MODELING THE DEPENDABILITY AND COST OF MAINTENANCE

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ABSTRACT

The paper deals with possibilities of stochastic approaches in risk modelling from a point of costs and data relating reliability aiming to define needed parameters of distribution of stochastic variables. It presents outputs from developed and applied simulation models, to assess reliability, maintainability, availability, costs and risks from operational data.

1 INTRODUCTION

Dependability issue can not been dealt in an insulated way as how it has unfortunately happened till now, but, only in a thorough full system approach in respecting technical, technological, economic and other interactions to assess a risk. From a general understanding of reliability it is not essential to express partial features of reliability, but to assess an optimum of a whole system taking all effecting components into consideration. A rate of optimum can be expressed using an interrelationship between relating models, that evaluate more partial features and they express e.g. an operational effectiveness of the system in a form:

$$PU(t) = (R(t), U(t), A(t), N(t), RM(t)) \qquad (1)$$

where:
$PU(t)$ ... operational effectiveness of the system,
$R(t)$ ... system reliability,
$U(t)$ ... system maintainability,
$A(t)$ ... system availability.
$N(t)$ ... maintenance costs,
$RM(t)$ ... risk of a mission

In an above mentioned simplified approach we can understand an operational effectiveness as an ability of a given technical system to meet given function in certain time period and in given conditions. An operational effectiveness understood in such a way is a certain quality and utility criterion of the system and it is expressed by its technical and economic parameters, in conditions in which the parameter has risen, in which it is operated and is maintained. It features an operational effectiveness as a relation of a level of a fulfilment of reliability and maintainability, costs and a risk.

It expresses an operational effectiveness through a probability, that a level of fulfilment of a system function will meet requirements, that a system will be working in a given time period with no breakdowns and that in a specified time period it will be ready for operation at allocated costs. It defines significant elements and evaluated cost kinds and amounts; it reviews an object – a personal land-rover and costs aiming to provide a high level of readiness.

Quantitative analysis through a simulation modelling provides a computation (an estimate) of some selected quantitative numeric values of chosen indicators of reliability.

A numeric value of an indicator can be obtained through experimenting with a model with a computer taking into consideration simple events, which the model structurally relates with behaviour and analysed states of the system. Model and all input parameters are of a stochastic nature, and a result of the analysis is stochastic, burdened with a certain rate of uncertainty, which can be reduced, but not completely eliminated.

It is very difficult, sometimes impossible to express an intersection of probability of several events with different kinds of distribution. Aim of a submitted paper is to explain simulation approaches to analyses on a particular example of an analysis of operational events with a sufficient sample of a reviewed type of personal land-rovers. Analyzing of data is to be used to define parameters of distribution of variables as reliability, maintainability, readiness, costs and assessment of risk rate. To carry out simulation experiments and their assessment.

2. APPROACH TO A PROBLEM BEING SOLVED, USED METHODS, EXPERIMENTS

2.1 Operational data a analysis

The above mentioned analysis represents an evaluation of 1451 failures of all kinds of particular group and systems. It comes from reports on failures in operation and from user service centres. The failures are statistically processed in a needed form for a next use in form of variables distribution parameters and used in simulation experiments. The subject-matter of the review was a set composed of 56 personal land-rovers with a different number of failures and kilometres driven by operational units. **Figure 1** and **Figure 2.**

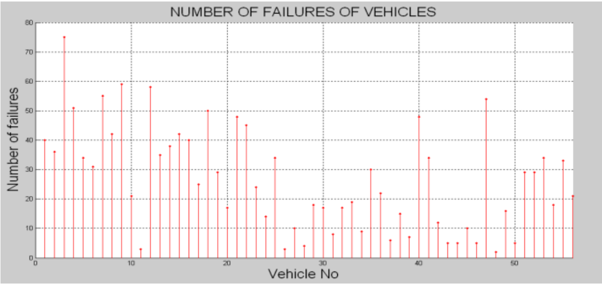


Figure 1 Number of vehicle failures

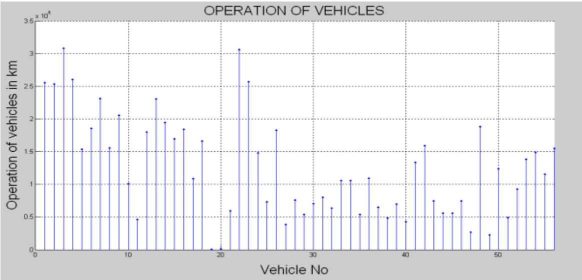


Figure 2 Number of km driven

The reviewed data were evaluated by groups as an engine with systems, gear system, steering, brake system, electrical installation, bodywork and a framework. Percentage portion of failures in particular groups are shown in **Figure 3**. Number of failures in particular groups in relation with number of km driven by cars is in the **Figure 4**.

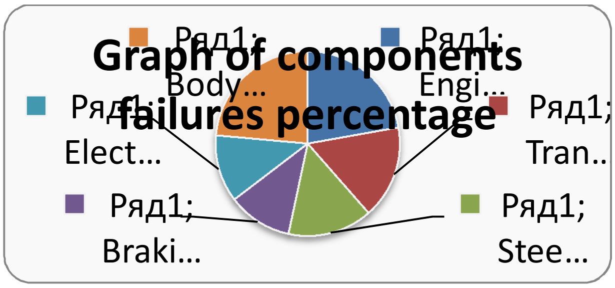


Figure 3 A chart of a portion of failure groups in percentage

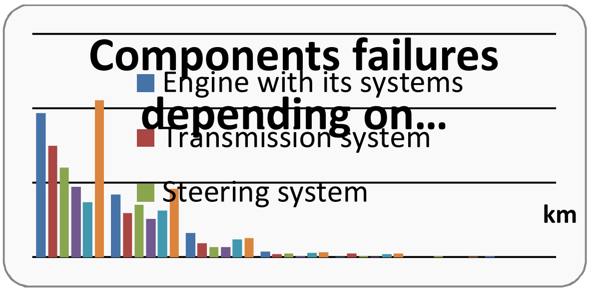


Figure 4 Failures in groups in relation with kms driven

From above mentioned data we assessed a drive turn failure– it is a distance driven by a vehicle between two failures - DTF and payload for a failure removal. We computed a distance between failures into time between failures –TBF in hours. We deduced a time to repair from payload for a failure removal (time to repair) – TTR in hours.

