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EFFICIENCY OF IMPLEMENTING PREDICTIVE MAINTENANCE IN THE LIFE CYCLE OF MILITARY TECHNICAL EQUIPMENT

Ioan VIRCA, Romana OANCEA, Stelian POPESCU, Florin ILIE

Abstract: *Military technical equipment has estimated its life cycle to meet the requirements of the battlefield, a cycle in which maintenance plays a decisive role in ensuring availability. The advanced technological level of technical systems in general has led to the emergence of predictive maintenance, which offers solutions for anticipating and preventing failures. Thus, the purpose of this article is to investigate the effectiveness and limitations of implementing predictive maintenance in the military field. The research method used is a comparative analysis of the existing preventive maintenance model with the predictive maintenance model, and the results obtained can be used by decision-makers to analyze the organizational, technical, and regulatory implications that the implementation of this maintenance system would entail.*

Keywords: *life cycle, failure, operational availability, military technical equipment, predictive maintenance.*

1. INTRODUCTION

The maintenance of military technical equipment is a basic component of the military logistics system, with the main purpose of ensuring the reliability and operational availability of technical equipment intended for activities and missions specific to the field of defense. Under current operational conditions, characterized by a high degree of technological advancement on the battlefield and the increasing complexity of weapon systems, combat vehicles, and other logistical support equipment, maintaining their performance becomes an essential requirement for the success of military operations. In the NATO Logistics Handbook, the definition of maintenance considers the notion of material as a generic term for military equipment, thus "Maintenance means all actions taken to keep material in a specified condition or to restore it to that condition. The operational effectiveness of land, naval, and air forces will depend largely on a high standard of preventive maintenance, in peacetime, of the equipment and associated materials used. Repair includes all measures taken to return the material to a functional state in the shortest possible time" [1]. The major importance of the preventive maintenance component expressed in the given definition is noteworthy.

Taking into account the fundamental purpose of the army, which is to "defend the sovereignty, independence, unity, and territorial integrity of the state, as well as to guarantee national security by deterring and repelling any form of armed aggression directed against Romania..." [2, 3], it can be considered that in the military field, maintenance is not only a technical activity, but also a complex component of logistical support, with significant managerial implications. It ensures the continuity of military technical equipment operation under conditions of intense demand and in complex operational environments, where the failure of one of their systems can directly affect the outcome of a mission. In this context, maintenance planning and execution must take into account several factors [4]:

- availability of spare parts;
- location where maintenance will be performed;
- response time of maintenance structures;
- level of training of technical personnel;
- interoperability requirements in multinational operations.

This will result in integrated maintenance planning with maximum efficiency in terms of the operational availability and reliability of military technical equipment throughout its life cycle, thus saving more resources [5]. In fact, an integrated approach based on life cycle management allows for performance optimization, cost reduction, and long-term resource sustainability.

It is important to understand the concepts and principles specific to *Life Cycle Management* (LCM) of military equipment, two of which are *Life Cycle Cost* (LCC) and *Total Ownership Costs* (TOC) [6]. LCC focuses on estimating costs from design to decommissioning and is an economic analysis tool for estimating TOC prior to acquisition. This concept includes the following costs: acquisition and installation costs; equipment usage costs; maintenance costs; logistics costs; and modernization and decommissioning costs. Approximately 60-80% of TOC is consumed by the above costs once military equipment has entered its useful life and must be estimated as early as the equipment design phase [**7**].

Of these cost categories, maintenance and operation of military technical equipment account for a significant percentage of total life cycle costs and may vary depending on the country, category of armed forces, type of equipment, etc. The literature on military procurement and logistics repeatedly confirms that 60% to 80% (or even 90%) of the total life cycle cost (LCC) of military equipment is spent on operation and maintenance (O&M) after the initial purchase. The authors [8] specify the value of 60% maintenance costs as a share of the total life cycle costs of military equipment.

Another major concern for LCM specialists is to monitor and manage military technical equipment so that "*maintenance costs are kept as low as possible, with all countries facing increasing maintenance problems*." [9].

Current military technical equipment is extremely efficient and reliable, and its life cycle can vary, depending on type and complexity, between 10 and 20 years or more. There is no unanimity in determining the life cycle, but the actual cycle can sometimes be shorter due to excessive wear and tear, especially in theaters of operations, or it can be extended through maintenance and upgrades [10]. For example, a recent report by the US Government Accountability Office (GAO) estimates that the average lifespan of some medium-class tactical vehicles will reach 20-22 years, both through their modernization with state-of-the-art technology and through predictive maintenance work to enable them to perform missions in different terrain and climatic conditions [11].

