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Elements of logistics in the diagnostic strategy of military vehicle operation

Elementy logistyki w diagnostycznej strategii eksploatacji pojazdów wojskowych

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Abstract. The work concerns management and logistics in the operation of military vehicles throughout their life cycle. The research objective of this work is to present the contribution of management and logistics principles in operation, including methods and techniques for testing the condition of vehicle serviceability, where the development of digital technologies is rapid and intensive, and users must keep up with changes. The work concerns trends in the management and logistics of vehicle use and service, including vehicle operation engineering, the role of logistics in maintaining serviceability, and safety management engineering supported by information technologies. In particular, an IT system monitoring damages, their frequency, structure, causes and effects supports the management of vehicle operation in the field of maintaining vehicles in operational readiness. The IT system should also support operational decisions in order to indicate possible corrective actions for practice along with the forecast of their effects and the assessment of their effectiveness. The work highlights the elements of safety, logistics and technical diagnostics as the main problems in maintaining the technical readiness of military vehicles. Operational practice and legal requirements indicate new trends in the field of maintaining vehicle efficiency, shaping modern vehicle service services. The research and considerations presented in this paper fill a research niche in the field of modern operation of complex technical objects such as mechatronic vehicles.
Keywords: logistics, operation, diagnostics, safety, vehicles

Abstrakt. Praca dotyczy zarządzania i logistyki w eksploatacji pojazdów wojskowych w całym cyklu ich życia. Celem badawczym tej pracy jest przedstawienie udziału zasad zarządzania i logistyki w eksploatacji, w tym metod i technik badania stanu zdatności pojazdów, gdzie rozwój technologii cyfrowych jest szybki i intensywny, a użytkownicy muszą nadążać za zmianami. Praca dotyczy trendów w zarządzaniu i logistyce użytkowania i obsługi pojazdów, w tym inżynierii eksploatacji pojazdów, roli logistyki w utrzymaniu zdatności oraz inżynierii zarządzaniu bezpieczeństwem wspomaganym technologiami informatycznymi. W szczególności system informatyczny monitorujący uszkodzenia, ich częstotliwość, strukturę, przyczyny i skutki wspomaga zarządzanie eksploatacją pojazdów w zakresie utrzymania pojazdów w gotowości operacyjnej. System informatyczny powinien również wspierać decyzje operacyjne w celu wskazania możliwych działań korygujących dla praktyki wraz z prognozą ich skutków i oceną skuteczności. W pracy wyróżniono elementy bezpieczeństwa, logistyki i diagnostyki technicznej jako główne problemy w utrzymaniu gotowości technicznej pojazdów wojskowych. Praktyka eksploatacyjna i wymagania prawne wskazują na nowe trendy w obszarze utrzymania sprawności pojazdów, kształtując nowoczesne usługi serwisowe pojazdów. Badania i wyniki rozważań przedstawione w pracy wypełniają niszę badawczą w danej dziedzinie nowoczesnej eksploatacji złożonych obiektów technicznych, jakimi są mechatroniczne pojazdy.
Słowa kluczowe: logistyka, eksploatacja, diagnostyka, bezpieczeństwo, pojazdy

Introduction

Logistic processes are an important part of the tasks in the diagnostic strategy of military vehicle operation, ensuring safe and reliable use and efficient and fast service of means of transport. Logistics is the conscious application of procedures aimed at efficient use and economic maintenance of the operating potential of systems in the part concerning the movement of objects and components of their systems (Brzeziński, 2024, Cempel, Natke, 1996). For these reasons, operation, where the issues of maintaining serviceability, safety and environmental protection are of great importance, is dependent on logistics. However, it is not the case that rationalization of operation consists only in professionalization of logistics, because the operating properties of objects are shaped by many different fields.

The paper presents:

- an integrated approach to logistics and operation of military vehicles, which should result in improved safety and cost optimization;
- advanced diagnostic methods used in the article (including vibroacoustic, OPTIMUM, SVD analysis) are important tools in the practice of maintaining vehicle airworthiness;
- considerations on vehicle safety, based on risk analyses (HAZID, HAZOP, ETA, FTA, etc.), indicate the complexity of the issue and the need for a systemic approach.

The proposed concepts and conclusions of this study can provide a solid basis for further, in-depth research on IT supporting diagnostics and logistics in the defense sector. The content of this study is a tangible contribution to the discussion on logistics and diagnostic strategies in the operation of military vehicles, presenting a broad perspective on issues related to management, logistics, safety, as well as modern methods of assessing technical condition using IT systems and vibration diagnostics (Ficoń, Krasnodębski, 2016).

Logistics activities include maintenance of fitness, supply of consumables, spare parts, energy, cleaning agents, financial resources and activities related to the flow of information. The issues of logistics and operation interpenetrate each other and are necessary for the efficient implementation of various tasks in transport (Łapuńka, 2014, Sokołowski, 2024, Weber, 1990).

Logistics is to ensure that materials (raw materials, fuels), energy and goods (semi-finished and finished products) are always available at the right time, in the right place, in the right quantity and of the right quality. In relation to means of transport, it indicates the role they play in the implementation of logistics tasks, when they are a tool enabling the achievement of the assumed goal of the action (flows of people, materials), but they can also become an entity when the necessary maintenance works are carried out to secure the achievement of the required technical condition of the vehicle (Brzeziński, 2015, Jałowiec, 2018, Marciniak, 2021).

In turn, operation is a set of purposeful organizational, technical and economic activities of people with a technical object and the mutual relations between them from the moment of taking over the object for use in accordance with its intended purpose until its liquidation (Weber, 1990). The vehicle operation system - supported by technical diagnostics - in transport companies consists of the subsystem of use, service and operation management (i.e. the decision-making-planning and accounting-reporting subsystem). The vehicle use subsystem is the implementation of logistic tasks assigned by the customers of the logistics company or the logistics departments of manufacturing companies. The vehicle service subsystem is extremely important because it ensures the proper functioning and effective use of this type of technical objects (Ahmad, 2012, Weber, 1990, Żółtowski, 2004).