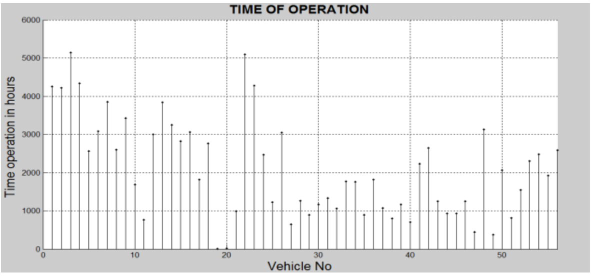


Figure 5 Time for operation of vehicles

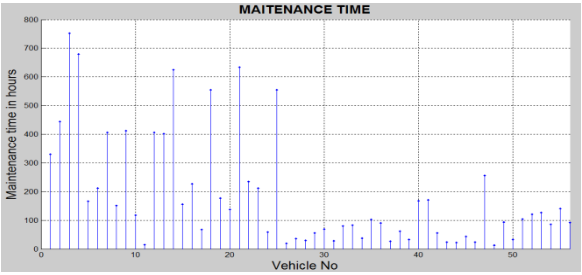


Figure 6 Maintenance time of vehicles

The costs have been reviewed by number of vehicle failures, number of kms driven and by costs on preventive and follow-up maintenance of particular groups.

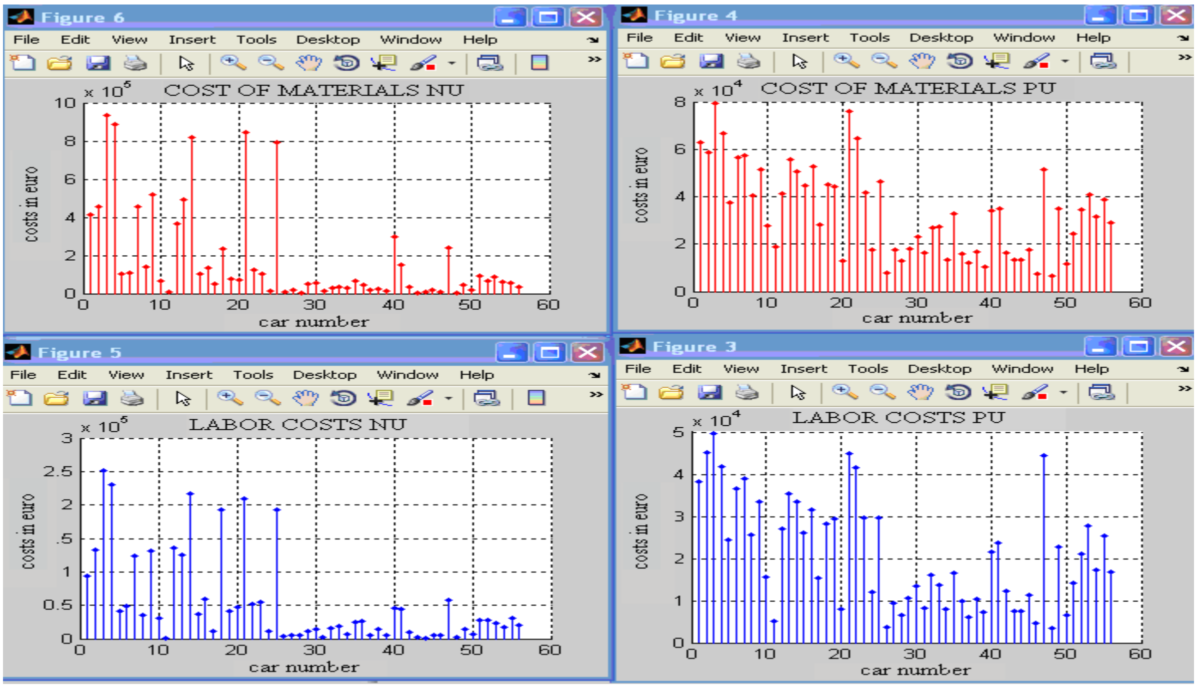


Figure 7 Input data on costs on individual vehicles

Other data have been deduced by simulation modelling.

We assessed the gained data; we expressed hypotheses on their probability distribution. We dealt with thesis Exponential probability and Weibull probability hypotheses.

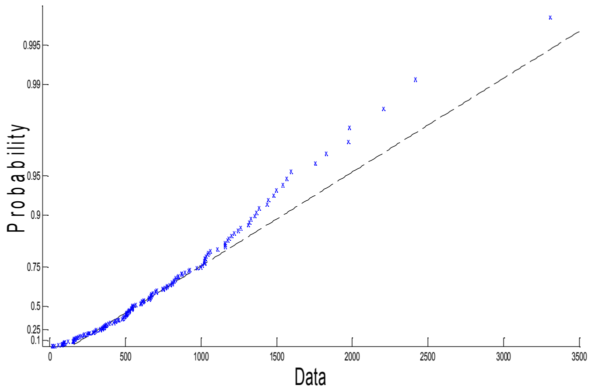


Figure 8 Verification of the probability distribution of the time between failure by means of exponential distribution

