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Dear readers,

publishing research findings is one of the fundamental pillars of academic life. It is not only a tool for communicating new knowledge, but also a key factor in an individual's professional growth. In a highly competitive academic environment, the ability to publish regularly becomes a crucial criterion for professional development and building a personal scientific reputation. The quality and visibility of publications are becoming an integral part of scientific work evaluation.

Publishing plays a significant role for PhD students as it enables them to learn the principles of academic integrity, formulate and defend their own research findings, and establish their first professional contacts. Publishing also helps them grow as young scientists and often opens doors to further projects, research stays, and international collaborations.

In addition, scientific publishing transcends individual dimensions. It is a vital tool for building the reputation of a workplace or an institution. Each published article is a contribution to the global space of knowledge and reflects the quality of research in a given field. At a time when international cooperation and open communication are emphasised across scientific disciplines, the transparent and accessible dissemination of research findings is becoming a matter of course and an obligation. Open Access represents an opportunity for authors to reach a wider range of readers and increase their citation potential, which is another important aspect of scientific reputation and evaluation. High-quality Open Access publishing thus contributes to the overall interconnection of research communities and strengthens their influence in an international context.

We believe that this issue of our journal will contribute to scientific debate and provide the space for presenting research findings that can inspire, stimulate, and support further scientific progress. Let me briefly introduce the contents of the current issue:

The first among the peer-reviewed papers in this issue is the article titled ***„Methods and Techniques for Countering Unmanned Combat Assets on the Modern Battlefield"*** *written by Tomasz Szulc. This paper provides a structured overview of current methods for countering unmanned combat systems, distinguishing between passive and active defence measures. Its most significant contribution lies in summarising existing tactical practices and proposing a conceptual framework for their application at lower command levels and analysis of methods and techniques of combating unmanned systems and their use in combat situations.*

The authors Pavol Lukášik, Vladimír Kadlub and Filip Valek wrote the paper titled ***„Economic and Ecological Balance Sheet of a Small LPG Vehicle in Urban Operation".*** *The aim of this paper is to present relevant results on the economy and ecological burden of LPG fuel (economic and ecological analysis, fuel consumption, financial return) in comparison to operation on automotive petrol, in the form of a mathematical and statistical analysis.*

Among the papers in this issue, you can find the paper written by Tomáš Rázga, Peter Baláž, Vratislav Kreheľ and Juraj Pagáčik titled ***„The impact of Aging on the Quality of Ballistic Protection".*** *This paper examines the effects of prolonged aging on ballistic resistance by evaluating a soft armour panel that has significantly exceeded its recommended lifespan. One of the main findings that the article focused on was the verification that even bulletproof panels in advertisements are still durable after years and provide sufficient protection for an individual from bullets from short firearms.*

The series of articles is closed with the paper titled ***"Analysis of Modular ROD Frame Construction for the 3D-Printed Multirotor UAVs"*** *written by Karol Semrád, Katarína Draganová, Eduard Dolný and Peter Droppa. The presented article deals with the analysis of the modular unmanned aerial vehicle (UAV) components, which were designed to be convenient for the assembly of the UAV in the various multicopper configurations.*

Dear readers, in conclusion, I would like to remind you that our Science & Military journal is open to high-quality scientific contributions from both domestic and foreign authors. I would like to take this opportunity to encourage anyone interested in presenting their findings to send their manuscripts to our editorial office. A high-quality journal is built on high-quality articles – and these are created thanks to authors who are willing to share their knowledge.

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METHODS AND TECHNIQUES FOR COUNTERING UNMANNED COMBAT ASSETS ON THE MODERN BATTLEFIELD

Tomasz SZULC

Abstract: The modern battlefield is characterized by rapid developments in new technologies used for military purposes. While the basic principles of armed conflict remain the same as in the past, the means of achieving them are undergoing intense change. Currently, unmanned systems are becoming one of the most effective means of combat used to carry out a wide range of military tasks. The effectiveness of autonomous vehicles requires the development of a comprehensive system to counteract them, which is the main objective of this publication. The article presents a general description of unmanned combat systems, their potential use in tactical operations, and a summary of passive and active methods and techniques for countering and combating drones. The result of the research is a model of actions that is highly recommended to be implemented by both commanders and soldiers of units at the lowest levels of command (section, squad, platoon, company, and battalion) in order to protect themselves against the enemy's unmanned combat vehicles.

Keywords: Unmanned Aerial Vehicles; UAV, Drones; Counter UAV; Unmanned Aircraft System; Remotely Piloted Aircraft; Unmanned Combat Assets.

1 INTRODUCTION

The analysis of contemporary armed conflicts since 2000 reveals a steady increase in the use of unmanned combat vehicles in tactical operations. These kind of weapons have been used in Iraq, Afghanistan, Azerbaijan, during the fighting between Israel and Hezbollah, in Georgia, in the riots in the Gaza Strip, in Syria and Libya, and in the Ukrainian-Russian war, which escalated in early 2022 [1]. The conflict between Ukraine and Russia is the best example of the development of modern unmanned technologies for military purposes. According to official government data, Ukraine currently (as of 2025) produces approximately 4 million combat drones per year [2]. Their effectiveness is constantly increasing, which in the potential armed conflict may lead to a point where they have become one of the primary means of combat used by both sides.

