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THESIS

Development of the vehicle maintenance process in order to reduce the ecological impact

- Resume -

DOCTORAL COMMISSION

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Content

Introduction

Addressing the climate and environmental crisis is an opportunity to revive the economy in a sustainable way. In response to this challenge, the *European agreement Stepping up Europe's 2030 climate ambition - Investing in a climate-neutral future for the benefit of our people* has set climate neutrality by 2050 by reducing greenhouse gas emissions by 90%. Transport. The impact assessment accompanying the agreement *European White Paper Roadmap to a Single European Transport Area - Towards a competitive and resource efficient transport system* has shown that in order to achieve this, a number of measures must be taken to make transport more sustainable. In this context, reducing the environmental impact of vehicle maintenance activities can have an impact on the overall reduction of pollutant emissions from the transport sector.

The reason why I chose the thesis "Developing the maintenance process of vehicles in order to reduce the environmental impact" is that in Romania theoretical information on the relationship between vehicle maintenance and environmental impact is almost non-existent.

The aim of the research is to analyze the complex framework of maintenance activities, highlighting the characteristics of technologies, the role and particularities of maintenance strategies and their impact on the environment.

* * *

Part I of the doctoral thesis covers the current state of research on vehicle maintenance in order to reduce the environmental impact and is structured on the following chapters:

Chapter 1, entitled 'Maintenance of motor vehicles', provides:

• a minimal inventory of mathematical models used in reliability theory;

• a presentation of the concepts of maintainability and availability;

• details the maintenance concept, vehicle-specific maintenance systems and strategies that can be used;

• models for analyzing and evaluating vehicle maintenance are presented: technical assessment, economic assessment and environmental impact assessment.

Chapter 2, entitled 'Ecotechnological process for preventive maintenance', presents:

• types of pollutants specific to some stages of the eco-maintenance process identified in their flow charts;

• statistical data from research studies on the ecological impact of vehicles on their entire life cycle;

• elements related to the environmental impact of the maintenance process with customizations for spare parts, oil, batteries and tires.

Chapter 3 presents conclusions on the current state of research on vehicle maintenance in order to reduce the environmental impact.

Part II of the doctoral thesis includes personal contributions to the development of the vehicle maintenance process in order to reduce the ecological impact and is structured on the following chapters:

Chapter 4 presents research and development directions for vehicle maintenance in order to reduce the ecological impact, the main objective of the research and development activity, as well as the research and development methodology used.

Chapter 5, entitled "Environmental Impact Assessment of Motor Vehicles", proposes:

• life cycle analysis of vehicles;

• the development of mathematical relationships on the impact on the environment throughout the life cycle of vehicles and the results corroborated with existing databases are interpreted graphically;

• developing a model for reducing the environmental impact of recycling and a model for reducing the environmental impact of reconditioning.

Chapter 6, entitled 'Development of the vehicle maintenance process', covers:

• a theoretical analysis regarding the criteria for optimizing maintenance strategies;

• a development of mathematical models of the cost, availability and environmental impact of vehicle maintenance activities.

Chapter 7 presents a case study on elements of optimization of the maintenance process for vehicles includes:

• a presentation of the characteristics of the fleet of vehicles under maintenance;

• a presentation of the significant data regarding the organization where the maintenance activity is performed;

• the comparison between the optimization elements developed in the theoretical part with the statistical data from the maintenance activity, depending on the criterion of availability and maintenance cost of the vehicles;

• developing its own decision-making model for maintenance and from an ecological perspective.

Chapter 8, entitled "Reducing the ecological impact of vehicle maintenance by implementing the environmental management system", provides a comparative analysis of environmental issues.

Chapter 9, “Final conclusions and main contributions to the development of the vehicle maintenance process in order to reduce the environmental impact″, presents:

• final conclusions;

• personal contributions;

• development directions in the field of reducing the environmental impact of maintenance.

Chapter 1. Vehicle maintenance

1.5.1. The role of maintenance activities

The implementation of the maintenance service, as an organizational structure of an economic agent, involves forms of organization that, depending on the purpose pursued, use the available resources and forecast future investments. Such an approach must be correlated with the maintenance systems shown in Fig. 1.6.

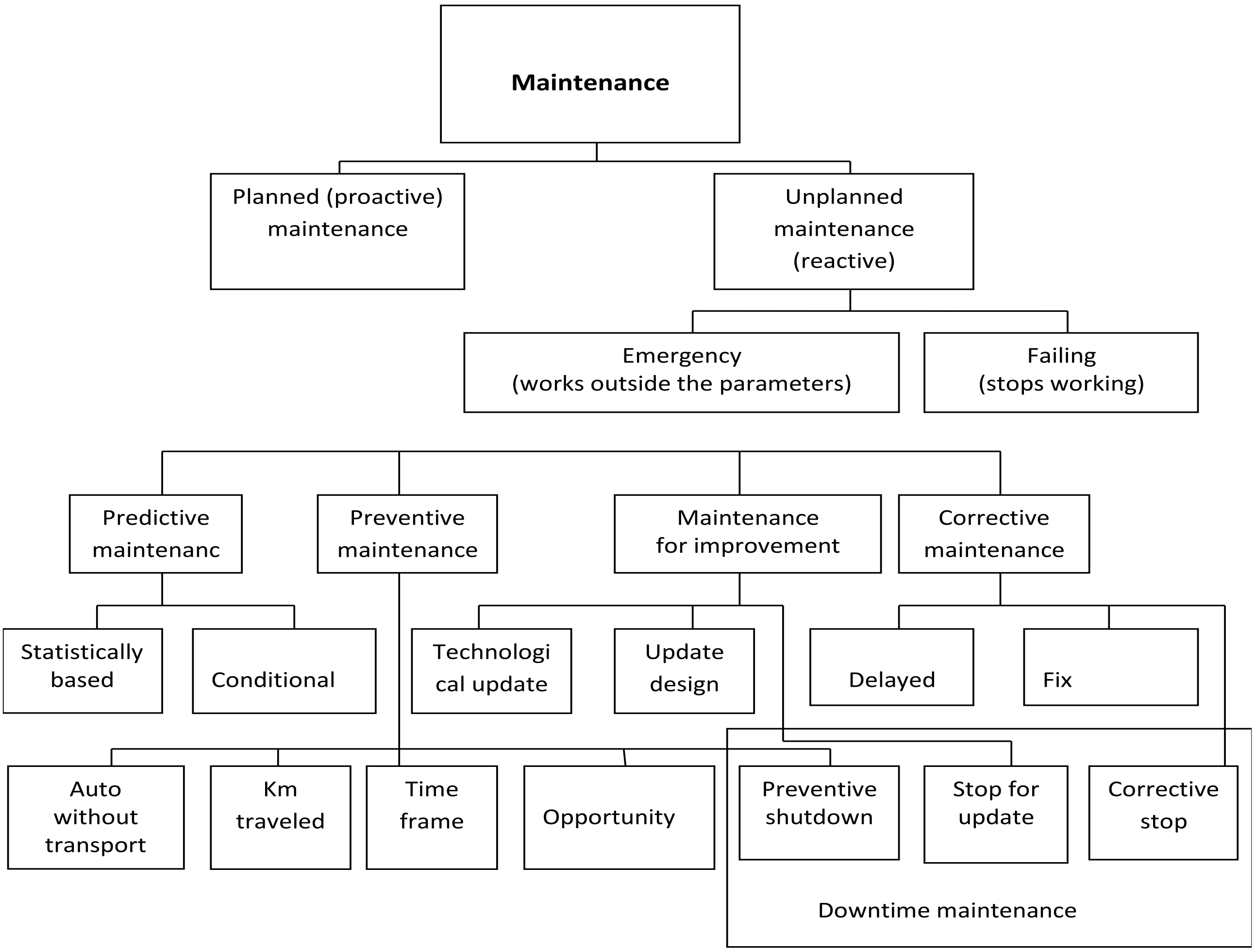


Fig. 1.6. Types of maintenance for motor vehicles [34]

In order to ensure the availability for operation of motor vehicles, maintenance involves:

- periodic diagnosis of vehicles
- diagnosis of equipment, installations, control equipment
- carrying out the planned maintenance actions
- repair of found faults
- purchase of new equipment
- design and implementation of new maintenance methods;
- staff training for the optimal use of new equipment.

Environmental protection is ensured by:

• diagnosis of the technical condition of the vehicles regarding the gas emissions;
• prevention of fluid leakage;
• implementation of procedures for reconditioning, recovery and recycling of used parts;
• gas filtration, decantation of technological and residual fluids.

The efficiency of the above-mentioned systems can be compared by indicators of cost, availability or, in the case of the topic addressed, the environment. The maintenance strategies are shown schematically in Fig. 1.8.

