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RELIABILITY AND REPLACEMENT OF VEHICLE FLEET

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Reliability of any product is an integral part of its quality. Depending on the phase of the product lifecycle, certain types of reliability analysis are appropriate. The operational reliability takes into account operational conditions. It can be specified by evaluating the operational data gained during the operation of the object. In the area of operation of road vehicles, it is possible to evaluate records of failures, repairs, maintenance, operation costs, etc. These are stored in an information system or in another digital evidence system and are usable for operation reliability evaluation. The operational data can be also used to prognosticate the development of some reliability parameters. Most of SMEs in the area of transport do not use special software for the monitoring and evaluating of the operational reliability of road vehicles. This article refers to the possibility to acquire some variables of operation reliability from a commonly used Information Systems and to the possibility to create simple programming tool for decision-making and management support in the area of maintenance and replacement of road vehicles by means of common used office software.

Keywords: evaluation, reliability, replacement, road vehicles, software, Excel

1. A Term of Reliability

Reliability is a term which has undergone a long development. It has various interpretations and it is used with many different connotations. In the last three decades the research in the theory of reliability has been intensified and new methods of analysis of reliability, new computational models, methods of reliability test as well as other tools enabling to deliberately influence reliability have been developed.

Reliability of any product is understood as an integral part of a sum of attributes influencing its ability to satisfy the anticipated needs of the user. This ability is called quality. It includes not only reliability, but also many other partial characteristics of the product, e.g. functionality, accuracy, manageability, safety, ecological soundness, aesthetics etc.

In the European norm International Electronical Vocabulary, Chapter 191: Dependability and quality of service, dependability is defined as the collective term used to describe the availability performance and its factors: reliability performance, maintainability performance and maintenance support performance. Dependability is used only for general descriptions in non-quantitative terms. Reliability is the ability of an item to perform a required function under given conditions for a given time interval [1].

There are some attributes of reliability that are commonly used but are not defined in current technical norms. These types of reliability are the following:

- Inherent reliability that originates in the phase of the development of the product and does therefore not include influences by operational conditions, maintenance etc.
- Operational reliability that takes into account operational conditions and can be evaluated after the object has been put in use.

There are different methods to evaluate reliability in every phase.

The reliability evaluation of a product or process can include a number of different reliability analyses. Depending on the phase of the product lifecycle, certain types of analysis are appropriate. As the reliability analyses are being performed, it is possible to anticipate the reliability effects of design changes and corrections. The different reliability analyses are all related, and examine the reliability of the product or system from different perspectives, in order to determine possible problems and assist in analysing corrections and improvements.

Reliability engineering can be done by a variety of engineers, including reliability engineers, quality engineers, test engineers, systems engineers or design engineers. In highly evolved teams, all key engineers are aware of their responsibilities in regards to reliability and work together to help improve the product.

The reliability engineering activity should be an ongoing process starting at the conceptual phase of a product design and continuing throughout all phases of a product lifecycle. The goal always needs to

be to identify potential reliability problems as early as possible in the product lifecycle. While it may never be too late to improve the reliability of a product, changes to a design are orders of magnitude less expensive in the early part of a design phase rather than once the product is manufactured and in service.

The methods for monitoring and evaluating system reliability used most often are Procedure for failure mode and effects analysis (FMEA, FMECA), Fault tree analysis (FTA) and Reliability Block Diagram method (RBD). These are used in the development stage and can evaluate inherent reliability [5].

Failure mode and effects analysis (FMEA) is one of the formal techniques for effective product development. Its main purpose is to avoid as many potential failures as possible by identifying actions in the early stages of design and development [8].

FMEA is an engineering technique used to define, identify and eliminate known and potential failures, problems and errors. Effective FMEA system is basically realized through the system engineering process, research and product development. The focus, in this stage, is to:

- Transform an operational need into a description of system performance parameters through the use of an interactive process of functional analysis, synthesis, optimisation, definition, test and evaluation;
- Integrate related technical parameters and assure compatibility of all physical, functional and program interfaces in a manner that optimises total system definition and design;
- Integrate reliability, maintainability, engineering support, human factors, safety, security, structural integrity, productivity and other related specialities into the total engineering effort.

The goal of the FMEA system is to define and demonstrate a proper balance among operational and economic factors. To accomplish the objective, the FMEA system must base its requirement on solid needs, wants, and expectations of the customer.

Fault Tree Analysis (FTA) attempts to model and analyse failure processes of engineering and biological systems. FTA is basically composed of logic diagrams that display the state of the system and is constructed using graphical design techniques. Originally, engineers were responsible for the development of Fault Tree Analysis, as a deep knowledge of the system under analysis is required. Often, FTA is defined as another part, or technique, of reliability engineering. Although both model the same major aspect, they have arisen from two different perspectives. Reliability engineering was, for the most part, developed by mathematicians, while FTA, as stated above, was developed by engineers.

FTA can be used as a valuable design tool, can identify potential accidents, and can eliminate costly design changes. It can also be used as a diagnostic tool, predicting the most likely system failure in a system breakdown. FTA is used in safety engineering and in all major fields of engineering.

