“POLITEHNICA” UNIVERSITY of BUCHAREST

The Faculty of ENGINEERING AND MANAGEMENT OF TECHNOLOGICAL SYSTEMS

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PhD THESIS

SUMMARY

Models of Analysis and Prevention in Proactive Maintenance

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INTRODUCTION

In the current context of the tendency towards globalization and the expansion of the competitive market, an important part is played by the deepening of the concern to implement quality management and the availability of industrial products.

In this case, it is advisable to ensure the quality of manufacturing activities by the existence of highly accurate and productive work equipment. Manufacturing activities must be carried out continuously, which requires the existence of industrial equipment which ensures a continuous operation and the lowest downtime possible in the event of a failure.

As an important element of the manufacturing process, maintenance must be highly qualitative or else decreased manufacturing productivity and inadequate economic and financial effects may occur.

Considering the new quality requirements and the European directives on machine and equipment safety, it is deemed important to approach machine and equipment availability issues (reliability and maintainability) which can settle numerous concerns of manufacturing.

Chapter I, titled THE CURRENT STAGE OF RESEARCH IN INDUSTRIAL EQUIPMENT MAINTENANCE, succinctly reviews the current research and trends in industrial equipment maintainability based on the studied bibliography. After presenting the concepts of product, product quality and life cycle, the author analyzes the place, role and significance of industrial maintenance activities and equipment availability. In this sense, the chapter briefly presents the concepts and parameters of industrial product maintenance and carries out an analysis of the predominantly applied types of industrial maintenance in modern industry. Considering the consequences of low industrial equipment maintenance, an important role is played by the technical and economic assessment viewed in terms of determining the specific indexes, respectively technical, economic and time indexes. By assessing the status of the equipment, in the event of failure, final decisions concerning the optimal time for equipment replacement can be taken at an organizational level.

Chapter II, titled OBJECTIVES OF THE PhD THESIS, summarily analyzes the main current trends, as they result from the bibliographical research carried out.

After pointing out the main approaches in current research, the author presents the aspects to be researched in the thesis, which will cover some of the less approached aspects, as they may become important and representative in the field of the PhD thesis.

Chapter III, titled THEORETICAL DEVELOPMENTS AND CONTRIBUTIONS TO THE STUDY OF MAINTENANCE POLICIES AND STRATEGIES, covers the theoretical analysis of aspects concerning maintenance policy models, economic aspects of the implementation of corporate maintenance management, respectively devising maintenance analysis and optimization programs. This chapter includes a comparative analysis of three maintenance policy models based on operational research methods, respectively the Markov chain theory. The economic strategies used in maintenance management analyze the cost assessment criteria based on time, expansion area, origin, maintenance type and purpose. Moreover, the economic method for determining the optimal maintenance method is analyzed based on the comparison of average prices per time unit. Furthermore, the research graph is presented for optimizing the maintenance method concerning personal and equipment security. As there are numerous methods for carrying out maintenance, subchapter 3.3 briefly analyzes their principles in view of their practical application in corporate activities. At the same time, the author develops stochastic processes for the study of industrial equipment maintenance in two cases, respectively independent processes and Markov chain processes. A significant contribution of the author is the drafting of specific maintenance documents, which may represent models for other organizations as well.

Chapter IV, titled PRACTICAL DEVELOPMENTS AND CONTRIBUTIONS. CASE STUDY includes analyses and developments on the establishment of human resource requirements for the maintenance activity which uses operational research methods – the Markov chain theory, respectively practical developments regarding the establishment of material resources for the maintenance activity. From this chapter stands out the case study carried out with the contribution of the author, concerning the drafting of an econometric model of the dynamics of flight hours for a Cessna 172S airplane owned by the Higher Civil Aviation School. The performed practical study demonstrated the reliability of the model, from which resulted that maintaining an optimal level of airplane maintenance expenses leads to an increase of flight hours.

Particularly interesting are the analysis, developments and contributions referring to the implementation of modern methods and techniques used in the proactive maintenance of industrial equipment. In this case stands out the method of approaching the proactive maintenance of industrial equipment according to the conditions for the occurrence of disruptive factors and the causes of industrial equipment failure.

Chapter V, titled PERSONAL CONTRIBUTIONS. FUTURE DEVELOPMENTS AND MEANS OF CAPITALIZING THE RESULTS OF THE RESEARCH, synthesizes the findings resulted based on the research carried out and the developments contributed by the author throughout the thesis, and emphasizes several future directions and approaches in the studied field.

CHAPTER 1

THE CURRENT STAGE OF RESEARCH IN INDUSTRIAL EQUIPMENT MAINTENANCE

1.1. The concept of product and the life cycle stages of industrial products

In the normal operation period, industrial products are exploited and used according to legal provisions in which the product capitalizes on its features in their life cycle stages.

It is noted that, to reach the final manufacturing objective, respectively **the product**, a correlation such as DEMAND – PRODUCT – QUALITY – EVOLUTION may be taken into consideration. As described in standard SR EN ISO 9000:2015, **the product is the result of a process** carried out in a manufacturing system in which the activities are correlated.

According to the aforementioned standard, the **process** is the “set of interrelated or interacting activities that use inputs to deliver an intended result.”

The life cycle stages of industrial products include the following aspects: conception, design-manufacturing, exploitation and service, as illustrated in fig. 1.1.

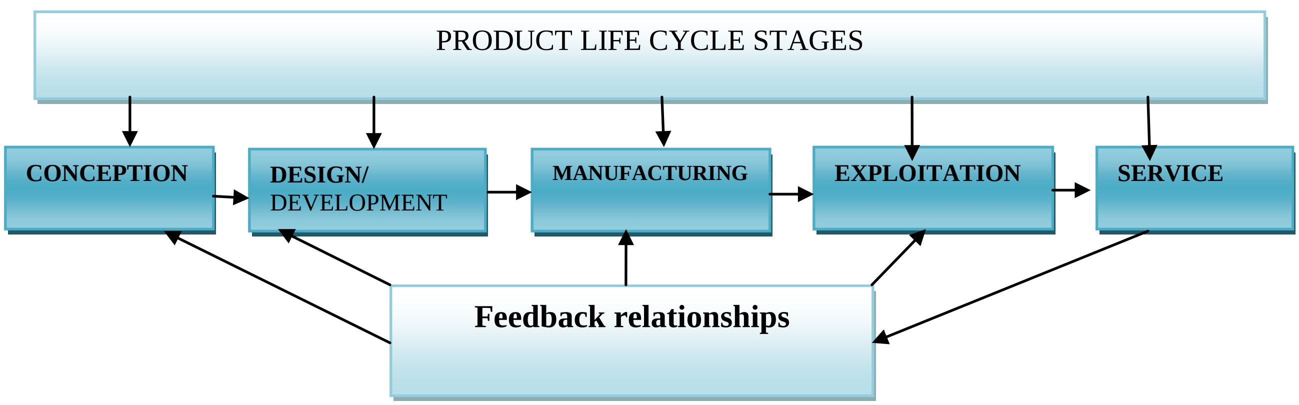

Fig. 1.1 Product life cycle stages

It is assessed that quality assurance is carried out in the manufacturing process and expressed in the client’s exploitation process, in which the correlation between quality and the manufacturing cycle is that presented in fig. 1.2.

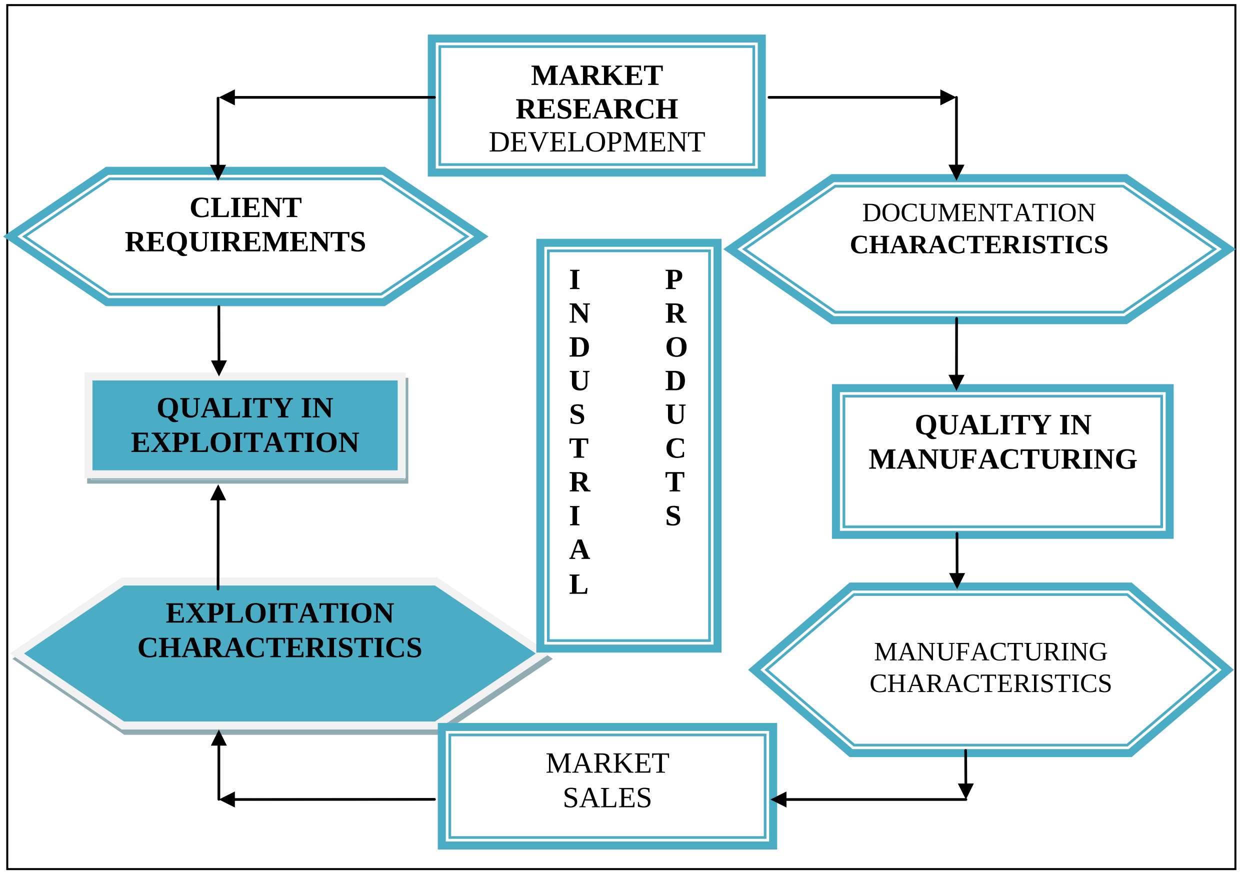

Fig. 1.2. Correlation between the quality of industrial products and the manufacturing cycle

These activities require the existence of a certain corporate organization for the purpose of determining the aforementioned relations, in conformity with the quality spiral suggested by J.M. Juran and specified in works [42, 46], which includes the following:

- research;
- conception, design;
- drawing up specifications;
- technological design;
- supplying materials, half-finished goods and byproducts;
- providing the required technological equipment;
- manufacturing;
- control of the manufacturing process, inspections, tests, functionality assays, conformity assays, etc.;
- selling products;
- **EXPLOITATION;**
- **SERVICE ACTIVITIES (MAINTENANCE).**

These stages indicate the important role of the final two activities, in which the product manifests its true characteristics for the client, respectively the significance of approaching these product life cycle stages.

1.2. Product life cycle (PLC)

The standard SR ISO/TS 14048:2005 defines the **life cycle** as consecutive and interrelated stages of a system – product, from raw material acquisition or natural resource exploitation to final disposal.

From the standpoint of the **manufacturer**, the product life cycle may be approached under two aspects: one referring to the actual production and the other referring to the marketing activity.

From the standpoint of the buyer, the life cycle of the product starts with its acquisition and ends with its disposal (when it is destroyed, thrown away, etc.) at the end of its lifespan or as a result of the obsolescence induced by the emergence of new technologies generating similar products with higher performance and a higher average lifespan.

Thus, for the client, the product life cycle has three main stages:

- product acquisition (directly from the supplier or from commercial networks);
- **product exploitation/use** and the performance of **service/maintenance** operations (if needed);
- product disposal and/or replacement when required or when the beneficiary so desires for various reasons.

Furthermore, **from the point of view of reliability**, the product life cycle has five stages:

- product conception;
- design and development;
- manufacturing and installation (if needed);
- **exploitation and maintenance;**
- conversion or improvement.

1.3. The concept of quality and the quality characteristics of products

1.3.1 The evolution of the product quality concept

As the competition specific to a competitive market economy continuously intensifies, ***quality*** has become the most important factor in competitiveness.

The concern for quality had a spectacular evolution in the past 50 years, from quality checks to quality management and control, as illustrated in fig. 1.6.

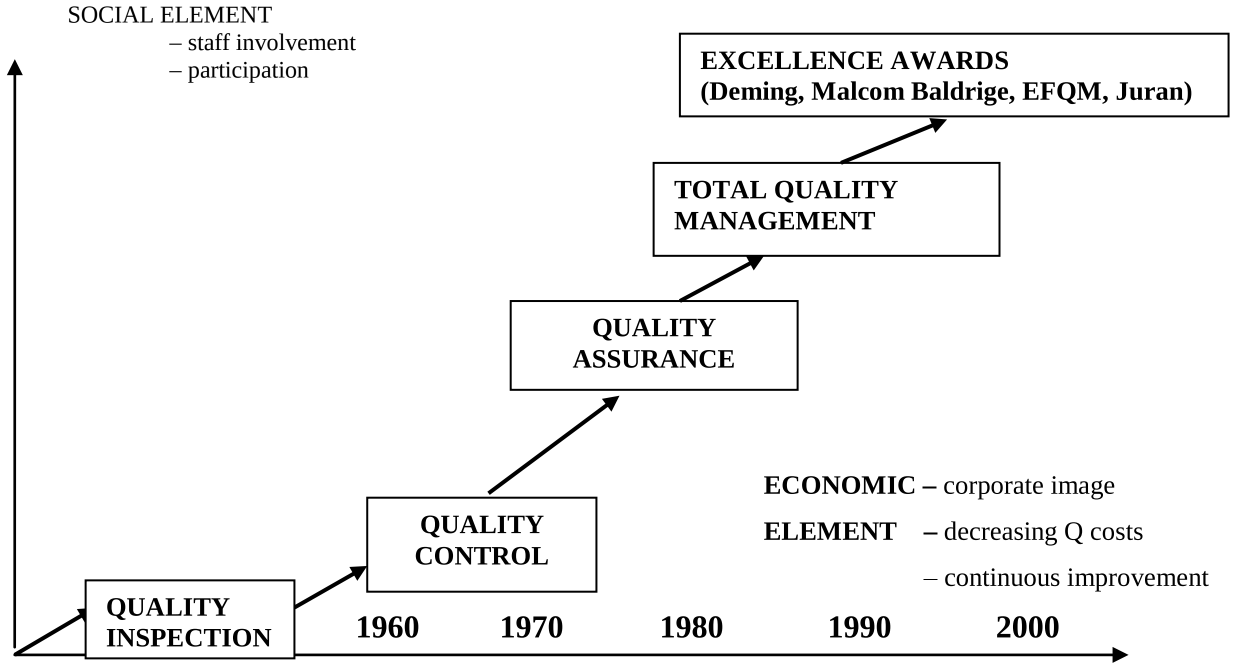

Fig. 1.6 – The evolution of the concept of quality

According to the standard SR EN ISO 9000:2015, quality is defined as *"the degree to which a set of inherent characteristics of an object fulfils requirements"* (pt. 3.6.2 of the standard).