The significant increase in the importance of unmanned combat vehicles used in various tasks in armed conflicts results in the need to develop effective methods and techniques to combat (active methods) and counteract them (passive methods). The lack of specific procedures for dealing with drone attacks requires this information gap to be filled. The main objective of this article is to develop effective methods and techniques for countering autonomous vehicles at the lowest levels of command (section-battalion). The study uses theoretical methods such as analysis, synthesis, comparison, and inference. A synthesis of the information obtained from the research leads to the conclusion that the use of drones in combat will continue to grow, which in turn requires updating the procedures for fighting them. The result of the research is a comprehensive proposal for a solution enabling effective defense against unmanned combat systems at the lowest levels of command.

2 GENERAL CHARACTERISTICS OF UNMANNED COMBAT SYSTEMS

Unmanned combat systems, as a set of technologies used in all combat environments (on land, in the air, and on water), have not yet been defined in military nomenclature. The North Atlantic Treaty Organization (NATO) dictionary only includes the terms Unmanned Aircraft System (UAS) and Remotely Piloted Aircraft (RPA). According to this source, UAS is defined as a system which components include the unmanned aircraft, the supporting network and all equipment and personnel necessary to control the unmanned aircraft. RPA is defined as an unmanned aircraft that is controlled from a remote pilot station by a pilot who has been trained and certified to the same standards as a pilot of a manned aircraft [3]. The commonly used term for unmanned systems is drone, which in the most general sense refers to a land, air, water, or mixed vehicle that does not require a human on board and is controlled remotely [4].

Figure 1 presents a proposed classification of unmanned combat vehicles based on four factors: the environment in which the unmanned system performs its tasks, the size of the vehicle, the extent of its autonomy, and the general manner in which the drone is used in combat.

Currently, the most commonly used type of unmanned combat vehicles are flying platforms (UAVs). Their effectiveness depends on several factors, namely: the time they can perform tasks without having to return to replace batteries or refuel, their range, the distances at which they can operate, their production costs, the functions they perform on the battlefield, the training of their operators, and the effectiveness of the anti-drone systems used by the enemy.

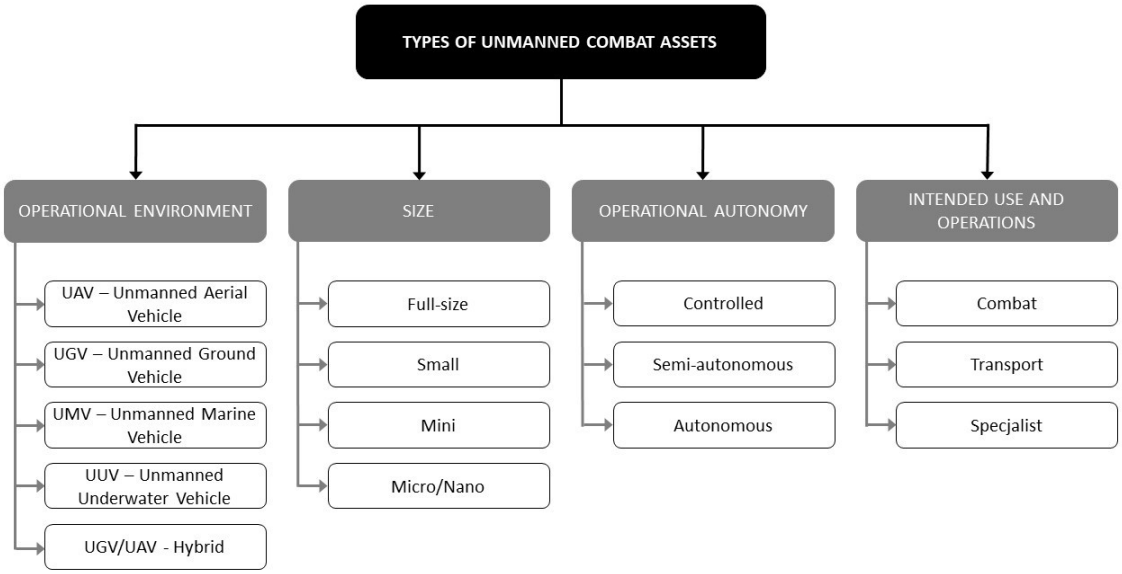

Fig. 1 Classification of unmanned combat assets
Source: author.

When analyzing the Russian Federation's use of unmanned combat systems, the Ukrainian military often divides the development of drones in the conflict into four stages. In the first stage, lasting from March 2014 to September 2022, the Russians mainly used Orion, Forpost, Orlan, and Granat reconnaissance drones, as well as combat drones with loitering ammunition, such as Cub and Lancet [5]. In the next stage, from September 2022 to June 2023, the Russian army introduced Iranian Shahed and Mohajer-6 combat drones. In the third stage, from June 2023 to July 2024, there was a significant increase in the number of First Person View (FPV) combat drones using improvised explosive devices. In addition, aircraft drones such as Chernika and Molniya, as well as ground-based unmanned platforms (UGVs) such as Prometei, Uran, Nerexta, Vixr, Egik, BR-1, BR-2, and Volnorez, have been continuously improved. According to Ukrainian military representatives, the fourth stage, lasting from July 2024 to the present, will be characterized by the further development of unmanned systems. They predict that the use of fiber-optic-controlled drones, which remarkably reduces their vulnerability to interference by the opposing side, will be of significant importance in this war. The next step in this evolution may also be the use of so-called drone swarms. The Russians are also likely to develop their standard unmanned aerial vehicle designs, such as Gerbera and Parodyia [5].