In this technique, an undesired effect is taken as the root ('top event') of a tree of logic. There should be only one Top Event and all concerns must tree down from it.

Another known method of analysis of reliability is the Reliability Block Diagram (RBD). It is designed mostly for systems where no repairs are carried out and for systems where sequence of failures is of no relevance. On the other hand, if the nature of the system requires to take into account the sequence of failures or to carry out repairs, the Markov's analysis is more appropriate.

All the analytical methods mentioned above are described in European norms and they are used in the phase of development of the product or system. Evaluation of the operational reliability is more complicated. As already stated, the operation reliability takes into account operational conditions. It can be specified by evaluating the operational data gained during the operation of the object.

2. Operational Reliability in the Maintenance and Reconditioning Management

The general development of the road transport, especially achieving high transportation capacity, depends on the effective use, organization and management of the road transport. The European Union protects the rights of the users of means of transportation and enhances the quality and security in transport.

Because of the current competitive environment, monitoring and managing the quality and reliability requires systematic approach, which has to focus on use of information and communication technologies.

The situation can be characterized as heavily influenced by extensive knowledge and multiple models of reliability based on the theory of reliability. This process is also influenced by some ISO norms that deal with building systems of quality. Fulfilling the transportation tasks requires securing the most stable reliability of the road vehicle in operation. This is achievable thanks to series of measures and activities, as maintenance, repairs, replacement, etc.

This is the time of important changes in the area of the replacement of vehicle fleet. Vehicles that were manufactured with the idea of pre-planned periodical operational maintenance are approaching the end of their service life. They are being replaced by vehicles manufactured with regard to the service life of individual spare parts as well as the vehicle as a whole.

Using the computer management of maintenance offers basic information documenting the system of maintenance management. It allows to create and access a plan of preventive maintenance of any vehicle, or to retroactively check maintenance of any vehicle, including such details as when, how, by whom, with what costs and what material the vehicle was repaired, and what was the cause for maintenance or repairs in any particular case. The system is also able to offer much additional information, such as the sum of monthly costs of repairs and maintenance or downtime according to the code of failure or of vehicle type, and the trend in their developments, the hours worked on the maintenance, indexes of efficiency and many others.

The management of operation reliability of a vehicle fleet is one of the most important tasks of the technical operation. It is important to know and be able to quantify necessary variables of operation reliability as it is an inseparable part of quality.

Reliability variables may be classified into three groups.

- technical variables, i.e. those characterizing service life, non-fault rate etc., e.g. the duration of service life, duration of operation, malfunction probability, malfunction intensity and the like;
- time variables, i.e. those characterizing time operation parameters, e.g. maintenance duration, repair duration, down time duration etc;
- costs variables, i.e. those characterizing vehicle operation reliability costs parameters, e.g. average costs of replacement per unit of drive output and the like.

Costs items related to the technical state of the respective object, or more precisely to the changes in the technical state of the respective object, which can be continuously observed while the respective object (road vehicle) is used, may be exploited as costs parameters. Changes in the technical state provoke changes in selected kinds of operation costs.

There are three significant forms of costs parameters related to operation of road vehicle: cumulative costs, average costs and immediate costs [7].

- Cumulative costs represent a function of operation duration; in a given time t reflect the total sum of costs since the beginning of the operation until the given time t. They inform about the total sum expended on operation through the time.
- Average unit costs express the average sum imposed on the unit of operation duration since the beginning of observation.
- Immediate unit costs express elementary increase in costs for elementary increase in operation duration. These are those most closely connected with changes in the technical state of a vehicle.

Costs parameters are characteristic not only of their dependence on the changes in the technical state, but on the current prize level as well. This can be perceived as a disadvantage as well as an advantage, as it is the prize level that influences the weight or the importance of any kind of interference in the area of maintenance and reconditioning in given operation conditions in given time [3].

3. Computer Support of Operational Reliability Evaluation

Observation and evaluation of operation reliability of road vehicles as well as acquisition and evaluation of other parameters, that could be helpful in decision-making and managing of the technological maintenance and reconditioning of road vehicles, can be integrated as a part of Information System.

Even if there are special information systems for the maintenance management, they are usually too expensive for smaller enterprises.

Currently, the most of the enterprises use centralized information system, which is usually modularly formed. Its only module is sometimes equal to a maintenance management module. However, IS are usually oriented on economics and logistics (accountancy, HR, storage, invoices, etc.) and there is minimal benefit for the maintenance management (if there are used for that purpose at all).

Available net applications aimed at maintenance management are suitable for that purpose regarding their utility characteristics and satisfaction of the needs of the management maintenance system, but their prize is not acceptable for SMEs. Therefore, many small enterprises prefer to order

bespoke software of lesser scope. The analysis and designing phase of an appropriate model of IS as well as the creation of a database (i.e. supplying the input parameters phase) is lengthy and there are many potential pitfalls for both partners – enterprise and programmers as well. If the designed system is too large-scale and relatively complex, its creation and initiation takes too long, not less than two years, and costs are too high for a small enterprise as well. Therefore, it is very common that an enterprise use a commercial system for accountancy, wages, logistics and the like. Then, the workers of maintenance use smaller-scale software, whose creation and initiation they supported themselves.