1.3.2. The quality characteristics of products

According to the standard SR EN ISO 9000:2015, **a requirement** is "a need or expectation that is stated, generally implied or obligatory" (pt. 3.6.4).

The complex nature of the concept of quality requires taking into consideration a large number of properties or characteristics. Firstly, for the quantitative assessment of quality it is required to identify all of the characteristics of a product (pt. 3.10.1). According to SR EN ISO 9000:2015, **a characteristic** is a distinguishing feature of a product (pt. 3.10.1), and **a quality characteristic** is an inherent characteristic of an object related to a requirement. Thus, these characteristics lead to the formation of typological groups according to various criteria, as depicted in figure 1.10 [49].

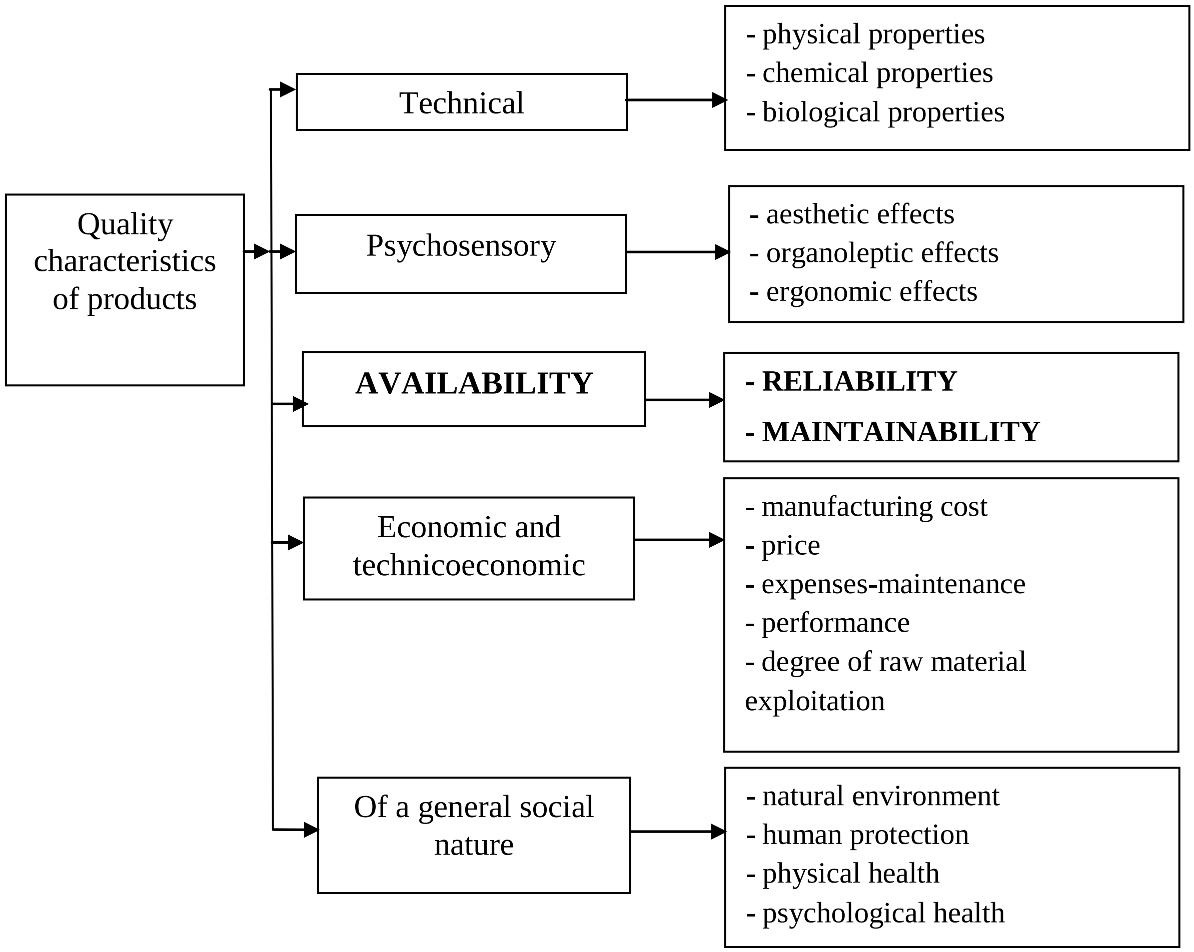

Fig. 1.10 – Quality characteristics

It may be stated that, regardless of the group used, these features or characteristics grant the product its quality.

1.4. The place and role of maintenance activities in the product life cycle

1.4.1. The significance, place and role of industrial maintenance

In the current economic circumstances, most companies are in competition, which involves meeting specific conditions, as follows:

- concerning **investments**, no quantitative or qualitative errors must be made. For this, a new technological reasoning is necessary concerning technological improvement by upgrading and automating equipment. In these conditions, economic criteria are needed to optimize the investments made.

- from an **organizational** standpoint, it is necessary to improve the activity of human resources, especially in terms of staff training, respectively the continuous training of all specialists for the purpose of establishing micro work teams at various ranks.

- from an **economic** standpoint, respectively concerning manufacturing expenses, the restructuring of cost planning is required to diminish and permanently improve costs concerning equipment servicing and maintenance and to increase the performance of employees who directly deal with quality assurance.

In these circumstances, **the role and importance of industrial equipment maintenance** also increase, as they are determined by the following **factors**:

- skill upgrade **by constructive and functional upgrades**, for the purpose of increasing equipment value;
- increasing complexity by improving their **automation degree**;
- the existence of **economic and financial losses** following technological equipment damages or repair downtime;
- the continuous increase of **maintenance expenses**, with economic and financial consequences for manufactured products;
- it is noted that with the **increase of maintenance activities** the involvement of the staff specialized in specific activities also increases.

1.4.2. The definition, evolution and objective of maintenance

Over time, the term maintenance was mistaken for the terms service and repairs, therefore explaining these concepts as follows is necessary:

- **maintaining** means ensuring the continuity of operation in adequate conditions, while **repairing** equipment means restoring the functionality of the equipment;

According to the SR EN ISO 9000:2015 standard (pt. 3.12.9), **repairing** is defined as "action on a nonconforming product or service to make it acceptable for the intended use."

"A successful repair of a nonconforming product or service does not necessarily make the product or service conform to the requirements. It can be that in conjunction with a repair a concession is required (NOTE 1 to the standard)."

"Repair includes remedial action taken on a previously conforming product or service to restore it for use, for example as part of maintenance (NOTA 2 to the standard)."

After repairs there are cases when certain parts of the product may be affected, but the operation of the product is not.

- **"maintenance"** involves selecting the prevention, correction or refurbishment methods for the purpose of monitoring the wear and tear of the equipment in view of diminishing costs; therefore, maintenance can be construed as "supervising" the machinery. The technical and economic justification takes into account the following aspects:
- manufacturing machines and equipment are more and more automated, being characterized by the compacting of subassemblies and the increase of component complexity, which leads to an increase of the equipment and specialized staff complexity;
- the equipment has low depreciation periods and increasingly higher acquisition costs;
- the occurrence of stops due to equipment operation leads to increased production costs and repair times, with consequentially increased product prices.

From the aforementioned aspects it can be deemed that **servicing** is the "action of maintaining equipment in good operational condition", while **maintenance** is "the ensemble of everything that allows the maintenance or restoration of the operation of a system or part of a system."

1.5. Defining the concepts and parameters of industrial product maintenance

To define the maintenance concepts and parameters, it is necessary to define the concept of **maintainability**, which represents the capacity of an equipment to maintain its technical status or to return in given use conditions to the technical status which allows the fulfillment of requirements specified in the technical documentation.

1.5.1. Maintenance as a process of renewing industrial equipment

From a qualitative standpoint, **maintainability** is the capacity of a product to be maintained in operation or recommissioned, able to fulfill its specified function, as soon as possible, using prescribed procedures and techniques. It is deemed that maintainability is characterized by:

- **repair times**, revision times and downtimes for performing maintenance;
- **resource size** and the skill level of the staff performing the actions;
- **quality and number of spare parts** in the safety stock;
- **quality of the operational procedures** required for maintenance;
- **maintenance management**, etc.

In maintenance, which is the process of restoring equipment after a failure, it can be deemed the renewal process defined by function $\varphi_{(t)}$ as the average number of renewals per time unit [26]:

$$\delta_{(t)} = \frac{d\varphi_{(t)}}{dt}, \quad (1.1.)$$

The definition of maintainability as a connection between the probability and the functional aspects is expressed as follows:

$$M(t_r) = Prob(t_r \leq T_r), \quad (1.5)$$

where:

t_r – the restoration time (repair or recommissioning),

T_r – maximum limit of the restoration period,

$M(t_r)$ – maintainability function.

According to the mean time between failures MTBF, the *mean time to repair* MTR is determined for maintainability. For a (design) forecast, if *n* – number of components of the same type; λ – the components' failure rate; $n_i\lambda_i$ – average hourly number of failures for the element group n_i of the equipment; $t_1^{'}$ – average time assessed for eliminating the failure of a component of group n_i, then the forecast value of MTR is:

$$MTR = \frac{n_1\lambda_1 t_1^{'} + n_2\lambda_2 t_2^{'} + \ldots + n_k\lambda_k t_k^{'}}{n_1\lambda_1 + n_2\lambda_2 + \ldots + n_k\lambda_k} = \frac{\sum_{i=1}^{k}(n\lambda t^{'})_i}{\sum_{i=1}^{k}(n\lambda)_i}, \quad (1.10)$$

If the exponential distribution of operation times and restoration times is taken into account, for assessment the index called *availability coefficient* is used:

$$K_D = \frac{MTBF}{MTBF + MTR} = \frac{\mu}{\lambda + \mu},$$

(1.14)

From an economic standpoint, the higher the reliability of an equipment in given technological conditions, the higher its investment cost C_I; however, the maintenance costs C_M are lower, considering the fact that failures are rare and low in intensity. Otherwise, cheaper and less reliable equipment involves higher maintenance costs, thus resulting diagram 1.15, where the resulting curve $C_D = C_I + C_M$ is the cost of owning the equipment in an available condition. This graph is used with the objectives and the requirements for certain equipment. Ordinarily, the solution C_D = minimum, corresponding to reliability R_m, is adopted. [2]

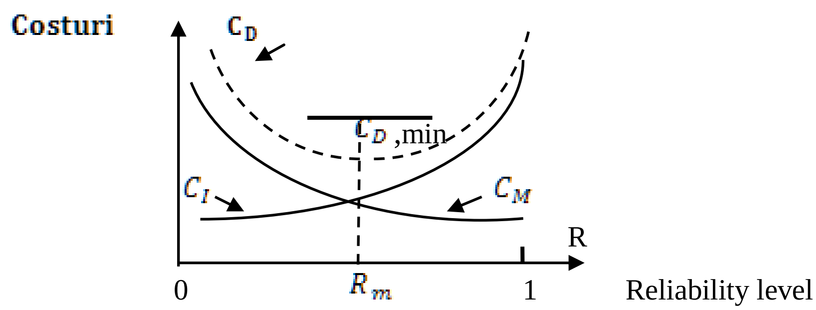

Fig. 1.15 Diagram of the reliability and maintainability costs

1.6. Classification and types of maintenance

As a consequence of the evolution and diversity of the types of maintenance presented at length in papers such as [3, 13, 24, 34, 37, 54, 74, 91], it is advisable to briefly present the maintenance types, the purpose of defining objectives being required by the complex research in the PhD thesis.

A. Maintenance types

According to the method of approaching equipment maintenance, there are several types of maintenance classifications, as follows [15, 20, 43]:

- **Corrective maintenance (CORMENT)**, which analyzes the failures occurring accidentally during the operation of equipment. It is based on the intervention on the equipment which accidentally failed during operation.
- **Preventive maintenance (PREMENT)**, which is carried out after certain planning, by performing preventive interventions on the equipment, regardless of its condition, thus intervening over the equipment to perform the required repairs to restore the equipment's normal operation.

Total productive maintenance (TPM) is a modern global maintenance concept based on the association of two more concepts: Total Quality Management (TQM) and Just-in-Time (JIT).

Total productive maintenance (TPM) has been promoted by Seiichi Nakajima since 1971 and has the following main objectives [6, 19, 23, 25, 30, 83, 91]:

- maintaining equipment to ensure high quality products;

- performing maintenance activities in maintenance conditions with the observance of ecological issues;

- improving the skills of maintenance workers to increase the service life of the equipment;

- implementing operational health system requirements and quality management requirements to increase maintenance efficiency, etc.

- **Integrative maintenance**

This type of maintenance takes into account the two unanimously accepted components, namely preventive and corrective maintenance, to maintain the equipment in operation for the purpose of increasing the time between failures and the maximum use time. Fulfilling the objectives of this maintenance type leads to an increase of availability by diminishing the repair downtime, decreasing breakdowns and accidents caused by part failures, ensuring occupational safety during maintenance and environmental protection for these maintenance operations without exceeding the allowed pollutant emissions.

- **Proactive maintenance** carried out before a breakdown, for the purpose of preventing breakdowns (revising the repair schedule, ensuring spare part stocks and according to the monitoring of operational parameters).

- **Reliability Centered Mentenance (RCM)** is a set of actions and measures carried out to establish the schedule and content of preventive maintenance works which must be carried out to maintain and potentially restore the technical status of equipment, when needed, using failure analysis, safety analysis, functional analysis, criticality analysis, etc. [53, 69, 81].

- **Corrective maintenance**

From the standpoint of practical application, corrective maintenance presents certain **advantages** concerning the following aspects:

- unscheduled equipment intervention;
- does not require monitoring the operation of the equipment;
- low cost equipment maintenance;
- higher equipment usage;
- fairly low spare part requirements.

CORRECTIVE MAINTENANCE is “maintenance carried out after detecting a failure and meant to restore a product to its status of permanently fulfilling the required function.” Another definition states that corrective maintenance is “the set of activities carried out after the failure of a means of production or after the unforeseen degradation of its function” (for instance, Maintenance Management, a component of the SIVECO Applications 2020 Integrated System).

In the industry sector, corrective maintenance includes repairs of low, average or high complexity carried out after the failure of a technical system or after the accidental (unforeseen) degradation of its function following fair wear and tear. It has the purpose of locating and diagnosing the fault, restoring the functionality of the faulty system or assembly, with or without modifications and the control of its working order. It is more inefficient from an operational standpoint and involves high costs.

The corrective maintenance system is deconstructed in two specific subcategories:

- ***Curative maintenance***, meaning *“corrective maintenance activities which have the objective of restoring a means of production to a specific operation status which allows it to fulfill its functions.”* These activities may be repairs, modifications or improvements which have the purpose of eliminating failures.

- ***Palliative maintenance***, meaning “corrective maintenance activities meant to temporarily allow a means of production to fully or partially fulfill its functions.”

Corrective maintenance may also be called "postponed maintenance" or "deferred maintenance", as it starts immediately after the detection of a failure. According to the location where the maintenance operation is performed, maintenance may be local/"on-site maintenance", meaning it takes place where the product is used, or "off-site maintenance", which may be carried out, for instance, in maintenance centers or, in certain cases, at the manufacturer.