3 POSSIBILITIES OF USING UNMANNED ASSETS

One of the greatest advantages of using unmanned combat systems in tactical operations is their versatility. Figure 2 shows the range of missions that drones can perform on the battlefield.

The most common tasks performed by unmanned platforms on the modern battlefield include reconnaissance, combat missions, and fire support [4]. Thanks to the use of UAVs, the contact zone between the warring parties at a depth of up to 3 kilometers is constantly monitored and virtually inaccessible to heavy vehicles. The use of autonomous vehicles has significantly increased surveillance capabilities without exposing soldiers to the risk of infiltrating enemy formations, which is practically impossible in the Russian-Ukrainian war.

Using information obtained from reconnaissance drones can be used to perform combat missions related to the direct and indirect fire delivery against enemy forces, for example Attack by Fire (ABF), Support by Fire (SBF), blocking the enemy or even ambush. Currently the most common method of combat is the use of FPV drones to destroy enemy targets, even a single soldier.

Unmanned assets can locate, identify and support the process of selecting and prioritizing targets and guide indirect fire to the target. Using mainly UAVs, commanders can assess the fire impact on enemy’s targets in real time in the live-view mode. At the moment, in order to reduce the time from target detection to target destruction, drones are assigned to a single artillery gun.

In terms of tasks related to transport in the broad sense, unmanned systems can be used to evacuate the wounded and deliver supplies to the front line. In the ongoing conflict in Ukraine, medical evacuation using heavy vehicles (helicopters, armored vehicles) on the front line is often impossible

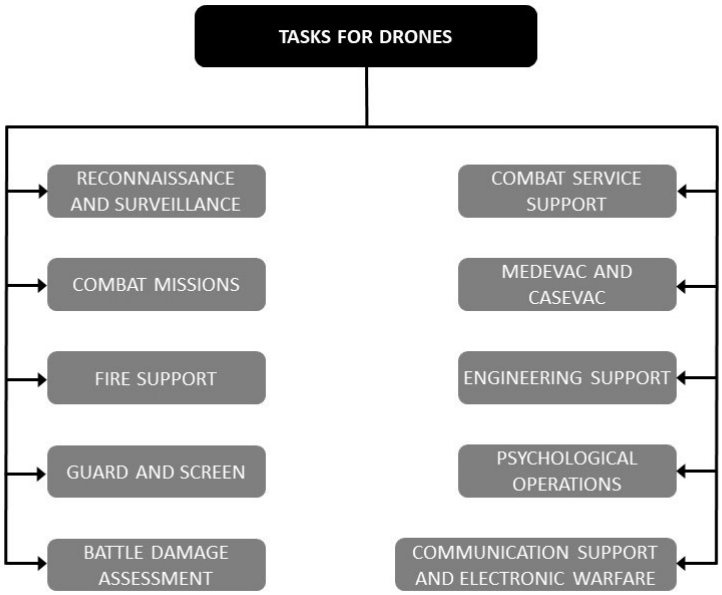

Fig. 2 Possibilities of using unmanned combat assets
Source: author.

due to the high probability of such vehicles being destroyed. Unmanned systems, in this case mainly UGVs, enable the evacuation of the wounded, even those under fire, without the need to expose additional forces and resources. The efficiency of supplying troops can be increased by the use of drones. Ground vehicles can successfully replace combat vehicles, soldiers or pack animals. UAVs can perform logistical tasks by delivering supplies after landing or by dropping cargo without having to land. In the Russian-Ukrainian conflict, drones deliver bottles of water dropped from the air, medical equipment (including even medical drips), and walkie-talkies to soldiers in order to provide instructions on how to perform first aid on wounded soldiers [6].

Unmanned systems can also perform numerous specialized tasks, such as screen and guard, engineering support, battle damage assessment, communication support, electronic warfare, and psychological warfare [6].

The ability to use unmanned combat systems in so many different tasks is undoubtedly their advantage. Another positive aspect of using drones is their relatively low production costs in relation to the effects they achieve, for example, by destroying an armored vehicle or tank. An important benefit of using autonomous vehicles on the battlefield is the minimization of human casualties by replacing them with drones in the most dangerous tasks. Furthermore the use of the discussed assets allows to gain time, thanks to which people can be assigned to perform more complex and important tasks. The use of unmanned systems also increases the combat capabilities of a unit by, among other things, expanding its mobility and firepower. Replacing heavy equipment with electric-powered drones maximizes the stealth of operations and reduces the chances of detection by the enemy. Unmanned combat assets, in conjunction with Battle Management Systems (BMS), significantly raise the situational awareness of commanders, who can make decisions based not on old and outdated maps, but on real-time data often transmitted in a live-view system. UAVs that perform combat tasks have the additional advantage of choosing the right moment to strike a target. Drones can observe the enemy and attack only when the operator decides that the strike will be most effective. In comparison, a fired artillery shell, even if guided during flight, cannot stop but must reach its target.