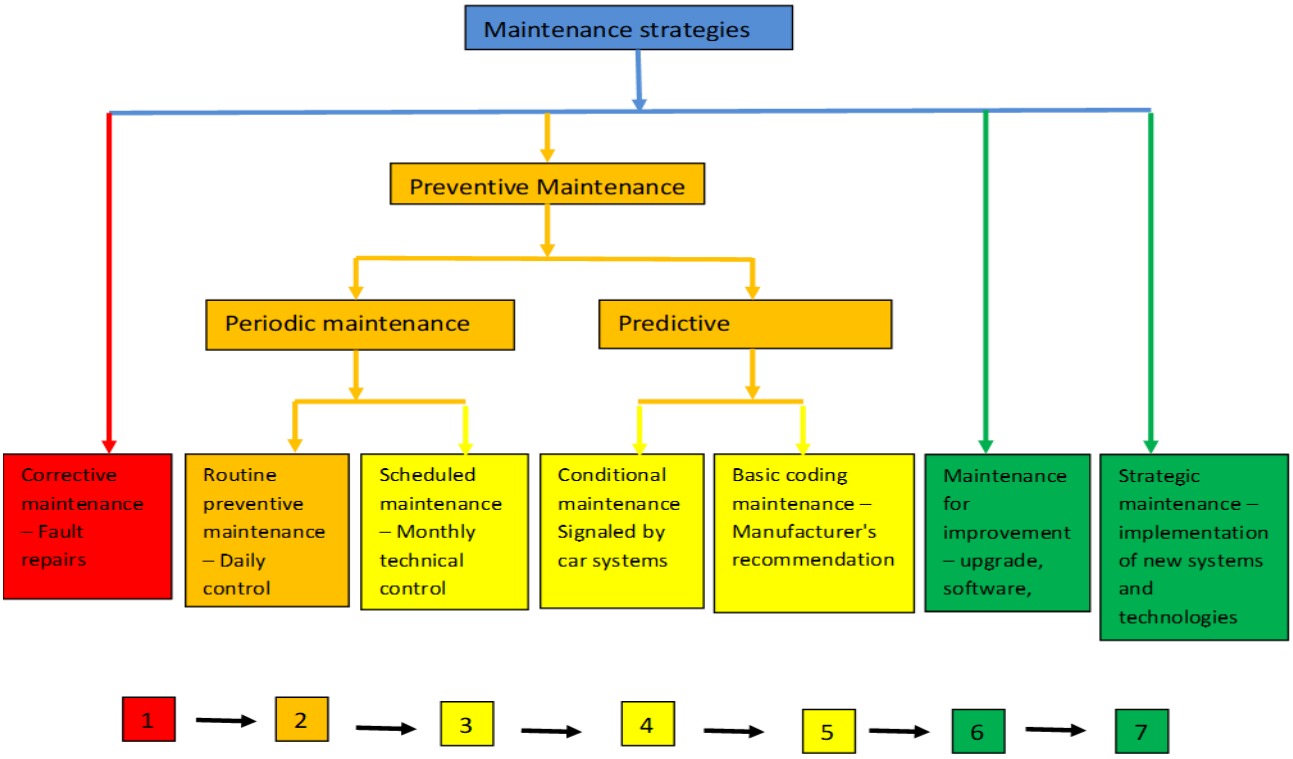


Fig. 1.8. Maintenance strategies, adaptation of [9, 35,37]

The development of maintenance can be done on four levels [61]:

• increasing the productivity of the system, ie the quantity of products at the best possible price, in a stable manner over time;
• participation in the continuous improvement of the quality of the products, respectively of the manufactured goods and of the offered services;
• guaranteeing the security of the good functioning of the system and of the people who serve it;
• guaranteeing environmental protection.

Vehicle maintenance technologies are also evolving with vehicle manufacturing technologies. Modern cars incorporate many electronic systems. Therefore, software upgrades and sensors are used to detect system defects before immobilization.

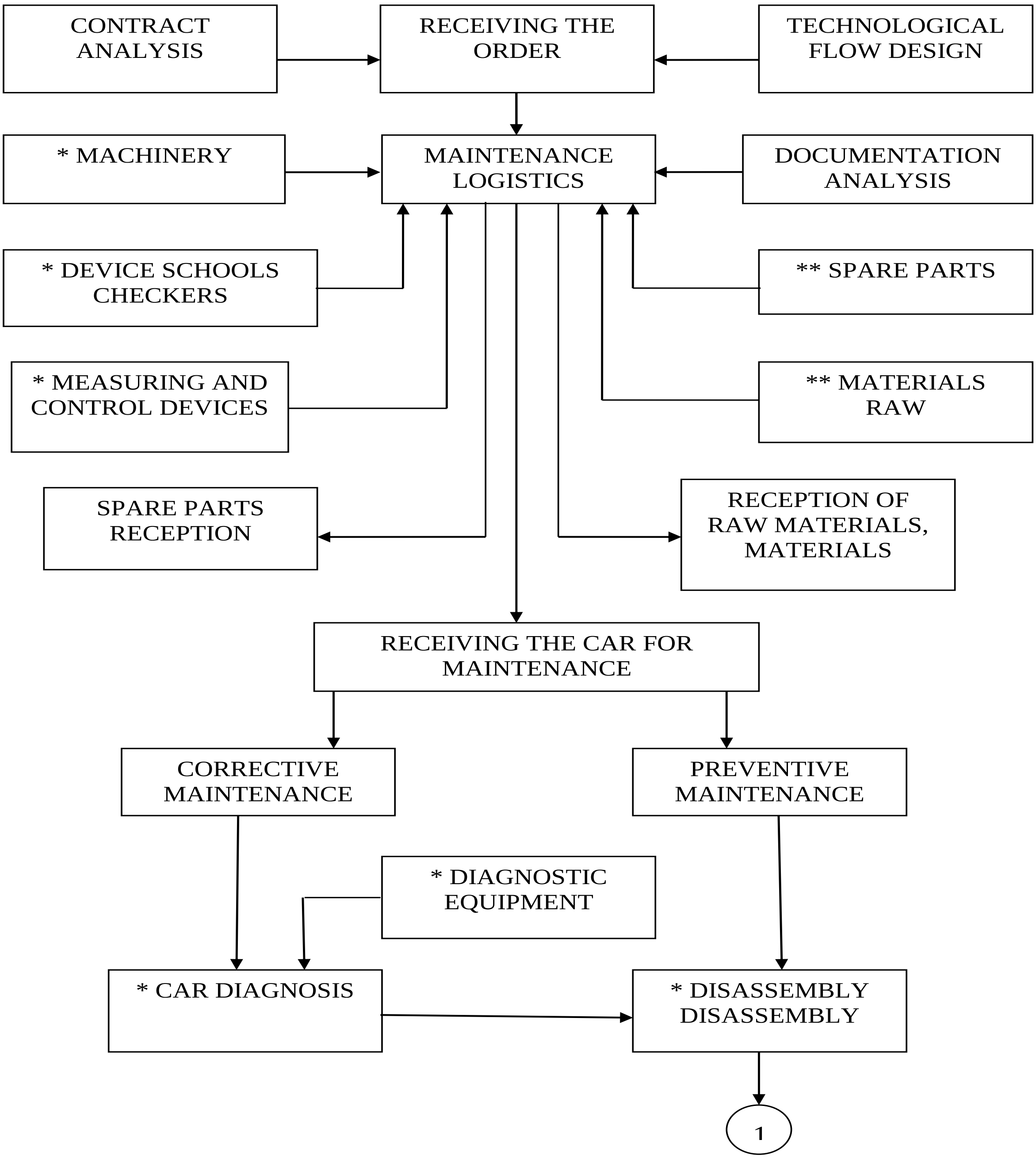
A common approach in vehicle maintenance, through the automatic transmission of data collected by sensors on board, is called CMMS (Computerized Maintenance Management System). In this approach, sensor data for various vehicle operations is collected and processed using the on-board computers. The anomaly in the functions of the vehicle is recorded and analyzed by the computer [47, 56]. The result is then extracted and interpreted by maintenance personnel to identify the error in the vehicle systems. This improves the efficiency of the maintenance process and reduces the costs as well as the maintenance time of the vehicle.

Chapter 2. The ecotechnological process of preventive maintenance

2.2. Ecotechnological analysis of the vehicle maintenance process

The main component of a maintenance eco-process is the basic eco-processes, which directly contribute to the transformation of raw materials into spare parts, materials, lubricants, tires, batteries, etc. or in their repair / reconditioning / recycling / regeneration in order to reduce pollutant emissions and the amount of waste.

In Fig. 2.3 describes the main stages of the maintenance eco-process, with the relationship between them and the specification of the category of impact (major or minor) on the environment.



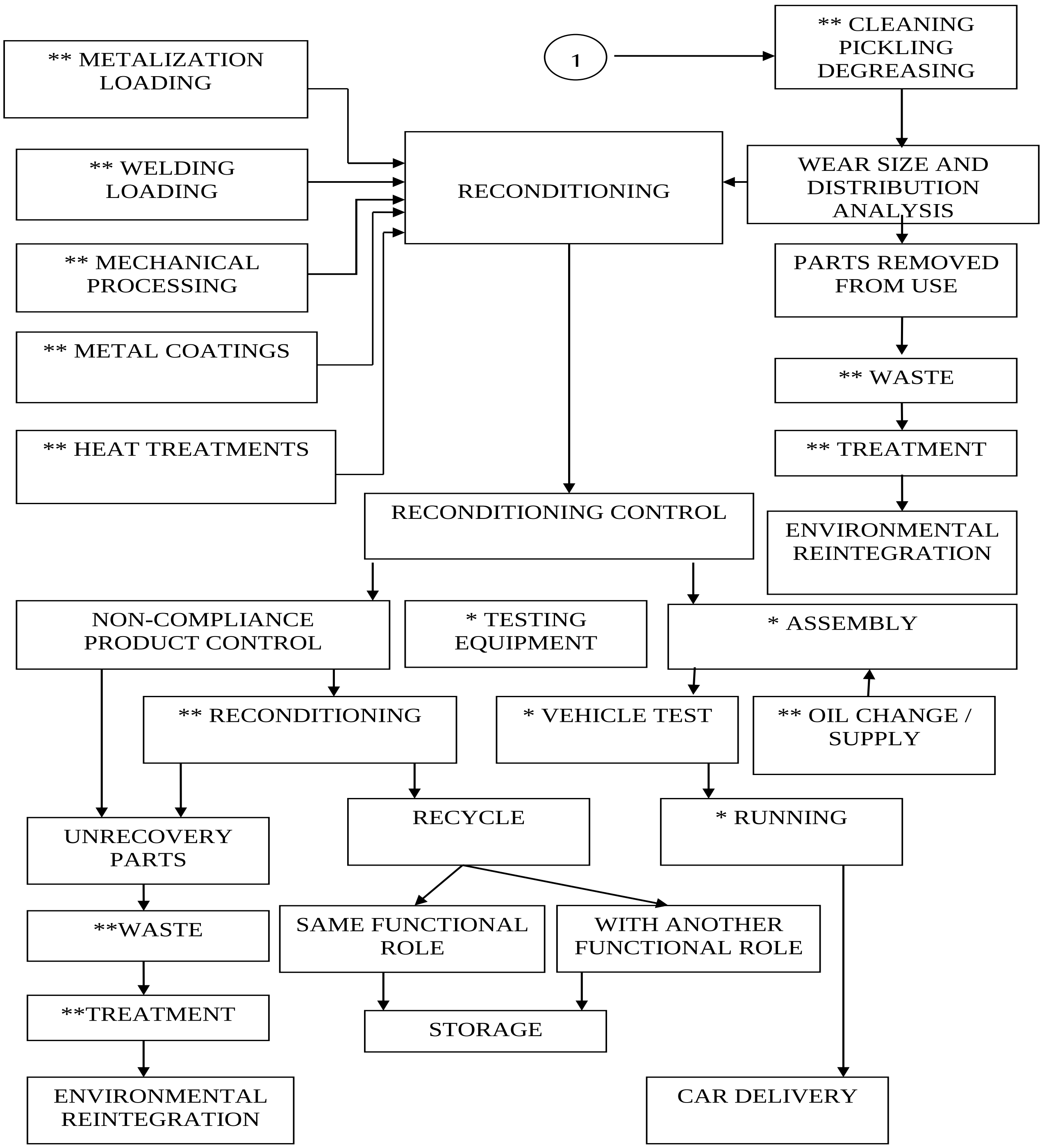


Fig. 2.3. Stages of the eco-maintenance process, adaptation of [7, 105]
* Low environmental impact ** High environmental impact

Flow chart of the ecotechnological process of mechanical repairs. The rational operation of motor vehicles requires the strict application of a plan of periodic preventive repairs. However, the experience gained during operation shows that the technical and economic indicators are directly influenced both by the way in which the repair plan is complied with and by the methods used in the repair and refurbishment operations.