New technologies (drones, robots, artificial intelligence, etc.) have radically changed and will continue to change concepts and doctrines about warfare and, implicitly, about the life cycle design of military technical equipment. In support of this statement, as early as 2018, Alexander Kott, chief scientist at the US Army Research Laboratory in Adelphi, Maryland, argued for the need for accurate forecasts regarding the development and procurement of military technology, with some horizons extending beyond 20 years, which are important for managerial decisions related to the allocation of funds for long-term research topics [12].

Given these conditions for the development and implementation of new technologies in military equipment and the application of doctrinal concepts in current and future military actions, the type of maintenance that is currently gaining ground is predictive maintenance [13], as a complementary solution to preventive maintenance, focusing on *non-serviceable or continuously worn components* that cannot be maintained preventively, but whose degradation affects the overall performance of the equipment. This type of predictive maintenance uses sensors placed on the structural subcomponents of military equipment, communication and storage infrastructure, data analysis software, and artificial intelligence algorithms to monitor the actual condition of components and anticipate the occurrence of defects.

2. PURPOSE AND OBJECTIVES OF THE RESEARCH

The increasing complexity of military technical equipment, the integration of digital technologies, and strict requirements for operational readiness call for an objective

reassessment of how the maintenance process is designed and implemented in modern armed forces. Against the backdrop of the digitization of logistics processes and the integration of smart infrastructures, it is becoming essential to identify methods that allow real-time monitoring of equipment status and maintenance decisions based on concrete data, not just theoretical estimates. The implementation of such an approach has direct implications for economic efficiency, operational availability, and interoperability with NATO partners.

In this context, replacing outdated military technical equipment with new or more advanced equipment leads to major changes in the strategic and operational framework for planning and executing maintenance. For the military system, *preventive maintenance* remains the basic form of work execution, at least during the warranty period of each piece of equipment, in accordance with the manufacturer's specifications regarding maintenance intervals, technical procedures, and operating conditions.

During the post-warranty period, when military technical equipment may suffer random changes in availability due to various technical, environmental, terrain, or combat factors, a key role is played by corrective maintenance, which involves technical operations that will restore the equipment to its operational condition.

Taking these specific aspects into account, the main purpose of this paper can be defined as *investigating the effectiveness and limitations of implementing predictive maintenance* in the life cycle of military equipment.

Thus, this paper has the following objectives:

O1. Analyzing the operational efficiency of preventive and predictive maintenance through a case study on a component of military technical equipment, namely an Iveco military truck;

O2. Evaluating the results and formulating conclusions regarding the appropriateness and efficiency of implementing the predictive maintenance system on the analyzed military equipment.

Based on the objectives formulated, the research is based on the following *working hypotheses:*

Hypothesis 1 – Implementation of the predictive maintenance system leads to an increase in operational availability and a decrease in the financial resources required, compared to traditional models.

Hypothesis 2 – Integration of sensor-based monitoring and data analysis systems into the military maintenance system would contribute to increasing the reliability of military equipment.

After establishing the research objectives and working hypotheses, the research questions that the authors ask themselves through their research and which they must answer through their research results in the final part of the paper or conclusions can be highlighted in accordance with scientific research guidelines and instructions for authors, in order to validate the entire scientific approach, as follows:

a) what are the benefits of predictive maintenance compared to preventive maintenance in the military system?

b) What are the limitations and challenges specific to predictive maintenance in the field of military technical equipment?

3. RESEARCH METHODOLOGY

Currently, the global trend in production systems, especially automated manufacturing systems, is toward predictive maintenance, which uses advanced monitoring, data analysis, and artificial intelligence technologies to anticipate defects before they actually occur [14].

In the military environment, the implementation of predictive maintenance is closely related to the concepts of integrated logistics and equipment life cycle management, being conditioned by the technical and economic efficiency of its implementation in real maintenance processes [15]. According to this general reference source (NATO Logistics Handbook, 2012), integrated logistics support is the managerial and technical process in which

maintenance, including predictive maintenance, is integrated with equipment life cycle management.

Predictive maintenance is based on the collection and analysis of data from the operation of technical equipment in order to anticipate the occurrence of faults and plan interventions at the optimal time. This approach involves the application of fundamental principles that combine sensor technology, data analysis, and the use of artificial intelligence algorithms to estimate potential failures [16].