Even in the case of absence of any software for management maintenance, it is possible to acquire data which can be used e.g. for the evaluation of operation reliability or for the prognosis of the development of some observed parameters from a "classical" Information System. There is an appropriate and often used programming tool: commonly used office software – database or spreadsheet calculator.

Owing to the nature of transport activities, the questions of maintenance, repairs, reliability monitoring etc. are handled together with logistics and transport services. In reality, monitoring and evaluating of reliability is often of secondary importance, or, eventually, there is no computer support for reliability monitoring at all. On the other hand, it may be expected that there is an evidence of failures and repairs in some form in any company. Moreover, it may also be expected that any company uses a spreadsheet calculator, usually the MS Excel. Among its more advanced tools are pivot tables and charts that can be successfully used to create outputs, overviews and calculations in the form of tables and charts regarding the maintenance, repairs, failure rare, reliability etc. The presented software is based on the very same pivot tables, which are simple and of great information value.

The system is based on a register of spare parts used and work done in maintenance and repairs of a road vehicle kept continuously in a database. Consequently, it offers an overview of some reliability variables displayed as tables or charts and it enables to check the logistics development trend for any component group or for the vehicle as a whole [4].

The software consists of a package of templates and books in MS Excel, named Evidence, Time, Cost and Replacement and a special program in Visual Basic named Prognosis [6].

It was generated by using the tools of the spreadsheet calculator MS Excel, especially pivot tables, charts and macro programming in Visual Basic for Applications.

The following pictures illustrate the whole software and the Evidence file that serves also to run the Time, Costs and Replacement modules [5].

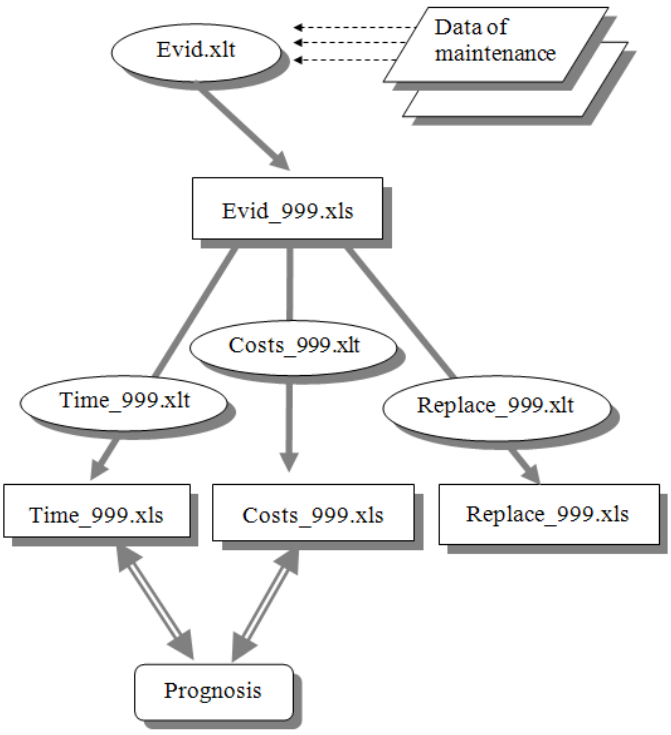
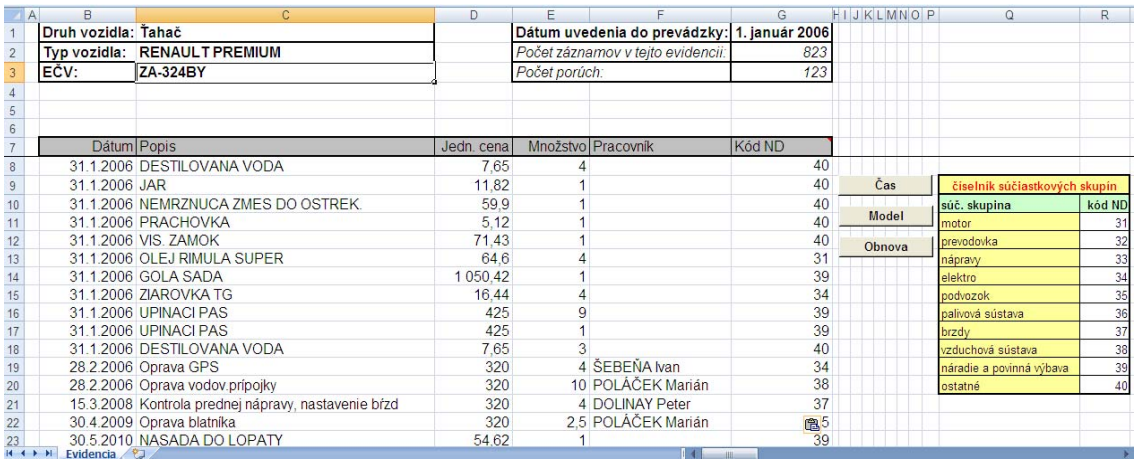


Figure 1. Scheme of the software

The Evidence file (Evid_999.xls) represents the basis of the whole processing. This book has a single sheet containing the evidence of individual spare parts and additional material used and work done in repairs of a specific road vehicle in the course of its service.