The design of the repair plan is made according to the flow chart of the ecotechnological process of mechanical repair, presented in Fig. 2.4**.**

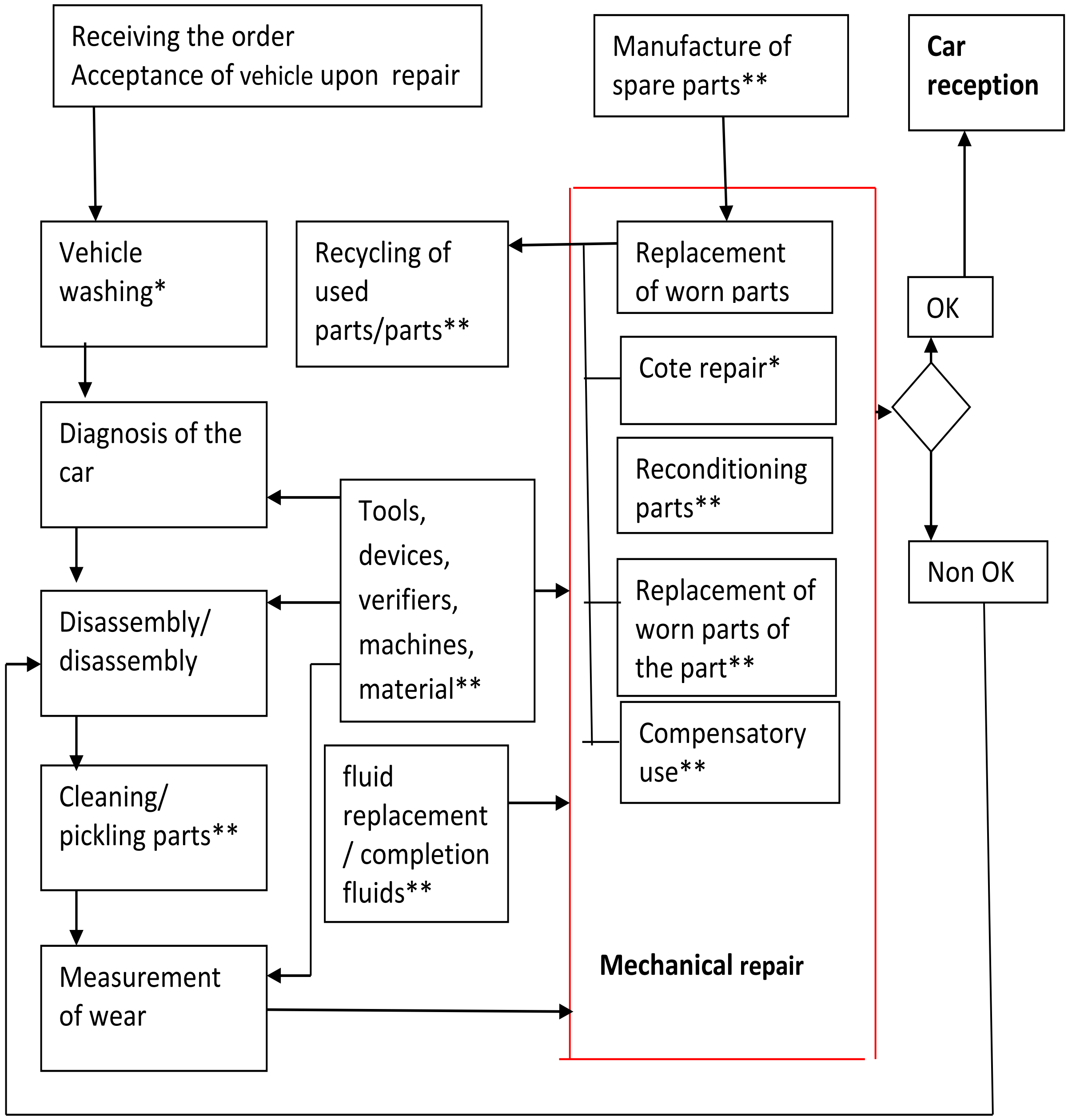


Fig. 2.4. Flowchart of the ecotechnological process of mechanical repair, adaptation from [7]
* Low impact on the environment ** Major impact on the environment

Flow diagram of the ecotechnological process of reconditioning by welding / metallization. Reconditioning, as part of the technological repair process, restores the operating characteristics and the initial dimensions of worn or damaged subassemblies and parts. By reconditioning, the considered mechanical system acquires the same functional characteristics (power, efficiency, emissions, etc.) as the new mechanical system [39].

Ecotechnology of reconditioning by welding load, represented by the logic diagram in Fig. 2.8, consists in depositing a layer of material by welding on the surface of a part in order to compensate for wear and restore the nominal dimensions of the part. Between the deposited layer and the part, the monolism is achieved through the continuity of the crystalline network, which is achieved either by melting or by pressure.

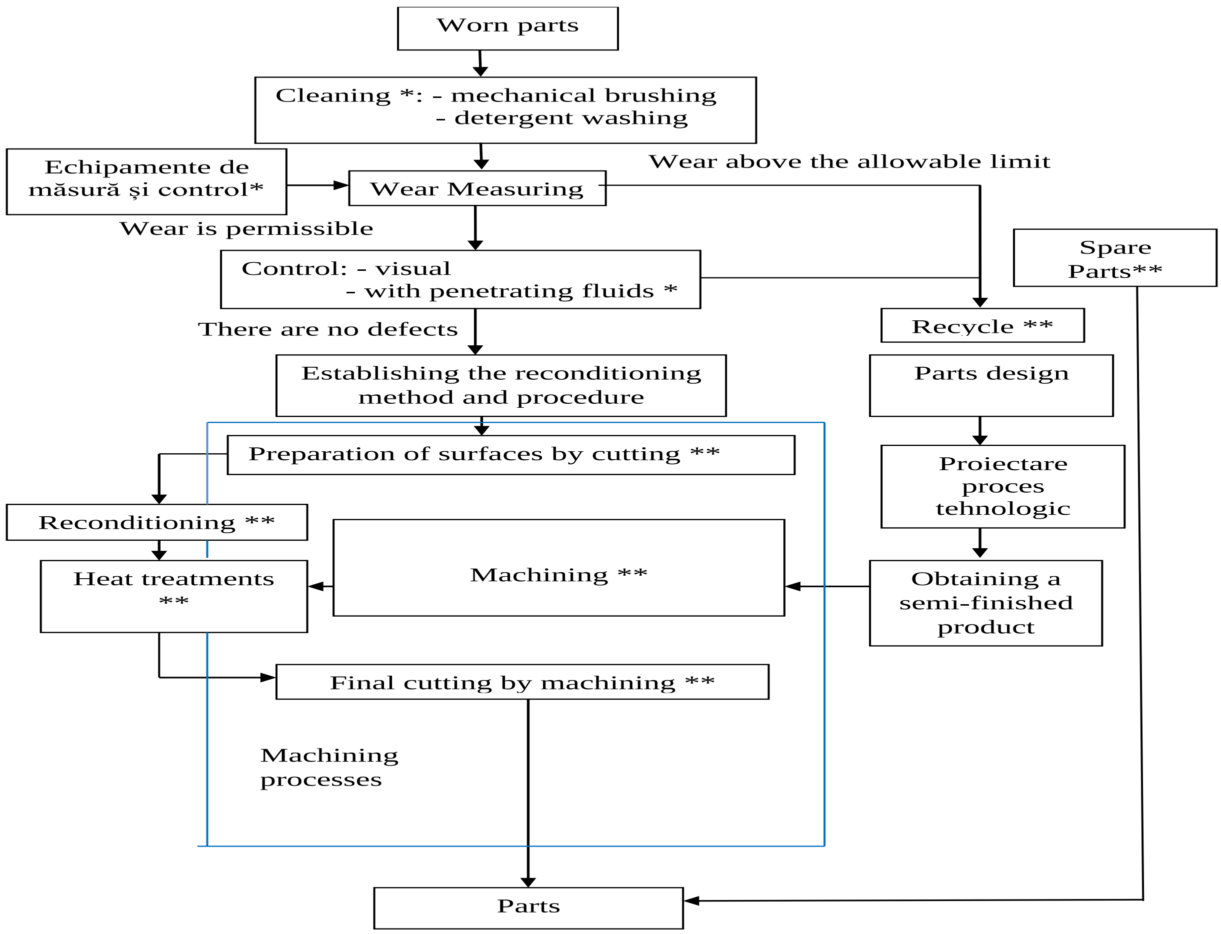


Fig. 2.8. Flow chart of the ecotechnological process of reconditioning by welding, adaptation of [6]
* Low impact on the environment ** Major impact on the environment

2.3. The ecological impact of vehicle maintenance

The end-of-life baseline scenario is based on estimates [127]. In summary, the data are presented in Table 2.20.