The research method used in this paper is the multi-criteria evaluation method [17, 18], which involves assigning numerical scores to the evaluation criteria divided into evaluation areas, weighting the scores according to the relative importance of each criterion or area, and calculating an overall indicator that allows the two types of maintenance to be ranked and the final decision to be substantiated.

4. CASE STUDY. RESULTS AND THEIR INTERPRETATION

For the case study, the AdBlue system (Fig. 1) of the IVECO Cargo 15t military vehicle were selected, which injects AdBlue solution (synthetic urea) into the exhaust gases to reduce nitrogen oxides below the limit imposed by Euro standards on pollution through SCR (Selective Catalytic Reduction) aftertreatment technology. This system was chosen due to its technical availability for predictive maintenance analysis.

From a preventive maintenance perspective, the technical standards stipulate periodic inspection and maintenance operations for the installation [19], which, when performed on time and with high-quality workmanship and maintenance materials, allow the installation to maintain a high level of operational availability.

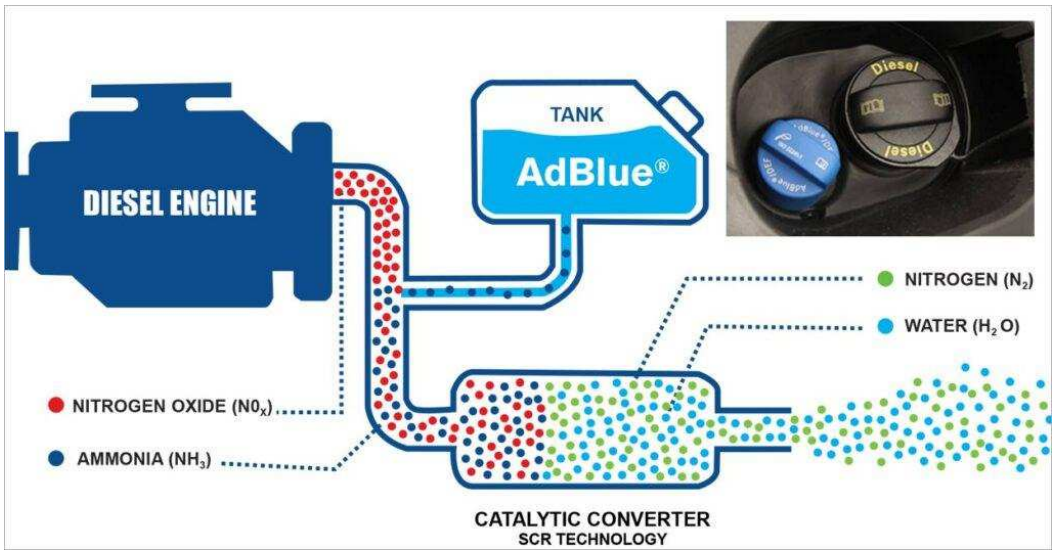


Fig. 1. AdBlue injection system (SCR) of the IVECO Cargo 15t military truck [23]

The catalytic reduction reaction of nitrogen oxides is that in equation (1):

$$2NH_3 + NO + NO_2 = 2N_2 + 3H_2O \quad (1)$$

The research stages are as follows:

a) the role and functioning of the main components of the Selective Catalytic Reduction system on the gas exhaust path (Figure. 2);

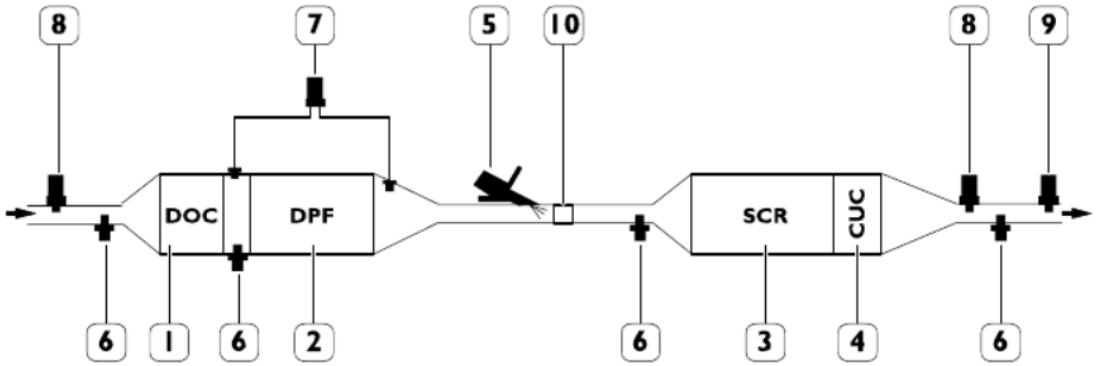


Fig. 2. The main components of SCR [24]