The diagnostic system for recognizing the condition of a vehicle is a set of measuring, matching, computational elements and programs designed to: extract, collect, store, process and present information about the state of destruction of the vehicle. The diagnostic system is a tool for controlling the maintenance of vehicle fitness and safety. The condition recognition system is a set of measuring, matching, computational elements and programs designed to: extract, collect, store, process and present information about the condition of vehicles. It allows the following decisions to be made: the condition of the vehicle at the moment t (fit object, unfit object); the condition of the vehicle at the moment $t+\Delta t$ – i.e. the date of the next diagnosis; the vehicle's mileage for liquidation, in order to direct the object to the recycling subsystem; the vehicle's mileage for major repair; states at the moment $t-\Delta t$, i.e. locating the causes of damaged elements (Cempel, Natke, 1996, Niziński, Michalski, 2002).

The work highlights key areas in which correct analysis of the technical condition of vehicles translates into reduced risk of failure and increased safety of military operations, which meets current challenges. It is also worth pointing out the relevant legal acts and EU directives related to vehicle/machine safety, emphasizing the importance of consistency of regulations with the practice of designing and using special vehicles (PN-EN 13460:2006).

It is particularly valuable to draw attention to the integration of the operational process with logistics activities, which in a systemic approach is the key to cost optimization, ensuring resource availability, and increasing user safety (Pawlisiak, Maslii, 2024).

In forward-looking concepts of logistics process management, an approach based on proven engineering technologies is now almost a necessity (Kurasiński, 2004, Kaleta, 2014).

Safety and risk of hazards

In the literature on the subject, the safety of any technical object is defined as a function of its unreliability and the extent of the threat resulting from the occurrence of undesirable events related to its unreliability. According to the definition, "safety is a property of a technical object consisting in the ability to function in specific conditions and within a specific period of time without accidents occurring" (Pawlisiak, 2024).

Military vehicles are designed to perform specific functions and have specific, diverse features that distinguish them from the group of special vehicles or those used for special purposes. The main criteria for modern military logistic and combat vehicles are defined below:

- universality – possibility of use in various conflicts (local, global);
- integrity – necessity of connection with other types of vehicles;
- modularity – assumes the existence of a base structure and the possibility of changing the purpose;
- transportability – possibility of transport by rail, sea and air;
- mobility – the ability of the vehicle to overcome various terrains;
- survivability – the ability to survive, continue tasks despite damage;
- lethality – the ability to destroy the enemy (arms, firepower).

The safety of using military vehicles is defined as active, passive and environmental safety. Active safety (active) – a set of factors that reduce the probability of a collision or road accident. Passive safety is a set of vehicle features aimed at reducing the effects of a collision or road accident from the point of view of all its participants. Environmental safety is a set of factors influencing the reduction of threats to the natural environment (Jaźwiński, Grabski, 2003).

The following types of safety related to the operation of a technical object are distinguished: process safety, operator safety, environmental safety (size and type of threats in an emergency). Most often, security assessment is associated with risk analysis and determining its acceptability. To assess the risk of a threat occurrence, the mutual relationships between existing threats and the applied or designed security and protection systems must be established. If the countermeasures are not properly designed, an unacceptable level of risk may occur.

The Hazard Identification Study (HAZID) method is a tool for hazard analysis used in the early stages of design. It uses tools such as flow charts for general and broad analysis of hazards without going into details, energy balancing, etc. Hazard and Operability Study (HAZOP) is most often used to assess process risk. It is a structural method for identifying potential hazards occurring in work processes carried out by a technical object. This method involves a systematic review of design assumptions and work processes in terms of possible failures and possible losses caused by various deviations from normal, assumed operating conditions of the work.

Probabilistic Risk Analysis (PRA) - a comprehensive, systematic and logical analysis methodology aimed at identifying and assessing risks in complex technical objects to improve their safety. This assessment is carried out by analysing various scenarios, the creation of which requires the adoption of appropriate models and parameters of these models, based on current knowledge of the physics of work and auxiliary processes carried out by the object.

Human Reliability Analysis (HRA) focuses on events caused by human activity. There are many methods for analysing human errors. These methods involve a systematic assessment of the factors that influence the behaviour of operating personnel, maintenance personnel, and management personnel in matters affecting the safety of the facility. HRA is usually undertaken after other types of analysis (e.g. HAZOP, FMEA) have been conducted that have demonstrated the influence of human errors on the occurrence of dangerous consequences (Jażwiński, 2003, Żółtowski, 2012).

Fault Tree Analysis (FTA) is a technique that deductively identifies, logically organizes, and visualizes the conditions and factors that contribute to a specific undesirable event (called a top event). In reliability analysis, failures are considered instead of failures.

Event Tree Analysis (ETA) is a technique used to identify possible outputs and, if required, their probabilities given the occurrence of an initiating event. It clearly defines the relationships between the functioning or failure of various mitigating systems and, ultimately, the threatening event resulting from the occurrence of a single initiating event (Ficoń, 2007).

Bow-tie logic is a combination of techniques: fault tree analysis and event tree analysis. FTA fault tree analysis identifies the causes of a problem, while ETA event tree analysis identifies their consequences. Bow-tie logic focuses on building barriers to counteract threats.

In the case of the specificity of military vehicle applications, some elements characteristic of the indicated types of security may temporarily not occur. These are cases of catastrophic events including: loss of life or health by a person (soldier), self-destruction of the system, destruction of coexisting systems, destruction of the environment and factors forcing a threat to security - damage to system elements, operator error or other random factors. Also important are threats related to the technical condition of the vehicle, e.g. errors in operation resulting in a low level of reliability or durability and threats related to logistic security, e.g. not guaranteeing proper organization, material security and exchange of information.

The previously distinguished types of safety related to the operation of a technical object determine the main directions of safety design.

Logistics in vehicle operation

Vehicles in operational logistics enable the movement of loads in time and space. In order for these tasks to be carried out effectively and efficiently, these objects must be maintained in an appropriate technical condition. Proper supervision of the technical condition of the vehicle allows for reducing the costs of its operation (e.g. fuel consumption, operating fluids) and maintaining the safety of the transported load, as well as the driver and the environment (Ahmad, 2012, Jałowiec, 2018).