Although this component structure is unanimously accepted, there is also the option of including a third component aside from the two major components. This is called **INTEGRATIVE MAINTENANCE.**

The integrative maintenance system includes *"preventive and corrective maintenance activities which take place to maintain the functionality of a technical system for the purpose of increasing the mean time between failures and the maximum admitted use time in comparison with the other two preventive and corrective maintenance systems."*

Self-maintenance

Self-maintenance has been applied in the industry for a long time. It is known especially as self-service, daily service, current inspections, etc. In relation to total productive maintenance, it is an innovative concept and its main pillar.

According to total productive maintenance, self-maintenance is the habituation of operators of maintaining the good condition of the equipment, machines, installations and machinery, and correctly measuring the operational parameters, which entails transferring certain maintenance tasks to the operators.

In the event of failures, the user must make the diagnosis and the cause which generated the issue and must intervene with the specific tools and instruments for the respective technical system to the extent the user is entitled to remedy the respective failure.

Maintenance as required

This type of maintenance occurs following the intensive use of the industrial equipment, respectively the lack of a norm of consumption or a specific norm. This situation requires taking ad-hoc maintenance measures specific to the moment when the failure takes place.

A.2. Preventive (prophylactic) maintenance

It is a set of activities which unfold at a pre-established time interval for the purpose of preventing functional failures of certain component elements or reducing the likelihood of the occurrence of certain malfunctions in time.

An important role in preventive maintenance activities is **the qualification and skills of the staff** that should be responsible and know the maintenance policy at organization level. In this regard, it is necessary to unfold certain activities, oriented towards:

- **the awareness** regarding the fact that preventive inspections and maintenance are very important within the general maintenance program;

- **knowing the quality policy** at the organization level for achieving the objectives related to maintenance;

- **increasing the skills and the responsibility of workers** with activities within the preventive maintenance program – increasing the role of training carried out by the human resources department, in order to hire qualified personnel for carrying out preventive maintenance activities;

A.3. Total productive maintenance

Total Productive Maintenance (TPM), which originated in Japan in the 1950s and which was implemented in the 1980s by many European developed companies, suggests a ***new modern view*** for industrial maintenance.

A.4. Proactive maintenance

Proactive maintenance is a method based on the combined analysis of:

- traceability of data concerning the behavior in the operation of pieces of equipment which should include the malfunctions occurred and the causes of their occurrence;
- measurements specific to predictive maintenance (vibrations, noises etc.);
- obtaining information specific to preventive and planned maintenance, which imply the mandatory use of advanced software products, for managing large data bases.

This type of maintenance may lead to the maximization of the production equipment availability (reliability and maintenance) under the conditions of minimizing the global maintenance costs.

It should be noted that the implementation with maximum efficiency of this type of maintenance may be unfolded if malfunctions and the causes of their occurrence are analyzed immediately.

Current stage of proactive maintenance

This type of maintenance is carried out before the occurrence of a malfunction and its purpose is to prevent any damage (fault).

Damage prevention can be ensured by the competent development of the maintenance program, by monitoring the equipment operating parameters, by providing the spare parts stock, the operative human resources etc.

In the field, proactive maintenance is seen as modern and promising, and it includes activities referring to: periodic verification of the equipment operation, replacing the elements which approach the end of their lifespan, regular inspections for the verification of the status of the equipment components, periodically supplying consumables.

Given the diversity of the types of references regarding the structure of industrial equipment, there are methods and means of measuring and monitoring used for the diagnosis of different systems, such as:

- **thermographic inspection** used for situations with possible occurrence of faults, such as:
    - ball bearings;
    - reducers with sufficient lubrication;
    - eccentricities occurring in high rotational speed shafts;
    - occurrence of cracks in the materials of the parts;
    - lowering the level of fluids in closed tanks (cisterns);
    - clogging of forced cooling circuits, etc.
- **visual inspection –** this technique is frequently used in monitoring equipment operation. This type of inspection is carried out fairly easy, it does not require special equipment, but it requires good knowledge and capability of the operator.
- **video camera inspection -** it has advantages because there is the possibility of detecting false elements from the point of view of maintenance (light bulbs, reflections of certain polished parts of the metal components etc.) In this situation, it is appropriate to use other types of tests.
- **sensors and indicators** for monitoring the operating status. They are used for establishing the global level of vibration speeds which provide some information regarding deterioration by wear of balls, increasing the temperature of bearings, etc.

- **acoustic analyzers** used for establishing the degree of wear of balls which provide information regarding the condition of the ball bearings and of the rotating elements of the industrial equipment.
- **stationary equipment**, fixed instruments (from the structure of any possible SCADA networks, or located inside/near the equipment/tools/machinery): sensors/transducers, measuring instruments, control panels, dispatchers, telecommunication networks (voice, data, VPN – Virtual Private Network) etc.;
- **portable equipment** from the category of: verification devices, measuring instruments, telecommunication devices, locating devices, thermal imaging video/photo camera, portable computers etc.

A.5. Reliability-Centered Maintenance

This type of maintenance (RCM) is similar to proactive maintenance, noting that, in this case, we use the foundations of mathematics regarding the system reliability theory.

Having a rich mathematical foundation, it is considered a modern model of maintenance, because it is based on an effective informational support.

The statistics at global level show that the computerization of maintenance brings important benefits, such as:

- reducing the global maintenance budgets by about 35%;
- reducing accidental failures by over 50%;
- reducing the number of failures by over 75%;
- reducing maintenance supply expenses by over 35%;
- reducing the assets in stocks, reducing the general management expenses of stocks by over 30%.

The category of *complex systems*, which are widely spread in Western and Eastern countries and which have a limited use in Romania, includes the **Maintenance Management System,** developed by SIVECO Romania software company.

The bibliographical research conducted [3,11,17,19,45,49,61,63] show the fact that the main cause of malfunction of technical and mechanical equipment is due to wear processes.

Failures are a consequence of the wear of the equipment elements during their operation, and this is when the analysis of the wear phenomenon is important, for which it is appropriate to classify forms, factor criteria and measurement methods.

The main types of wear are:

a. **Static** physical wear – caused by the external atmospheric agents or internal changes, which take place during the equipment lifespan and it may establish the extreme lifespan limit. During this period, the equipment may be placed in the warehouse or in a future operating place, without being used.

b. **Dynamic** physical wear – takes place during the equipment operation by: changing the physical and geometrical status of the surfaces in contact, of the sizes, of macrogeometry, of the orientation and beat position, changing the microstructure, the physical and mechanical properties. During the service life of the equipment, this type of wear is located after the initial break-in period, when wear is linear over time.

c. **Obsolescence** by technological obsolescence – it is estimated based on reducing the equipment effectiveness as compared to the manufacture of a new one, which ensures better performances at comparable use prices.

1.7. Analysis and assessment methods for industrial equipment maintenance

In order to analyze industrial product reliability and maintenance in industrial practice, different methods are use, including the following:

A. Fault tree method
B. Markov chain method
C. Monte Carlo method
D. "FMECA" method

Other used methods are described in specialized literature papers [4, 15, 19, 23, 26, 59]

A. Fault tree method

This method is approached in different specialized literature papers [15, 26, 60] and is based on the concept according to which a certain malfunction is the effect of the fault of one or several elements within a technical system. In the case of this method, the fault process is quantified at structural level, considering that the system fault is the result of a quantified sequence of the statuses of a fault process.

B. Markov chain method

Markov chain method is used for solving reliability and maintainability of large systems and is based on the operation of the systems with several statuses, by using the following hypotheses [8, 19, 37]:

a) the features of the system can be expressed according to the features of the components;

b) the malfunction of a component does not depend on the condition of the other components;

c) restoration is established by restoration rate.

C. Monte Carlo method

This method simulates the system operation by using static methods by means of random processes. It is applied for systems which evolve through a large number of statuses, namely which are modeled with different types of distribution functions, described in different papers [8, 13, 19, 37], the method implies two stages.

D. FMECA method

This method called FMECA (Failure Mode, Effects and Criticality Analysis) allows the rigorous analysis of "possible malfunctions" (possible technological and design errors) of the products, from the user's or manufacturer's point of view [4, 46].

Failure mode, effects and criticality analysis (FMECA) means: highlighting potential failures, studying them in the light of the probability of occurrence, and classifying malfunctions according to the effect they have on the proper operation of the system.

FMECA method consists of the analysis of:

- the degree of seriousness of possible malfunctions;
- the likelihood of its occurrence;
- the user's perception regarding the failure.

1.8. Technical and economic assessment of maintenance

1.8.1 Technical indicators for maintenance assessment

1.8.2 Economic indicators for maintenance assessment

1.8.3. Time indicators for maintenance activity

1.9. Determining the optimal time to replace equipment

When defining an optimal policy of industrial maintenance, there are other questions which should be answered, namely: When does maintenance need to be stopped? Should we keep the old equipment which requires increasing maintenance expenses? When is the optimal time for replacement?

Given the topic of the paper, we further wish to present a new method for establishing the optimal time for replacing the equipment, method which takes into consideration the wear of the equipment and the maintenance expenses.

CHAPTER 2
GOALS OF THE PhD THESIS

2.1. Main current trends in industrial maintenance

Using industrial equipment at high performance and productivity parameters ensures their productivity and the precision which generates the quality of manufactured products. In this sense, an important organizational role is played by maintenance, as a support process which ensures the smooth running of the manufacturing process, respectively product manufacturing.

The smooth operation of the equipment can be ensured by applying maintenance strategies and appropriate methods based on the permanent monitoring of its operation. As a result, maintenance activities must be planned following the permanent monitoring and diagnosing of the equipment operation and the rational application of specific maintenance methods.

Moreover, it is noted that there is a current tendency to implement and develop maintenance management by using modern maintenance methods (TPM, AMDEC, preventive-proactive maintenance, etc.) which lead to the decrease of the equipment failure risk while observing the requirements of risk management and **the environmental standards**, the quality and environmental standards (SR EN ISO 9001:2015 and SR EN ISO 14001:2015).

2.2. Demarcating the research field

Taking into account the existence of wide and various approaches of the issue of industrial maintenance, there is the opportunity of demarcating the theoretical and practical research field in an appropriate and approachable framework which corresponds to the requirements of the topic of the PhD thesis. Based on the aforementioned aspects, following the analysis and findings of the bibliographic research performed, the author aimed to direct her research to approach the following aspects:

- analysis of the theoretical and practical approaches referring to the current research stage in the field of industrial equipment quality and maintenance;
- analysis of the current stage of analyzing and assessing industrial equipment maintenance;
- analyzing the main models of maintenance policies and the economic maintenance strategies;
- the analysis and economic approach of product maintainability;
- improving the maintenance process by drafting and implementing specific documents for these activities, which would lead to increased performance;
- analyzing and approaching aspects of determining the human and material resource requirements in the maintenance activity;
- improving maintenance activities by expanding the application of modern methods and techniques specific to proactive maintenance.

Taking into account the wide development of the issue of industrial product maintenance, it is required to approach certain aspects which represent the author’s points of view, developments and contributions in the field of research of the PhD thesis, subject to being potentially expanded with other aspects of the studied field.

2.3. Main research objectives

Following the bibliographic research carried out referring to the current stage of the PhD thesis topic, from the resulting analyses and findings, the author aims to approach certain theoretical and practical aspects in the PhD thesis, as follows:

A. **Theoretical** objectives:

- theoretical analysis referring to the current stage of the research concerning product quality and maintenance quality;
- the analysis of the main concepts and parameters of industrial product maintenance;
- the comparative study of the methods of analyzing and assessing industrial equipment;
- the study of the technical and economic assessment of equipment maintenance;
- the analysis of economic models and strategies in maintenance management;
- contributions to drafting documents specific to maintenance, which would ensure product capability and quality.

B. **Practical** objectives:

- practical developments and contributions on establishing the human resources requirements by using the techniques of operational research;
- developments and contributions on the material resource requirements in preventive maintenance and preventive-proactive maintenance;
- practical case study for determining maintenance expenses and applying statistical methods for drawing up an econometric model for repairs in the aircraft industry;
- developments, proposals and contributions on the application of modern methods and techniques in proactive maintenance and diagnosing the operational status of industrial equipment.

Following the theoretical and practical research, at the end of the paper, the author presents the findings of the performed study, reveals her personal contributions and foresees some future research directions in the field of the PhD thesis topic.

CHAPTER 3

THEORETICAL DEVELOPMENTS AND CONTRIBUTIONS TO THE STUDY OF MAINTENANCE POLICIES AND STRATEGIES

3.1. Analysis of maintenance policy models

To this end, if redundancy is inevitable, the additional loading of the used resources must be avoided. Therefore, we consider **the case of a system comprised of two identical subassemblies** with a derivation flow chart. For this situation, the selection is made according to one of the three maintenance policies described below [53]:

a. *Policy no. 1* – consists of having two maintenance teams and recommissioning each failed subassembly.
b. *Policy no. 2* – consists of having one maintenance team which repairs each failed subassembly.
c. *Policy no. 3* – consists of having one maintenance team which only intervenes in the event of a system failure, fully repairing said system. The issue at hand is determining which policy corresponds to the highest possible availability and the lowest possible maintenance cost.

a. **For *policy no. 1***, the possible system statuses are the following:
- status 1 – both subassemblies are operating;
- status 2 – one subassembly is operating and the other is in the process of being restored;
- status 3 – both subassemblies are in the process of being restored.

The MARKOV diagram is presented in figure 3.1 and the status transition matrix is the following:

(3.1)

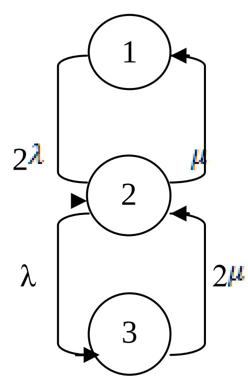

Fig. 3.1. The MARKOV diagram for maintenance policy no. 1

b. For *policy no. 2,* the possible system statuses are the following:

1 – both subassemblies are operating;
2 – one subassembly is operating and the other is in the process of being restored;
3 – both subassemblies are faulty and the maintenance team is working to recommission one of them.

The MARKOV diagram corresponding to the system statuses is shown in figure 3.2. The matrix has the following form:

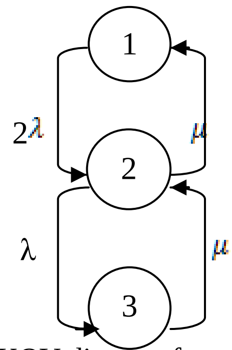

Fig. 3.2. The MARKOV diagram for maintenance policy no. 2

In this case, the instantaneous availability is:

$$A(t)=P_1(t)+P_2(t) \tag{3.4}$$

and the mean value is:

$$A(\infty)=\frac{\mu^2+2\lambda\mu}{\mu^2+2\lambda\mu+2\lambda^2} \tag{3.5}$$

c. For *policy no. 3*, the possible system statuses are the following: 1 - both subassemblies are operating; 2 - one subassembly is operating and the other is faulty; 3 - both subassemblies are faulty; 4 – one subassembly was recommissioned by the maintenance team, which will proceed to recommission the second subassembly.

