008-5.

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