1. DOC – diesel oxidation catalyst
2. DPF – diesel particulate filter
3. SCR – selective reduction catalyst
4. CUC – residue cleaning catalyst
5. Solution injector (dosing module)
6. Temperature sensors
7. DPF pressure sensors
8. Nitrogen oxide sensor
9. Ammonia sensor
10. Mixer for homogenizing the mixture

From the analysis in Fig. 2, starting from the solution injector 5 and the homogenization device 10, four sensors can be seen that monitor the process of selective catalytic reduction of nitrogen oxides present in the exhaust gases, namely the temperature sensors 6, the nitrogen oxide sensor 8, and the ammonia sensor 9.

The sensors continuously transmit signals to the ECU (electronic control unit), which processes them and controls the solution injector, determining the amount of urea injected based on the engine's operating parameters. This ensures optimal operation of the AdBlue system.

b) The sensor system required for the AdBlue system in the predictive maintenance version (table no. 1)

Table 1

Monitored components and sensors installed in the predictive maintenance version

Component	Sensor type	Monitored variable	Purpose
AdBlue tank	Ultrasonic / float sensor	Urea level (liters)	Checks for abnormal drops/leaks
AdBlue pump	Hall/CAN current sensor	Outlet pressure (bar) Pump motor current (A)	Detects pressure loss/cavitation Mechanical wear/pump blockage
AdBlue pipes	Flow meter	Flow rate (ml/s)	Blockages or insufficient injection
SCR injector	Thermistor	Nozzle temperature (°C)	Freezing/overheating
SCR catalyst	Upstream NOx sensor Downstream NOx sensor	NOx upstream (ppm) NOx downstream (ppm)	Input pollution level Catalyst conversion
Electronic system	ECU / CAN-bus	Tensiune alimentare, erori ECU	Complete diagnosis

Based on their study of specialized literature and their professional experience, the authors of this paper believe that, for comprehensive monitoring of all AdBlue system components and their availability for sensor installation, the elements specified in Table 1 would be suitable.

Basically, all components of the installation are assisted by a type of sensor, which increases the complexity of the entire predictive maintenance system both in terms of data collection and database creation, as well as the level of training of the operating personnel (Table 2).

c) developing a predictive maintenance plan based on the frequency of interventions

Table 2

Predictive maintenance plan template

Stage or intervention	Action/Intervention	Frequency	Responsible personnel
Sensor check (NOx, pressure, current)	ECU scan + calibration	Weekly	Maintenance technician
Data download + model retraining	RUL (Remaining Useful Life) model update	Monthly	Maintenance data analyst
AdBlue filter replacement / injector check	Preventive	At 500 hours / RUL < 500 min	Maintenance staff
Complete SCR system overhaul	AdBlue circuit cleaning	At 2000 hours	Maintenance team
MTBF / MTTR indicator reporting	Logistics report	Quarterly	Head of maintenance

The predictive maintenance plan outlined in Table 2, in a general form for only a few interventions, not transposed into a standard format, shows the high complexity of the predictive maintenance system both in terms of the type of actions to be performed and the diversity of personnel involved in the process.
In order to assess how well the objectives of the paper have been achieved, Table 3 evaluates the main process characteristics of the two types of maintenance studied, preventive maintenance and predictive maintenance, using status indicators.

d) assessment of the common characteristics of the types of maintenance analyzed

Table 3

Characteristics of preventive and predictive maintenance types and their evaluation

Type of maintenance► / Characteristic ▼	Preventive maintenance	Predictive maintenance
Restoration of operational capacity	Partial	Partial
Nature of maintenance interventions	Periodic	Conditional
Complexity of maintenance planning of maintenance work	Average	Reduced
Nature of maintenance work execution	Planned	Flexible
Actual time required to complete total resource	Partial	Maximized
Level of staff training	Universal	Specialized
Information on the degree of wear and tear of assemblies	General	Detailed
Downtime/overhaul time	Average	Reduced
Costs of maintenance work	Average	Low
Total costs of implementation and operation in the military field	Average	High