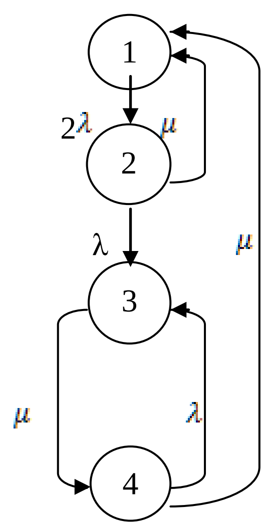

Fig. 3.3. The MARKOV diagram for maintenance policy no. 3

The MARKOV diagram is shown in figure 3.3 and the transition matrix has the following form:

$$[q]=\begin{bmatrix} 1-2\lambda & 0 & 0 & \mu \\ 2\lambda & 1-\lambda & 0 & 0 \\ 0 & \lambda & 1-\mu & \lambda \\ 0 & 0 & \mu & 1-(\lambda+\mu) \end{bmatrix} \tag{3.6}$$

The instantaneous availability will be:

$$A(t)= P_1(t) + P_2(t) + P_4(t) = 1 - P_3(t) \tag{3.7}$$

And the mean value will be:

$$A(\infty) = \frac{3\mu^2+2\lambda\mu}{3\mu^2+4\lambda\mu+2\lambda^2} \tag{3.8}$$

Therefore, given the values **λ** and **μ**, the mean annual unavailability time for each of the three adapted policies can be deducted. Afterwards, the following costs can be assessed:

- the cost of one hour of unavailability for the system;
- the fixed labor cost per subassembly and per year;
- the replacement cost per system for each policy;
- the annual unavailability cost;
- the annual labor cost;
- the annual recommissioning cost;
- total annual cost.

Furthermore, the ratio **λ / μ** plays a fundamental part in material stock management, as it allows the adaptation of the maintenance effort to the reliability level of the system components.

3.2. Economic strategies in maintenance management

In the maintenance of industrial equipment, **the economic concept of cost** is highly complex, since it has a rich significance referring to the field, origin, manifestation, etc. As a result of cost diversity, it was advisable to classify the cost based on criteria shown in fig. 3.4:

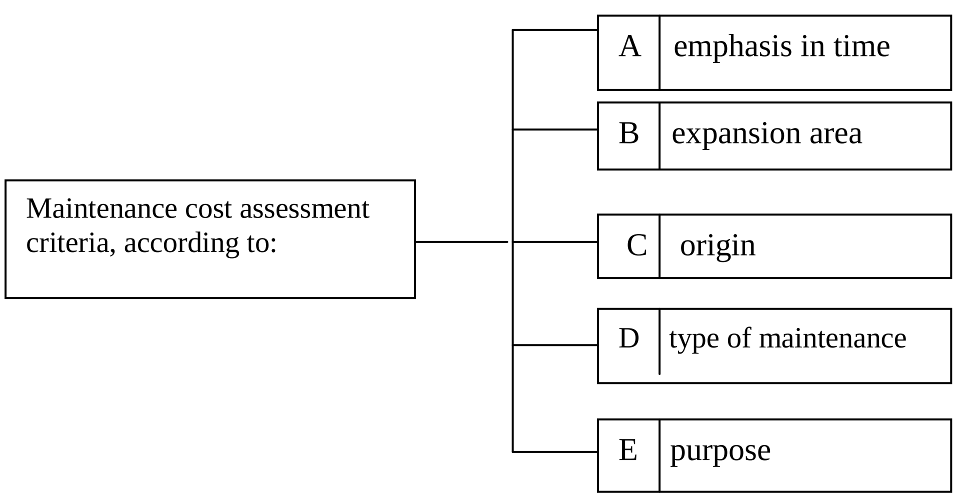

Fig. 3.4 Maintenance cost classification criteria (adapted by the author after [89])

A. Maintenance costs according to **emphasis in time**.

These costs take into consideration the aspects concerning the life cycle of the equipment, event when the **global cost** concept is used; global cost is comprised of the components shown in figure 3.5 below [91]:

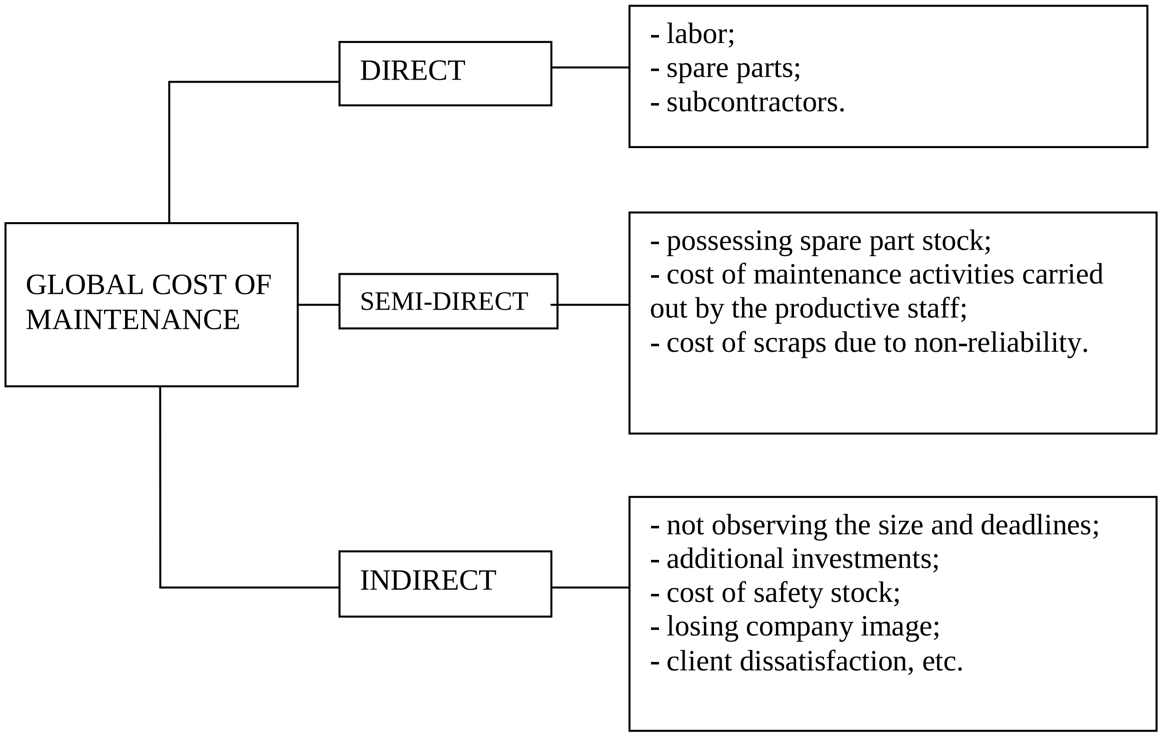

Fig. 3.5 – Main components of the global cost of maintenance

B. Maintenance costs according to **expansion area**

If there is a well-structured information system in which the maintenance activity traceability can be emphasized, then there is the possibility of differentiating maintenance costs on manufacturing system components, respectively: the analyzed equipment, its technological line, product section and organization.

C. Maintenance costs according to **origin**

Following the analysis referring to the diagnosis of equipment unavailability, caused by the various types of failures, the corresponding costs of failures may be presented as a diagram.

D. Maintenance costs according to **system type**

Taking into consideration the existence of corrective and preventive maintenance, the types of organizational costs reveal the degree of competitiveness, respectively the technological degree based on the policy implemented in the maintenance activity.

E. Maintenance costs according to **purpose**

Mainly, the apportioning of financial resources meant for the maintenance department is oriented towards costs for:

- acquiring spare parts;
- storing spare parts and various utilities;
- transporting spare parts;
- salaries of the maintenance staff, etc.

The economic model for determining the optimal maintenance method

Taking into account the fact that maintenance is not an objective in itself, but a necessity of manufacturing, which the financial department deems too expensive, we believe that we cannot discuss an optimal maintenance method without taking into account the economic aspect, respectively the costs of this activity.

The economic model is based on estimating and comparing the average price of implementing the three maintenance methods, with the observation that human safety is not affected in the case of an accidental failure.

1. **The systematic maintenance method** involves interventions carried out systematically, namely critical element replacements or refurbishments after a certain period (or wear and tear units).

It results that the optimum period of systematic intervention depends on the reliability law of the critical elements in question.

As shown before, the reliability law may be defined by the following indexes:

- $\lambda(t)$ = failure rate;
- $R(t)$ = survival probability (reliability);
- $F(t)$ = failure (fail) probability;
- $f(t)$ = density of failure probability.

In systematic maintenance, by definition there is a failure probability $F(t)$ for the intervention period "T".

Consequently, the total probable maintenance and unavailability (Ct_s) will result from the equation [23, 62]:

$$Ct_s = Cd + Ci \times F(t) \,, \tag{3.9}$$

where:

Cd = the direct or maintenance costs;

Ci = indirect (additional) costs of unavailability in case of failure;

$F(t)$ = failure probability.

2. For **conditional preventive maintenance** in relation to the evolution of a characteristic symptom, the mean time between successive interventions, m (t), comes very close to MTBF. It can be calculated using the equation:

$$\mathbf{M(t) = K \times TMBF}, \tag{3.12}$$

where:

K – coefficient taking into account the necessary reaction time between the alarm threshold and the admissible threshold for conditional preventive maintenance, with a value very close to 1.

A series of implementation costs are specific to conditional preventive maintenance (for instance, costs for acquiring various measurement and control machines for using said machines).

These costs for implementing conditional preventive maintenance between two successive interventions are calculated using the equation:

$$C_c = \left(\frac{A}{D} x TMBF\right) + C_a, \tag{3.13}$$

C_c - costs for implementing conditional preventive maintenance;

A - acquisition costs for measurement and control equipment which may be required;

D - probable use duration of said equipment;

Ca – control and measurement expenses for the considered critical elements, for a period equal to MTBF.

3. For **corrective maintenance**, namely intervening after the failure, the mean cost per time unit will be:

$$\left(\bar{C}_{tc} = \frac{C_d + C_c}{TMBF}\right) \tag{3.15}$$

3.3. Methods for carrying out maintenance works

To carry out maintenance works for equipment within an organization, the latter may choose to apply one or several methods recommended by the specialty literature, namely [3, 8, 13, 49]:

- the individual maintenance method;
- the subassembly maintenance method;
- the backup equipment maintenance method;
- the maintenance in flow method;

For instance, it is recommended to use the graph method to organize and schedule the performance of maintenance works.

Furthermore, from the standpoint of preventive maintenance management, it is advisable to draw up the documentation corresponding to the specific activities, case when it is suggested to draw up certain documents, procedures and forms which will represent the informational basis for the activities.

A. Individual maintenance method

This method is usually applied to equipment found in low numbers (or even one of a kind) in the industrial unit.

The main characteristic of this method is that, after the dismantling, cleaning, control and refurbishment operations, the parts are reinstalled on the same equipment and all of the operations related to equipment maintenance, including the manufacturing of new spare parts which could not be obtained as backup parts, are performed during the repair.

B. Subassembly maintenance method

This method is applied for industrial units which include several pieces of equipment of the same type. The method is characterized by the fact that for a group of same-type pieces of equipment, a backup stock of subassemblies is created to replace the subassemblies uninstalled from the equipment being repaired. The repair of the uninstalled subassemblies is carried out in parallel in specialized maintenance departments and after repair they are included in the backup stock.

C. Spare equipment maintenance method

This method is recommended for highly complex maintenance works, which imply very ample downtime for their execution.

The method consists of dismantling the equipment and transporting it to a special location where the maintenance works will be carried out. Backup equipment will be installed in its place [10].

The main advantage of this method is the diminished downtime of equipment under maintenance, which only includes the time required to dismantle it and to install the backup equipment. Therefore, the effective time for performing the maintenance works does not influence its removal from the production process.

D. Maintenance in flow method

This method is based on a high degree of job specialization to carry out the operations required for maintenance works.

Lines of maintenance in flow can be organized to repair spare parts and equipment subassemblies.

To apply the method the following activities must be performed:

- differentiation of the technological product on various stages and operations;
- accurately setting certain operations related to the repair, installation or assembly of parts or subassemblies for each workplace;
- locating the workplaces in the order imposed by the succession of the technological process;
- ensuring the rhythmicity of production based on the synchronization of the operation execution time and establishing the optimal number of workplaces;
- providing special means for the continuous transportation of work objects, in conformity with the technological process.

3.4. Developing stochastic processes in the study of industrial equipment maintenance

Taking into account the aspects presented in paragraph 3.1, the application of the theory of Markov process chains is presented below for two types of processes, based on virtual data, as follows:

Developing and applying decision-making methods for the study of equipment maintainability

Markov decision processes in aircraft maintenance

1. Independent processes

In their turn, they are presented in two forms:

a) Within each phase, all of the arcs with the same node of origin are equal.

The graph of such a process is shown in figure 3.13.

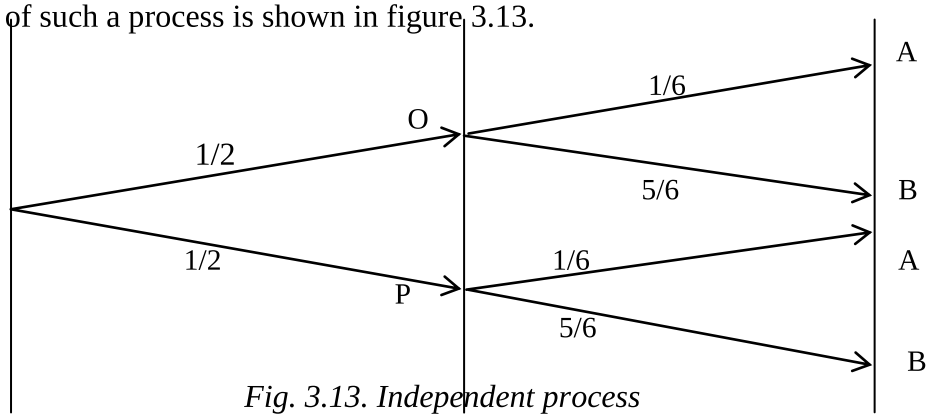

Fig. 3.13. Independent process

b) All arcs are equal both in each phase and in between phases.

The graph of such an independent process is shown in figure 3.14.

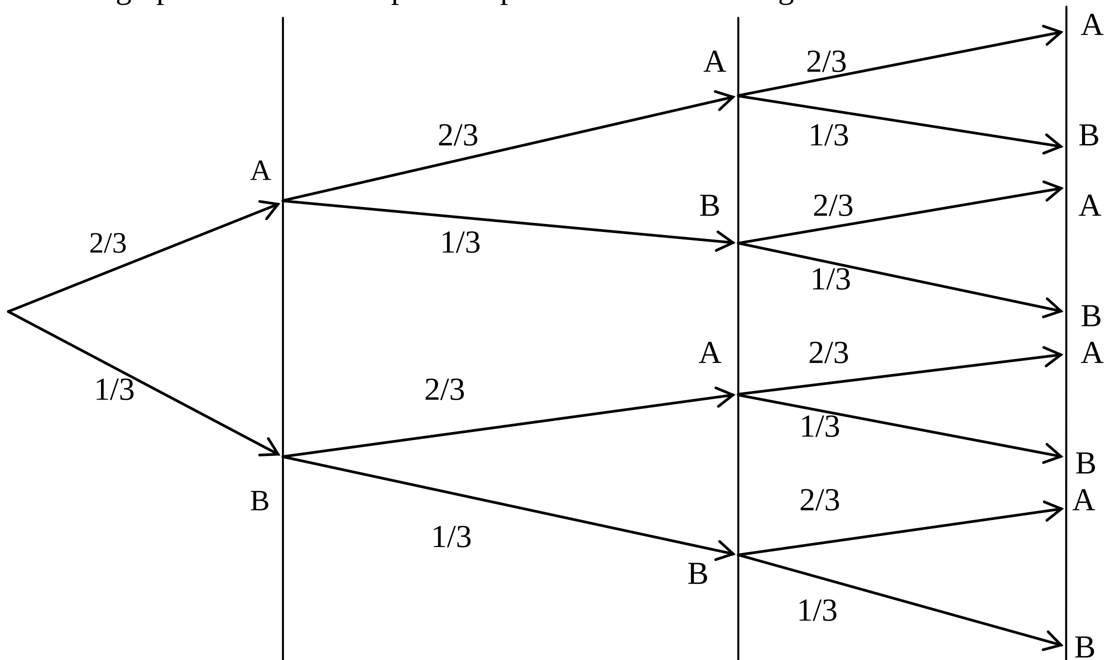

Fig. 3.14. Independent process

2. Markov chain processes

The arc of an experiment only relies on the immediately previous one. Dependency remains unchanged for all phases.