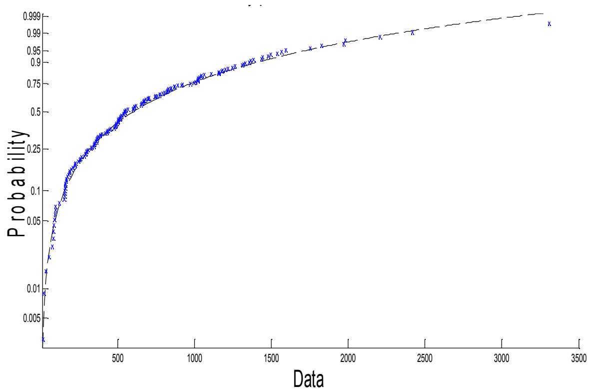


Figure 9 Verification of the probability distribution of the time between failure by means of Weibull distribution

Figure 8 and **Figure 9** show that TTF can be simulated by Weibull distribution.

We chose a more suitable hypothesis, that we have verified and defined the parameters of distribution with a confidence level 100(1 - alpha) = 99.9. We acted in the same way in defining all distribution parameters.

2.2 A Stochastic approach to the analysis of reliability, maintainability and availability

It stems from a term model of a Reliability Block Diagram. It makes provision for a probability of rise of events in complex systems, representing various arranged structures being formed by elements. A structure of the system can be expressed by a record:

$$M_k = \{ E_1, E_2, \ldots\ldots E_k \} \tag{2}$$

Particular symbols mean:
M_k – a system with „k“ number of elements,
E_i – i-th element of the system.

A structure of elements can be serial one, parallel or combined. The systems with a serial connection, which are typical for mechanical systems, are arranged one behind the other and they are independent. A failure of one element causes a loss of an operation capability of a whole system. The system is operational, if all elements are in a serviceable state. If we designate a reliability of the i-th element E_i as R_i, so the reliability of the system is a product of reliabilities of all elements:

$$R_S = R_1 \times R_2 \times R_3 \cdots R_n = \prod_{i=1}^{n} R_i \tag{3}$$

The reliability of a serial system is lower that the most reliable element of the system. Confidence of a reliable operation of a serial system with an increasing number of elements decreases and a probability of a failure occurrence increases. A vehicle in a model can be presented as a system with a serial arrangement of elements, where the elements represent the main design groups of the vehicle. A serial arrangement is chosen because if one system fails, so the whole vehicle becomes operationally incapable. If we can express a probability of a reliable operation of elements through the parameters of distribution of random variable intervals between failures, a total probability of a reliable operation can be expressed through aggregate statistical parameters defined from values of a total number of generated data.

A simulation model of an analysis of reliability with a selection of a decisive event is based on the following principles:

- The system will be divided in serial subsystems.
- We generate values of periods between failures of particular elements.
- From a time of a failure rise of subsystems we are selecting the highest values of the time rise of failure and we use them in incorporating the system in a serial structure.
- From the times of a rise of a failure of serial arranged subsystems we select the least value of time of a failure rise.
- Process of generating a selection of events is repeated until number of executions is completed.
- We collect statistical data about periods of operation, a total number of failures and other needed data.

As a rule we assess only non-reparable elements and systems. The elements of repairable system can be analyzed separately aiming to define statistic parameters of reliability or to define a final probability of a reliable operation of the system. Generally we have to suppose a final level of reliability characterized by an availability of a system in a draft of repairable mechanical systems composed of several subsystems or elements. One of possible ways is an assessment, resulting from a known or an estimated level of availability of particular subsystems. The aim is to define an availability of a system from knowing indicators of partial features of reliability maintainability and provision of maintenance of individual components.

A starting point for a draft of a model of system availability is a so called state analysis, in which the state may occur. The system may be in many and different states, whereby each of them is defined by a combination of individual elements. Likewise each element of the system may occur in different states that randomly take turns. Such process, when the states of objects being monitored change randomly in time, are called the Markov random process.

The states in mechanical system are expressed the most often through a bi-state model. The system may occur either in a functional or a non-functional state depending of a state of particular elements. If the transition between these states take turn randomly and they can appear any time, that random process is called a simple process of a restoration. Reliability of objects being repaired is characterized first of all by indicators of availability, that describe in a complex way their reliability and maintainability. Indicator of availability is a function or a numerical value being used for a description of a distribution of probability of a particular (random) parameter characterizing an availability of the object. Generally such parameter is a state of object that changes randomly in time.

The probability, in which state the object (an element, a system) occurs in a given time period is describe by a function of an immediate availability $A(t)$ for a serviceable state or a function of an immediate non-availability $U(t)$ for a non-functional (unable for operation) state. The $A(t)$ and $U(t)$ function are complementary each other, an aggregate of their values in a given moment is equal to 1.

The function of an immediate availability $A(t)$ expresses a probability, that an object is able in a given time period to fulfil a requested function in given conditions, provided that the necessary external means are assured.

This indicator is not used in practice very often, as an immediate availability is not generally a point of interest, but a level of its availability related to a certain time period.

A factor of an asymptotic availability A is used very often in a technical practice and for a stabilized process of renovation provided that:

- logistic, administrative and technical delays are negligible,

- distributions of a random variable for a reliability and maintainability are exponential ones.

The relation for a deterministic computation:

$$A = \frac{MTBF}{MTTR + MTBF}$$

(4)

where

MTBF – mean time between failures,

MTTR – mean time to repair.

A factor of an asymptotic availability characterizes a certain stable level of availability that the object gradually approaches with an increasing time of operation.

All other statistic methods established based on stochastic principles lead always to a non-constant function of availability *A*, i.e. a function of availability dependent on an operational time *t*.

Building of deterministic models of availability stems from a notion, that a time function between failures and a time needed to remove a failure in failing of the *Ei* element have the same distribution of parameter probability, as the elements, they consist thereof.