Many of these operational activities are typical logistic processes (transport, storage, spare parts supply, etc.). One of the areas securing the correct course of the set goals is to ensure reliable use and efficient and fast service of means of transport. The basics of operational sciences, shaping the quality of vehicles include knowledge from the following fields: operation systems, reliability, tribology, technical diagnostics and safety.

Operation (maintenance) of vehicles includes the following processes (Żółtowski, 2004, Łukasiewicz, 2012, Świątnicki, 1995):

- use;
- technical servicing;
- technical condition diagnostics;
- evacuation and technical assistance;
- personnel and material supplies.

Considering the use (technical, operational readiness) of vehicles as the main stage of verifying their suitability and meeting expectations, more and more often at this stage intensive tests of their correct operation in formalized operation structures are conducted.

Such a structure of the operation system contains the previously known main elements of this system (use and maintenance), with maintenance being a subsystem ensuring suitability treated as subordinate to the use subsystem.

In the vehicle operation system, in addition to the information provided, it is also important to collect, process and use information for efficient operation. The decision-making object generates control information (decisions) based on the information received and the appropriate processing algorithm.

A separate, highly developed department (subsystem) of logistics in the operation of vehicles and other technical objects is spare parts logistics. It is part of the entire logistics system and is closely related to other subsystems. It also has a significant impact on the achievement of the goal by the entire system.

Cooperation within Integrated Logistics Chains, in which processes go beyond the boundaries of enterprises and extend from suppliers of raw materials and components through manufacturers and sellers to the customer - these are new areas of logistics solutions. In operational logistics, these solutions allow for (Pawlisiak, 2024):

- better planning of transport, production and sales;
- reduction of inventories in all links of the chain;
- shortening of transport, flow and settlement times;
- elimination of unnecessary costs;
- improvement of the level of service and maintenance.

This approach also uses new management methods, organizational solutions and tools and technologies that reduce costs and time, which have emerged as a result of the intensive development of IT techniques and technologies (Ficoń, 2007, Weber, 1990).

In the aspect under consideration, the main goal of the optimization activities is primarily to find an answer regarding the determination of the capabilities that should characterize stationary and mobile logistics structures. This will allow for the optimal use of available technical and material resources and will help determine the capabilities necessary to obtain them. In turn, the technical aspect of optimization activities is primarily related to the search for tools that enable the implementation of effective logistics support that allows for the full use of the potential of the Armed Forces.

Diagnostics in vehicle operation logistics

The essence of technical diagnostics is to determine the condition of a machine (assembly, subassembly, element) indirectly, without disassembly, based on the measurement of generated diagnostic signals (symptoms) and comparing them with nominal values. The value of the diagnostic signal (symptom) must be related to a known relationship with the diagnosed feature of the vehicle condition, characterizing its technical condition (Żółtowski, 2004, Żółtowski, 2012). The field of knowledge of technical vehicle diagnostics, already formed within the operational sciences, deals with the assessment of the technical condition by examining the properties of work processes and those accompanying work, as well as by examining the quality of services.

Combining theory with practical aspects of military vehicle operation throughout their life cycle, it is worth emphasizing the importance of technical efficiency and operational effectiveness in the context of the growing requirements of modern armed forces. A review of modern diagnostic methodologies, including an example explanation of the principles of using vibration measurements to assess repeatable vehicle elements (bearing and gear condition), as well as an indication of how specific algorithms and procedures (e.g. OPTIMUM, SVD analysis or MATLAB tools) can improve the decision-making process in the field of maintaining vehicles in operational readiness (Żółtowski, Cempel, 2004.).

According to the general theory of systems, operating systems are open systems with the flow of mass, energy and information, and therefore they are systems transforming energy with its inherent internal and external dissipation. The technical condition of an object can be determined by observing the functioning of the object, i.e. its main output of transformed energy (or product) and dissipative output, where we observe various types of residual processes (thermal, vibration, acoustic, electromagnetic) - Fig.1.

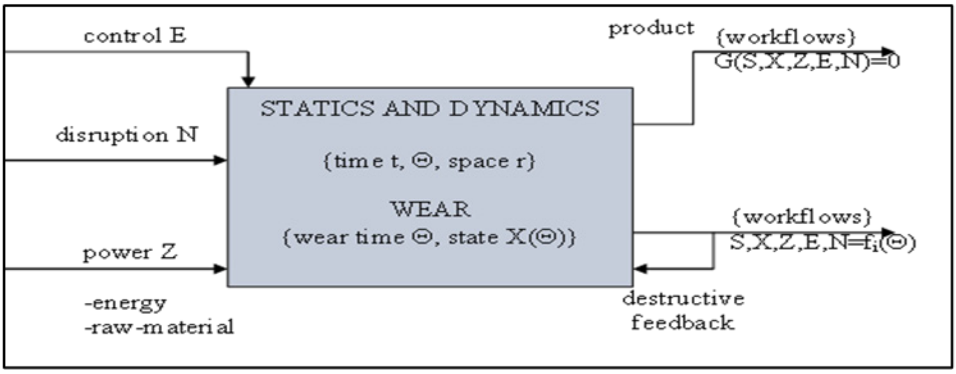

Fig.1. Model of the object in the aspect of technical diagnostics
Source: Own study

The presented diagnostic object in accordance with the notations adopted in Fig.1, is described by the vector equation:

$$G (X, S, E, Z, N) = 0 \quad (1)$$

The state of the object X determined from the relationship:

$$X = g\ (S, Z, E, N) \tag{2}$$

The experimental implementation of the above relationship is possible after adopting simplifications that assume constancy in the sense of the mean values of the vectors E, Z = 0, and resulting from the adopted object model. We have:

$$X = F\ (S)\ Z{,}E{=}const + N \tag{3}$$

Taking into account the domains of specificity of individual vectors of this relation, we obtain the already known, basic diagnostic equation in the form:

$$X\ (\theta, r) = A\ (r)\ S\ (\theta, r) + N\ (\theta, r) \tag{4}$$

The vector description of the object structure, its inputs: power supply, control and interference, and energy outputs (useful and residual) leads directly to the description of possible relationships between variables: parameters of diagnostic symptoms and features of the object›s state, features of the state and parameters of diagnostic symptoms, states and diagnostic symptoms. Information from research is always incomplete or uncertain, which forces us to use the help of statistics, and this convinces us that every decision is made in terms of probabilities (Cempel, 1996, 2004, Baryłka A., 2018).