The graph of a Markov chain process is shown in figure 3.15.

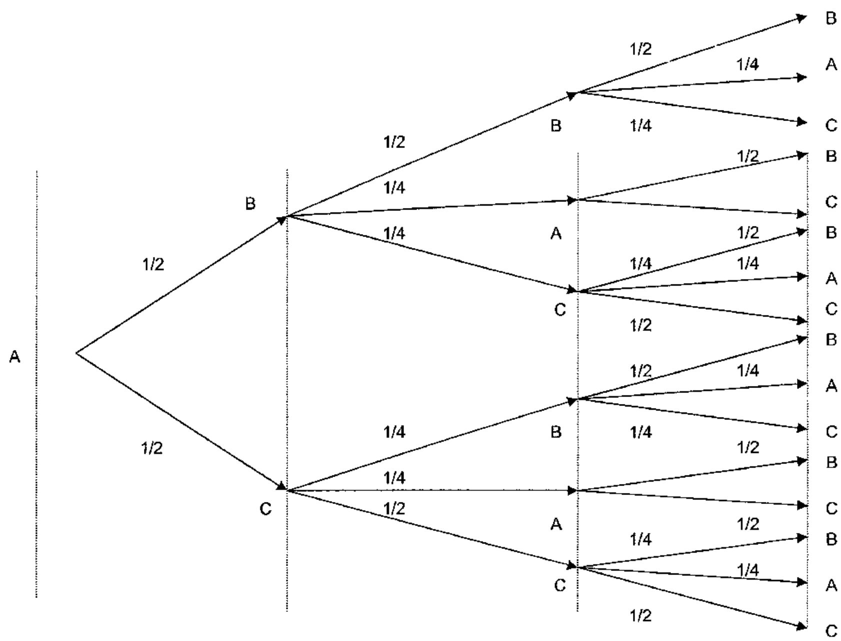

Fig. 3.15. Markov chain process

3.5. Contributions to drawing up documents specific to maintenance activities (author's contribution)

For the performance of various activities within equipment maintenance, **the author suggested and drew up** an operational work procedure presented in Annex 1.

Furthermore, models of the main operational documents accompanying the operational procedure were drawn up, respectively:

- specific documents for the equipment repair shop – Annex 2;
- delivery document for the machine/machinery being repaired and repair reception – Annex 3;
- inspection report – Annex 4;
- list of performed checks and tests – Annex 5;
- table recording the maintenance activities and works performed – Annex 6;
- nomination of works on repair types– Annex 7;
- technological repair sheet – Annex 8;
- measurement sheet – Annex 9;
- material requirements – Annex 10;
- stages for the execution of spare parts – Annex 11;
- technological machinery summary sheet – Annex 12.

These documents **suggested by the author** can be deemed applicable models for any shop where industrial equipment checking and repair activities are performed.

Chapter 4.

PRACTICAL DEVELOPMENTS AND CONTRIBUTIONS. CASE STUDY.

1.1. Practical developments and contributions to the establishment of human resources and material resource requirements in preventive and proactive maintenance

Establishing the necessary human resources within the maintenance department is carried out according to different categories, specific to the activities unfolded, namely: workers, engineers, economists, administrative staff etc. As a result of the diversification of maintenance activities, given its different types, it can be considered that said staff may be grouped as follows:

a. Staff with responsibilities for carrying out proper maintenance activities, unfolding works within the maintenance teams (for instance, mechanics, electricians, welders etc.)

b. Staff unfolding activities in different departments which contribute to a good unfolding of the maintenance process, such as “Methods-maintenance” and “Maintenance planning and programming”.

Regarding the staff necessary for different categories, we can say that there are difficulties in specifying this staff, because the activities, namely **the afferent workload** may be established with certain difficulty. On the other hand, as a result of the activities unfolded, of the features and of the **equipment statuses**, namely **of the capacity of the information system** afferent to maintenance activities, there are certain difficulties in establishing a proper organization of the department.

The data from specialized literature papers [23,62], estimate that the share of the personnel in this category is of 5 up to 8% as compared to the number of the employees directly involved.

1.1.1. Establishing the human resource requirements for maintenance activities

Also, in maintenance activities, for the component operations of the maintenance technological process, it is necessary to establish the number of employees who are directly involved in the maintenance works, as it is mentioned in the plans for preventive and conditioned maintenance of equipment within said organization. The number of employees is established in a differentiated manner for the workers who carry out **basic works with time standards**, namely for those who work according to service standards. For the first category, the afferent calculation can be carried out with relation [23]:

$$N_{mi} = \frac{V_{mti}}{F_{pm} \times K_n}, i = \overline{1, t} \qquad (4.1)$$

where:

N_{mi} is the necessary number of workers with occupation i;

V_{mti} – global workload, expressed in hours/employee, necessary for carrying out the maintenance works appropriate for occupation i, as shown in the maintenance plan;

F_{pm} – the amount of time for one worker;

K_n – planned coefficient for complying with the standards;

i = $\overline{1, t}$ types of occupations necessary for different activities.

Thus, for the **workers who carry out mechanical processing operations,** their number can be calculated with the following relation:

$$N_{mp} = \frac{T_{ntp}}{F_{pm} \times K_n} \quad (4.2)$$

where:

N_{mp} is the necessary number of workers for mechanical processing operations;

T_{ntp} – total amount of time necessary for carrying out mechanical processing operations, in hours/employee.

Also, for **the workers who unfold activities based on service standards** for systematic preventive maintenance or for surveillance operations, we propose to establish the necessary number of workers [23]:

$$N_{ms} = \frac{N_e \times K_s}{N_s} \quad (4.3)$$

where:

N_{ms} is the number of workers;

N_e – number of pieces of equipment which should be operated by these workers;

K_s – coefficient of the number of shifts;

N_s – service standard of the equipment, defined by the number of pieces of equipment operated by one worker.

It should be mentioned that, under the conditions of applying TPM method, in which self-maintenance is the basic element of the method, the activities of this category of workers are taken over by workers who are directly involved in equipment maintenance.

In order to give a practical example of the model presented above, we further take into consideration the following example, using virtual data, similar with practical data.

Assuming that within the **aircraft engine repair and maintenance section** there are six identical pieces of equipment, with a probable damage rate of o,o1 per hour, and the maintenance team specialized in repairs consists of three workers, the probable repair rate is of 0,10 per hour. The average hourly wage is of 15 units per hour, and the cost of the unavailability of equipment is of 120 currency units per hour.

The equations of state will be:

For i = 0, initial state, replacing in equation [2.61] gives:

$6 \text{ x } 0.001p_c + 0{,}1p_1 + 0 \Rightarrow$

$$\boxed{0{,}01p_0 + 0{,}1p_1 = 0}$$

For 1 = (i < M), replacing in equation [2.62] gives:

$(6 + 1 - 1)0{,}01p_0 - [(6 - 1) \text{ x } 0{,}01 + 1 \text{ x } 0{,}1]p_1 + (1+ 1)0{,}1p_2 = 0 \Rightarrow$

$$\boxed{0{,}06p_0 – 0{,}15p_1 +0{,}2p_2 = 0}$$

For i = 2 (i < M), replacing in equation [2.62] gives:

$(6+1-2)0{,}01\,p_1 - [(6-2) \times 0{,}01 + 2 \times 0{,}1]p_2 + (2+1)0{,}1p_3 = 0 \Rightarrow$

$\boxed{0{,}05pi - 0{,}24p2 + 0{,}3p3 = 0}$

For i = 3 (i = M), replacing in equation [2.63] gives:

$(6+1-3)0{,}01p_2 - [(6-3) \times 0{,}01 + 3 \times 0{,}1]p_3 + 3 \times 0{,}1p_4 = 0 \Rightarrow$

$\boxed{0{,}04p_2 - 0{,}33p_3 + 0{,}3p_4 = 0}$

For i = 4 (i > M), replacing in equation [2.63] gives:

$(6+1-4)0{,}01p_3 - [(6-4) \times 0{,}01 + 4 \times 0{,}1]p_4 + 4 \times 0{,}1p_5 = 0 \Rightarrow$

$\boxed{0{,}03p_3 - 0{,}42p_4 + 0{,}4p_5 = 0}$

For i = 5 (i > M), replacing in equation [2.63] gives:

$(6+1-5)0{,}01p_4 - [(6-5) \times 0{,}01 + 5 \times 0{,}1]p_4 + 5 \times 0{,}1p_6 = 0 \Rightarrow$

$\boxed{0{,}02p_4 - 0{,}51p_5 + 0{,}5p_6 = 0}$

For î = 6 (i = M), replacing in equation [2.64] gives:

$0{,}01p_5 - 0{,}3p_6 = 0 \Rightarrow$

$\boxed{0{,}01p_5 + 0{,}3p_6 =}$

Therefore, the established equations of state are:

$$\begin{cases} -0{,}06p_0 + 0{,}10p_1 = 0 \\ 0{,}06p_0 - 0{,}15p_1 + 0{,}20p_2 = 0 \\ 0{,}05p_1 - 0{,}24p_2 + 0{,}30p_3 = 0 \\ 0{,}04p_2 - 0{,}33p_3 + 0{,}030p_4 = 0 \\ 0{,}03p_3 - 0{,}42p_4 + 0{,}40p_5 = 0 \\ 0{,}02p_4 - 0{,}51p_5 + 0{,}50p_6 = 0 \\ 0{,}01p_5 - 0{,}30p_6 = 0 \end{cases}$$

By solving the system, we get the following solution:

Po = 0,564083 probability of operation of all pieces of equipment;
P1 = 0,338450 probability that a piece of equipment is faulty;
P2 = 0,084612 probability that 2 pieces of equipment are faulty;
P3 = 0,011283 probability that 3 pieces of equipment are faulty;
P4 = 0,0001128 probability that 4 pieces of equipment are faulty;
P5 = 0,0000338 probability that 5 pieces of equipment are faulty;
P6 = 0,00106 probability that 6 pieces of equipment are faulty.

We have:

$$\sum_{i=1}^{N} ip_i \Rightarrow 0{,}564083 + 0{,}338450 + 0{,}084612 + 0{,}001128 + 0{,}000106 = 1$$

g(3) = 1 · 0,338450 + 2 · 0,084612 + 3 · 0,011283 + 4 · 0,001128 +
+ 5 · 0,000338 + 6 · 0,000106 = 0,548361

Therefore, assuming that there are three workers in the maintenance team, the probability of not using the pieces of equipment in the system is of 0,548361, and the cost is average,

C(3) = 120 · 0,548361 + 15 · 3

C(3) = 110,80 units/hour.

By simulating the number of workers in the maintenance team (M) and by calculating the probabilities of not using the pieces of equipment in the system g(M), we can calculate the number of workers in the maintenance team, and, finally, the appropriate number of workers of the maintenance team.

4.1.2. Practical developments to the establishment of material resources (spare parts) for industrial equipment maintenance

Taking into consideration the fact that the proposed preventive maintenance methods aim at increasing the level of equipment reliability, as well as at improving their maintainability, the **main objective of providing spare parts is the supply with spare parts which should prevent the equipment from turning off due to accidental failures**.

The optimum level of the spare parts stock is the one which minimizes the total cost established by the size of the spare parts stock.

If the **stock is larger than necessary**, the expected value of surplus (Ee) is given by the relation [62]:

$$Ee = \sum_{x=0}^{S_s}(S_s - x)\frac{e^{-m}m^x}{x!} \tag{4.13}$$

where:

S_s – is the safety stock;

x - random variable representing the number of failures of a part;

m – average number of failures.

If the stock is less than necessary (the number of parts which would fail is larger than the number of parts in the safety stock) the expected value of deficit (Ed) is given by the relation:

$$Ed = \sum_{x=S_s+1}^{\infty}(x - S_s)\frac{e^{-m}m^x}{X!} \tag{4.14}$$

The optimum size of the stock is obtained by minimizing the total cost (C_t), given by the expression:

$$C_t = C_s\sum_{x=0}^{x=S_s}(S_s - x)\frac{e^{-m}m^x}{x!} + C_c\sum_{x=S_s+1}^{\infty}(x - S_s)\frac{e^{-m}m^x}{x!} \tag{4.15}$$

For the **practical application of the problem of the optimum level of the** spare parts stock, we take into consideration the following example:

For part “A” we have the following information:

- delivery time: one month;
- annual average of accidental failures: 10/year;
- the unit cost of the part: 1000 units;
- the storage cost of the part: 30% of the part price;
- losses due to decommissioning of the equipment: 3200 units/month.

Based on these elements, we have:

- the cost of preventive storage, for one month:

$$C_s = \frac{1000 \times 0{,}3}{12} = 25 \text{ units}$$

- average number of part failures:

$$m = \frac{10}{12} = 0{,}84 \text{ failures per month}$$

- the probability of having “x” number of shutdowns, taking into consideration Poisson distribution, will be:

By simulating the number of parts in the stock and by calculating the total cost according to relation (1), we will have:

x = number of failures	P(x) = probability of having x failures
0	0,43
1	0,36
2	0,15
3	0,04
4	0,008
5	0,0015
9	0,0002

- For a safety stock equal to 0 ($S_s = 0$):

$C_t = 0 + 3200(1 \cdot 0{,}36 + 2 \cdot 0{,}15 + 3 \cdot 0{,}04 + 4 \cdot 0{,}008 + 5 \cdot 0{,}0015 + 6 \cdot 0{,}0002) =$
$= 2645{,}4$ units

- For a safety stock equal to one part ($S_s = 1$):

$C_t = 25(1 \cdot 0{,}430 + 3200(1 \cdot 0{,}15 + 2 \cdot 0{,}04 + 3 \cdot 0{,}008 + 4 \cdot 0{,}0015 + 5 \cdot 0{,}0002) =$
$= 858$ units

- For a safety stock equal to 2 parts ($S_s = 2$):

$C_t = 25(2 \cdot 0{,}43 + 1 \cdot 0{,}36) + 3200(1 \cdot 0{,}04 + 2 \cdot 0{,}008 + 3 \cdot 0{,}0015 + 4 \cdot 0{,}0002) =$
$= 230$ units

- For a safety stock equal to 3 parts ($S_s = 3$):

$C_t = 92$ units

- For a safety stock equal to 4 parts ($S_s = 4$):

$C_t = 84$ units

- For a safety stock equal to 5 parts ($S_s = 5$):

$C_t = 104$ units

Therefore, for a safety stock larger than 4 parts, the total cost increases, the optimum level of the safety stock being of 4 parts, level for which the total cost is minimal.