On the other hand, the use of unmanned combat systems also has disadvantages that must be taken into account when planning military operations involving their use. One of the most significant problems with the use of drones in combat is their vulnerability (especially UAVs) to adverse weather conditions. In the Russian-Ukrainian conflict, the intensity of unmanned systems on the line of contact between the armies is so high that important tasks such as assaults, troop relief, and supply delivery are carried out in difficult weather conditions when UAVs cannot fly. Another drawback of drones, especially small commercial ones, is their short battery life, which requires the creation of a permanent system for replacing and recharging them. In addition, unmanned combat systems that are not controlled using cables and fiber optics are vulnerable to interference from the enemy. Depending on the type of drone, the distance between the operator and the device, as well as weather conditions, communication problems may arise between the unmanned vehicle and the operator

controlling it. Managing the combat of numerous autonomous vehicles requires the creation of an effective battlefield management system using high-speed data transmission via the internet. Currently, the Ukrainian army uses Starlink devices, which, together with numerous applications (e.g., Kropywa, ATAK, Delta), enable the coordination of activities and without which the effective use of drones would be impossible. The final downside of using unmanned systems, especially combat systems with a high degree of decision-making autonomy, is moral issues. Entrusting a machine with the decision to kill enemy forces is highly controversial, which delays the development of autonomous combat drones.

4 METHODS AND TECHNIQUES FOR COUNTERING AND COMBATING UNMANNED COMBAT SYSTEMS

The characteristics of unmanned combat systems presented above justify the growing trend of using various types of autonomous vehicles on the modern battlefield. In order to counteract the identified threat posed by unmanned systems to one's own forces and resources, procedures for effectively combating them must be developed. The basis for this can be the air defense methods and techniques used to date, supplemented by the specifics of countering drones and experience from current armed conflicts [7]. Figure 3 presents a proposal for passive and active measures aimed at countering and combating unmanned combat systems.

The first passive measure that has a significant impact on protecting forces and resources against attacks by unmanned systems is the dispersion and decentralization of troops. The greater the distance between soldiers, fewer soldiers and limited equipment in one place, the lower the chance of aerial reconnaissance and attack by enemy drones. In this regard, the principle of maximum dispersion before performing a task and concentration of forces only for the purpose of performing it should be applied.

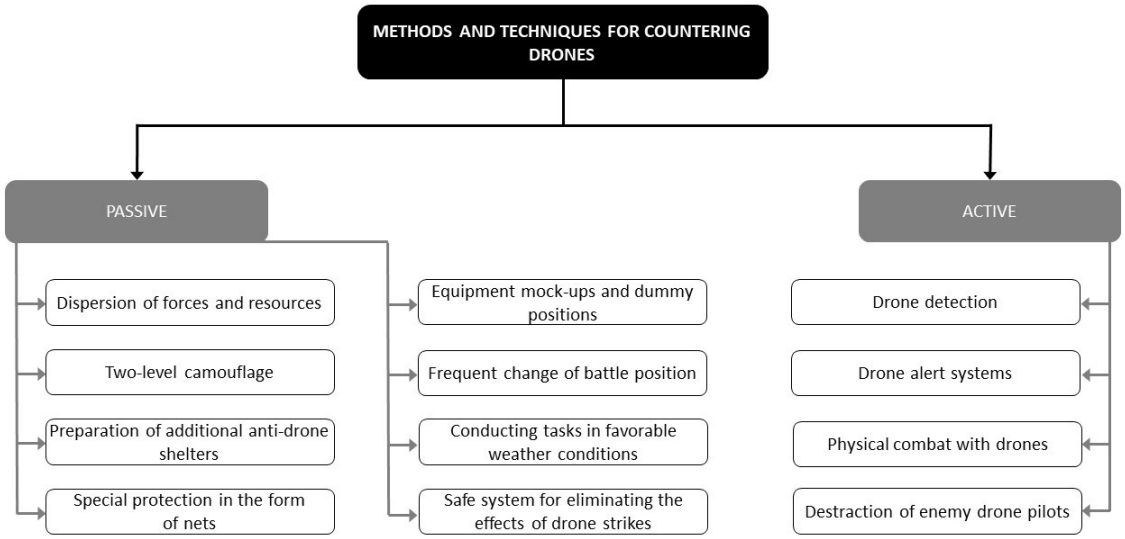

Fig. 3 Methods and techniques for countering drones
Source: author.

Unconventional actions also have a significant impact on protection against drones. Procedures and patterns that are constantly repeated in the same formation make it easier for the enemy to detect friendly troops and destroy them using autonomous vehicles. Open areas should also be avoided and if additionally there is a high risk of the enemy using drones, active, irregular movement in a dispersed formation should be performed. On the other hand, it should be remembered that the dispersal of forces and resources must not have a negative impact on the performance of tasks and on command and communication between soldiers.

The best way to avoid contact with enemy unmanned systems is to remain undetected. Therefore, another important aspect of passive protection against drones is two-stage masking. The first one is a standard level of masking, which involves using all available means to minimize the possibility of detection of friendly forces. Camouflage should be active, continuous, credible, and diverse. It is highly recommended to use the terrain's relief and cover, background contrast, weather conditions and time of day, artificial masks, camouflage painting, smoke, light, sound, and anti-thermal camouflage. The second level of camouflage is based on the experience of soldiers participating in the Russian-Ukrainian conflict and consists of masking, which even if detected by the enemy's unmanned systems, will not be classified as the target worth attacking. As part of the target prioritization process, the enemy decides which targets to engage

first. A target which does not appear threatening and does not have significant weaponry may be ignored [8].