These analyzes determine the initial and justified selection of qualitative measures, processed further to distinguish the components of the main model. Statistical analysis of the obtained data is also the basis for many interesting descriptions and trends of the analyzed events.

The considerations presented briefly cover selected issues from the area of the use of statistical procedures in the study of vibration measures to assess the state of wear of machines. The indicated procedures are particularly important in research, where the multidimensionality of diagnostic signals requires a wide application of various statistical procedures at the stage of processing and decision making.

The basis of the IT system is the MATLAB program used to determine the symptom matrix, software tools for reading and exporting files to the unv format, for the implementation of OPTIMUM algorithms, computer algorithm for distribution analysis (SVD) and the program for analyzing the state matrix using the MAC theory. The statistically supported methodology for vibration, include tasks in the following areas (Cempel, 1996, Żółtowski, 2004):

- measurement data - a method of data registration for the purposes of processing, data bank, statistical analysis;

- observation matrices - scoreboards, data ordering (dimension lessness through normalization, measurement scales unified by precision constants);
- elements of statistics - measures for data presentation (numerical, graphical, location measures, dispersion, interdependencies, regression in cause-effect modeling);
- software - MATLAB and STATISTICA procedures;
- methods of information selection (PCA, OPTIMUM, SVD) and cause and effect modeling;
- reliability testing: technical availability, failure intensity, time to and between failures ii);
- elements of artificial intelligence in vehicle research: advisory systems, fuzzy sets, neural networks in the classification of states, genetic algorithms in the optimization of sets.

It is difficult to discuss the individual tasks in detail in one study, so the decisive elements and the general algorithm for processing information from vibration tests are shown in Fig.2.

Innovative and exemplary information selection procedures for the multidimensional observation matrix in the qualitative and quantitative assessment are presented in the OPTIMUM and SVD algorithms (Żółtowski, Cempel, 2004).

On Fig.2 shows the general idea of an agent system to be used for diagnosis and observation of critical systems as well as for information flow handling in the future of diagnostics.

We can also see a need to provide some other information concerning the system operation including load, current time of system life, and some previous records on the system history contained in the maintenance data base.

If such an agent is added to hardware properties in the form of sensorimotor transducers and actuators - it is possible to implement the concept of the Independent Agent Diagnostic (SAD). Such an entity supporting the application of innovative technical systems must have an array of intelligent sensors embedded in the phenomenal facility, where the SAD collects all the information about the evolution of the state.

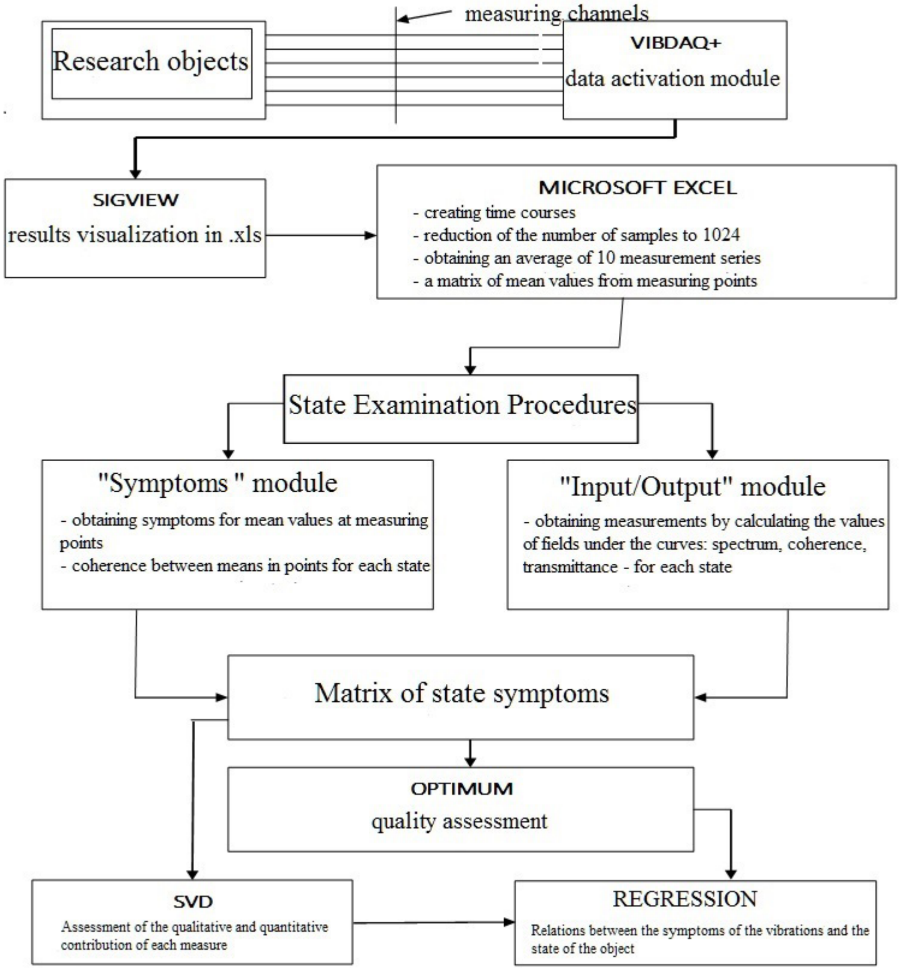

Fig.2. Vibration test algorithm with elements of statistical procedures
Source: Own study

The provided symptoms have independent status which enables creation of Vector Diagnostic Observation and symptoms observation matrix for the next lifetime value of an object. After each reading, an observation vector is derived from generalized damage symptoms as well assessment of the current intensity of damage is provided – Fig.3. In cooperation with the local knowledge base enriched with information and environmental control the damage classification and the final diagnosis of the object is possible (Cempel, 2004).