Tab. 2.20. End-of-life auto component material [127]

Materials	Reused [%]	Recycled [%]	Recovered [%]	Waste [%]
Ferrous metals	5	94	0	1
Non-ferrous metals	10	87	0	3
Plastic and polymers	1	0	0	99
Tires	21	0	66	13
Glass	0	0	0	100
Batteries	8	92	0	0
Fluids	29	71	0	0
Textiles	0	0	0	100
Rubber	0	0	0	100
Other	0	0	0	100

Chapter 3. Conclusions on the current state of research on vehicle maintenance in order to reduce the environmental impact

Periodic maintenance, as part of preventive maintenance, is based on the theory of reliability. Most studies consider the Weibull distribution law best describes the stages of life, early failures, useful life and aging, a repairable component, being used in the study of vehicle reliability. (see § 1.2).

Requirements for the design of a maintenance eco-process for motor vehicles (see § 2.1):

• promoting reconditioning;
• use of recyclable materials;
• reduction and capture of waste at source;
• minimizing material and energy inputs;
• modeling and balancing energy consumption;
• compliance with regulated environmental requirements.

Refurbishment, as part of the technological repair process, restores operating characteristics (power, efficiency, emissions, etc.) and the initial dimensions of worn or damaged subassemblies and parts. Reconditioning of parts by welding is one of the most common methods of reconditioning. If, at present, the refurbishment of car parts is no longer economically feasible, regulations and directions on sustainable development, reduction of resource consumption and the need to reduce the impact on the environment, can bring the refurbishment process back on track (v. § 2.2).

The ecological impact of maintenance is analyzed by studying three aspects (see § 2.3):

• necessary resources;
• efficiency of equipment;
• waste management.

Chapter 4. Directions, main objective and research and development methodology of the vehicle maintenance process in order to reduce the ecological impact

4.1. Research and development directions

Research and development directions regarding the maintenance process of vehicles in order to reduce the ecological impact:

• identification of different approaches to vehicle maintenance modeling in relation to availability, cost and environmental impact;

• analysis of the impact on the environment throughout the life cycle of vehicles;

• developing a model for reducing the impact on the environment through recycling and / or reconditioning;

• development of a modeling element regarding the optimization of the time between the periodic technical controls in order to maximize the availability of the vehicle;

• development of a modeling element regarding the optimization of the time between the periodic technical controls in order to minimize the maintenance costs;

• developing a mathematical decision model to study the relationship between the economic criterion and the ecological criterion on maintenance;

• identifying the potential to reduce the impact on the environment, implementing the documented measures of an environmental management system.

4.2. The main objective of the research-development activity

The main objective of the doctoral activity is the development of elements for modeling the periodic maintenance for vehicles with highlighting the aspects related to availability, cost and environment.

4.3. Research and development methodology

The study of the environmental impact of motor vehicles throughout the life cycle, as well as the analysis of the ecological impact of some elements used in the maintenance of motor vehicles will be performed by applying the simplified life cycle impact assessment method. This method uses 9 indicators from the Ecoinvent database. For these indicators, mathematical relationships will be formulated regarding each stage of the life cycle. The data processing will be done by using computer programs that will generate graphical statistical interpretations. The data on the environmental impact of components used in the maintenance and repair of motor vehicles will also be processed.

The case study involves an in-depth investigation of the maintenance of vehicle samples in organizational, technical and economic terms to look for (quantitative) models to streamline maintenance and repairs and to highlight the causes of inefficiency (qualitative). Maintenance planning is specific to the organization. Among the strengths of the opportunity to conduct this study we can list:

• homogeneous lots of vehicles considered;

• high market share of these types of vehicles;

• the existence of complex procedures regarding the maintenance of vehicles;

• carrying out maintenance in its own maintenance and repair shop;

• the existence of files regarding the maintenance history;

• the existence of several organizations that use very similar maintenance procedures.

The reduction of the ecological impact of vehicle maintenance by implementing the environmental management system will be based on the data represented by the answers to a questionnaire handed to 2 samples of companies, including 17 service providers in the field of car maintenance and repairs, in the Bucharest metropolitan area. period 2019-2021. The choice of the 17 service providers will take into account the contractual relations that the car park owner has for the maintenance of his vehicles. The 2 samples are differentiated by the fact that a first sample of 10 service providers has implemented at least one environmental management system, and the second sample, consisting of 7 service providers, only complies with the legislation. A number of questions will return qualitative records, and the others, for which grades will be required, will return quantitative records.

Chapter 5. Environmental impact study of motor vehicles

5.1. Environmental impact on the whole life cycle of vehicles

5.1.1. Vehicle life cycle

An own approach to the life cycle of vehicles, with emphasis on their operation is proposed in Fig. 5.1. This scheme highlights both the energy consumption in operation and the spare parts, materials and oil used in maintenance processes, be it preventive - according to the manufacturer's instructions or corrective. Reconditioning and recycling activities were highlighted.

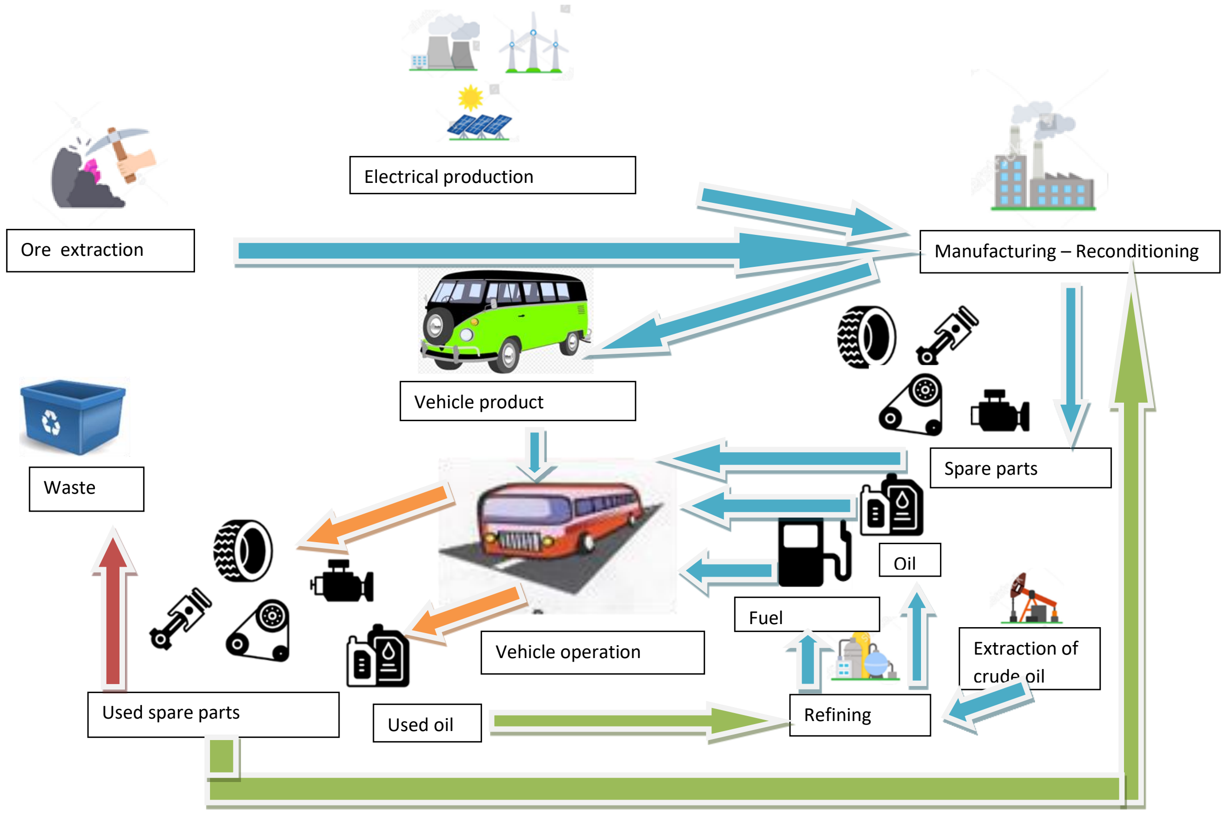


Fig. 5.1. Sketch of the life cycle of the vehicle

5.1.2. Ecological impact of the life cycle stages of motor vehicles

The major stages of the life cycle from ore extraction to decommissioning are shown in Fig. 5.2. Extraction and processing of raw materials, production of basic material, assembly process, use of the car, and recovery, recycling and disposal of materials are the steps considered, related to five main types of processes:

• Production of vehicles (including production of materials and assembly of the car);

• Crude oil exploitation and refining processes;

• Operating fuel consumption;

• Vehicle maintenance, production of spare parts and fluids used in maintenance operations (including tires, batteries, lubricants, refrigerant, etc.);

• Disposal and treatment of waste.