They lead the most often to an exponential or Weibull distribution of probability. The time flowcharts of failure rate and repairs, or other stochastic effects during provision of reliability of complex systems in real operation are not considered in such models.

In a real case, the operational reliability, or its partial features are related with processes, needed to provide a removal of a failure (a control process, a supply system, repair process, etc.). Therefore a model can have as well several states and distributions of randomly variables.

These facts can be expressed by a simulation modelling.

We use the fact, that probabilities of the time of a rise of part failure and time of a failure removal are parameters with stochastic nature that may occur in wide range of parameters.

A proposed solution can be expressed in the following way:

A. We divide the *Mk* system in subsystems, or elements

Partial systems are analyzed separately and the conclusions are final ones for a system assessment.

B. Statistic regularities of subsystems (elements) of a model are described by:

- distribution of probabilities of intervals of the rise of failures,
- distribution of probabilities of an active period of maintenance,
- or distribution of probabilities of next shut-downs.

C. We define, which states are important for analysis of a system and which we want to express through a simulation. We can merge some states.

D. We define output parameters; we want to process statistically and to express them graphically.

E. We establish a computer-aided simulation model and we perform experiment that we evaluate.

2.3 Simulation modelling of costs and their risk rate

Specification of requirements for reliability of a transport means is first of all an issue of looking for an acceptable compromise between a requested level of reliability and a level of costs, which will be needed for its achievement. Provision of reliability in a stage of application is however dependent on allocated sources for a provision of maintenance.

If we start from a definition of a reliability, which is understood as an ability of the object in meeting a needed function in given conditions and in a given time interval, we can note, that a main reviewed feature of a reliability is a functionality of the object. From this view knowledge of function is a starting point in defining requirements for reliability, whose fulfilment is expected from an object. Amount of costs for provision of maintenance is conditioned on maintainability in addition to reliability. We achieve knowledge of assessment functions by above mentioned approaches. Costs on maintenance of particular groups and a vehicle as a whole and their division may serve as a background for assessment of risks related to the failures of equipment. It represents an effective tool and an important source of information for decision-making in area of management.

There is a certain rate of uncertainty connected with each function of transport means, that it will be carried out in a different way than requested and that possible deviations from an expected function will have an unwanted consequence on a result of the function of the object as a whole. Therefore there is a certain risk, understood as a combination of probability, that a certain event occurs (a failure) and consequences (costs), which would occur, if an event would happen.

The existence and knowledge of consequence itself or a probability of an event rise does not need to lead to a rise of an unacceptable risk. If an unwanted event has no serious consequence, then even at a high probability of its rise, the risk related with it can be acceptable as well. It is valid vice-versa, of course.

Risk is a quantitative and a qualitative expression of a menace; it is a rate of a menace or a level of a menace. It defines a combination of a probability of a rise of an unwanted event (a failure) and a range of relevance of a possible amount of costs, resulted from a rise of a transport means failure. Such definition being in line with valid legislation enables monitoring of a rate of occurrence of negative events (failures, accidents, disasters) but their consequences as well, that means a great advantage for a strategy of risk management.

The risk expression is made the most often through a function of a probability of a rise of a negative case or an event and as a consequence of an unwanted event (Note: not always it relates a product of these events):

$$R = P \ x \ D, \qquad (5)$$

where: R – is a value of a risk,
P – probability of a rise of a negative case, event,
D – consequence of an unwanted event.

The input parameters of risk expression are random parameters; we can express and model their relations, which will be mentioned in the next point of the paper.

3 DESCRIPTION OF ACHIEVED RESULTS

3.1 Analysis of reliability, maintainability and availability

We performed simulation experiments with parameters of distribution of accepted hypotheses, through programmes developed in MATLAB. Simulation experiments were done by a discontinuous simulation with a variable time step. We registered necessary data of simulation experiments at advance of simulation time.

Periods between failures of particular groups of vehicle and a maintenance period are illustrated by probability density in the **Figure 10** and **Figure 11**.

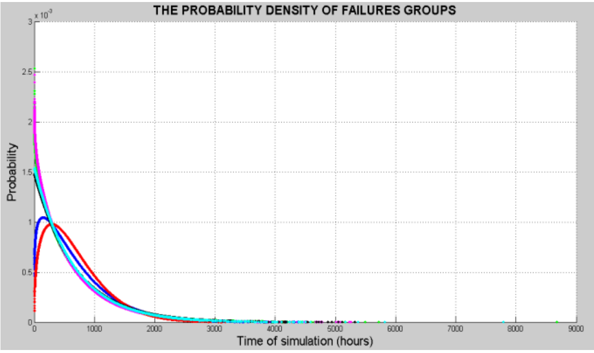


Figure 10 Density of a probability of time between failures of groups

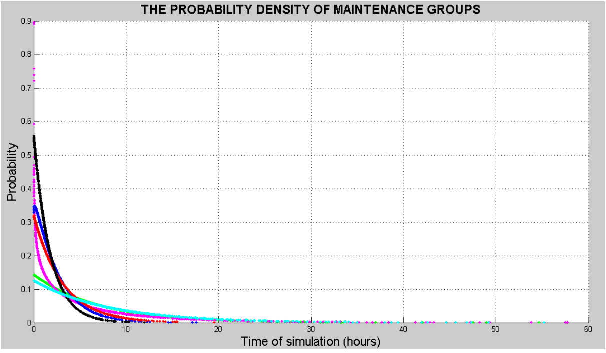


Figure 11 Density of probability of time of maintenance of groups

The reliability is assessed with a model mentioned in Chapter 3.1. Generating failures and their visualization creates a notion about a rise of failures and a ratio of particular groups in failures and failures of vehicle as a whole **Figure 12** and about time between failures **Figure 13**.