There are identification data of a vehicle, the date of the start of its service, the number of records in a given time and the number of registered failures. (Cells G1 to G3).



1	Druh vozidla:	Ťahač		Dátum uvedenia do prevádzky:	1. január 2006
2	Typ vozidla:	RENAULT PREMIUM		Počet záznamov v tejto evidencii:	823
3	EČV:	ZA-324BY		Počet porúch:	123

Dátum	Popis	Jedn. cena	Množstvo	Pracovník	Kód ND
31.1.2006	DESTILOVANA VODA	7,65	4		40
31.1.2006	JAR	11,82	1		40
31.1.2006	NEMRZNUCA ZMES DO OSTREK.	59,9	1		40
31.1.2006	PRACHOVKA	5,12	1		40
31.1.2006	VIS. ZAMOK	71,43	1		40
31.1.2006	OLEJ RIMULA SUPER	64,6	4		31
31.1.2006	GOLA SADA	1 050,42	1		39
31.1.2006	ZIAROVKA TG	16,44	4		34
31.1.2006	UPINACI PAS	425	9		39
31.1.2006	UPINACI PAS	425	1		39
31.1.2006	DESTILOVANA VODA	7,65	3		40
28.2.2006	Oprava GPS	320	4	ŠEBEŇA Ivan	34
28.2.2006	Oprava vodov.prípojky	320	10	POLÁČEK Marián	38
15.3.2008	Kontrola prednej nápravy, nastavenie brzd	320	4	DOLINAY Peter	37
30.4.2009	Oprava blatníka	320	2,5	POLÁČEK Marián	5
30.5.2010	NASADA DO LOPATY	54,62	1		39

Čas
Model
Obnova

číselník súčiastkových skupín	
súč. skupina	kód ND
motor	31
prevodovka	32
nápravy	33
elektro	34
podvozok	35
palivová sústava	36
brzdy	37
vzduchová sústava	38
náradie a povinná výbava	39
ostatné	40

Figure 2. Example of data in the Evidence sheet

The specific records consist of the data: Date, Description, Unit price, Amount, Worker, ND Code (Cells B7 to G7). These records are created gradually in the course of service of the road vehicle and are ranged in accordance to date. The "Worker" data contains the name of a worker in the case of work done in repairing the vehicle; in the case of spare parts used the column rests empty. An example of input data can be seen on Figure 2.

Evidence file serves as the source of data for consecutive processing the Costs, Time and Replacement books, that are activated by macro buttons (Čas, Model, Obnova), as seen on Figure 2. The data in the Evidence can be acquired also by exporting and adjusting the data from the business information system into an Excel table, if the system used contains such data but does not monitor the reliability. The ND code is assigned to the records according to the encoding contained in the Table 1.

Table 1. Encoding

Spare parts groups encoding	
Spare parts group	**Code**
motor	31
gear	32
axles	33
electronics	34
chassis	35
fuel system	36
brakes	37
air system	38
tools and compulsory equipment	39
other	40

To enable a successful use of this book, continuous evidence including the correct ND codes is required. Moreover, the data from the book are to be used as the single common data source for the Costs.xls (button "Model"), Time.xls (button "Čas"), and Replacement.xls (button "Obnova") books.

The Costs.xls and Time.xls books allow acquiring various overviews and values concerning the reliability indexes by using the pivot tables and charts. These books can be created by running macro directly from the Evidence book. The macro copies the records on evidence into the Costs.xlt and Time.xlt templates and so the prepared pivot tables, pivot charts and calculations of reliability indexes are updated [6].

The module Prognosis is a program to search for Logistic Curve ("Logkrivka" button) variables that can be run on some sheets of Costs and Time books. This enables to prognosticate the development of monitored indicators in the future [5].

Logistic function or logistic curve is the most common sigmoid curve. It models the S-shape of growth or decreasing. These functions find applications in a range of fields, e.g. neural networks, ecology, biology, medicine, economics and reliability, too.

A logistic function is defined by the mathematical formula:

$$y(x) = \frac{a}{1 + c.e^{-b.x}} . \tag{1}$$

Parameters a, b, c >0 in the case of increasing function.

This program uses the smallest square method to search the parameters a, b, c on the bases of data from the evidence book. Idea of this method is minimalizing the sum of squares of expressions:

$$\sum_{i=1}^{n} \left(y_i - \overline{y}_i \right)^2 , \tag{2}$$

where $[x_1,y_1]$, $[x_2,y_2]$,…, $[x_n,y_n]$ are in our case the data from the Evidence file exported to the Cost and Time books. This module computes the values of logistic function on the basis of data from the pivot table, and prognosticates the trend.