Another passive measure implemented to defend against unmanned combat systems is the preparation of additional shelters and hiding places, especially during static operations. The designated locations should be L-shaped and have at least two entrances/exits. Their additional equipment has to include blankets, protective curtains hung at entrances and exits, smoke grenades ready for activation in case of a drone attack, camouflage nets, and thermal imaging mats. As part of the defense of a squad, platoon, or company, each commander should remember to prepare several alternative firing positions for each fire weapon. This makes it difficult for the enemy to detect the current location of soldiers. The multitude of firing positions also ensures the freedom of maneuver of a given unit. A useful technique for checking the effectiveness of dispersion, camouflage, and the preparation of additional cover against the enemy's unmanned weapons is to use your own military drone to observe soldiers and equipment from the air. By using the same tool as the enemy it is possible to notice one‘s own mistakes and identify areas that need improvement and refinement.

As a part of passive defense against attacks by unmanned systems, specialized protective nets are also used, mainly to protect equipment, firing positions, and logistics transport. Metal nets or lattice screens, which do not protect against anti-tank missiles, often constitute a significant obstacle for combat drones, especially FPV drones. Such countermeasures can be installed on virtually any combat equipment, such as tanks, armored personnel carriers, or off-road trucks. This solution must meet several requirements. The most important of these include quick assembly and disassembly, no negative impact on the vehicle's weaponry, and no collision of the mesh or screen with the possible evacuation of the crew. In the war between Russia and Ukraine, the construction of corridors and tunnels made of nets is also increasingly applied to protect logistics transport, medical evacuation, and troop rotation from combat drone strikes along access roads to the front line [9].

Fig. 4 Ukrainian infantry fighting vehicle with improvised protective metal net against Russian FPV drones
Source: [9].

An important element of passive defense against unmanned combat vehicles is the use of various types of equipment mock-ups and the creation of dummy positions designed to mislead the enemy about the location of one's own troops. Each effectively prepared dummy position engages the enemy drone operator in destroying a false target. The operator then wastes time on destroying the dummy, as well as resources in the form of a missile or kamikaze drone. The effectiveness of the above-mentioned mock-ups is greater the more realistically they reflect the real equipment. They are most often created from available materials using camouflage, heat emission, electromagnetic radiation, and imitation of gunfire, which makes them look real and thus they mislead the enemy. The higher number of dummy positions are created, the greater the chance of protecting the real forces and resources of one's own military [10].

Fig. 5 A fake D-20 Howitzer (left) made of plywood and plastic. The real thing fires on Russian targets on the front line near Bakhmut
Source: [10].

As a part of passive defense, it is also important to remember to frequently change the position of your own troops. Stagnation and staying in one place for a long time increases the likelihood of detection by unmanned combat systems. The exception to this rule are very well and meticulously prepared locations and positions (especially in built-up areas), which should not be abandoned until they are exposed. A convenient time for movement and other dynamic tactical actions is during periods of the day when weather conditions prevent UAVs from flying. Such conditions include strong winds, fog, and heavy rain or snow. When dealing with the effects of drone strikes, it should be borne in mind that they rarely operate alone. Before proceeding with the elimination of the effects, it is necessary to ensure that the area of operations is safe. On many occasions, operators of unmanned combat vehicles destroy one insignificant target in order to strike again when it is evacuated and more soldiers are concentrated in one place.

In addition to the passive countermeasures against unmanned combat vehicles, active measures should also be taken to combat them. In order to eliminate

enemy drones, they must in the first place be detected. Reconnaissance should be carried out by soldiers specialized in drone detection at observation posts, designated airspace observers in each unit, as well as civilians supporting military operations. Specialized sections for detecting unmanned combat systems have to be trained and equipped with equipment capable of analyzing the frequencies at which they operate, which requires long-term training. Observers assigned from each unit are required to conduct airspace surveillance using optical, optoelectronic, and thermal imaging devices. After detecting a target using battlefield management systems, communications equipment, or established signals, they report the detected target to the commander and alert other soldiers.

The civilian environment is also an important element of the system for detecting and identifying enemy drones. The Ukrainians have created a dedicated application that, when an unmanned aerial vehicle is detected, allows information about its location to be forwarded to the military. The actions performed by civilians consist of launching the application, pointing the phone in the direction of the detected vehicle, and confirming the report. An additional tool for noticing drones are individual alarm systems, such as the Ukrainian device Cukor. The mechanism, which is the size of a power bank and equipped with an antenna, emits a loud audible signal when an approaching unmanned aerial vehicle is identified, informing the soldier of the threat. The downside of this solution is the lack of information about the direction from which the drone is approaching [11].

The detection and identification of unmanned combat systems must be linked to a military alert system and active threat response. For this purpose, the observer's action algorithm after drone detection, shown in Figure 4, can be used.