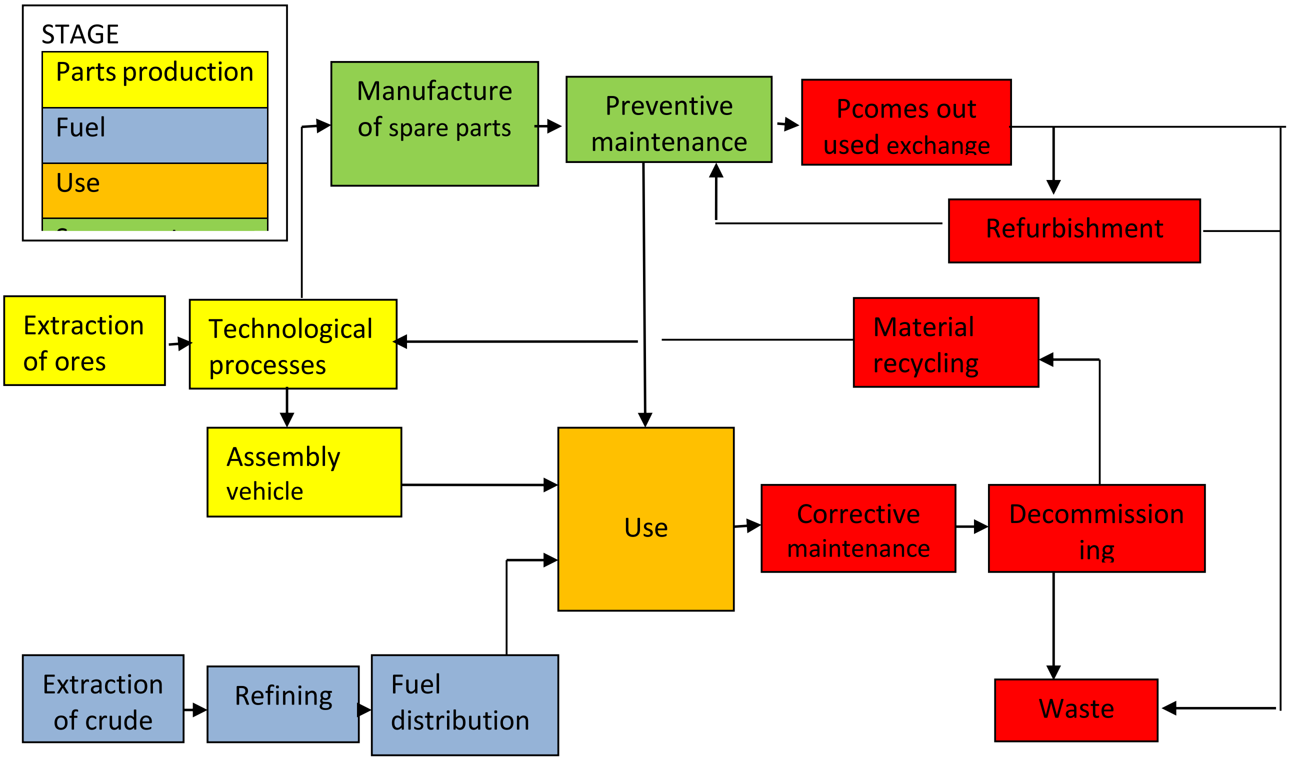


Fig. 5.2. Vehicle life cycle diagram

By covering all stages of a product's life cycle, the holistic approach allows quantification of the whole and the product. The impact on the environment is expressed in terms of agreed indicators, ex t CO_2 - equivalent for greenhouse gases, kg Sb - equivalent for abiotic depletion, etc. Data (see Table 2.11) and information (see § 2.3) were used, such as:

• the impact on the environment associated with the production of a certain unit (kg, MJ, etc.) of material or energy;

• use of materials and energy in the manufacture of a vehicle depending on its size or weight;

• use of spare parts (eg batteries, tires, lubricating oil, etc.) depending on the course of the vehicle;

• fuel consumption and pollutant emissions related to car use depending on specific conditions (eg urban, extra-urban, highway, etc.);

• the functional relationship between the weight of the car and the fuel consumption;

• recovery and recycling rate of metals and plastics.

The results of the environmental impact assessment throughout the life cycle of the vehicle are calculated by summing the values obtained from the databases consulted, at each stage of the life cycle and each impact factor, in relation to the total energy consumed over the life cycle.

Thus, if we talk about the environmental impact of the consumption of mineral resources, we will consider the production stage, the stage of use of the vehicle and the stage of production of spare parts. The mathematical expression propose in this case can take the form (5.1):

$$I_{AD} = I_{AD,PP} + I_{AD,C} + I_{AD;PS} \quad \text{[kg Sb-eq/GJ]} \qquad (5.1)$$

where: I_{AD} represents the coefficient of environmental impact of the depletion of resources throughout the life cycle; $I_{AD,PP}$ is the environmental impact factor in terms of resource depletion for the production stage; $I_{AD,C}$ represents the environmental impact factor in terms of oil depletion and $I_{AD,PS}$ is the coefficient of environmental impact in terms of resource depletion in the stage of manufacturing spare parts.

Similarly, the expressions for the environmental impact coefficients for global warming (5.2), ozone depletion (5.3), photochemical oxidation (5.4), acidification (5.5), eutrophication (5.6) and emission of microparticles (5.7) are proposed:

$$I_{GW} = I_{GW,PP} + I_{GW,C} + I_{GW;U} + I_{GW,PS} + I_{GW,EoL} \quad [\text{kgCO}_2\text{-eq/GJ}] \tag{5.2}$$

$$I_{ODP} = I_{ODP,PP} + I_{ODP,C} + I_{ODP,PS} \quad [\text{kg CFC 11-eq/GJ}] \tag{5.3}$$

$$I_{POCP} = I_{POCP,PP} + I_{POCP,C} + I_{POCP;U} + I_{POCP,PS} + I_{POCP,EoL} \quad [\text{kg C}_2\text{H}_4\text{-eq/GJ}] \tag{5.4}$$

$$I_{AP} = I_{AP,PP} + I_{AP,C} + I_{AP;U} + I_{AP,PS} + I_{AP,EoL} \quad [\text{kg SO}_2\text{-eq/GJ}] \tag{5.5}$$

$$I_{EP} = I_{EP,PP} + I_{EP,C} + I_{EP;U} + I_{EP,PS} + I_{EP,EoL} \quad [\text{kg PO}_4\text{-eq/GJ}] \tag{5.6}$$

$$I_{PM} = I_{PM,PP} + I_{PM,C} + I_{PM;U} + I_{PM,PS} + I_{PM,EoL} \quad [\text{kg /GJ}] \tag{5.7}$$

Another element of the environmental impact is the disposal of waste. In the manufacturing stages, in addition to the addition of remote processing, scrap also appears. The existence of waste at all stages of the life cycle except the use of the car can be described by the proposed mathematical relation (5.8):

$$I_D = I_{D,PP} + I_{D,C} + I_{D,PS} + I_{D,EoL} \quad [\text{kg/kg}] \tag{5.8}$$

The developed mathematical expressions 5.1 - 5.7 represent coefficients for the indicators of environmental impact as a ratio between the agreed pollutant emissions and the amount of energy consumed, and expression 5.8 represents the environmental impact coefficient of the waste throughout the life cycle as a ratio between the mass of waste and the total mass of components or fuel used in operation.

The impact on the whole life cycle was obtained by applying the above formulas to the available database mentioned in § 2.3. The results are summarized in Table 5.1. For each of the factors that contribute to the ecological impact, we can quantify the contribution of each stage.

Tab. 5.1. Quantitative analysis of the ecological impact on the stages of the life cycle

	Unit	Parts production	Fuel	Use	Spare parts	EoL Stage	TOTAL
Resource depletion	kg Sb - eq /GJ	0.158	0.0005	0	0.172	0	0.3305
Global warming	kg CO_2 - eq /GJ	4.5	8.05	45.05	0.45	0.1	58.15
Ozone depletion	kg CFC - eq /GJ	0.0002	0.0064	0	0.0001	0	0.0067
Oxidare fotochimică	kg C_2H_4 /GJ	7.3	28.15	21.5	1.9	0.02	58.87
Acidification	kg SO_2 - eq /GJ	45	100.05	14.95	2.55	0	162.65
Eutrophication	kg PO_4 - eq /GJ	4.9	8.7	3.4	0.25	0.03	17.28
Particle	kg / GJ	0.9	2.7	1.8	0.15	0	5.55
Primary energy	GJ / GJ	66.7	90.1	602.25	13.65	0.05	772.75
Waste	kg	353.3	197.3	0	16.85	293.4	860.85

A major impact on resource depletion is the spare parts manufacturing stage (52%). The production of spare parts is higher than that of finished products, in terms of production volumes and thus the amount of raw material used (Fig. 5.2). Speaking of global warming, the emission of exhaust gases in the use phase, contributes more than 77%. Upstream fuel is the second contributor due to the oil refining process (14%). The stage of the manufacturing process also has a significant contribution (Fig. 5.3).

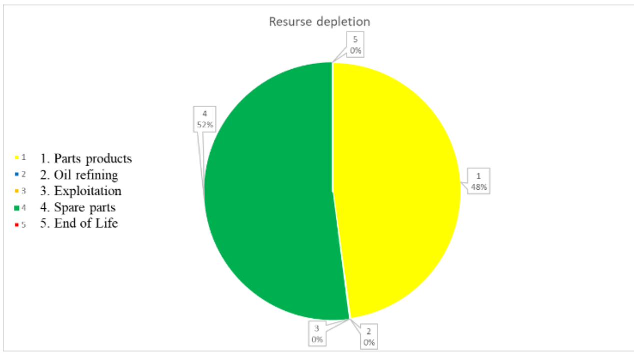


Fig. 5.2. The contribution of life cycle stages to resource depletion

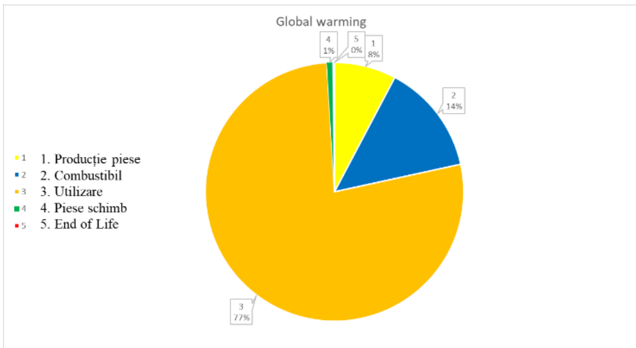


Fig. 5.3. The contribution of life cycle stages to global warming

5.2. Analysis of the ecological impact of some elements used in the maintenance of vehicles

The contribution to the environmental impact of the vehicle maintenance process, depending on the main elements (spare parts, tires, lubricants, batteries) was calculated and summarized in Table 5.3, based on the data mentioned in § 2.3 and those in Table 5.2.

Tab. 5.3. Percentage contribution, by categories of environmental impact, of some components used in the maintenance of motor vehicles

Impact category	Spare parts [%]	Batteries [%]	Engine oil [%]	Tires [%]
1	2.31	2.38	0.01	1.57
2	0.11	0.2	0.04	0.1
3	25.54	44.44	6.35	14
4	5.56	7.81	0.95	7.17
5	23.35	1.25	0.01	2.15
6	2.78	4.35	1.07	2.16
7	2.67	0.46	33.94	1.49
8	4.98	5.32	0	0.05
9	32.69	33.7	57.62	71.34

The graphs refer to 1 resource depletion, 2 global warming, 3 ozone depletion, 4 photochemical oxidation, 5 acidification, 6 utrophication, 7 particulate matter emission PM 2,5, 8 primary energy use and 9 resulting waste.