The last step of SAD is to develop a measure of further operation risk and make other decision of service type/repair resulting from the assessment of the status and information about the object and the environment. Thus, it can be implemented as shown graphically and as you can see for innovative objects which lack experience in operation and have no operating history there is only one chance to fulfill this mission by using a self-learning mode.

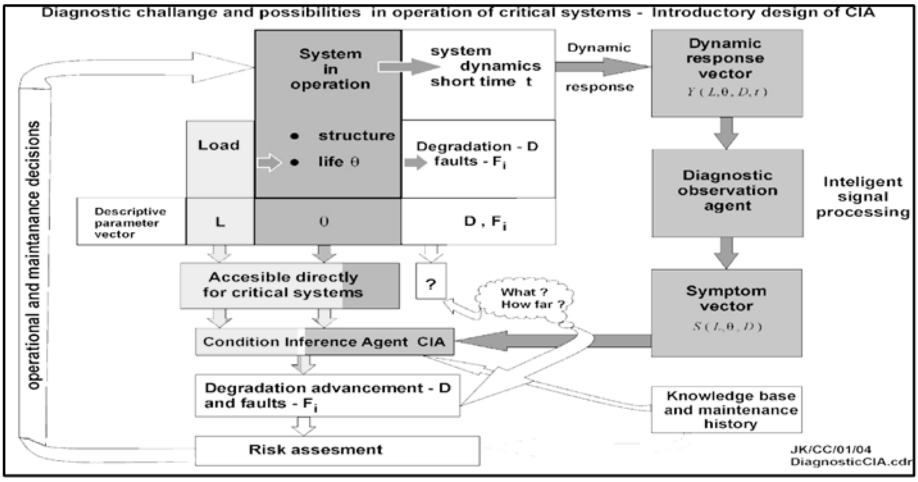

Fig.3. The information flow and processing of intelligent monitoring system
Source: Own study

Operation practice according to technical condition

In order to expand the presented issues and indicate the adopted argumentation for the applications of selected fragments of this study, examples of practical applications carried out in training ground conditions in selected military formations were indicated, which gives the publication a greater application value.

Correct functioning of the diagnostic system of vehicle operation logistics requires the implementation of many organizational, training and investment tasks. The functioning of the system in the enterprise (Fig.4), from the perspective of using diagnostic tools for current assessment and forecasting of the vehicle condition, requires knowledge of (Żółtowski, 2004, Żółtowski, 2012):

- machine condition symptoms: $\boldsymbol{s_1, s_2, ..., s_m}$ (5)
- limit values of condition symptoms: (6)
- periodicity of diagnostic tests: $\boldsymbol{t_d} = \frac{(1-P_r)(S_{gr}-S_m)}{S_m}\theta_m$ (7)

The basic condition for the success of this strategy is the availability of simple and effective diagnostic methods, preferably designed into manufactured vehicles, which in turn are supervised in the condition monitoring system. It also requires overcoming the distrust of decision-makers regarding the effectiveness of such a method of operation. The economic effects of such a method of operation are disproportionately higher than in other strategies, which determines the success and huge interest in this solution.

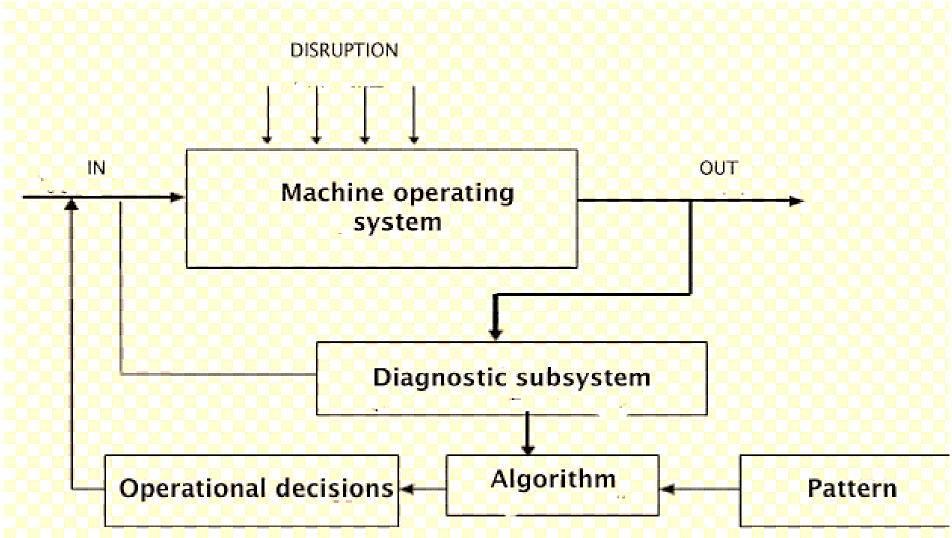

Fig.4. Diagnostic control of the machine operation system
Source: Own study

The basic condition for the success of this strategy is the availability of simple and effective diagnostic methods, preferably designed into manufactured vehicles, which in turn are supervised in the condition monitoring system. It also requires overcoming the distrust of decision-makers regarding the effectiveness of such a method of operation. The economic effects of such a method of operation are disproportionately higher than in other strategies, which determines the success and huge interest in this solution.

The scheme of determining vehicle condition recognition procedures is shown in Fig.5, while the algorithm for using the set of diagnostic parameters in the condition assessment procedure, generation, forecasting and optimization of the condition recognition procedure is shown in Fig.5 (Niziński, Michalski, 2002).

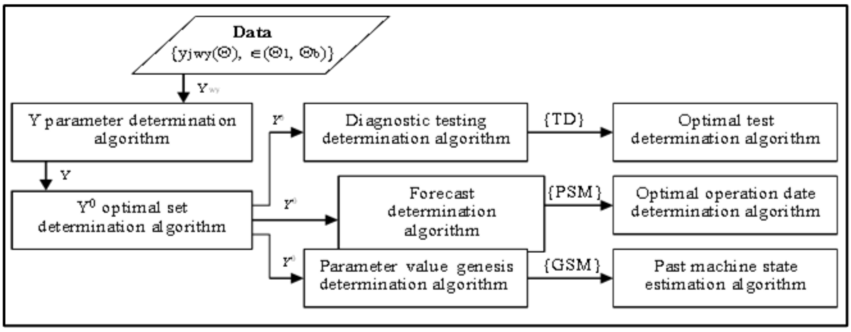

Fig.5. Scheme of determining the procedures for recognizing the state of machines
Source: Own study

The indicated principles of diagnostic practice use diagnostic signals from the vehicle's CAN network and use periodic additional tests using complex multi--symptom procedures (vibroacoustic, modal analysis ii).