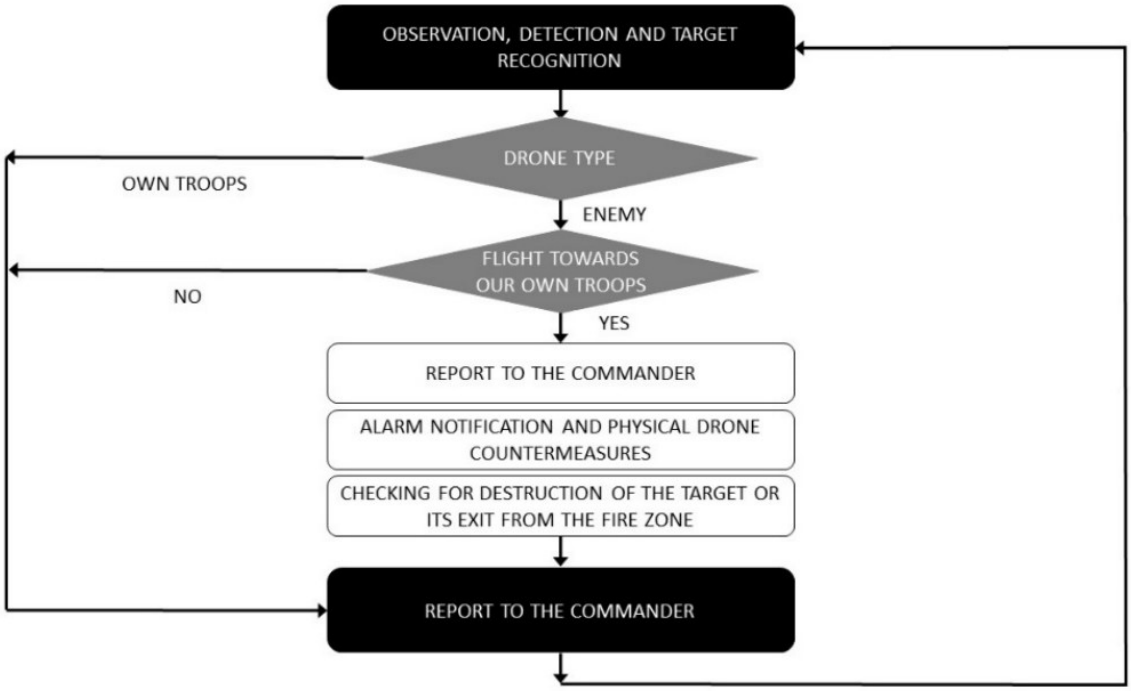

Fig. 6 Algorithm of observer actions after detecting a drone
Source: [12].

Airborne threats can be alerted by voice, siren, gong, flare, technical means of communication, and a battlefield management system using dedicated applications for phones, smartphones, and tablets [7]. The threat alert signal should include the type of detected asset and the direction of its attack.

After detecting and identifying an unmanned combat vehicle heading towards friendly forces, active countermeasures should be initiated. The fight against drones is to be carried out by designated soldiers equipped with dedicated equipment and weapons. An example division of forces to carry out this task at various levels of command may be as follows: in a squad – at least one soldier, in a platoon – a section or squad, and in a company or battalion – a platoon. Active combat against unmanned combat systems can be carried out using several methods, including: jamming drones, Global Positioning System (GPS) or satellite navigation signals using electronic warfare measures, destroying unmanned aerial vehicles with anti-aircraft weapons, using small arms and team weapons, and combating enemy drones with friendly drones.

Technical measures for jamming unmanned combat systems are based on jamming the control and navigation system and intercepting intelligence

information. To this end, various types of stationary or vehicle-mounted jamming stations, as well as handheld drone jammers resembling firearms, are used in the Russian-Ukrainian conflict [13]. Another element of active anti-drone warfare is various types of anti-aircraft measures, often mobile, mounted on vehicles (including civilian ones) equipped with night vision and thermal imaging sights and high-powered searchlights for illuminating targets. The next level of combating unmanned vehicles is small arms and team weapons. The most effective tool in this regard are smoothbore shotguns, which can shoot down a drone at a distance of up to 50 meters [11]. Suppress fire conducted by several soldiers and other technologies (such as firing nets at the aircraft to trap it) may also be implemented. In the fight against enemy drones, friendly military unmanned aerial vehicles can also be used, which additionally employ mounted nets to capture enemy autonomous aircraft. Work is currently underway to develop technology that enables optical interference with a drone's camera through the use of laser devices with a wide beam of light.

The last and very important element of active defense against unmanned aerial vehicles is the elimination of enemy drone operators. In the conflict between Russia and Ukraine, they are a priority target. The destruction of a single unmanned aerial vehicle, which is relatively inexpensive to produce, results in its replacement by another device. Eliminating the pilot operating the drone is much more painful due to the psychological aspect, as well as the time and cost of training him.

Fig. 7 A variant of combating a drone using the unmanned system of one's own armed forces
Source: [12].

The presented model for countering unmanned combat assets is a universal set of passive and active methods and techniques that can be applied, in particular at the lowest levels of command, from squad to battalion. The most important challenges and limitations of the proposed solution include the involvement of a significant number of soldiers and civilian personnel in the fight against drones, the costs associated with the development and dissemination of technologies for detecting and fighting unmanned systems, as well as the time-consuming training of operators in the specialized detection of drones based on frequency analysis.

The effectiveness of the algorithm in question depends on the integration of all the activities it contains, which constitute a multi-system solution. The performance of the selected passive and active measures described in the article is constantly verified during various types of research, experiments, and military exercises. An example of the improvement of methods and techniques for combating drones is the international Flytrap project, during which military and civilian entities develop and verify technological and tactical solutions for fighting unmanned aerial assets [14].

A serious threat to any country is a situation involving a mass drone attack at a single moment, targeting both military and civilian targets. Protection against such aggression is extremely difficult and requires a comprehensive approach to combating drones through the active engagement not only of the military but also of the civilian population. In such a case, the activities described in the proposed model should be intensified and applied on a larger scale, with maximum saturation of forces and resources for detecting and fighting drones. Effective tools for countering a large number of unmanned systems, depending on the altitude, speed, and range at which they operate, may include barrel anti-aircraft artillery with programmable ammunition, mobile anti-aircraft patrols (air and ground), and various types of unmanned aerial vehicles in combat against drones. Given the rapid pace of technological change on the modern battlefield, it is crucial to remember to constantly improve methods, techniques, and tools for countering unmanned combat systems.