Methodology for evaluating the two types of maintenance

According to the established research method, Multiple-Criteria Decision Analysis (MCDA), Table 4 divides the status indicators into assessment areas and assigns numerical scores based on the degree of fulfillment of the analyzed characteristic (scale from 1 to 5: 1-very low/unfavorable; 2-low level; 3 medium/acceptable level; 4-high level; 5-favorable/very high/optimal level) and the weights of the indicators are established by evaluation area: technical indicators, economic indicators, and organizational or administrative

indicators. The weights were chosen to reflect the specific nature of the military environment and the requirements for operating technical equipment [20].

Table 4

Scores and weights assigned to status indicators, individually and by assessment area

No.	Indicator name	Preventive maintenance score	Predictive maintenance score	Justification for score determination
1.	**A. Technical indicators (45%)**			
	Restoration of operating capacity	4	5	Predictive maintenance optimizes intervention, but preventive maintenance is sufficient
	Actual time to complete total resource	3	4	Limited by the sensors available on the truck
	Information on the degree of wear and tear of assemblies	2	4	Predictive maintenance partially possible (oil, vibrations, ECU errors)
	Actual time to complete total resource	3	4	Predictive maintenance reduces unplanned downtime of the AdBlue system
	Average technical score	**3,00**	**4,25**	
2.	**B. Economic indicators (35%)**			
	Maintenance intervention costs	4	3	Sensors and diagnostics increase costs in predictive maintenance
	Total implementation and operating costs in the military field	4	2	Predictive maintenance requires specialized equipment and personnel
	Average economic score	**4,00**	**2,50**	
3.	**C. Organizational/administrative indicators (20%)**			
	Nature of maintenance interventions	5	2	Preventive maintenance is regulated and standardized
	Complexity of planning maintenance work	5	2	Predictive maintenance is difficult to integrate into military plans
	Nature of maintenance work	4	3	Predictive maintenance requires additional skills
	Level of staff training	4	2	Maintenance personnel are generally trained for preventive maintenance work
	Average administrative score	**4,50**	**2,25**	

The global indicatorE_{global} is calculated using the following formula (2):

$$E_{global} = \sum_{i=1}^{n}(score_i x\ weight_i) \quad (2)$$

Thus, using the data in Table 4, scores, and weights, the overall indicator for each type of maintenance analyzed is calculated using equation 3:

$$E_{global} = (E_{technical}\ x\ 0{,}45) + (E_{economic} x\ 0{,}35) + (E_{administrative}\ x\ 0{,}20) \quad (3)$$

The corresponding results are those in relations 4 and 5:

$$E_{global\ Preventive\ maintenance} = (3{,}00\ x\ 0{,}45) + (4{,}00\ x\ 0{,}35) + (4{,}50\ x\ 0{,}20) = \mathbf{3{,}65} \quad (4)$$

$$E_{global\ Predictive\ maintenance} = (4{,}25\ x\ 0{,}45) + (2{,}50\ x\ 0{,}35) + (2{,}25\ x\ 0{,}20) = \mathbf{3{,}23} \quad (5)$$

The results show a slight advantage for preventive maintenance (score 3.65) over predictive maintenance (score 3.23) in terms of the efficiency of the full implementation of one of the maintenance systems analyzed, taking into account all the necessary resources, namely material, financial, and human. Higher scores indicate the favorable nature of each status indicator. The weights assigned to the evaluation areas were determined based on the operational role of the Iveco military truck, in which technical and functional availability are the most important (45%). The economic indicators area (35%) plays a significant role in

the budget, but can be considered secondary in terms of secure budgeting, while the organizational or administrative area is of a supporting nature, with a lower weighting (20%).

5. CONCLUSIONS

Predictive maintenance is technically superior, but at the administrative level it requires a series of requirements and involves specific restrictions on implementation and operation in the case of military technical equipment, including:

- the mobility of military actions requires the massive deployment of military technical equipment and, consequently, significant logistical support, interoperable with that of the NATO alliance, within which predictive maintenance is not widely applicable at present;
- current military technical equipment is high-performance and reliable, and the preventive maintenance system that is applied meets maintenance, diagnosis, and repair requirements, with relatively low costs and average downtime over the life cycle;
- preventive maintenance is carried out both in-house by maintenance units and outsourced, which would require additional costs for predictive maintenance in terms of travel and maintenance operations;
- predictive maintenance software applications usually involve the use of cloud-based solutions, which, in the context of the military system, may represent a constraint or even a prohibition from the perspective of military information security requirements;
- predictive maintenance software applications typically involve the use of cloud-based solutions, which, in the context of military systems, may represent a constraint or even a prohibition from the perspective of military information security requirements.
- the implementation of predictive maintenance is also subject to constraints regarding NATO auditing, standardization, and interoperability requirements;
- there is no NATO directive imposing it as a uniform policy for all military technical equipment of all member states, but the concept of predictive maintenance based on artificial intelligence is increasingly being taken into acount by military specialists and decision-makers [21, 22].

As such, based on the results obtained and the conclusions drawn above, the implementation of predictive maintenance in the life cycle of military technical equipment is not effective at present, both from a technical-economic and administrative point of view.

Based on the research conducted and the conclusions listed above, the authors consider that the research objectives of the paper, specified in section 2, have been achieved and validated by the results obtained. Regarding the confirmation of the hypotheses formulated, the analysis of the results indicates the following conclusions: hypothesis I1 is partially confirmed in terms of increasing the operational availability of military technical equipment through the application of predictive maintenance, but the costs of implementation and operation increase. The second hypothesis is fully confirmed, predictive maintenance leading to increased reliability of military equipment through early identification of wear processes and functional anomalies, a conclusion supported by the technical indicators *Restoration of operating capacity and Information on the degree of wear of assemblies* (table no. 4).

Regarding the answers to the research questions formulated in section 2, the authors state that as emerging and disruptive technologies penetrate the structure and management of military technical equipment, predictive maintenance will become an obligation for its implementation and operation, with great benefits in maintaining them in a state of maximum availability.

This evolution in sensor technology and artificial intelligence poses major challenges for military personnel in terms of professional training, integrating technologies into maintenance strategies, and creating a new procedural framework.

Finally, the authors' contributions can be summarized as follows: the method of analysis through a case study of a component system of military technical equipment with technical availability for predictive maintenance; comparison, using the research method

employed (MCDA), of the characteristics of preventive maintenance with those of predictive maintenance; interpretation of the research results to establish the effectiveness of implementing a new type of advanced maintenance, namely predictive maintenance, in the life cycle of military technical equipment.

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Eficiența implementării mentenanței predictive în ciclul de viață al echipamentelor tehnice militare

Rezumat: Echipamentele tehnice militare au estimat ciclul de viață astfel încât să răspundă cerințelor câmpului de luptă, ciclu în care mentenanța are un rol decisiv în asigurarea stării de disponibilitate. Nivelul tehnologic avansat al sistemelor tehnice în general a determinat apariția tipului de mentenanță predictivă, care oferă soluții pentru anticiparea și prevenirea defecțiunilor. Astfel, scopul acestui articol este de a investiga eficiența și limitele implementării mentenanței predictive în domeniul militar. Metoda de cercetare folosită este analiza comparativă a modelului de mentenanță preventiv existent cu modelul de mentenanță predictivă, iar rezultatele obținute pot constitui pentru factorii de decizie subiect de analiză a implicațiilor de natură organizatorică, tehnică și normativă pe care le-ar impune implementarea acestui sistem de mentenanță.

Ioan VIRCA, Assoc.Prof.Eng., PhD., "Nicolae Bălcescu" Land Forces Academy of Sibiu, Department of Technical Science, virca.ioan@armyacademy.ro, +40 269 432 990, 3-5 Revoluţiei Street, Sibiu, Romania.
Romana OANCEA, Assoc.Prof., PhD., Vicedean for International Relations, "Nicolae Bălcescu" Land Forces Academy from Sibiu, Department of Technical Science, oancea.romana@armyacademy.ro, +40 269 432 990, 3-5 Revoluţiei Street, Sibiu, Romania.
Stelian POPESCU, Assoc.Prof.Eng., PhD., "Nicolae Bălcescu" Land Forces Academy of Sibiu, Department of Technical Science, popescu.stelian@armyacademy.ro, +40 269 432 990, 3-5 Revoluţiei Street, Sibiu, Romania.
Florin ILIE, Assoc.Prof.Eng., PhD., "Nicolae Bălcescu" Land Forces Academy of Sibiu, Department of Technical Science, ilie.florin@armyacademy.ro, +40 269 432 990, 3-5 Revoluţiei Street, Sibiu, Romania.