Pivot table with the rate of occurrence of failures of spare parts group 37-brakes for a specific road vehicle complemented by output from the module Prognosis (Logistic curve/Logkrivka) is on Figure 3 [6].

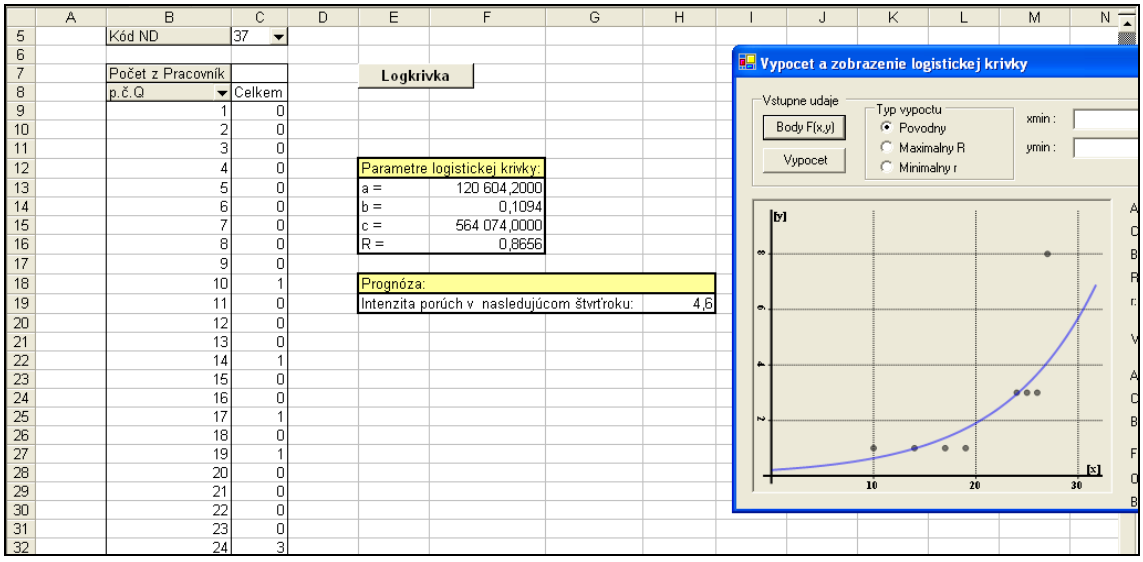


Figure 3. Rate of occurrence of failure complemented by logistic curve and prognosis

The book Costs has some other sheets with various outputs. They can be used for managers to show rather overviews of development of number and costs of maintenance, spare parts and work done in all spare parts groups during the operation of road vehicle. Here is some another of them:

Figure 4 illustrates review of price of work done in maintenance in accordance with spare parts groups (ND codes 31-40) by quarters of years in operation duration.

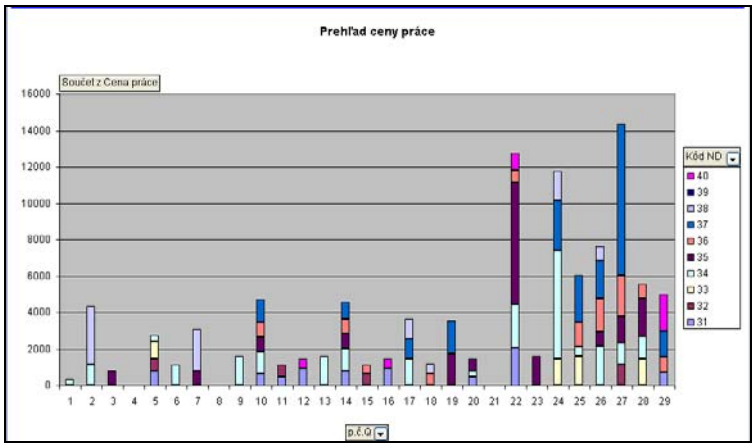


Figure 4. Pivot chart - price of work in maintenance

Another sheet contains the chart based on the same data as the last one. But this is created not as pivot, and it is complemented with trend lines and equations of regression polynomial functions. This sheet is designed more for students of informatics and road transport than for managers.

Figure 5. Chart with trend lines

There is an output with development of all costs of maintenance according to spare parts groups by quarters of years in operation of road vehicle at another figure. It is a pivot table complemented with output from the Prognosis (Logkrivka) module.