4.2. Case study (carried out with the **author's contribution)**

This study presents the way of establishing the expenses for maintenance and preparing an econometric model for establishing these expenses within an aircraft industry repair workshop. For this, we take into consideration the following case (situation): the econometric model of the number of hours of flight according to the maintenance expenses which return to 1 euro as undepreciated value for the aircraft Cessna 172 S.

Defining the econometric model of the dynamics of the number of hours of flight according to the maintenance expenses which return to la 1 euro as undepreciated value for the aircraft Cessna 172 S

The number of hours of flight for an aircraft expresses, in absolute form, the level of its operation. By the particularities of this indicator, in direct relation to the maintenance expenses, we carry out a statistical and mathematical analysis of their interdependence. A viable econometric model will have an importance and a current utility for substantiating the decisions targeting the increase of the flight performances, as duration and safety.

The methodology for analyzing the number of hours of flight is customized by preparing an econometric model which brings into discussion the role and importance of a determining factor represented by the maintenance expenses which return to 1 euro as undepreciated value of the aircraft.

The analysis of the correlation between these two variables, the dynamics of the number of hours of flight and the maintenance expenses which return to 1 euro as undepreciated value, is carried out by applying an econometric method, using as information support the data presented in table 4.1 which makes reference to January-December 2014, for a Cessna 172S aircraft.

Table 4.1. Monthly dynamics of the hours of flight, maintenance expenses, undepreciated value and maintenance expenses which return to 1 euro as undepreciated value, for Cessna 172S aircraft

Month	Hours of flight	Expenses for maintenance materials (Euro/1 hour)	Expenses for maintenance manpower (Euro/1 hour)	Total maintenance expenses (Euro/1 hour)	Coefficient of maintenance expenses which return to 1 euro as purchase cost	Undepreciated value (Euro)	Coefficient of maintenance expenses which return to 1 euro as udepreciated value
Jan.	34,90	17,45	1032,342	1049,792	0,023329	44250	0,023724
Feb.	29,60	14,80	875,5680	890,3680	0,019786	43500	0,020468
March	122,80	61,40	3632,424	3693,824	0,082085	42750	0,086405
Apr.	366,30	183,15	10835,15	11018,30	0,244851	42000	0,262340
May	420,80	210,40	12447,26	12657,66	0,281281	41250	0,306852
June	219,70	109,85	6498,726	6608,576	0,146857	40500	0,163175
July	264,70	132,35	7829,826	7962,176	0,176937	39750	0,200306
Aug.	186,40	93,20	5513,712	5606,912	0,124598	39000	0,143767

Table 4.1 (continued)

Sept.	132,80	66,40	3928,224	3994,624	0,088769	38250	0,104435
Oct.	149,10	74,55	4410,378	4484,928	0,099665	37500	0,119598
Nov.	63,00	31,50	1863,540	1895,040	0,042112	36750	0,051566
Dec.	12,90	6,45	381,5820	388,0320	0,008623	36000	0,010779

Data source: Civil Aviation Senior School

The graphical representation of the correlation between the variables of the studied system (Fig. no. 4.1) provides suggestive information, by the arrangement of the point cloud, regarding the form of the interdependence between the number of hours of flight and the maintenance expenses which return to 1 euro as undepreciated value of Cessna 172S aircraft. During this stage of econometric investigation, we believe it is useful to choose two model versions, which will also ensure a methodological support for comparing and estimating the viability of each of these two models:

- a simple parabolic regression function with the general formula:. $\hat{y} = a + bx + cx^2$ and
- a simple linear regression function with the general formula:. $\hat{y} = a + bx$

In the optional version of the parabolic model, the following calculation and verification operations are unfolded, regarding the statistical hypotheses.

The estimation of the parameters in the parabolic simple regression equation which is seen as analytical form of the studied interdependent system is carried out by the means of the least squares method and it gives the following equation system:

$$\begin{cases} \Sigma y = na + b\Sigma x + c\Sigma x^2 \\ \Sigma xy = a\Sigma x + b\Sigma x^2 + c\Sigma x^3 \\ \Sigma x^2 y = a\Sigma x^2 + b\Sigma x^3 + c\Sigma x^4 \end{cases} \quad ,(4.16)$$

After solving the system of equations, we define the econometric model of the two variables, formalized by the following regression equation: $\hat{y} = 2.488737 + 1226,911 \cdot x + 491,0467 \cdot \mathrm{x}^2$

The values of the parameters from the chosen regression equation, which were estimated by means of the least squares method, are presented in the synoptic table of results (Table 4.2).

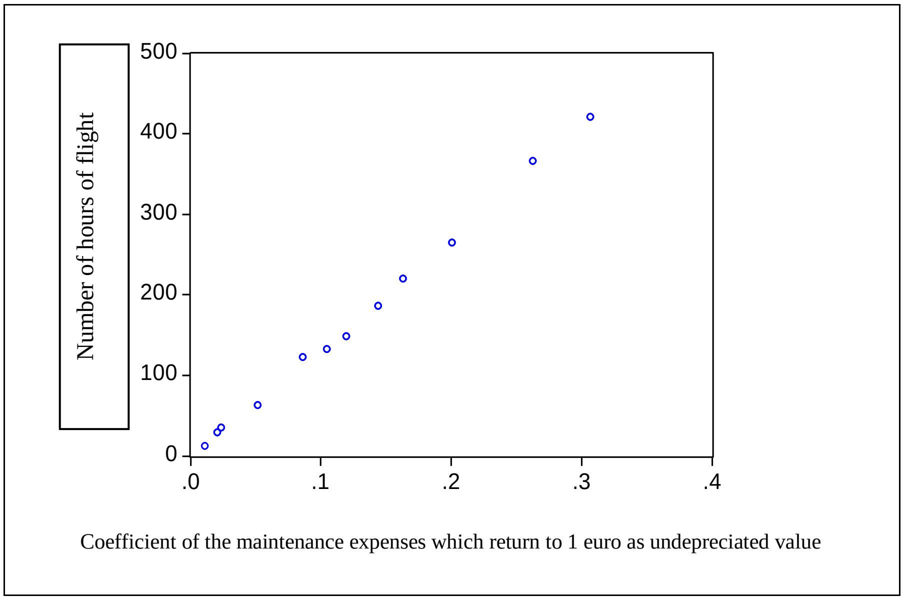

Fig. 4.2 Graphical representation of the correlation between the monthly dynamics of the hours of flight and the maintenance expenses which return to 1 euro as undepreciated value

Calculation and graphical presentation of the main indicators of econometric representation

In the version of the parabolic model of mathematical formalization of the dynamics of the number of hours according to the maintenance expenses which return to 1 euro as undepreciated value, as well as other econometric information results are presented in *"The synoptic table of econometric representation indicators"*, which allow the estimation of the level of certification of the econometric model viability, (Table 4.2).

Table 4.2 The synoptic table of econometric representation indicators which certify the econometric model viability of the correlation between the dynamics of the number of hours of flight and the maintenance expenses which return to 1 euro as undepreciated value (parabolic unifactorial model)

Dependent (endogenous) variable: Hours of flight				
Least squares method				
Analyzed period : January – December 2014				
Number of observations : 12				
Regression equation: $\hat{y}=\mathrm{a}+\mathrm{b}\cdot x+\mathrm{c}\cdot \mathrm{x}^2 \rightarrow \hat{y}=2.488737+1226,911\cdot x+491,0467\cdot \mathrm{x}^2$				
Variables	Coefficient	Estimation of the standard error of the coefficient (Std. Error)	*t*-Statistic	Probability or materiality threshold
„*b*”	1226,911	66,51167	18,44656	0,0000
„*c*”	491,0467	212,6403	2,309284	0,0463
„*a*”	2,488737	4,097869	0,607325	0,5586
Simple coefficient of determination (*R*-squared) $R^2_{y.\mathrm{x}}$	0,998273	Mean dependent variable (Mean dependent var) $\bar{y}$		166,9167
Adjusted simple coefficient of determination (Adjusted *R*-squared)	0,997889	Estimation of the standard deviation of the dependent variable		131,8296

Table 4.2 (continued)

Standard error estimation of regression equation (S.E. of regression) $\pm\hat{\sigma}_{y,\hat{y}}$	6,056563	Akaike statistical information criterion	6,652480
Residual sum of squares (Sum squared resid) $\Sigma(y-\hat{y})^2$	330,1376	Schwarz statistical criterion	6,773707
Log likelihood	-36,91488	F-statistic	2601,269
Durbin-Watson statistical coefficient: *DW*	1,187460	Probability to accept the null hypothesis or the materiality threshold (*F*-statistic)	0,000000
Correlation ratio: $R = R_{y;x} = \sqrt{R^2_{y,x}}$	0,9989439		

<u>Note</u>:

- The indicators presented in the synoptic table of the results were obtained by means of Eviews software.

- In the synoptic table of results, there are also two econometric information indicators (Akaike statistical information criterion and Schwarz statistical criterion) which are useful in making decisions regarding the mathematical model of correlation, the typology and the number of exogenous variables, under the conditions of releasing several model variants. The two indicators have similar values and they confirm a correct decision, or even better, when they have lower values.

Knowing that the statistical and mathematical (econometric) model which formalizes interdependence between the dynamics of the number of hours of flight and the maintenance expenses which return to 1 euro as undepreciated value is represented by the equation of the following parabola: $\hat{y} = 2.488737 + 1226{,}911 \cdot x + 491{,}0467 \cdot \mathrm{x}^2$, we proceed to testing the model viability based on the correlation ratio. We obtain significant support of the model by the confirmation of the statistic hypothesis reffering to the meaning of the correlation ratio between the two variables of the studied system. For this, we use **"*Criterion F*"**, while the proposed verification is carried out as follows:

Calculation of *F*-statistic,

$$F-\text{statistic} = \frac{\Sigma(\hat{y}-\bar{y})^2}{k-1} : \frac{\Sigma(y-\hat{y})^2}{n-k} = \frac{190839{,}3402}{3-1} : \frac{330{,}1376}{12-3} =$$
$$= \frac{95419{,}6701}{36{,}68195556} = 2601{,}269$$

which is compared with *F* – table.

From the table with the values of Fisher distribution function**,** we extract F – table, which corresponds to a probability of 95%, (q = 5%) and to the number of degrees of freedom, $f_1 = k - 1 = 3 - 1 = 2$ şi $f_2 = n - k = 12 - 3 = 9$,

$$F\text{ - table} = F_{P;\, f_1=k-1;\, f_2=n-k} = F_{0,95\,;\, f_1=3-1=2\,;\, f_2=12-3=9} = 4{,}26$$

$$F\text{ - statistic} = 2601{,}269 > F\text{ - table} = 4{,}26$$

In the case of parabolic correlation, between the dynamics of the number of hours of flight and maintenance expenses which return to 1 euro as undepreciated value, F – statistic = 2601,269. Thus, we see that this value significantly exceeds the table value which is 4,26 (F– table = 4,26).

This test fully confirms that the correlation ratio is significantly different than zero or, in other words, the correlation ratio validates the existence of a real correlation between the variables of the studied system.

Table 4.3 Set of real values, of the estimated levels regarding the dependent variable (number of hours of flight) according to the maintenance expenses which return to 1 euro as undepreciated value, based on a parabolic model and the set of residual levels and residue range

<table>
<tr><th>month</th><th>Hours of flight (y)</th><th>Estimated values of the hours of flight, based on the parabolic model $(\hat{y})$</th><th>Set of residual values $(u = y - \hat{y})$</th><th>Residue range $\pm\hat{\sigma}_{y,\hat{y}} = \pm 6{,}056563$
$-\hat{\sigma}_{y,\hat{y}}$ 0 $+\hat{\sigma}_{y,\hat{y}}$</th></tr>
<tr><td>1</td><td>34,90</td><td>31,8724</td><td>3,02756</td><td>| . | * . |</td></tr>
<tr><td>2</td><td>29,60</td><td>27,8069</td><td>1,79309</td><td>| . |* . |</td></tr>
<tr><td>3</td><td>122,80</td><td>112,166</td><td>10,6338</td><td>| . | . *|</td></tr>
<tr><td>4</td><td>366,30</td><td>358,151</td><td>8,14854</td><td>| . | .* |</td></tr>
<tr><td>5</td><td>420,80</td><td>425,205</td><td>-4,40490</td><td>| .* | . |</td></tr>
<tr><td>6</td><td>219,70</td><td>215,765</td><td>3,93540</td><td>| . | * . |</td></tr>
<tr><td>7</td><td>264,70</td><td>267,948</td><td>-3,24821</td><td>| . * | . |</td></tr>
<tr><td>8</td><td>186,40</td><td>189,028</td><td>-2,62754</td><td>| . * | . |</td></tr>
<tr><td>9</td><td>132,80</td><td>135,977</td><td>-3,17706</td><td>| . * | . |</td></tr>
<tr><td>10</td><td>149,10</td><td>156,249</td><td>-7,14881</td><td>| *. | . |</td></tr>
<tr><td>11</td><td>63,00</td><td>67,0613</td><td>-4,06134</td><td>| .* | . |</td></tr>
<tr><td>12</td><td>12,90</td><td>15,7706</td><td>-2,87057</td><td>| . * | . |</td></tr>
<tr><td>Total</td><td>2003,00</td><td>2003,00</td><td>0,00000</td><td></td></tr>
</table>

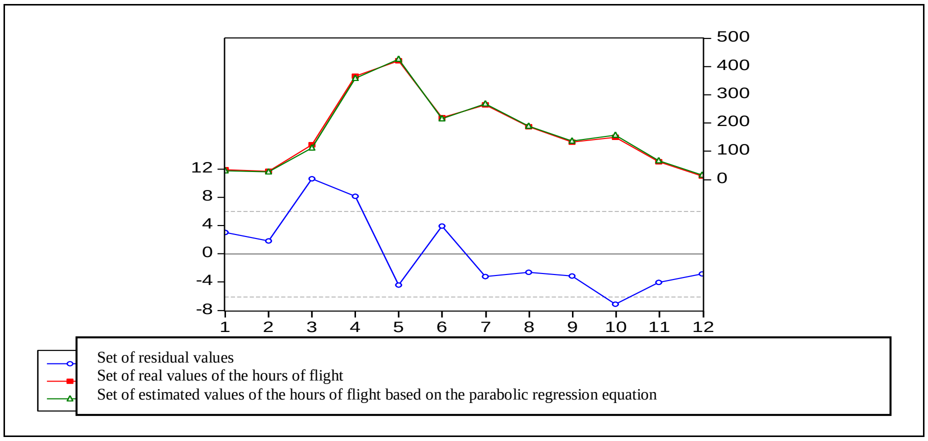

Fig. 4.2 Graphical representation of residues, of the real levels and of the estimated values for the dynamics of the number of hours of flight according to the maintenance expenses which return to 1 euro as undepreciated value

The histogram and the static representation indicators of the set of the error (residual) term are presented in Fig. 4.3. Indicators: mean, median, maximum value, minimum value, standard deviation, (average squared deviation), asymmetry coefficient (Skewness), peakness-flatness coefficient (Kurtosis), Jarque-Bera statistic coefficient (*J-B* = 1,207463) which follow the form of the distribution law χ^2, with 2 degrees of freedom, as well as the probability afferent to *J-B* coefficient (54,6767%) explicitly ensure the statistical features of the residual variable. This group of indicators has as information completion, according to the value of Jarque-Bera statistic coefficient and of the afferent probability, the test for the arrangement of the residual variable in relation to the normal-normalized theoretical distribution. There is enough statistical support for accepting an indecision conclusion regarding the hypothesis of normal positioning of the residues (accepting the null hypothesis) because Jarque-Bera statistic coefficient has a value of 1,207463 and a probability between 50% and 60%, (54,6767%) . Through this conclusion, the indecision solution is supported.