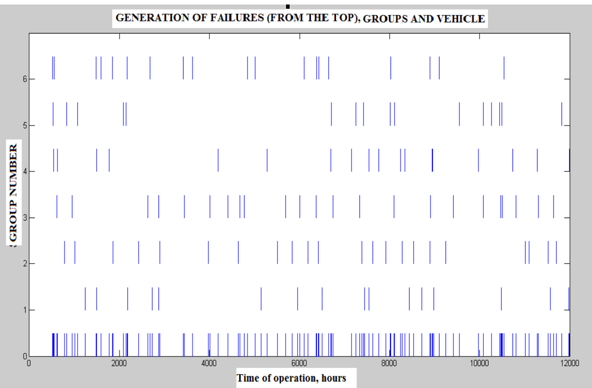


Figure 12 Ratio of particular groups in failures and failures of vehicle

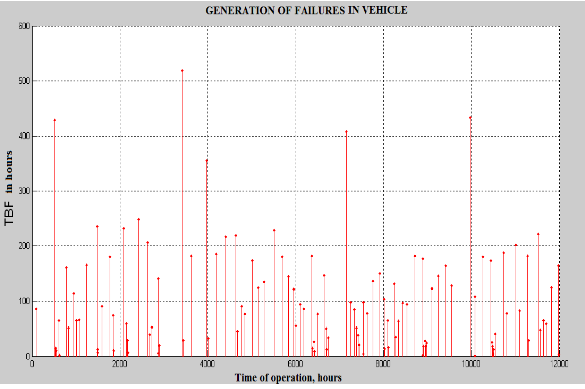


Figure 13 Generated periods between failures of vehicle

The same procedure was used in analyzing maintainability. Availability of particular groups was assessed through simulating 10000 hours of operation, representing 600000 km driven, with parameters of periods between failures and time of maintenance distributions for accepted hypotheses. The availability of a land-rover was simulated with a precondition, that in a case of a failure of any of groups the vehicle is to be repaired, it means, and that a serial repairable system is dealt. Principle of a shift by a time step accepted a choice of a decisive event. They have been generated from a time of rise of group failures. A minimum event of a group with the least time to failure has been chosen. A time till repair has been chosen for a group failure and a next period between failures was included into events calendar. The simulation time has been shifted.

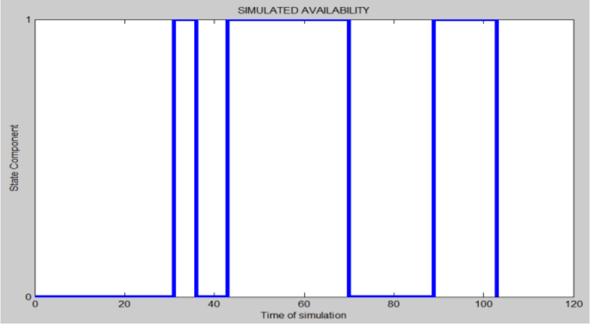


Figure 14 Simple process of restoration

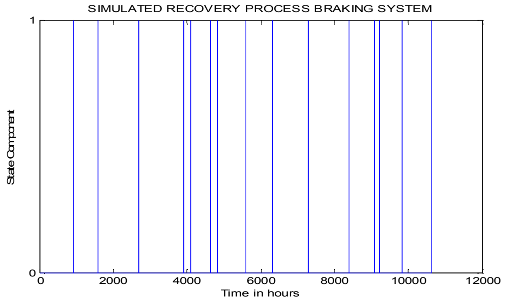


Figure 15 Process of renovation for a braking system

Particular groups show high factors of an asymptotic availability. The values of the factors do not differ significantly the groups are balanced from a view of reliability.