5 CONCLUSION

The intensive development of unmanned combat systems, as well as their expanding effectiveness in modern armed conflicts, means that they are increasingly becoming one of the basic means of combat used to carry out a variety of tasks. The widespread use and potential of military autonomous vehicles requires the development of a system based on procedures, methods, and techniques for countering and combating drones.

This publication presents a comprehensive proposal for a solution enabling effective protection against unmanned combat systems. The suggested model is based on existing air defense activities, divided into passive and active measures. It has been enriched with additional tasks resulting from the specific nature of combat against unmanned systems compared to manned aircraft, as well

as the current experiences of soldiers fighting against autonomous vehicles on the modern battlefield.

It should also be remembered that despite the use of various new technologies, people remain the most valuable resource in the army of any country. Only a comprehensive approach to countering and combating unmanned combat vehicles, as well as the continuous improvement of operating procedures resulting from the intensive development of autonomous technologies, can ensure the effective protection of soldiers' lives on the battlefield.

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ECONOMIC AND ECOLOGICAL BALANCE SHEET OF A SMALL LPG VEHICLE IN URBAN OPERATION

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Abstract: In the current era of the global energy crisis of the 21st century and the advent of electromobility, this work brings a look at one of the less used petroleum derivatives in combustion engines – LPG (Liquefied Petroleum Gas). So far, many predictions have been made about the return on LPG fuel, which are commonly solved by universities, transport companies, taxi services, delivery companies, etc. On the other hand, fewer retrospective studies have been made about the real operation of vehicles running on LPG compared to petrol. This article at least partly covers the mentioned deficit of publications. All information cited in the article comes from peer-reviewed literature (web, ISBN). The analytical part is focused on evaluating the long-term operation of the small motor vehicle KIA Rio 1.4i, which was mainly used in urban traffic for 14 years. The aim of the article is not a comparative study, but a case study. The aim of this causal report is to present relevant results on the economy and ecological burden of LPG fuel (economic and ecological analysis, fuel consumption, financial return) in comparison to operation on automotive petrol, in the form of a mathematical and statistical analysis. Is the conversion of a small vehicle with indirect fuel injection to LPG drive for an urban environment a suitable choice?

Keywords: Fuels; LPG; Ecology; Operating economy; Exhaust emissions.

1 INTRODUCTION

We include LPG as an alternative fuel despite its fossil origin, which is oil. According to some sources, approximately 25 to 28 million cars in the world run on LPG fuel. In Europe, this number is around 10 to 13 million vehicles. [1].

The main advantages of LPG are the simplicity of production, easy achievement of the liquid state in which it occupies several times smaller volume compared to the gaseous state, storage, transportation, distribution, usability in both ignition and diesel engines. LPG is also more environmentally friendly than petrol. Nowadays, there is no longer a problem of its production from renewable sources, where the resulting fuel was named BIO LPG [1].

The advantage of LPG over petrol is mainly its lower consumption tax (in the Slovak Republic as of 1/1/2025 the consumption tax on petrol was € 0.514/liter, on LPG it is € 0.07/liter).

The price of LPG varies according to prices on world markets because LPG is produced from crude oil [2].

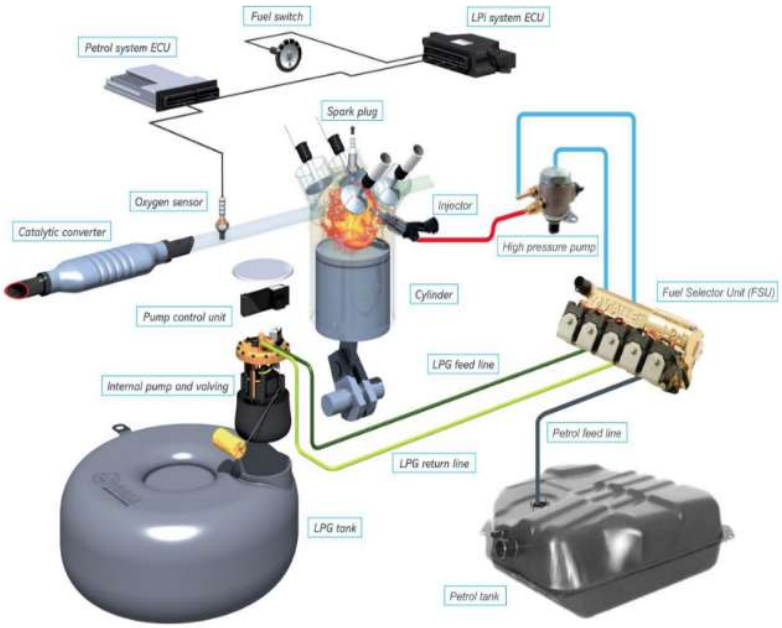

Fig. 1 1.4i DOHC petrol engine after conversion to LPG
Source: [4].

The disadvantage of LPG for engines with direct (Fig. 1) and indirect fuel injection is manifested during start-up, where the start is conditioned by petrol fuel. Direct start on LPG is possible only with carburetor engines. Switching modes from petrol to LPG occurs automatically after the coolant has warmed up to 40-60 °C. The minimum threshold is 30 °C. During engine warm-up, the vehicle travels a distance of 1-2 km and consumes 0.2-0.4 liters of petrol, depending on external conditions (engine temperature at start-up, ambient temperature, driver's driving style etc.). The LPG mixture has a lower burning rate than petrol, which requires adjustment of the ignition advance, increased thermal stress on the exhaust valves and cylinder head, which can reduce engine life. More frequent replacement of spark plugs is required after 20,000 to 30,000 km [3].