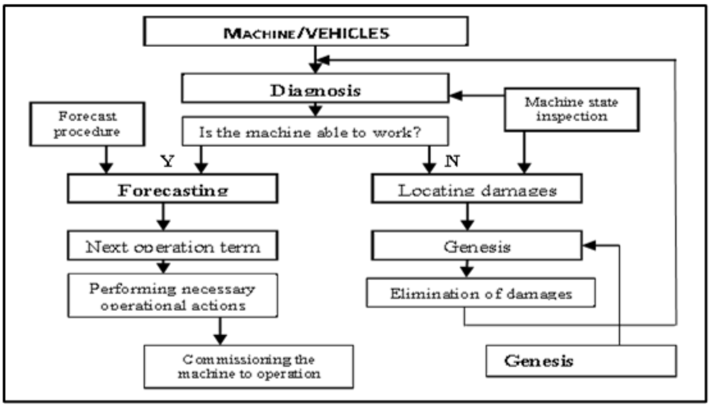

Fig.6. Scheme of the implementation of machine condition recognition
Source: Own study

To illustrate this issue, examples of using multi-symptom vibration information in assessing the condition of repeatable parts and assemblies (vibration diagnostics) in many technical structures (vehicles, machines) are given below.

The increasingly frequent identification tests used to assess changes in the condition of vehicles, the development of damage and the location of the causes of the condition constitute the basis for the creation of a specialized software system. It enables the acquisition and processing of measurement data, the creation of many measures of diagnostic signals, their diagnostic sensitivity tests, statistical processing and diagnostic inference. The case studies for the content of the study are limited to periodic tests of repeatable elements in many technical objects, using the proposed procedures (Żółtowski, Łukasiewicz, 2012).

Vibration diagnostics of selected structural elements

By combining theoretical analysis with practical references, the exemplary research methodology presented below helps to improve decision-making at many levels of logistics and security management. Vibration tests of the condition of bearings and gears are examples of practical verification of developed procedures for using diagnostics in improving the system for maintaining the airworthiness of vehicles and machines. The current state of methods for testing these objects in vibration diagnostics has been characterized in many studies (Cempel, 2007, Żółtowski, 2004, 2012) and allows for an assessment of the originality of the proposed innovative procedures for obtaining and processing vibration information.

A. Vibration methods for testing the condition of bearings

A bearing is the most responsible and common machine element, and its main task is to safely transfer working loads from the rotating element to the housing with low resistance to movement and good positioning of the rotating working element.

The share of bearings in the total cost of industrial machines is usually small or very small, but due to the function they fulfil and due to the statistics of damage, correct operation of rolling bearings is of fundamental importance in industrial practice. The value most predisposed to operational diagnostics of rolling bearings is vibration acceleration, and less so their velocity as a value not containing frequencies higher than 2 kHz. Measurement of vibration velocity gives only 70% probability of detecting damage to bearing elements. These faults induce vibrations in adjacent bearing usually generating high-frequency vibrations that are easy to capture in terms of accelerations or derived quantities (Żółtowski, Łukasiewicz, 2012).

The simplest method of diagnosing bearings is periodic or continuous measurements of broadband vibration levels. These measurements are based on tracking the trend of vibration level changes in wide frequency bands (2 Hz ÷ 10 kHz). The simplest measurement system consists of a piezo quartz sensor, an A/C card and software for processing the vibration signals recorded in digital form. The basic signal recorded from the sensor is the amplitude in time A(t). Such a signal can be described in the time, frequency or amplitude domain, obtaining many measures from a single signal that facilitate the identification of possible developing damage.

The easiest way to detect bearing damage is by measuring (Fig.7) the acceleration of their housing and comparing it, for example, with the guidelines for the qualification of vibration symptoms of the condition of rolling bearings.

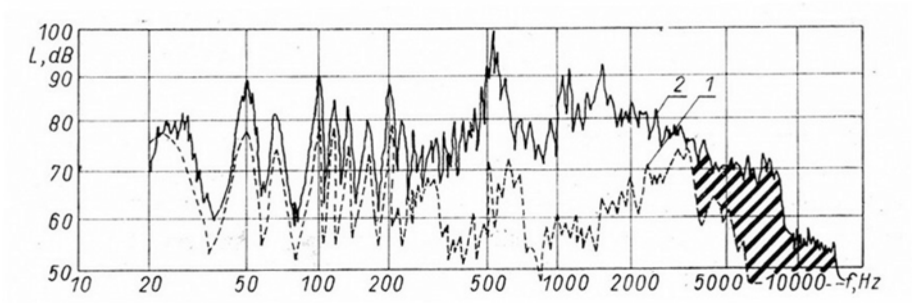

Fig.7. Comparison of the acceleration spectra of the bearing housing
Source: Own study

for variant 1- Θ = 25 h of operation — 107 dB; (Δf = 10 Hz for f < 500 Hz);
for variant 2 - Θ = 2050 h of operation — 120 dB; (Δf = 30 Hz for f > 500 Hz)

In addition to spectral analyses, it is also possible to perform digital measurements of various (in the domain of time t, frequency f and amplitudes A) vibration measures and their redundancy selection to best reflect the technical condition of bearings, as shown in Fig.8.