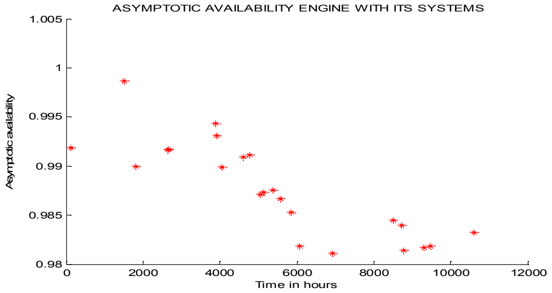


Figure 16 Asymptotic availability for an engine and its systems

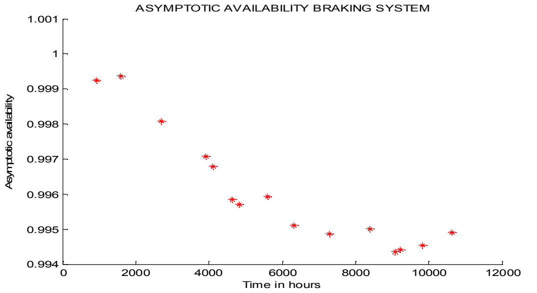


Figure 17 Asymptotic availability for a braking system

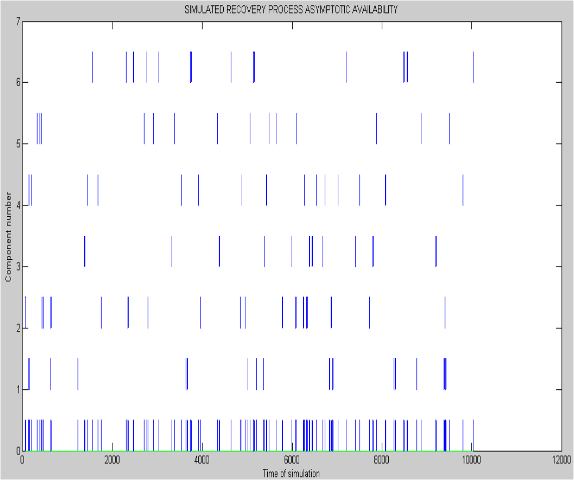


Figure 18 Renovation process of the vehicle and its groups

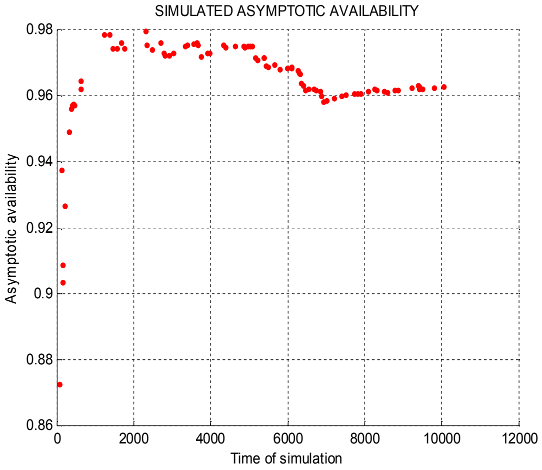
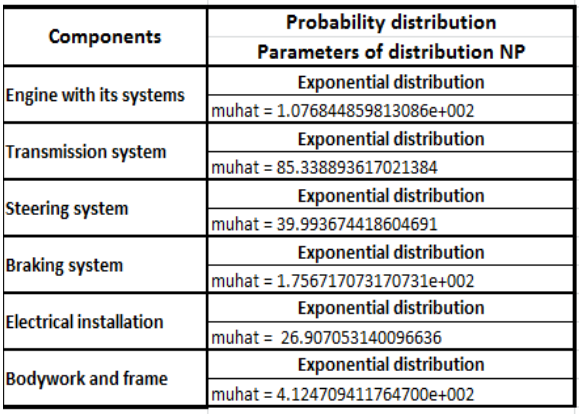


Figure 19 Asymptotic availability of the vehicle

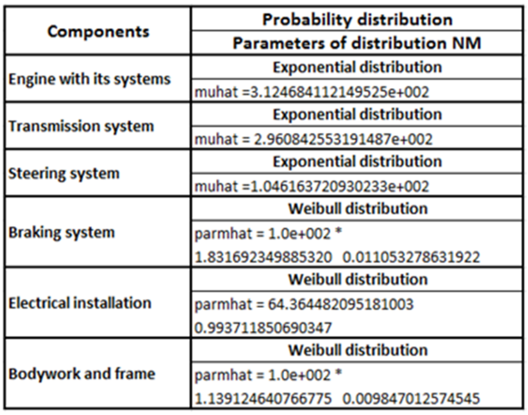
3.2.Analysis of costs and a rate of their risk

Maintenance costs for particular groups of vehicle statistically processed and they show the distribution parameters illustrated in the **Figure 20** and **Figure 21**.
and courses of function for a probability of density and distribution function in the **Figure 22** and **Figure 23.**



Components	Probability distribution
	Parameters of distribution NP
Engine with its systems	Exponential distribution
	muhat = 1.076844859813086e+002
Transmission system	Exponential distribution
	muhat = 85.338893617021384
Steering system	Exponential distribution
	muhat = 39.993674418604691
Braking system	Exponential distribution
	muhat = 1.756717073170731e+002
Electrical installation	Exponential distribution
	muhat = 26.907053140096636
Bodywork and frame	Exponential distribution
	muhat = 4.124709411764700e+002

Figure 20 Distribution parameters of labor cost groups



Components	Probability distribution
	Parameters of distribution NM
Engine with its systems	Exponential distribution
	muhat =3.124684112149525e+002
Transmission system	Exponential distribution
	muhat = 2.960842553191487e+002
Steering system	Exponential distribution
	muhat =1.046163720930233e+002
Braking system	Weibull distribution
	parmhat = 1.0e+002 * 1.831692349885320 0.011053278631922
Electrical installation	Weibull distribution
	parmhat = 64.364482095181003 0.993711850690347
Bodywork and frame	Weibull distribution
	parmhat = 1.0e+002 * 1.139124640766775 0.009847012574545

Figure 21 Distribution parameters cost of materials groups

From a course of costs distribution functions we can conclude a range in which the costs would occur. The costs for material, assessing a mean of probability 0.5, define an increasing order for costs in cost groups as electric installation, steering, body, and a frame, braking system, gear system, engine with systems **Figure 22**.

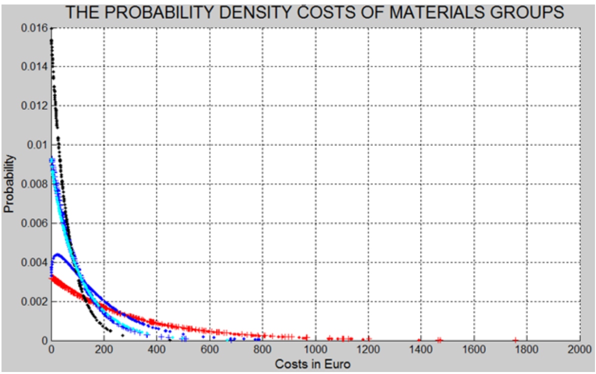


Figure 22 The probability of density costs of material groups

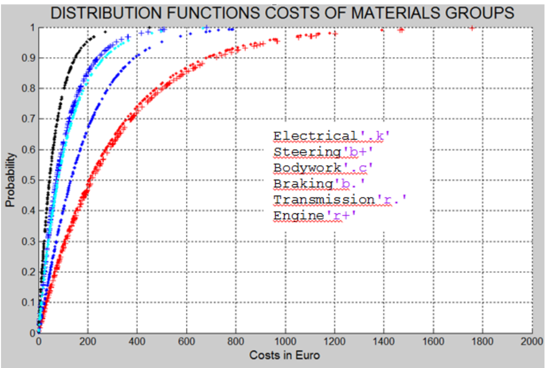


Figure 23 Distribution functions of costs of material groups.