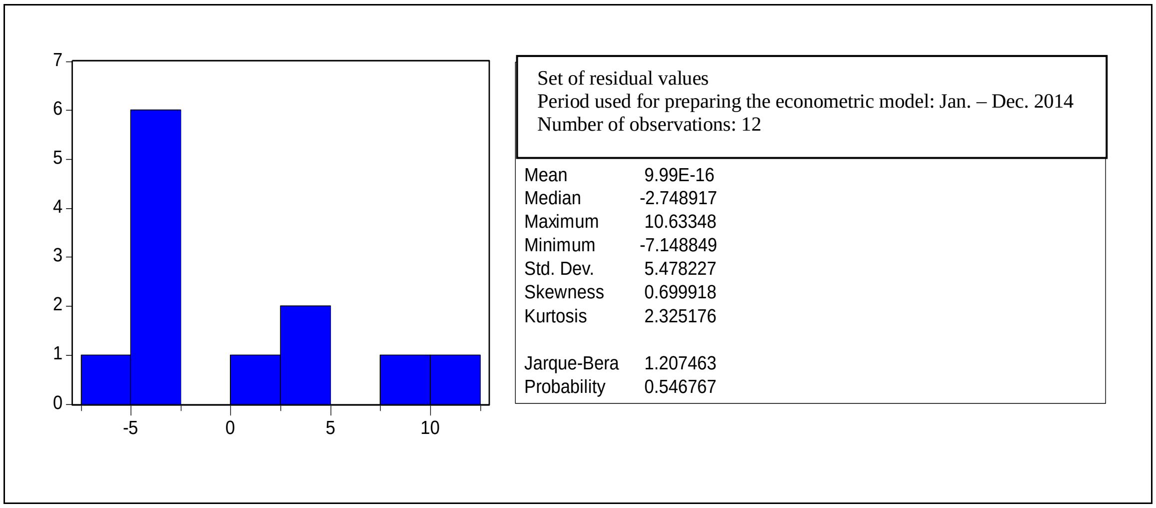

Fig. 4.3 Statistical description of the residual variable and normality test of the residual variable distribution (*parabolic* unifactorial model)

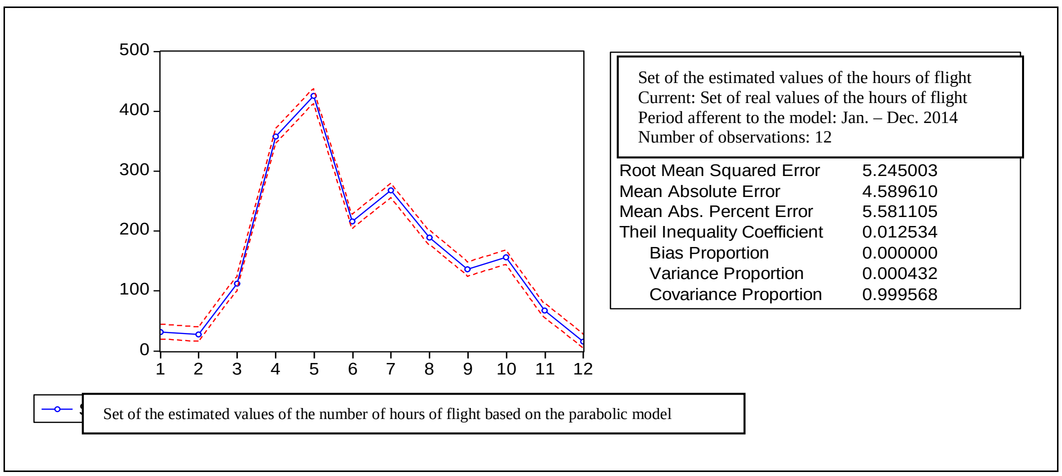

Fig. 4.4 Graphical representation of the set of estimated values of the dynamics of the number of hours of flight according to the dynamics of the maintenance expenses which return to 1 euro as undepreciated value, and of the limits included under the conditions of $\pm 2{,}262$ estimations of the mean error of the parabolic simple regression equation (based on the Student's distribution law with bilateral distribution of the materiality threshold)

$$(\pm t_{q=0{,}05;\ f=n-k=12-3} \cdot \hat{\sigma}_{y;\hat{y}} = \pm 2{,}262 \cdot 6{,}056563)$$

In order to test if the parabolic model is reliable enough for the calculation of certain prognosis estimations, we use:

a - the estimation of the mean error of the relative parabolic regression equation and

b- Theil's coefficient of irregularity (inequality) [84,85].

The mentioned indicators have the following expressions and values:

The estimation of the mean error of the parabolic regression equation,

Absolute expression: $\hat{\sigma}_{y.\hat{y}} = \sqrt{\frac{\Sigma(y-\hat{y})^2}{n-k}} = \sqrt{\frac{330{,}1376}{12-3}} = 6{,}056563$

Relative expression: $\hat{V}_{y.\hat{y}} = \frac{\hat{\sigma}_{y.\hat{y}}}{\bar{y}} \cdot 100 = \frac{6{,}056563}{166{,}9167} \cdot 100 = 3{,}6285\,\%$

Theil's coefficient of irregularity (inequality)

$$Th = \frac{\sigma_{y\cdot\hat{y}}}{\sqrt{\frac{\Sigma y^2}{n}} + \sqrt{\frac{\Sigma \hat{y}^2}{n}}} \cdot 100 = 1{,}2534\%$$

Both the estimation of the mean error of the parabolic regression in relative expression and Theil's coefficient of irregularity (inequality), as shown in figure 4.4, have a value which is positioned under the rejection limit of 5% and thus, we confirm the viability of the model for the representation of the mathematical form necessary for performing an extrapolation calculation.

Heteroscedasticity/homoscedasticity state of residues is tested by means of White test. The results included in the synoptic Table of *"White Heteroskedasticity Test"*, (Table no.4) were obtained by applying Eviews software and they confirm that the residual variable is not heteroscedastic (heteroscedasticity hypothesis is rejected); therefore, the residual variable is homoscedastic. The formulated conclusion is validated both according to "*Criterion F*", *and to "Criterion* χ^2*"*, the materiality thresholds of 48,8924% and of 37,6571% motivate the rejection of the heteroscedasticity hypothesis because they exceed the maximum permissible limit of 5%.

Table 4.4 Synoptic table of "White Heteroskedasticity Test" for parabolic unifactorial model

White Heteroskedasticity Test:			
F-statistic ***„Criterion F"***	0,950530	Probability (materiality threshold)	0,488924
Obs**R*-squared $= n \cdot R^2 = 12 \cdot 0{,}351979$ ***„Criterion*** χ^2 ***"***	4,223750	Probability (materiality threshold)	0,376571
Auxiliary regression equation test; Dependent variable: $u^2 = (y-\hat{y})^2$			
Auxiliary regression equation: $u^2 = z = a + b\cdot x + c\cdot x^2 + d\cdot x^3 + e\cdot x^4$			
Least squares method			
Analyzed period: Jan.- Dec. 2014			
Number of observations included in the research: 12			

Table 4.4 (continued)

Variables	Coefficient	Estimation of the standard error of the coefficient	*t*-statistic	*q* = materiality threshold
"a"	-53,31916	42,71733	-1,248186	0,2521
"b"	4171,048	2255,074	1,849628	0,1068
"c"	-52199,02	30241,81	-1,726054	0,1280
"d"	236928,6	145977,8	1,623046	0,1486
"e"	-353364,6	230494,2	-1,533074	0,1691
R-squared (R^2 - Coefficient of determination)	0,351979	Mean dependent var (Mean value of the dependent variable)		27,51147
Adjusted *R*-squared (R^2 - adjusted – Corrected coefficient of determination)	-0,018318	S.D. dependent var (Estimation of standard deviation of the dependent variable)		33,07877
S.E. of regression (Estimation of the standard error of the auxiliary regression equation)	33,38037	Akaike info criterion (Akaike statistical information criterion)		10,14815
Sum squared resid (Sum squared residue)	7799,744	Schwarz criterion (Schwarz statistical criterion)		10,35019
Log likelihood	-55,88890	F-statistic		0,950530
Durbin-Watson stat	2,221439	Probability (materiality threshold for *F*-statistic)		0,488924

Based on the results presented in the *Synoptic table of "White Heteroskedasticity Test"*, (Table 4.4), we conclude that the residual variable is not heteroscedastic (the heteroscedasticity hypothesis is rejected) and, therefore, the residual variable is homoscedastic, the dispersion of the residual variable is constant, because:

According to ***"Criterion F"*** we have,

$$F-statistic < F-table = F_{q=0,05;\, f_1=k-1=5-1=4;\, f_2=n-k=12-5=7} = 4{,}12$$

$$F-statistic = 0{,}950530 < F-table = 4{,}12$$

$$F-statistic = \frac{\dfrac{\sum_i (\hat{z}_i - \bar{z})^2}{k-1}}{\dfrac{\sum_i (z_i - \hat{z}_i)^2}{n-k}} = 0{,}950530$$

We mention that, among the sums of the squared deviations, which represent the objection for the application of **"Criterion F"**, we can write the following recurrence relation:

$$\Sigma(\hat{z}_i - \bar{z})^2 + \Sigma(z_i - \hat{z}_i)^2 = \Sigma(z_i - \bar{z})^2$$

According to ***"Criterion*** χ^2 ***"*** we have,

$$n \cdot R^2 < \chi^2 - table = \chi^2_{q=0,05,\, f=k-1=5-1=4} \rightarrow 12 \cdot 0,351979 = 4,223750 < 9,49$$

In order to provide broader methodological support, we also prepared a linear unifactorial model of the two variables. The mathematical form of the model (linear regression equation) and the main indicators of information and econometric representation, in this modelling variant, are presented in table 4.5, fig. 4.5 and fig. 4.6.

Table 4.5 Synoptic table of the indicators of econometric representation which confirm the viability of the econometric model of the correlation between the dynamics of the number of hours of flight and the maintenance expenses which return to 1 euro as undepreciated value (linear unifactorial model)

Dependent (endogenous) variable: Hours of flight				
Least squares method				
Analyzed period: Jan. – Dec. 2014				
Regression equation: $\hat{y} = a + b \cdot x \quad \rightarrow \quad \hat{y} = -4,087311 + 1374,064 \cdot x$				
Number of observations: 12				
Variables	Coefficient	Estimation of the standard error of the coefficient (Std. Error)	*t*-Statistic	Probability or materiality threshold
"b"	1374,064	22,81851	60,21706	0,0000
"a"	-4,087311	3,527848	-1,158585	0,2735
Simple coefficient of determination (*R*-squared) $R^2_{y.x}$	0,997250	Mean value of the dependent variable (Mean dependent var) $\bar{y}$		166,9167
Adjusted simple coefficient of determination (Adjusted *R*-squared)	0,996975	Estimation of the standard deviation of the dependent variable		131,8296
Estimation of the standard error of the regression equation (S.E. of regression) $\pm\hat{\sigma}_{y,\hat{y}}$	7,250896	Akaike statistical information criterion		6,951139
Sum squared residues (Sum squared resid) $\Sigma(y-\hat{y})^2$	525,7549	Schwarz statistical criterion		7,031957
Log likelihood	-39,70683	F-statistic		3626,095
Durbin-Watson statistical coefficient: *DW*	0,410099	Probability to accept the null hypothesis or the materiality threshold (*F*-statistic)		0,000000

Correlation ratio: $R = R_{y;x} = \sqrt{R^2_{y,x}}$	0,998624		

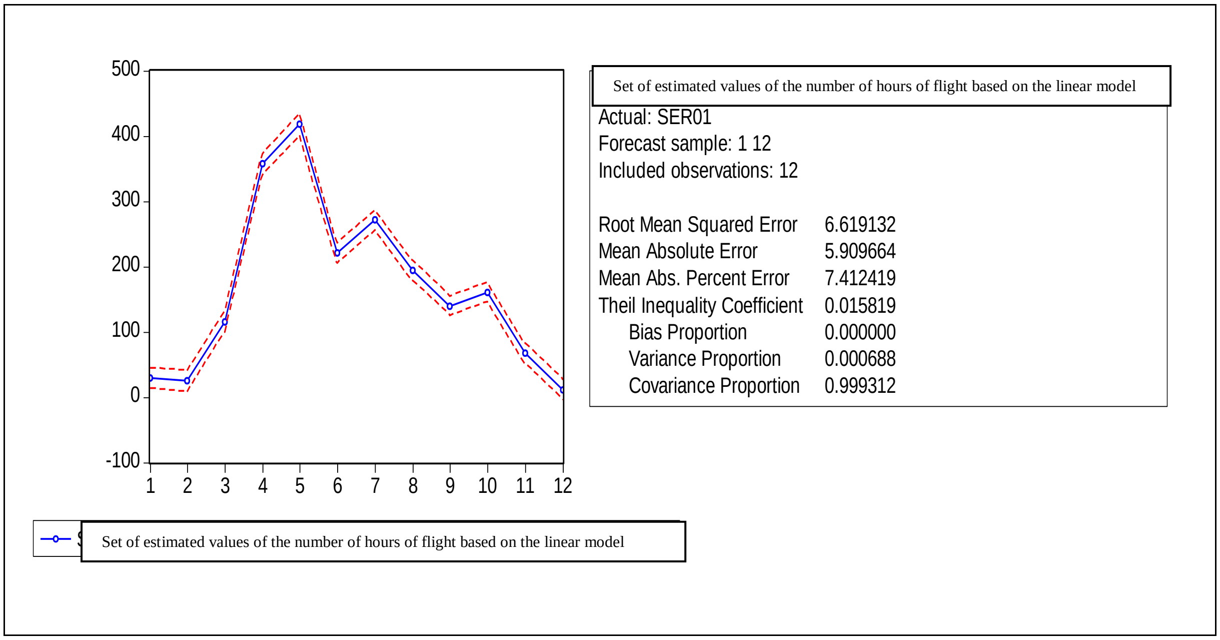

Fig. 4.5 Graphical representation of the set of estimated values of the dynamics of the number of hours of flight according to the dynamics of the maintenance expenses which return to 1 euro as undepreciated value, and of the limits included under the conditions of $\pm 2{,}228$ estimations of the mean error of the parabolic simple regression equation (based on the Student's distribution law with bilateral distribution of the materiality threshold)

$(\pm t_{q=0{,}05;\ f=n-k=12-2} \cdot \hat{\sigma}_{y;\hat{y}} = \pm 2{,}228 \cdot 7{,}250896)$

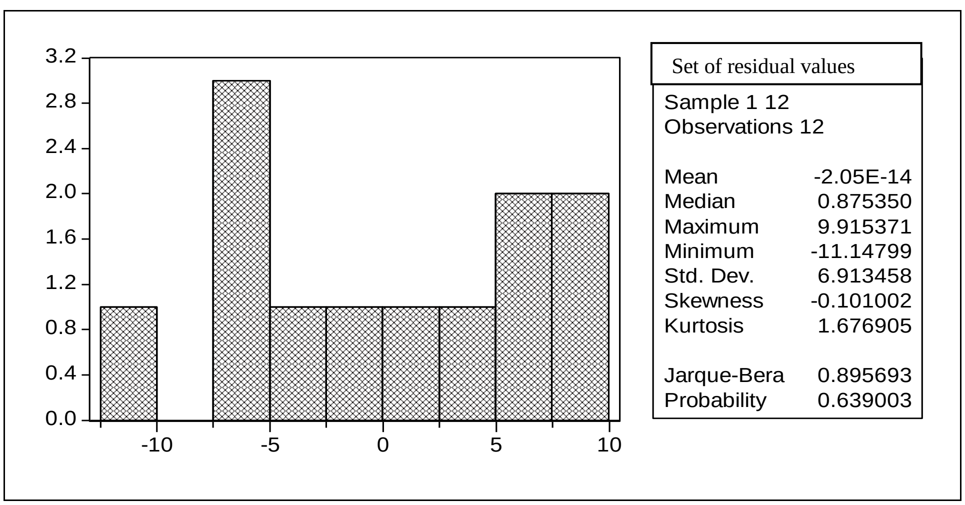

Fig. 4.6 Statistical description of the residual variable and normality test of the residual variable distribution (unifactorial linear model)

The table summarizing comparatively the results for the two linear and parabolic models (table no. 6), identifies very similar values, with a slightly "plus" in favor of unifactorial parabolic model. It concludes, therefore, that the two models are equivalent, whichever provides an acceptable mathematical representation.