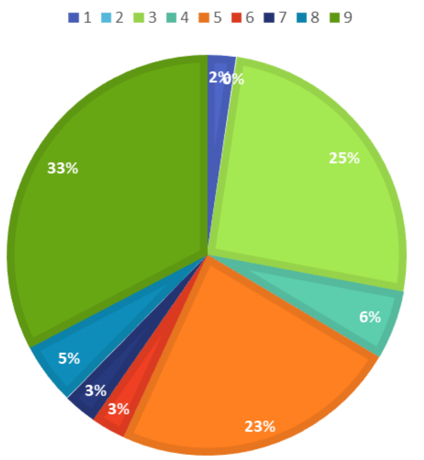


Fig. 5.15. Environmental impact of spare parts

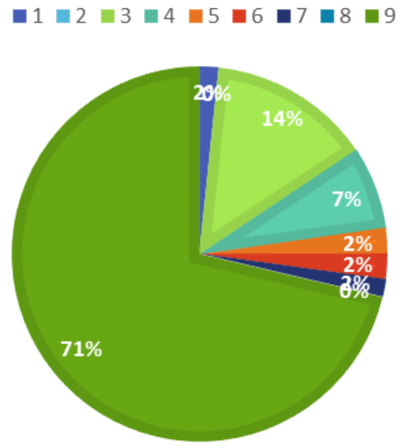


Fig. 5.16. Environmental impact of tires

5.3. Development of a modeling element to reduce the impact on the environment through recycling

Modeling to reduce the impact on the environment consists in analyzing the reuse in the manufacturing process of recycled materials. This approach makes the environmental impact of the LCA study to be complemented by the inclusion in the mathematical model of the recycling of materials collected for this purpose. Waste recycling and treatment scenarios are important parts of the LCA study. The limitations of the proposed system are related to the manufacture of several types of products through the same processes; manufacture of similar products by different technological processes; successive recycling, etc.

Consider the manufacture of a spare part for vehicles. This is often a subassembly of several parts of different materials. The impact on the environment of new raw materials is described in Equation (5.9):

$$EI_1 = \sum_{i=1}^{n} M_i \cdot I_{i1} \tag{5.9}$$

where EI_1 represents the total environmental impact of the production of new raw materials; My table is a component part of the spare part; I_{i1} represents the impact on the environment of the production of a spare part with material i, relative to its mass; i is the type of material that is part of the spare part, and n is the total number of materials used in the manufacture of the spare part.

If only recycled materials are used, the environmental impact is proposed to be described by equation (5.10):

$$EI_2 = \sum_{i=1}^{n} M_i \cdot I_{i2} \tag{5.10}$$

If new raw material can be used in the manufacture of the spare part in combination with recycled materials. The proposed equation (5.11) must take into account the meanings of the weights p_{i1} and p_{i2}, with the necessary adjustments.

$$EI_2 = \sum_{i=1}^{n} M_i \cdot (p_{i1} \cdot I_{i1} + p_{i2} \cdot I_{i2}) \tag{5.11}$$

where p_{i1} represents the percentage of virgin material, i, used in the manufacture of spare parts and p_{i2} represents the percentage of recycled material, i .

In this case, avoiding the negative impact of waste disposal by manufacturing another spare part of the same or different type from recyclable materials or energy recovery (energy production) takes the form of the relationship (5.13) describing the proposed modeling element [29]:

$$EI_A = \sum_{i=1}^{n} (M_i \cdot p_{i1}) \cdot (1 - r_i) \cdot (I_{i1} + I_{i2}) \tag{5.13}$$

where EI_A is the total impact on the environment avoided.

5.4. Development of a modeling element to reduce the impact on the environment through reconditioning

The development of the modeling element regarding the reduction of the impact on the environment consists in the analysis of the reconditioning of some parts in order to reuse them. The limits of the proposed system are related to the share of reconditioned parts relative to reconditioned parts; the diversity of technological reconditioning processes for the same type of parts; successive reconditioning, etc.

In the case of reconditioning the part, the impact on the environment is given by the impact on the environment given by the reused part of the reconditioned part, the impact on the environment given by the material used for reconditioning and the impact on the environment given by the reconditioning process. The impact on the environment given by the reused part of the reconditioned part is to be described by the expression (5.15):

$$EI_r = q \cdot M \cdot I_n \tag{5.15}$$

where: EI_n represents the total impact on the environment in the case of production of new raw materials; M is the mass of the component material of the part; I_n represents the coefficient of impact on the environment of the production of a part of the component material.

Parts reconditioning is only effective in reducing the impact on the environment if the relationship is met (5.18):

$$EI_n - EI_{rec} > 0 \tag{5.18}$$

In this case, the total impact on the environment avoided by reconditioning is given by the expression (5.19) which describes the proposed modeling element:

$$E_{evitat} = (1 - q) \cdot M \cdot \left(I_m + I_{proces} - I_n\right) \tag{5.19}$$

Chapter 6. Development of the vehicle maintenance process

6.1. Criteria for optimizing maintenance strategies

The following list of criteria can be used to optimize the maintenance process, as required:

- Maintenance cost;
- Availability;
- Maintainability;
- Risk of operational safety;
- Personnel management;
- Inventory of spare parts;
- Quality of maintenance;
- Number of vehicles under maintenance;
- Life cycle optimization;
- Logistics;
- Reliability;
- Effectiveness of the equipment used.

The effectiveness of periodic technical inspections, in addition to the manufacturer's recommended overhauls, is assessed by their costs in relation to their number. Mathematical models are proposed for the calculation of maintenance indicators for a Weibull distribution of time to failure. The aim is to reduce the costs associated with maintaining the availability of vehicles in service.

6.2. Elements of modeling the cost of the preventive maintenance process

The results of the periodic technical inspections are divided into the following four categories:

- n_1 cases where there are symptoms of degradation or failure and are likely to be detected p_1;
- n_2 cases where there are symptoms of degradation or failure but are not detected, so failure is likely to occur p_2;
- n_3 cases where the vehicles are in a normal state, and the CTP indicates this result, with probability p_3;
- n_4 in cases where the vehicle is in a normal condition, but CTP indicates damage or symptoms of failure (false alarm), most likely p_4.

If the vehicle is damaged in time τ, $\tau \in (k\Delta t, (k+1)\Delta t]$, then *p1* , according to the Weibull distribution law, for the introduction in the maintenance, the probability p_1 becomes the rate (intensity) of failure, corrected with probability p_{ctp} is described by the proposed function (6.8):

$$p_1 = Z(\tau) = \frac{\beta}{\eta} \cdot \left(\frac{\tau - \alpha}{\eta}\right)^{\beta - 1} \cdot p_{ctp} \tag{6.8}$$

where: τ is a time parameter, β is a shape parameter that models the shape of the curves of the failure intensity graphs, calibrating the behavior of vehicles at different times in the life of parts, subassemblies (constant at intervals) and η scale parameter which graphically, adjusts its length in relation to the time of distribution of the Weibull law (constant). The probability of p_{ctp} is an average value that takes into account the facilities of the workshop where the control is performed and the competence of the staff involved in this activity.

Probabilities p_2 , p_3 and p_4, is calculated with the proposed functions (6.9), (6.10) and (6.11).

$$p_2 = \frac{\beta}{\eta} \cdot \left(\frac{\tau - \alpha}{\eta}\right)^{\beta - 1} \cdot (1 - p_{ctp}) \tag{6.9}$$

$$p_3 = \left(1 - \frac{\beta}{\eta} \cdot \left(\frac{\tau - \alpha}{\eta}\right)^{\beta - 1}\right) \cdot p_{ctp} \tag{6.10}$$

$$p_4 = \left(1 - \frac{\beta}{\eta} \cdot \left(\frac{\tau - \alpha}{\eta}\right)^{\beta - 1}\right) \cdot \left(1 - p_{ctp}\right) \tag{6.11}$$

In order to highlight CTP, depending on the cost of maintenance, the following will be considered:

• time when the vehicle was immobilized due to lack of spare parts or place at the checkpoint, T_d
• average time the vehicle was repaired, t_{rc} , constant
• time during which the vehicle was periodically checked, t_{ctp} , constant

The problem of determining the cost of a CTP depends on their number, denoted by N. The average maintenance cost [31] is calculated in this case with the expression developed (6.12):

$$\begin{aligned} C_M = N \cdot \{ & p_1 \cdot \left[t_{ctp} \cdot c_{ctp} + t_{rc} \cdot c_{rc} + \left(t_{ctp} + t_{rc}\right) \cdot c_{inl} + \left(t_{ctp} + t_{rc}\right) \cdot c_i + C_{ps}\right] \\ & + p_2 \cdot \left[t_{ctp} \cdot \left(c_{ctp} + c_{inl} + c_i\right) + t_{rc}(c_{rc} + c_{inl} + c_i) + C_{ps}\right] \\ & + p_3 \cdot t_{ctp} \cdot \left(c_{ctp} + c_{inl} + c_i\right) \\ & + p_4 \cdot \left[t_{ctp} \cdot c_{ctp} + t_{rc} \cdot c_{rc} + \left(t_{ctp} + t_{rc}\right) \cdot c_{inl} + \left(t_{ctp} + t_{rc}\right) \cdot c_i\right]\} + T_d \cdot c_{inl} \end{aligned} \tag{6.12}$$

where: c_{ctp} is the cost of labor per unit time of the periodic check; c_{rc} is the cost of labor per unit time of repair; c_{inl} is the cost per unit time of vehicle replacement; c_i is the cost per unit time of the organization's management and C_{ps} is the average cost of spare parts per repair, values considered constant.

6.3. Elements of modeling the availability of the vehicle in the conditions of preventive maintenance

The models taken into account by preventive maintenance, studied so far, do not take into account the probabilities of correct and incorrect decisions taken by the results of periodic inspections (CTP). The objective is to develop a model for determining the optimal periodicity of CTP, in terms of maximizing the availability of the vehicle.