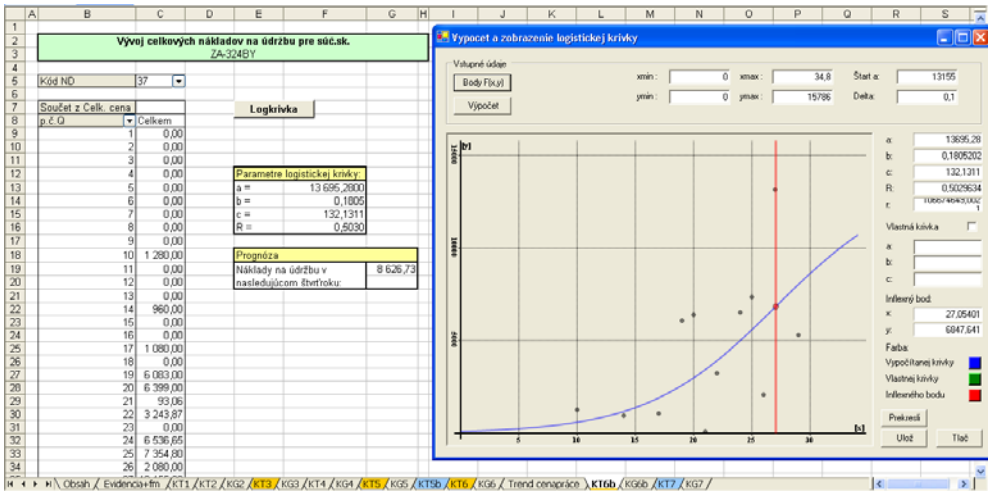


Figure 6. Development of all costs of maintenance

Time indicators are contained in the Time.xls book. Pivot table and pivot chart offering the information on gradually decreasing time between failures of the spare parts groups 37-brakes are seen on Figures 7 and 8.

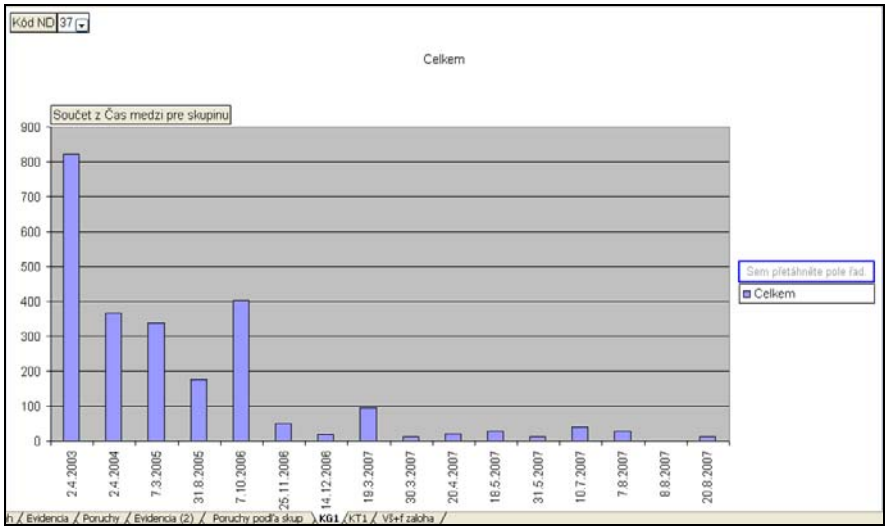


Figure 7. Pivot chart – decreasing time between failures

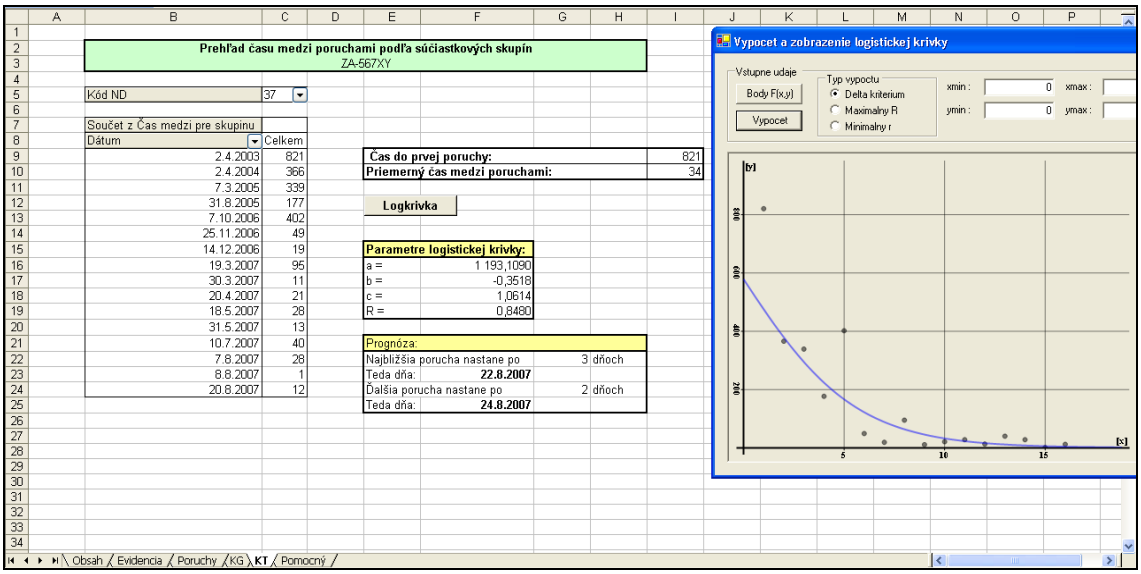


Figure 8. Output of the Time book with prognosis the next failure

The macro ran from Evidence book can also activate the Replacement template and create the Replacement book, aimed to calculate the time for optimal replacement of the object. by using the function of immediate costs of replacement with the help of the Excel function to add a trend line to the chart and get corresponding equation of regression function. While applying the regression function for a few periods ahead, we acquire some prognosis of development of the observed variable.