Table 4.6 Table of comparative results of unifactorial parabolic model with the unifactorial linear model

Name of the econometric representation indicator	Unifactorial parabolic model	Unifactorial linear model
Simple coefficient of determination	0,998273	0,997250
Correlation report	0,9989439	0,998624
The coefficient of irregularity / inequality of Theil	1,2534%	1,5819%
Jarque-Bera Associated probability	1,207463 54,6767%	0,895693 63,9003%
Estimation of the standard error of the regression equation	6,056563	7,250896
Akaike information criterion	6,652480	6,951139
Schwarz information criterion	6,773707	7,031957

In conclusion, it can be considered that the unifactorial parabolic model of dynamics of the number of hours flown by dynamics of maintenance costs returning to 1 euro depreciated value has a viability above the straight model, but limited especially when extrapolation or interpolation calculations are intended to be carried out. The model can be retained and constitute a mathematical solution of formalization of relatively safe statistical regularities, among the variables included in the model as a source of justification of operational and functional intervention decisions for flight safety of **Cessna 172 S.**

In this context of results that support the viability of the model, it was concluded that maintaining an optimum level of aeroplane maintenance costs propagates a positive trend in the number of flight hours. Maintenance costs relate both to the nature of the materials used and workmanship for inclusion thereof in the work.

4.3. Development and contributions on the application of modern methods and techniques in proactive maintenance of industrial equipment

Given the current state of proactive maintenance described in section 1.8 (pg.12) and point A.4 (pg.41) based on bibliographic research conducted by the author to meet the objectives of the PhD thesis, some approaches of proactive maintenance in terms of industrial practice shall be further analyzed.

After conducting a comparative analysis of the causes of equipment failure, it was noted that the major effect of equipment failure is the wear phenomenon which leads to vibration or malfunction due to misalignment between assembly components. Therefore, the author further presents the issue of proactive maintenance and practical solving in case of certain disturbing factors, as follows:

a. VIBRATIONS

The implementation of the new computerized concept

The design and implementation of the new concept (computer system) should be done as a necessity, such as to answer the following requirements:

- the new system to be practical;
- to be carried out by stages;
- to suit the purpose for which it was created;
- to contain all the functions of maintenance;
- to cover all technical and economic activities (planning, programming, launch and monitoring thereof);

Diagnosis by noise

Numerous experimental and theoretical research shows that between the vibration and the noise level, between the vibration and noise characteristics (dominant areas and peaks in frequency, etc.) for all the elements of the machines in operation, there are correlations.

Diagnosis by noise of the operation status appears as an immediate solution, especially in subjective assessments, on the one hand due to simplicity and productivity and secondly due to the particular sensitivity compared with that of the auditory organ. In other cases, the noise is a parameter preferred the beneficiary in consideration of quality, in relation to certain conditions of use (bearings for electric motors, householding appliances etc.). Finally, diagnosis by noise can be aimed at research, substantiating and quantifying of the noise-vibration correlation.

Vibroacustical diagnosis of machine parts

Diagnosing gear transmissions

Sources of vibration and noise in gears

Usually, the gears are the most important sources of noise and vibration from the structure of mechanical machinery and equipment, with a significant weight in determining overall noise and vibration. The strong growth of power and speed on modern machinery, while reducing gauge, may cause a worsening of vibroacoustic behavior of sprocket transmissions, especially when in the design, fabrication and assembly phase, the optimization criteria of this view have not been observed.

To study the behavior of the gear transmission, the system excitation mechanism has to be established. Excitation sources in the operation of gear transmissions can be internal or external to the system.

Diagnostic in technological control

Diagnostic by vibration or noise in the technological flow is recommended in order to obtain overall indications on the precision of execution and efficiency of the washing, particularly for small and medium-size bearings for applications intended to be silent, of low vibration or uniform rotation.

Due to fitting difficulties in premises where the measurement is made (anechoic rooms), diagnostic by noise are used rarely and only on demand, based on the unified instructions. Diagnostic by controlling the uniformity of rotation is also limited to special applications.

Control, monitoring and diagnosis of balls in operation

In order to prevent ball brutal damage, with consequences in malfunction of other elements of the machine in operation, with high repair costs (balls for large bearings, wheel vehicles, etc.), controlling and monitoring the operation is recommended. Control by vibrations, with mobile or fixed equipment, with data sampling at given intervals or continuously with information for a single point of control, or for multiple points, concurrently or through multiplexing is preferred also in this case.

The easiest method is to use an acoustic probe, placed as close to the controlled ball; the probe transmits through direct contact to the hearing device vibrations captured by direct contact, thus providing subjective information on the bearing state.

Diagnosing sliding bearings

Although sliding bearings as sources of noise and vibration are negligible in construction of mechanic machinery and equipment, they can cause an additional disturbance in operation kinematic chains, usually with a side effect, and they are an important means of transmitting energy vibration in the chassis.

In case of sliding bearings, noise and vibration generated during operation are determined mainly by friction.

Insufficient lubricant supply to bearing, overloading thereof or reversing the rotation of the spindle, results in the mitigation of the lubricant film and the appearance of "bow" phenomenon that produces a noise whose spectrum shows peaks at a frequence equal to the frequency of rotation of the shaft and, at its harmonics, respectively.

b. Excitation caused by dimensional deviations and geometric shape

Dimensional deviations in machine parts undergoing rolling contact.

A global analysis with simultaneous consideration of all dimensional and shape errors is virtually impossible.

An analysis of the separate influence of various errors on vibration energy spectrum is however possible.

Imbalances. When the mass center of a body in rotation does not coincide with the center of rotation, a static imbalance occurs.

Straightness measurement. In the straightness measurement program, the laser beam is used as a reference, using ED unit, measuring the deviations (the distance between the laser beam and the measured object) in two or more positions.

c. Misalignment. The vibrations due to misalignment are characterized by the existence in the spectrum, of a frequency component equal to the frequency of rotation.

Misalignment can cost you money and time. Over 50% of failures of dynamic rotating machinery are due to misalignments of the coupling elements. These failures will cause production stops that directly mean higher costs. In addition, a misalignment means an overload on machine components - shafts, balls, seals, couplings, resulting in wear thereof.

Misalignment is present when the centers of rotation of the two coupling machines shafts do not coincide. There are two types of misalignment: parallel and angular. In most cases, machinery misalignment is caused by a combination of the two types.

d. Mechanical clearance. The existence of games between the elements of an assembly, requested by a load with harmonic evolution in time, modifies the form of response which, although periodically, is no longer harmonic.

e. Mechanical resonance. For mechanical equipment, the resonance regime is performed when the rotation or harmonic frequency thereof will coincide with one of the own frequencies of shafts, housing or attached structures. The vibration due to mechanical resonance is easy to diagnose, since the change in the rotation frequency, distinguishment from other possible causes is performed using the phase which is not maintained constant in relation to the speed.

g. LDE-10 leak detector locates internal and external leaks in pressurized systems. In combination with an ultrasonic generator, it is used to check the tightness of tanks, containers and automobiles.

ELS - 12 stethoscope is a sensitive listening device used for locating any noise source of machinery.

Following those presented in this chapter, the existence of a broad approach of the techniques and tools used in the practice of preventive and proactive maintenance is mentioned. The method of application thereof depends on the complexity of the activities, the type of industrial organization and their infrastructure (types of equipment, human resources, diagnostic tools, etc.)

CHAPTER 5.
PERSONAL CONTRIBUTIONS. FUTURE DEVELOPMENTS AND MEANS OF CAPITALIZING THE RESULTS OF THE RESEARCH

5.1. Final conclusions of the research carried out for the PhD thesis

Following the bibliographic research and theoretical and applied studies presented in this thesis, the following findings and conclusions can be highlighted, as follows:

- the quality of industrial products is determined by a number of notable features of which the reliability and maintenance features, such as an expression thereof with the user;
- the maintenance activity is thought to be regarded as an investment in the future as the increased productivity and equipment precision require manufacturing processes being conducted continuously without failures;
- increasing concerns to monitor equipment operation using the diagnosis methods and techniques specific to proactive maintenance is required.
- given the complexity of the organization and planning of maintenance activities, it is appropriate to collect information on the operational status of the equipment;
- in the event of equipment failure it is necessary to establish the volume of human and material resources to decrease repair times and reduce their costs;
- with the **standards series ISO 31000 (risk management)** and techniques and instruments in risk management (ISO 31010), namely quality management systems – **SR EN ISO 9001: 2015** and environmental management systems – SR EN ISO 14001: 2015, **the global approach to the management of maintenance activities impacting on quality and environment emerges as appropriate**;
- it appears appropriate to provide specific maintenance documentation, which by its nature of documented information is consistent with the above mentioned standards.

5.2. Personal contributions to the research field

In the theoretical and practical research conducted in the field of PhD thesis, the author highlights the following developments, contributions and results as follows:

A. In the field of theoretical research

- an analysis on the topic appropriateness and the approach in terms of theoretical and practical research has been conducted;
- an analysis of the **current state of research** on the quality of products and their lifecycle has been conducted;
- an analysis of the theoretical framework concerning the **place, role and evolution** of maintenance activities in the organizational system has been conducted;
- a **summary of the main concepts and parameters** of industrial maintenance products has been presented;
- a comparative analysis of **methods of analysis and assessment** of industrial equipment maintenance has been conducted;
- a brief presentation of **key indicators** for technical and economic maintenance assessment, referring to the availability of equipment, repair costs, productivity and time;
- an **analytical study** on **determining the optimal timing of replacement of an**

equipment given that in the final phase of its life cycle, the only solution is to replace it with a new unit to match in terms of performance and acquisition costs was presented;

- an **analysis of economic models and strategies** in the maintenance management using operational research methods, namely the cost-based economic analysis was conducted;
- **the author developed a set of documents specific to maintenance** of industrial products, characterized by a high level of generality, being useful for organizations that have not outsourced this work, being carried out internally.

B. In the field of applied research

- considering the importance of human resources, namely establishing their appropriate needs for maintenance activities, **a case study was conducted** with virtual data, for which the author used operational research techniques, namely the Markov chain theory;
- since the proper performance of maintenance requires the existence of spare parts, the author carried out **a case study** (with virtual data) for **determining the optimal level** of the spare parts stock;
- the development after the direct participation of the author of a case study on the determination of maintenance costs and **development of an econometric model** within an aerospace industry workshop, namely for repair of Cessna 172S. This econometric model has proper relevance and usefulness for substantiation of decisions aimed at increasing flight performance as duration and safety level.
- the **use of methods specific to mathematical statistics**, namely the interpretation of econometric indicators for the model viability assessment should be noted;
- highlightment and development focused on practical side of modern methods and techniques used in proactive maintenance of industrial equipment. The adequacy of such approaches is that today there is a development trend of the concerns directed towards **monitoring and diagnosis of equipment operation** as a guarantee of decreasing the number of failures, disruptions in operation and increase in their productivity.

5.3. Future developments in the research field

Given the theoretical and applied studies developed and presented in the PhD thesis, new developments aimed at the following can be provided:

- development of specific methods and techniques of risk management in the maintenance activity;
- rational development and application of diagnostic techniques and methods of operation of industrial equipment;
- development of a centralized database system on factors and analysis of equipment failures;
- the development and widespread development of software on information database (SIVECO Maintenance type);
- increasing the knowledge and capabilities of workers specialized in maintenance activities;
- extending the T.P.M. method in the maintenance activities;
- implementation in Romania of the LEAN Maintenance method;
- greater accountability approach to maintenance activities at the organizational level, one of solutions is the implementation of integrated management systems, namely the quality-risk system, etc.

5.4. Means of capitalizing on the research carried out

PhD formation and, respectively, its deployment have been capitalized by publishing a total of five scientific papers in scientific journals or newsletters.

- Bendic V., Mohora Cristina, Tilina Dana și **Turcu Elisabeta** „Econometric Model of Multiple Equation of Different Shape" 28th IBIMA Conference, *Seville, Spain, 9 - 10 November 2016, http://www.ibima.org/SPAIN2016/papers/vcde.html ;*
- Bendic V., Mohora Cristina, Tilina Dana și **Turcu Elisabeta** „Multifunctional Econometrics Models of Turnover Dynamics of using Primary Factors of the Economic Process" 28th IBIMA Conference,Seville,Spain,9-10November 2016, *http://www.ibima.org/SPAIN2016/papers/vctt.html*;
- *Iacob, Oana Camelia, Volintiru Ana-Maria, Cristea Anca, **Turcu Elisabeta*** – Sustainable position of european countries based on life expectancy at birth and the risk of poverty, Scientific Papers Series Management, Economic Engineering in Agriculture and Rural Development, Vol. 15, Issue 4, 2015 http://managementjournal.usamv.ro/pdf/vol.15_4/Art18.pdf;
- *Ustinia Răchită, N. Mihăilescu, **Turcu Elisabeta**, V.A. Turcu* – Estimarea fondului de rulment financiar al operatorilor economici – Revista Corpului Experților Contabili și Contabililor Autorizați din România;
- *Ustinia Răchită, N. Mihăilescu, **Turcu Elisabeta**, V.A. Turcu* – Analiza dinamicii ratei rentabilității economice și ratei rentabilității capitalului permanent la o societate comercială- – Revista Corpului Experților Contabili și Contabililor Autorizați din România.

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[7] Bendic V., Mohora Cristina, Tilina Dana and **Turcu Elisabeta** "Multifunctional Econometrics Models of Turnover Dynamics of using Primary Factors of the Economic Process" 28th IBIMA Conference, Seville, Spain, 9 - 10 November 2016, *http://www.ibima.org/SPAIN2016/papers/vctt.html*

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