Maintenance decisions - true decisions (TD) or false decisions (FD) are made based on the professional experience of the decision maker, depending on the condition of the vehicle, which may be in the following situations:

• S1: $B\text{-}A(k\Delta t)=x_k\leq 0$, the correct decision - the vehicle enters maintenance operations (TD)

• S1: $B\text{-}A(k\Delta t)=x_k\leq 0$, the right decision - the vehicle enters maintenance operations (TD)
• S2: $B\text{-}A(k\Delta t)=x_k\geq 0$ and $B\text{-}A((k+1)\Delta t=x_{k+1}\leq 0$, the decision in conditions of uncertainty, the vehicle enters maintenance operations (TD)
• S3: $B\text{-}A(k\Delta t)=x_k\geq 0$ and $B\text{-}A((k+1)\Delta t)=x_{k+1}\leq 0$, the decision in conditions of uncertainty, the vehicle is waiting for the next one CTP (FD)
• S4: $B\text{-}A(k\Delta t)=x_k\geq 0$ and $B\text{-}A((k+1)\Delta t)=x_{k+1}\geq 0$, the decision in conditions of uncertainty, the vehicle enters maintenance operations (FD)
• S5: $B\text{-}A(k\Delta t)=x_k\geq 0$ and $B\text{-}A((k+1)\Delta t)=x_{k+1}\geq 0$, the decision in conditions of uncertainty, the vehicle is waiting for the next CTP (TD)

The likelihood of correct or incorrect decisions depends largely on the diagnostic capabilities of the control devices and the competence of the workers performing the CTP. In order to try to model predictive maintenance for technically inspected vehicles on a regular basis, decisions leading to the introduction of vehicles for repair are useful. The likelihood of a decision to bring vehicles into repair is determined by the development (6.16):

$$P_R = \frac{n_1 + n_2 \cdot p_2 + n_3 \cdot (1 - p_3)}{n_1 + n_2 + n_3} = \frac{n_1 + (n_2 + n_3) \cdot p_2}{N} \tag{6.16}$$

The probability that the vehicle will continue to be used is determined in accordance with the assumption described by (6.14) and takes the form of the expression (6.17):

$$P_D = \frac{n_2 \cdot (1 - p_2) + n_3 \cdot p_3}{n_1 + n_2 + n_3} \tag{6.17}$$

The problem of determining the optimal number of predictive checks (CTP) based on the availability criterion, denoted by *N*, depends on the selected optimization criterion. In order to highlight the CTP, in relation to the time of unavailability, it is composed of:

• time during which the vehicle was immobilized as out of use, T_d
• average time during which the vehicle was repaired, t_{rc}
• average time of planned revisions, t_{pm}
• time during which the vehicle was periodically checked, t_{ctp}

When the observation is made at time intervals, given by the periodicity of CTP, (1.21) it takes the form of the developed expression (6.18):

$$D = \frac{T - \{T_d + \left[n_1 + (n_2 + n_3) \cdot p_2\right] \cdot t_{rc} + r \cdot t_{pm} + N \cdot t_{ctp} \}\big)}{T} \tag{6.18}$$

Deriving as a function of *N*, we obtain the derivative relation (6.21) :

$$\frac{\partial I}{\partial N} = \frac{\partial [n_1 + (n_2 + n_3) \cdot p_2]}{\partial N} t_{rc} + t_{ptc} \tag{6.21}$$

The solution is obtained (6.26):

$$N_{opt} = \frac{t_{ctp}}{\left(1 - \frac{\beta}{\eta} \cdot \left(\frac{\tau - \alpha}{\eta}\right)^{\beta - 1}\right) \cdot t_{rc}} \tag{6.26}$$

where N_{opt} is the optimal number of CTP [30] at the time of operation τ.

6.6. Decisions to optimize preventive maintenance activities

The proposed decision model is the ELECTRE multicriteria decision model.

In order to optimize the maintenance activity, the following 5 periodic maintenance strategies are proposed:

• V1 - periodic maintenance with monthly technical control;

• V2 - periodic maintenance with minimal costs;

• V3 - periodic maintenance with maximum availability;

• V4 - periodic maintenance through revisions specified in the manufacturer's technical book;

• V5 - periodic maintenance with minimal impact on the environment.

The criteria that characterize the above proposed variants are:

• C1 - total maintenance cost / no. motor vehicles of the same type;

• C2 - amount of waste and polluting emissions / no. motor vehicles of the same type;

• C3 - value of investments / total number of vehicles;

• C4 - volume of reconditioned, reused and recycled or regenerated parts;

• C5 - use of modern eco-technological processes;

• C6 - volume of spare parts;

• C7 - the amount of oil used

Chapter 7. Case study on elements for optimizing the maintenance process for vehicles

7.1. The characteristics of the fleet of vehicles under maintenance

Statistical data were obtained by analyzing two samples of cars with different characteristics.

A first sample of 50 cars of the same manufacturer, the same models, with the years of construction and commissioning 2005 (25 cars lot 1) and the rest in 2007 (lot 2) consists of sedan cars, powered by Otto engines, with Euro4 pollution norm. Of the vehicles manufactured in 2005, 3 were taken out of service after 13 years, 10 after 14 years and of those manufactured in 2007, 2 were withdrawn after 12 years. The average lifespan is currently estimated at 13 years and an average mileage of 312,000 km.

A second sample consists of 51 4x4 cars, with the year of manufacture and commissioning of 2014, powered by diesel engines, with Euro5 pollution norm. The average lifespan is currently estimated at 12.5 years and the initial estimated average mileage of 450,000 km. So far (May 2021), they have an average distance of 197,000 km.

7.2. Significant data regarding the organization where the maintenance activity is performed

The transport department provides the means of transport necessary for the proper conduct of the institution's specific activities and through the maintenance and repair service. The car repair and maintenance workshop, based on the act of carrying out the testing and technical analysis activities, is authorized by the Romanian Car Registry, according to the regulations. There are separate ramps and flows for:

• periodic technical inspections;

• repairs of defects signaled by the driver or detected during periodic technical inspections;

• predictive repairs based on the analysis of data obtained from periodic inspections;

• periodic technical inspection, regulated by regulations in force.

7.3. Elements for optimizing the periodicity of periodic technical inspections according to the criteria of vehicle availability

The statistical approach in calibrating the model developed in paragraph §6.3, respectively the relation (6.26), took into account the life stages of the vehicles. For sedan cars, the following data was obtained:

• periodicity of the Monthly Technical Control, with the acronym CTP, monthly
• periodicity of RT-2, considered as Annual Technical Revision, annually or at 10,000 km covered for the 2005 batch and 15,000 km for the 2007 batch and for the SUV batch. RT-2 was intended to coincide with the monthly technical inspection.
• average CTL time is 2 hours, $t_{ctp}=2$ *hours*
• average time of RT-2 is 4 hours, $t_{pm}=4$ *hours*

The input data, collected from the file on the maintenance history of each vehicle are summarized in Table 7.1.

Tab. 7.1. Input statistics data for model calibration - sedan cars

Considered period	Life stage	N	n_1	p_1	n_2	p_2	n_3	p_3
1	Early falls	6	2	1	1	0,7	3	0,3
2	The rest of the first standard life	54	2	1	32	0,8	20	0,2
3	Second standard life	60	4	1	28	0,75	28	0,25
4	The aging period	36	15	1	18	0,66	3	0,34

The optimal total number of CTP revisions depending on the operating time is graphically illustrated in Fig. 7.1.

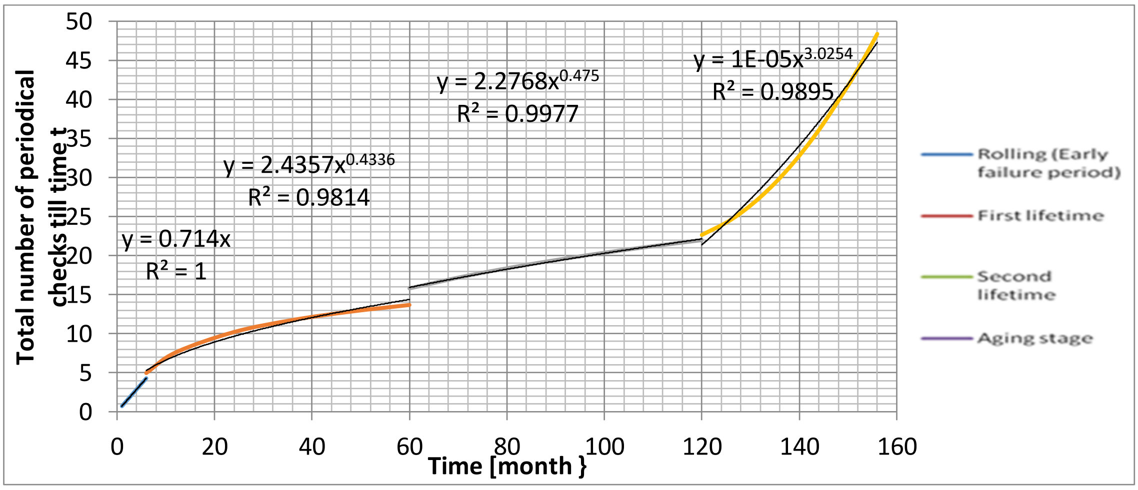


Fig. 7.1. Variation of the optimal total number of CTPs at time *t*, for sedan

Calibrate the function containing maintenance modeling elements for the park owned under the conditions of its specific operation and obtain the values of β and λ for the stages of the operation cycle:

$\beta_1=2;\ \beta_2=1,48;\ \beta_3=1,48;\ \beta_4=4,03$

$\lambda_1=0,36;\ \lambda_2=1,65;\ \lambda_3=1,54;\ \lambda_4=2,48x10^{-6}$

7.4. Elements for optimizing the periodicity of periodic technical inspections according to the criterion of the cost of vehicle maintenance

In addition to the statistical records used previously, cost elements have been added:

• cost of labor per time unit (hour) of the periodic check c_{ctp} = *50 u.m.;*
• cost of labor per time unit of repair c_{rc} = *50 u.m.;*
• cost per time unit of vehicle replacement c_{inl} = *12,5 u.m.*;
• cost per time unit of the organization's management c_i = *9 u.m.*;
• average cost of spare parts per repair C_{ps} = *157 u.m.*.

The input data are summarized in Table 7.3.