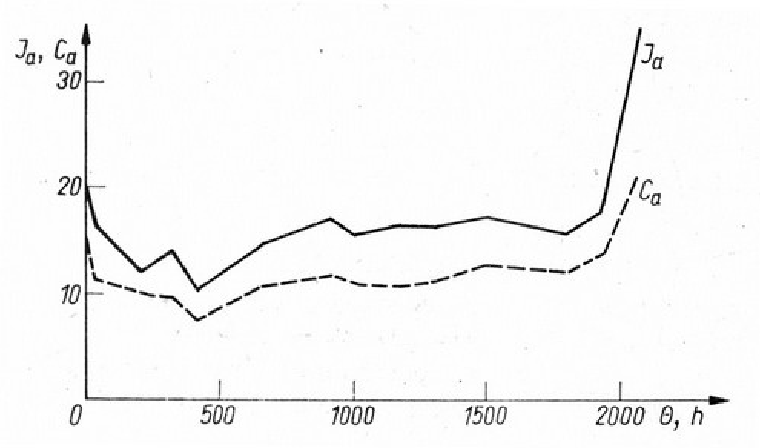

Fig.8. Operational trend of impulsiveness coefficients *Ia* and peak *Ca*
Source: Own study

The reliability of diagnostic methods, as well as their effectiveness, allows us to assess the practical aspects of the proposed solutions, which helps the user to make an informed choice of the appropriate diagnostic technique (Cempel, 1996, Żółtowski, 2012).

B. Vibration methods for testing the condition of gears

In vehicle/machine designs, there is often a need to change the direction and rotational speed or torque in the drive system. In most cases, a gear transmission is used, especially when it comes to transmitting high power. Gears, due to the discrete transfer of load through successive teeth entering the buttress, are, in addition to rolling bearings, important sources (generators) of vibrations. Here, the periodically changing (with the frequency of meshing) number of teeth in the buttress is the cause of the periodic fluctuation of the mesh stiffness, which for a shaft with variable stiffness and for rolling bearings is the cause of parametric vibrations with characteristic modulation effects.

Vibrations of gears are assessed by measuring the speed - V or acceleration - a of vibrations - Fig. 9 (Żółtowski, 2012).

The following parameters are recommended to assess the condition of the gear:

- ❖ to assess the correct operation of the high-speed shaft, the V parameter reflected in the frequency range of 10—100Hz should be used;
- ❖ to assess the condition of the meshing, the parameters V and a should be used, defined in the frequency range of 100—3500Hz;
- ❖ to assess the condition of the bearings in a given bearing node, the parameter a should be used — defined for the range of 3.5—10kHz.

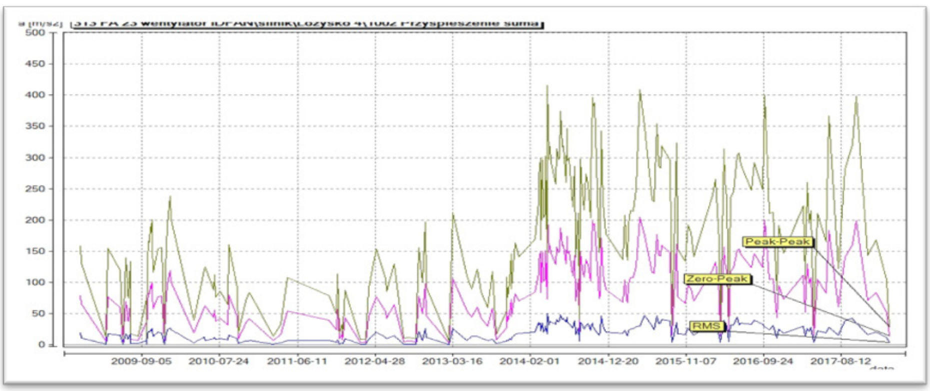

Fig.9. Measurements of the vibration acceleration amplitude of the gear unit on the housing
Source: Own study

The evaluation of the vibration spectrum of the gear unit (amplitude-frequency characteristic) – Fig. 10 – is therefore general and requires improvement by determining various measures and symptoms of the condition in the proposed IT procedures. The results of vibration tests of these objects include amplitude levels, vibration spectra and tabulated lists of the results of tests of vibration velocity levels in the individual years of the test.

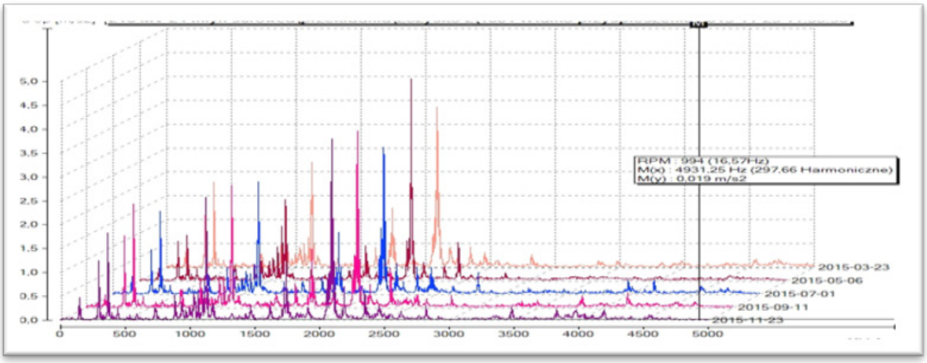

Fig.10. Spectral wave forms of gear vibrations
Source: Own study

The possibilities of information technology create new available solutions in the field of acquiring and processing vibration signals, for which the developed procedures enable the detection of regularities in the form of cause-effect relationships occurring in the studied phenomena.

Vehicle safety

Special vehicle – a motor vehicle or trailer designed to perform a special function that requires the body to be adapted or to have special equipment; this vehicle may carry people and objects related to the performance of this function (Cempel, 2013, Jałowiec, 2018). Vehicle used for special purposes – a motor vehicle specially adapted to transport people or cargo, used by the Armed Forces. The main terms referring to modern military logistic and combat vehicles are defined below, but they are important of military vehicles:

- ❖ versatility – the possibility of using the platform in both local and global conflicts;
- ❖ integrity – the need to connect with other types of equipment; primarily in terms of logistics or communications;

- ❖ modularity – assumes the existence of a base platform of changing the purpose;
- ❖ transportability – the possibility of transport by rail, –– mobility – the vehicle's ability to overcome terrain;
- ❖ survivability – the ability to survive, continue tasks despite damage;
- ❖ lethality – the ability to destroy the enemy (arms, firepower) (Baryłka, 2018).