4. Determining Optimal Time for Replacement

Various methods of determining optimal time for replacement of a machine to be based on information on costs of replacement of the machine and history of costs related to the operation of the machine.

The value of costs of replacement N_0 can be for each object (a vehicle, a machine or its part) easily calculated basing on actual market price of the machine C_P and qualified estimate of costs related to

machine's installation C_I, transport C_T, necessary downtime due to replacement C_{DT} and salvage value of the machine C_{SV}:

$$N_O = C_P + C_I + C_T + C_{DT} + C_{SV} . \quad (3)$$

The operational costs $N_P(t)$ represent the financial amount that must be expended in order to ensure the desired machine's operation. The value of operational costs is typically a function of machine's time of operation and for a complex of the following items [2]:

$$N_P(t) = N_b(t) + N_e(t) + N_z(t) + N_u(t) , \quad (4)$$

where

N_b – costs of labour (wages of operating staff)
N_e – costs related to energy (fuel) consumption
N_Z – costs related to loss or deterioration of working material, scraps, etc.
N_u – costs of maintenance

The method used in this software is based on the cumulative operational costs function, from which, by derivation, the function of instantaneous unit costs $v_p(t)$ is obtained. Then the value of t_o is found by measuring the area above the curve of $v_p(t)$ according to Figure 9. At the time of t_o the shaded area equals N_o:

$$N_0 = t.v_p(t) - \int_0^t v_p(t) . \quad (5)$$

Basing on the indicated equation, the formula for direct calculation of t_o can be determined (this formula is specific for different types of approximation functions).

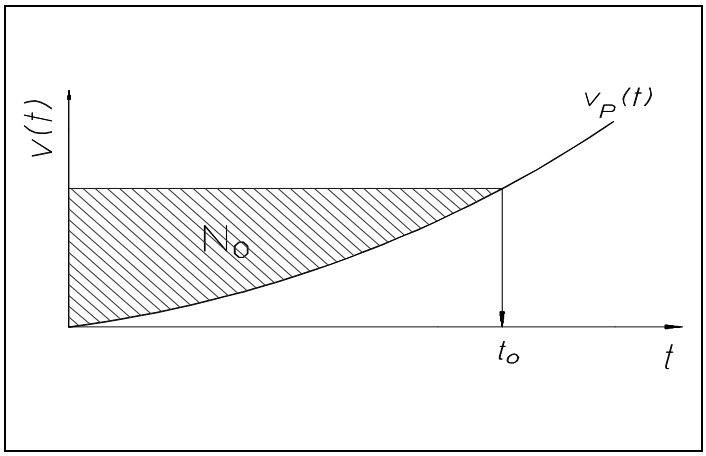


Figure 9. Function of instantaneous unit costs

This algorithm is implemented into the Replacement module by using the following MS Excel tools and functions:

- The operational costs during the operation are summed
- The chart of cumulative costs is created
- The trend line in this chart is added and the analytical expression of regression function is shown
- The derivation of this function is obtained – it is the function of instantaneous unit costs $v_p(t)$
- The time for optimal replacement is calculated

All this steps are full automatically by using prepared macros. There are two types of approximation function used in this module:

- Polynomial function
- Power function

In the case of approximating of polynomial function $y = a.t^2 + b.t + c$ its derivation is the function of instantaneous unit costs $v_p(t) = 2.a.t + b$.

If N_0 is the value of costs of replacement, the formula for calculating of optimal time to replacement is

$$t = \sqrt{\frac{N_0}{a}} \,. \tag{6}$$

In the case of approximating of power function $y = a.t^b$ is the function of instantaneous unit costs $v_p(t) = a.b.t^{b-1}$ and the formula to calculating of optimal time t for replacement is as follows:

$$t = \sqrt[b]{\frac{N_0}{a.(b-1)}} \,. \tag{7}$$

These formulas are used in cells of Excel and the optimal time for replacement is calculated. Output of the Replacement book is shown on Figure 10.