At labor costs the order is electric installation, steering, gear system, an engine with systems, a braking system, body and a frame **Figure 25.**

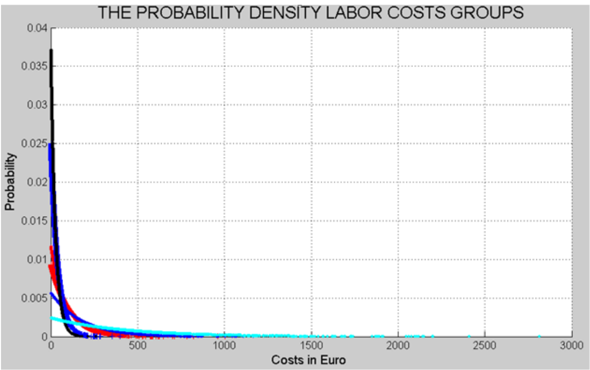


Figure 24 Probability of density of labor costs groups

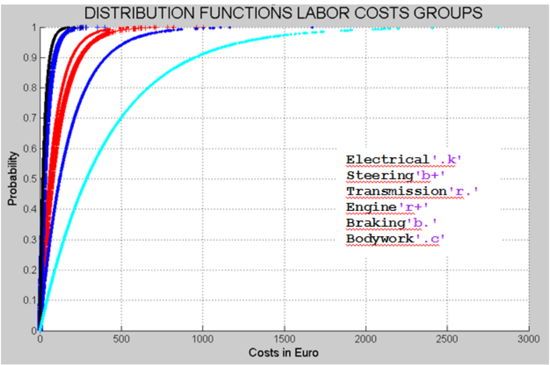


Figure 25 Distribution functions of labor costs groups

We use a function of density of a failure probability as a rise of a negative event – a failure and an amount of total costs as a result of an unfavourable event.

Visual expression of an intersection of these events gives us a notion about a rate of rise of critical situation. We can quantify this fact and to express it by probability of risk matrix.

We will use a distribution of a failure probability to generate a rise of a negative event – a failure and a distribution of a probability of costs to generate the amount of costs resulted from an unwanted event.

Graphic expression of an intersection of these events in a point of costs matrix and operation in hours provides us with a perception relating with quantification if a risk situation rises. Aggregations of their occurrence and their quantification on the legs enable comparing the risks from costs for maintenance of objects being assessed.

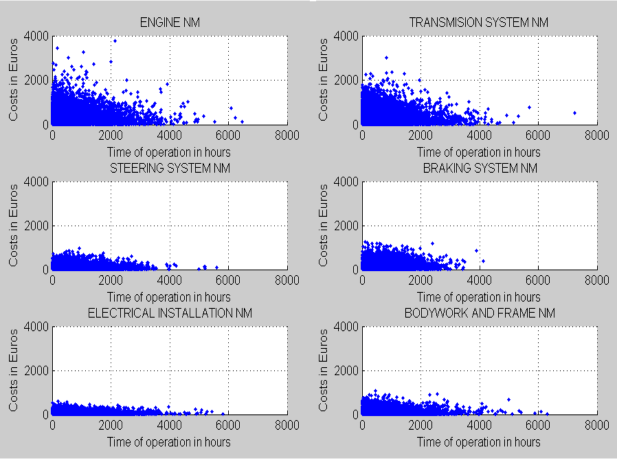


Figure 26 Probable risk matrix of costs of materials

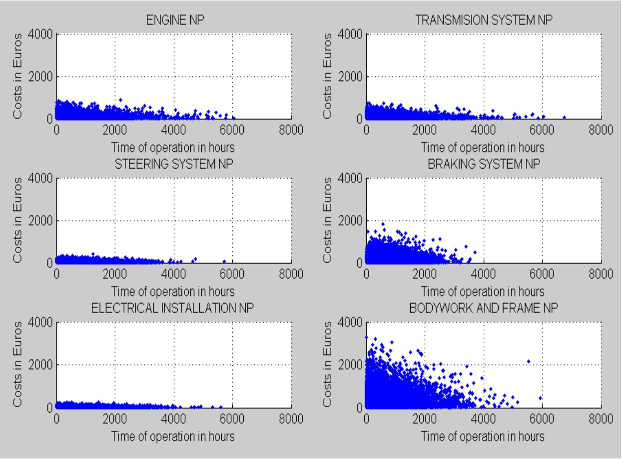


Figure 27 Probable risk matrix of labor costs groups

We can quantify this probability and to define it with a probability of elements, lines or columns of the risk matrix.

With an increased number of simulated events, representing a longer distance of kilometres driven, the ranges of affected risks increase as well. **Figure 28** and **Figure 29**.

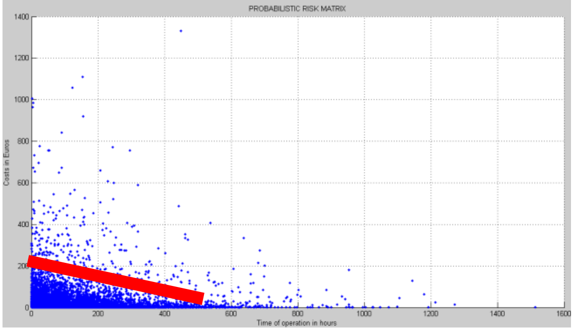


Figure 28 Probable risk matrix 1000 simulations

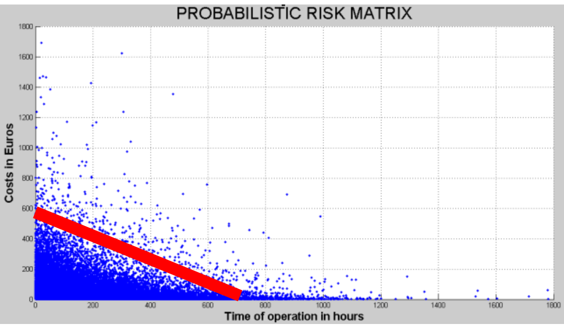


Figure 29 Probable risk matrix 10000 simulations

If we use a leg to define the most often occurrence of events and we compare the risk matrices of particular groups, we can obtain an opinion relating a risk in expanding costs for maintenance of particular groups of expenses **Figure 30**.