Vehicle safety does not have a direct definition, but active and passive vehicle safety is defined. Active safety (active) – a set of factors that reduce the probability of a collision or road accident.

In the case of special military vehicles, some elements characteristic of active and passive safety may not be present. The following concepts can be used to describe the theoretical safety of military vehicle use (according to (Żółtowski, 2004)):

- ❖ system safety – the resistance of the system to the impact of factors forcing (causing) the occurrence of safety hazards;
- ❖ safety hazards – the possibility of catastrophic events – this is therefore a state of the system in which the number of catastrophic events increases significantly;
- ❖ catastrophic events – an event resulting in:
  - • loss of life or health by a person (soldier) involved in the operation and use of the system, using the system's services, cooperating with the system;
  - • self-destruction of the system,
  - • destruction of coexisting systems,
  - • destruction of the environment;
- ❖ safety reliability – a feature related to maintaining the system's resistance to damage - it is the probability of failure resulting in a safety hazard.

Threats related to the vehicle structure, arising for example at the design stage, result in a reduction of the vehicle's essential technical parameters. Due to the specific nature of threats, the safety of using military vehicles requires the combined consideration of, among others: mobility, armament, crew protection, special devices, system functionality.

The construction of special versions causes, for example, a shift in the position of the centre of mass and changes in the mass moments of inertia, negatively affecting traffic safety. Significant threats to the safety of militari vehicles include:

- ❖ low level of ballistic protection against mines and IEDs;
- ❖ limited mobility (traction properties and mobility);
- ❖ loss of lateral stability (rolling over, skidding);
- ❖ body injuries caused by dynamic loads while driving;
- ❖ body injuries resulting from the organization of the interior (e.g. sharp edges, lack of escape routes);

- loss of health due to long-term work in a harmful environment (noise, vibrations, tightness, microclimate);
- weakening of the main structural nodes due to excessive vehicle weight;
- high centre of mass of the vehicle;
- random selection of tires and geometry of the running gear;
- improper functioning of additional systems.

Safety requirements on the EU and Polish markets

The principles and procedures for manufacturing and introducing machines and their safety components to the markets of the European Community are governed by the provisions of Directive 98/37/EC of the European Parliament and of the Council of 22 June 1998 on the approximation of the laws of the Member States relating to machinery.

European Union directives are addressed to the Member States and are binding on them in terms of objectives and tasks, while the form and means of their implementation result from national law aimed at achieving compliance with the provisions of the Directive (Brzeziński, 2024, Jałowiec, 2018).

Directive 98/37/EC was implemented into Polish law by the Regulation of the Minister of Economy of 20 December 2005 on the essential requirements for machines and safety components (Journal of Laws 05.259.2170). In 2006, a new version of the directive on the harmonization of the laws of the Member States relating to machinery was adopted – Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006.

This directive applies to machinery; interchangeable equipment; safety components; lifting accessories; chains, ropes and webbing; removable mechanical transmission devices; partly completed machinery (PN-EN 13460).

Taking into account the nature of the risks involved in the use of machinery, procedures for assessing conformity with the essential health and safety requirements should be established. Such procedures should be designed in the light of the degree of risk inherent in the machinery in question. Consequently, there should be an appropriate procedure for each category of machinery, in accordance with Council Decision 93/465/EEC of 22 July 1993 concerning the modules for the various phases of the conformity assessment procedures and the rules for the affixing and use of the EC conformity marking, which are intended to be used in the technical harmonisation directives, taking into account the nature of the verification required for such machinery.

The manufacturer or his authorised representative should also ensure that a risk assessment is carried out for the machinery which he intends to place on the market. For this purpose, he should identify which of the requirements are essential health and safety requirements applicable to his machinery and in respect of which he must take measures. A computer program may be a tool to assist in this. The main method of preventing a decrease in the level of safety should be indicated as:

- ❖ comprehensive approach to mobility and armouring in the vehicle design phase;
- ❖ introduction of modifications (armouring, systems, etc.) within the limits of the vehicle's technical capabilities, supported by research;
- ❖ use of experimental and simulation studies in the field of shaping vehicle characteristics and their confirmation in the event of changes;
- ❖ monitoring operation, drawing conclusions and introducing design changes.

Conclusions

Motor vehicles, enabling the movement of people and goods, are a fundamental element of the logistics system of enterprises and households, as well as the military. When looking for ways to minimize security threats, logistics costs, coordination of material flows and information, it is worth improving the standards related to the operation of vehicles - their use and maintenance. Patterns should be sought in proven methods of maintaining serviceability and readiness and in modern IT solutions supported by AI elements.

The developed and presented modern methods of creative control of safety and operation of technical objects using modern information technologies constitute an innovative approach to maintaining the serviceability of vehicles. Rational operation of vehicles within the framework of logistics is a source of savings of raw materials, energy and capital expenditures and a basic strategy for obtaining benefits and profits.

The subject of the study is an area of interest for a wide range of military operational community, contributing to the development of methods and methodologies for shaping and maintaining the operational readiness of military vehicles. In particular, an information system monitoring changes in condition, development of damages, their frequency, structure, causes and effects, can support the management of vehicle operation in terms of maintaining vehicles in operational readiness. The information system should also support cause-effect analysis in order to indicate possible corrective actions for operational practice of use and maintenance with a forecast of their effects and an assessment of effectiveness.

The possibility of functioning of highly advanced diagnostic systems, diagnosing the vehicle condition on an ongoing basis and a fast flow of information provide conditions for actions aimed at improving the quality of logistics processes, also in the area of motor vehicle operation.

The content of this study is related to innovative management of the vehicle fleet leading to creative solutions that increase the efficiency of operation using the tools of maintaining serviceability in the diagnostic strategy of operation.

The subject of the publication is well embedded in the literature on the subject, contains detailed references to the state of knowledge and fills a research niche in the area of modern operation of military vehicles, making a significant contribution to the field of logistics and technical diagnostics, presenting many innovative elements of maintaining vehicles in serviceability and readiness.

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