Tab. 7.3. Input statistics data for cost model calibration for sedans

Considered period	Life stage	N	n_1	n_2	n_3	n_4
1	Early falls	6	3	1	1	1
2	Exploitation stage	114	28	61	19	14
3	The aging period	36	25	8	2	1

In this case, from the graphical interpretation of the information collected experimentally, by simplifying (6.13) to form (7.2) the Weibull parameters $K\beta$ and λ were determined by the *add trendline* function of the graphics editor, specifying the function and the degree of concordance, *R*.

$$\frac{C_M}{N}(t) = K \cdot \beta \cdot \lambda \cdot t^{\beta-1} \tag{7.2}$$

where: *K* is a correction factor that takes into account the time and cost values specific to the maintenance of the vehicles in this case study.

The estimate of the average cost of maintenance during periodic technical inspections, CTP, is illustrated in Fig.7.3. The values of the obtained parameters are:

$\beta_1=1,13;\ \beta_2=0,99;\ \beta_3=1,67$

$K\lambda_1=561;\ K\lambda_2=498;\ K\lambda_3=12043$

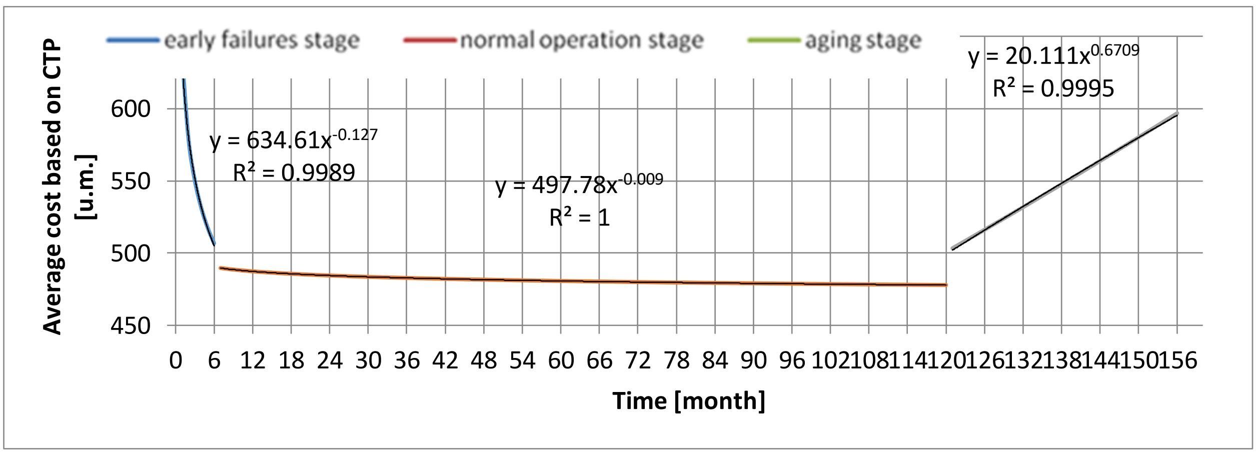


Fig. 7.3. Estimation of the average cost of maintenance during CTP controls

Chapter 8. Reducing the ecological impact of vehicle maintenance by implementing the environmental management system

This research was conducted in the Bucharest metropolitan area, in the period 2019-2021.

The choice of the 17 service providers in the field of car maintenance and repairs was made taking into account the contractual relations that the car park owner has for the maintenance of his vehicles.

A significant improvement in waste treatment and disposal was observed in units that implemented environmental management systems. Fig. 8.5. represents the weighted average of compliance with certain requirements in the environmental impact assessment. A high average is higher in terms of environmental concerns.

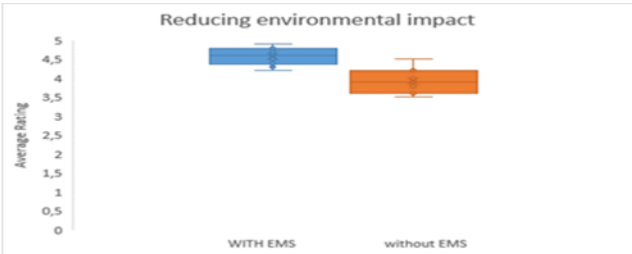


Fig. 8.5. Comparative analysis between types of workshops on the potential for reducing environmental impact

The results of the study showed that in terms of legal regulations related to the environment, 59% of employees attended formal training courses, of which 87.5% came from services that had implemented at least one environmental management system.

The differences can be explained by the two-way link between the allocated budget and the company's ability to cope with environmental issues, including the accreditation of a management system. Fig. 8.6. illustrates the share by service categories of the allocated environmental budget.

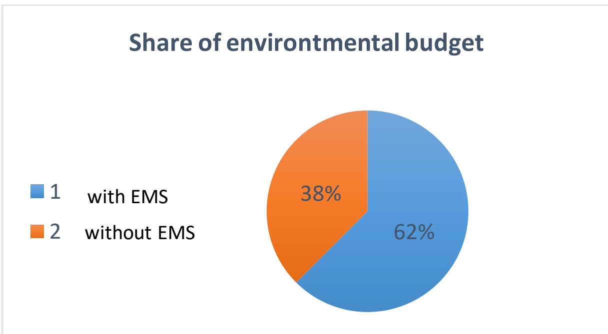


Fig. 8.6. The share of the environmental budget according to the type of service analyzed

Respondents estimated that the financial allocations for environmental protection are 63% higher for companies that have implemented an environmental management system. However, the environmental budget is underestimated compared to what is needed. There are at least two reasons for this discrepancy: the obsession with the profitability of most multi-brand services and the social responsibility of car dealers, based on considerably larger total budgets.

Chapter 9. Final conclusions and main contributions to development of the vehicle maintenance process in order to reduce the ecological impact

In view of the data and conclusions from the analysis of the current state of research on vehicle maintenance in order to reduce the environmental impact, the research and development directions regarding:

• analysis of the environmental impact on the whole life cycle of motor vehicles and spare parts used in the maintenance of motor vehicles

• formulation of mathematical models for streamlining the periodic technical controls

• designing a multicriteria economic-ecological decision model.

Based on the pollution coefficients, the ecological impact of the vehicles on the stages of the whole life cycle was synthesized by the type of effects studied: depletion of resources, global warming, ozone depletion, photochemical oxidation, acidification, eutrophication, material particles, primary energy and waste. For a suggestive image, the results were presented graphically (see § 5.1).

Using the coefficients of pollution, the pollutant emissions and the resulting waste determined by the replacement of the main components considered were determined: lubricants, spare parts (brake elements, clutch, joints, suspensions), tires and batteries. Based on the results obtained, the impact on the environment of the components used during the total operation was determined. For a suggestive image, the results were presented graphically (see § 5.2).

The theoretical assessment of the environmental impact of reconditioned / recycled components took into account the share of the mass of materials from which they are made by recycling (see § 5.3) or by reconditioning (see § 5.4).

Optimizing maintenance against unique criteria is unproductive because they depend on each other, influencing each other. This problem is solved by adopting a number of criteria and performing a multi-criteria optimization. Criteria such as maintenance cost, vehicle availability, spare parts inventory, staff training are analyzed in § 6.1.

The effectiveness of periodic technical inspections, in addition to the manufacturer's recommended overhauls, is assessed by their costs in relation to their number. Mathematical models are proposed for the calculation of maintenance indicators for a Weibull distribution of time to failure. The novelty is the introduction of probabilities related to the moment of detection of symptoms of degradation or failure depending on the planning of technical controls, making through this new approach a theoretical estimate of maintenance costs for technically controlled vehicles periodically. The introduction of a probability of a good diagnosis is related both to the endowment of the service with high-performance equipment and, above all, to the professionalism of the diagnostic and maintenance team (see § 6.2 and § 6.5.1).

The case study involved investigating the maintenance of vehicle samples in organizational, technical and economic terms to look for (quantitative) models for streamlining maintenance and repairs and to highlight the causes of (qualitative) inefficiency. The case study was carried out on the basis of the data contained in the files on the maintenance and repair history and the data entered in the roadmaps for the vehicles in the 3 homogeneous lots considered. The obtained results were compared with our own theoretical development based on the Weibull distribution law of the failure rate of some mathematical models that describe the efficiency of the number of periodic technical inspections depending on the cost of maintenance (see § 6.5.1) and the availability of vehicles (see § 6.5.2).

Reducing the environmental impact of vehicle maintenance operations by implementing an environmental management system was analyzed by a comparative study between a reference sample, consisting of maintenance and repair shops that did not have a management system and the target sample , consisting of organizations that had implemented at least one integrated quality management system, based on an original questionnaire on environmental management and how to manage waste. A management system involves identifying the key points of the system and its cyclical-permanent improvement based on the Deming cycle, thus explaining the potential to reduce the environmental impact of organizations that plan their business (see § 8).

The partial results were drafted as scientific papers and were presented as follows:

• The article "Environmental impact assessment regarding predictive maintenance operations for passenger cars based on spare parts life cycle" [29] was presented as a co-author at the IBIMA International Conference held in Madrid in 2019. The volume of articles is indexed by Thomson Reuters (Web of Sciences) since 2006.

• The articles "Periodic control optimization according to availability for vehicles" [30] and "Theoretical estimation of maintenance costs for periodically controlled vehicles" [31] were presented at the COMEC International Conference, organized by the University of Brașov in 2019. The articles presented are published the volume of the conference, BDI listed publication.

• Article "Reducing the environmental impact of vehicle maintenance activities by implementing an integrated quality-health-environment management system. A comparative analysis. " is accepted for publication in the Scientific Bulletin - PUB, indexed by ELSEVIER.

Theoretical contributions

• The life cycle of vehicles is analyzed, with an emphasis on maintenance in operation, in the light of the quality characteristics of the car manufacturing industry and the current trends in repair-reconditioning and manufacturing of spare parts.

• A development of some elements of modeling of the impact on the environment on the whole life cycle of the vehicles is realized and the obtained results are synthesized.

• A theoretical analysis is performed regarding the criteria for optimizing the maintenance strategies and mathematical modeling elements of the cost, availability and ecological impact of the maintenance activities of the vehicles are developed.

• Based on the developed modeling elements, vulnerabilities are identified and following a multicriteria analysis, described, optimization decisions can be made.

Practical contributions

• The results obtained were theoretically applied to an organization with its own fleet and car maintenance and repair workshop, in order to calibrate the modeling elements developed.

• The reduction of the impact on the environment is also analyzed through the implementation of an integrated quality management system - health and safety at work - environment.

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