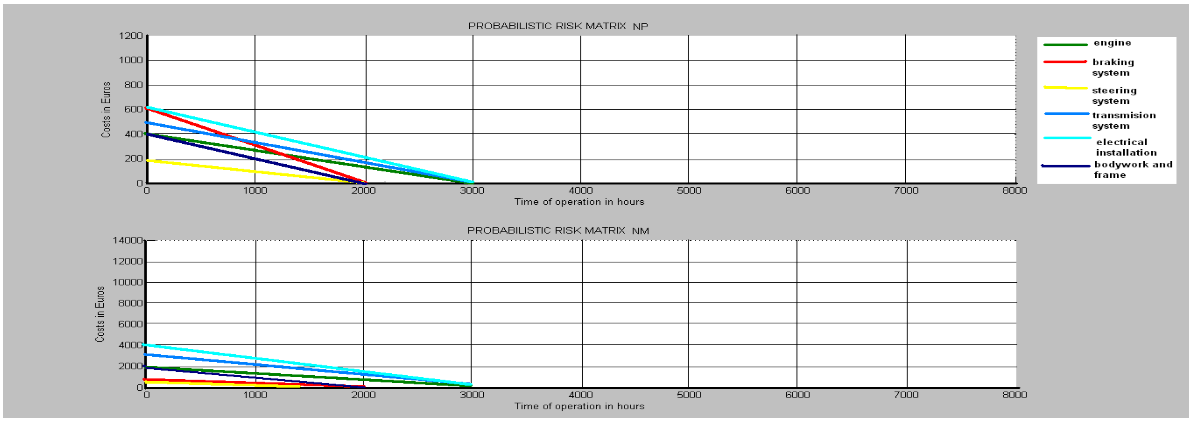


Figure 30 Matrices of risks of Figure 26 and Figure 27

If we use probability distributions of failure and costs probability for a discrete simulation with a variable time step, we can obtain a perception on amount of costs for maintenance of particular groups depending on hours of operation **Figure 31**.

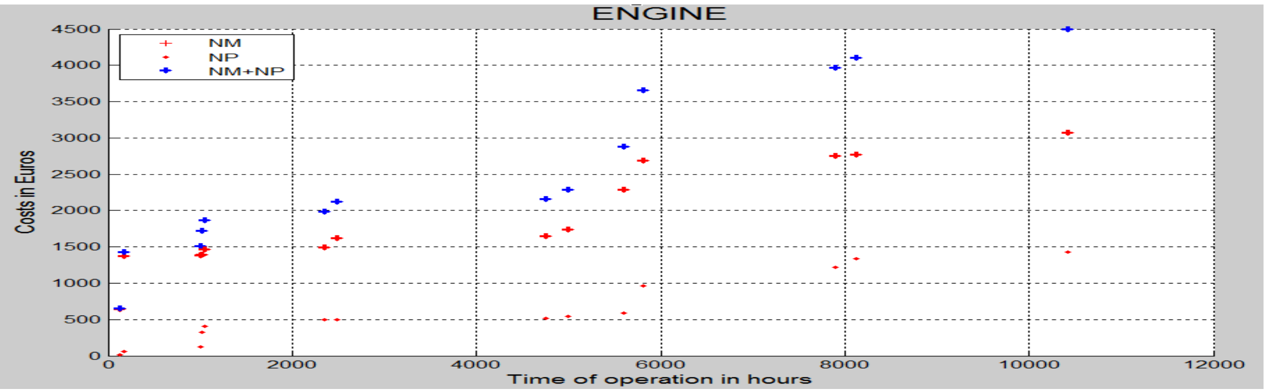


Figure 31 Simulation of failures and costs for engine maintenance.

4. CONCLUSIONS

From above mentioned results of data processing and from executed experiments results the following.

The results have shown that a level of reliability of particular groups is on a comparable high level. None of the groups is significantly different in a viewpoint of reliability except of a braking system. The same is for maintainability. The number of simulated failures of groups in operation up to 300000km ranges in particular simulation experiments from 6 to 15, a total number of a vehicle failures ranges from 40 to 48.

A sense of a mathematic expression of an availability factor has been supported, that relationship between reliability and maintainability expresses possibilities of an increase of availability of designed and operated devices that interfere with technological limits of periods when the activities are performed. Availability can be increased practically only through shortening of intervals of components of the device maintainability that interferes with technological limits of the action being performed. Asymptotic availability of a terrain vehicle is lower than the availability of groups, it becomes stabilized on 0.958- 0.966 level.

The statistic characteristics of a failure-free operation of vehicles and particular groups and statistic characteristics of costs are used for application of theory of risks and solution of tasks related to issues of maintenance and logistics issues.

They provide details for assessment of different risks and their quantification. They are more suitable than qualitative assessment and thy give a better visualization than balance methods resulting from mean values, or semi-quantitative methods of a risk assessment.

Mathematic and simulation modelling is for an analysis, modelling and prediction of stochastic phenomena in the operation, maintenance, logistics, risk assessment very favourable, first of all for a possibility of monitoring through graphic outputs, which give more visual perception about stochastic processes.

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