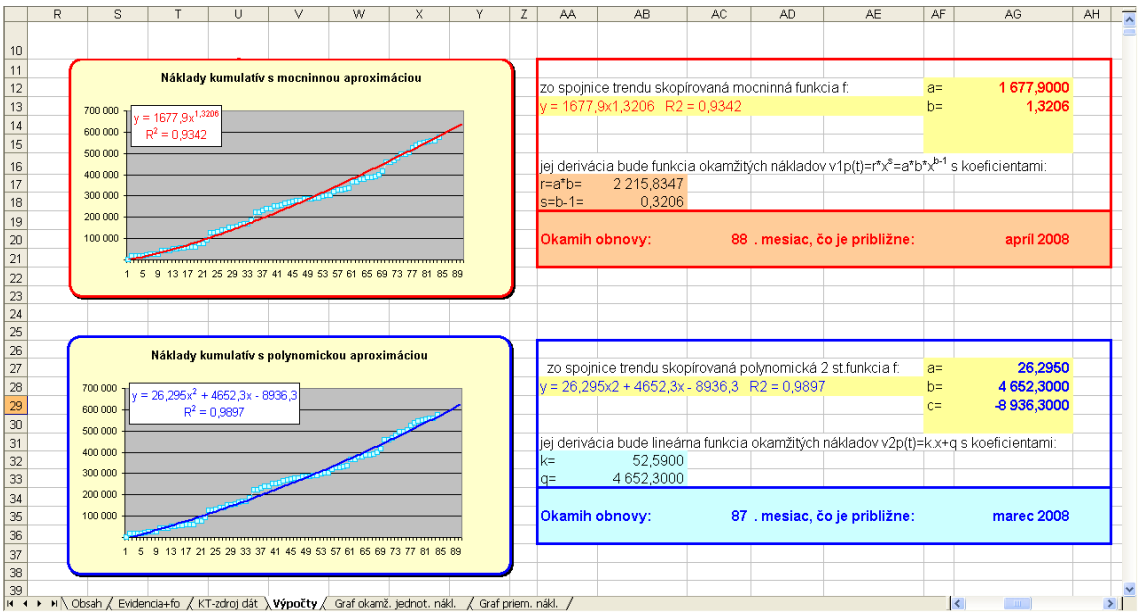


Figure 10. Charts of cumulative costs with trend lines and optimal time for replacement in case of power and polynomial function (optimal time is 88th or 87th month of operation of road vehicle)

After running macro "Replacement" from the Evidence book the user needs to enter or update the values in the "Costs of replacement" field for the actualised value of optimal time for replacement of the vehicle to be calculated.

A situation can occur, when none of the trend lines offered by the spreadsheet (MS EXCEL in our case) for the chart design is appropriate for the regression of development. Then it is possible to use its complementary part Solver or to create a simple application using e.g. searching for a regression function by the smallest squares method. Of course, many activities may be automated even in Excel by using macros.

5. Conclusions

This software support of decision-making in the maintenance and repair process has been created on the basis of an analysis of the use of an IS for maintenance in a few firms providing cargo transportation. The survey was carried out in three firms in the Žilina region. All deal with national and

international cargo transportation; each has around 80 vehicles and the firms are comparable also in terms of amount of number of employees, transport capacity, and outputs.

The first firm has not yet implemented an IS. The firm has opted for creation of its own, relatively complex and massive system that is being developed by an external IS firm. The overall conception and some modules are already finished, but the user firm has realized that there is a human-resources related problem with inputting data into databases. The data processing needed for operational management is not carried out systematically and it's done mostly via MS Excel. The software presented in this paper has not yet been tested in the firm.

The second firm does not implement a complex IS and it uses only the software for specific tasks such as dispatching or accounting. This firm decided to test our software even if it does not keep appropriate digital data from past operation of road vehicles. Since January 2009, it has been keeping evidence for 5 selected vehicles. It is too soon to evaluate the results.

The third firm uses two independent information systems, one for accounting and the other for other agendas. The second system includes databases Stock and Repair. By importing data from these databases, a file with the evidence of maintenance and repairs needed for testing our software. The testing has been carried out for six vehicles and further evidence and data-processing are ongoing. The management of this firm is aware of possible assets of the software for maintenance management support and they intend to start keeping evidence for each vehicle.

As the processing is automatic and supported by various macros, this software product can be also used by a not very skilled MS Excel user. This tool has a potential to be used in information system of operation reliability of road vehicles for the needs of managing the technological process of maintenance and repairs. After a little adjustment, this software support for monitoring and evaluating the reliability can be also used for other objects of maintenance than road vehicles.

Similar approach is appropriate if there is an SME not using any special Information System for the maintenance management, that would offer suitable ground for decision-making and managing in the technological process of maintenance and reconditioning of road vehicles.

The software is simple and user-friendly, with low hardware requirements and it's easily compatible with other platforms of business information systems or maintenance management systems. Thanks to these qualities, as well as its low cost, it is especially suitable for SMEs in the transport business that could find the purchase of a complex information system with an integrated support for the operation, maintenance and repairs of road vehicles beyond their needs and means.

Given example can provide a basis for special software, which, if being developed with knowledge of the given enterprise and not expected to be grand and universal, can provide higher quality in the process of maintenance management, while costs are kept low and design period short. This can profoundly influence the operation reliability of the enterprise's vehicle fleet, lower the costs of reconditioning, and lower the inventory level in the spare part warehouse and the like. In this way, the total costs can be lowered and the profit increased.

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