Another disadvantage is the reduction of lubricating properties, as the gaseous fuel burns more and the combustion chamber remains drier. The installation of a valve cooling and relubrication system is required [2]. Great care must be taken when converting to LPG on engines with variable valve timing. For some variable systems, conversion to LPG is not recommended.

From the above disadvantages it is preliminary clear that the most unsuitable environment for modern fuel-injected engines converted to LPG is frequent starts and short city trips in combination with winter operation. The KIA Rio 1.4i city car under monitoring (Fig. 2, Fig. 3) has driven most of its kilometers in such adverse conditions.

2 CHARACTERISTICS OF THE VEHICLE UNDER STUDY AND COLLECTION FROM OPERATION

The analytical part is based on the collected data from the operation of the passenger car Kia Rio 1.4i (Fig. 2, Fig. 3). The bivalent vehicle has an atmospheric 4 - cylinder DOHC petrol engine type G4EE with an output of 71.2 kW with the EURO 4 emission standard. Since the beginning of its operation, the owner has kept a diary, where the values were recorded after each trip with the vehicle. This is therefore reliable and accurate first-hand information. After each tank refill (petrol tank and LPG fuel tank), the owner noted the current date, odometer reading, amount of fuel refilled and the amount paid.

The vehicle was purchased new on 9/9/2010 and converted to LPG on 16/9/2011 with an odometer reading of 9,602 km. The economic and ecological balance was carried out from 9/9/2010 (with an odometer reading of 0 km) to 29/12/2023 (with an odometer reading of 147,592 km). There was no change in the vehicle owner during the 14 – year data collection period. The vehicle was regularly serviced.

Fig. 2 Monitored vehicle KIA Rio 1.4i LPG
Source: authors.

Fig. 3 1.4i DOHC petrol engine after conversion to LPG
Source: authors.

It is important to recall the fact that our observed car using LPG fuel also burns petrol after starting (indirect fuel injection). This fact complicates the calculation of exhaust emissions, because the odometer only records the total mileage of the vehicle (it is therefore not possible to determine exactly how many kilometers the vehicle has traveled on petrol and how many on LPG). In this case, this problem can only be solved by a calculation method from the fuel consumed and specific emissions given by the vehicle manufacturer. Based on information substantiated and verified from practice, we further assumed that the vehicle burns petrol for the first kilometer of driving after starting, when the current consumption reaches a high value of 10.5 l/100 km.

Table 1 shows the basic performance and emission parameters of the KIA Rio 1.4i LPG. The parameters in the Petrol BA 95 column are available in the production documentation (vehicle technical certificate). The parameters in the LPG column are obtained from the homologation protocol of the MP Gas s. r. o. service center, which provided the installation of the LPG system.

The article does not deal with the calculation of performance for the Gasoline and LPG modes. The data come from the manufacturer's test facilities.

Tab. 1 Manufacturer´s specifications for KIA Rio 1.4

Fuel	Petrol BA 95	LPG
Engine power G4EE (kW)	71,3	66
Consumption (l/100 km)	5,9	7,9
Carbone monoxide-CO (g/km)	0,388	0,547
Carbone dioxideň-CO_2 (g/km)	139	132
Nitrogen oxides-NO_x (g/km)	0,047	0,059
Hydrocarbons-HC (g/km)	0,037	0,056

Source: Operating documentation from Kia Motors Corporation (petrol BA 95), MP Gas s. r. o. (LPG).

To determine the number of kilometers traveled based on the amount of fuel added, we used the following formula:

$$x = \frac{100}{10.5} \quad (1)$$

The variable "x" then means the number of kilometers traveled per liter of petrol, which in our case is 9.52 km/l. Subsequently, it is enough to multiply this value by the amount of fuel added from the vehicle's operation history and we will find out the total number of kilometers that the driver has traveled on petrol. During such operation, the engine warms up sufficiently and only then does the system automatically switch to burning LPG fuel.

$$FC = \frac{0.1212}{0.538}\,(0.825 \cdot HC + 0.429 \cdot CO + 0.273 \cdot CO_2) \quad (2)$$

FC – consumption in l/100 km for the given driving cycle
HC – HC emissions in g/km for the given drive cycle
CO – CO emissions in g/km for the given drive cycle
CO_2 – CO_2 emissions in g/km for the given drive cycle

The empirical conversion relationships (equation 2) for calculating LPG consumption are internationally determined by regulation (ECE No. 101) [3].

3 ECONOMIC BALANCE SHEET OF PETROL/LPG OPERATIONS

During the monitored period (2010-2023), the prices of LPG, petrol and diesel were highly correlated with each other. They reacted sensitively to oil prices on world stock exchanges. (Tab. 2, Fig. 4).

Tab. 2 Fuel price trends in Slovakia 2010-2023

Year	LPG (€/l)	Petrol (€/l)	Diesel (€/l)
2010	0.498	1.249	1.114
2011	0.696	1.446	1.340
2012	0.728	1.541	1.441
2013	0.724	1.487	1.390
2014	0.714	1.449	1.334
2015	0.621	1.287	1.135
2016	0.562	1.209	1.038
2017	0.578	1.286	1.132
2018	0.599	1.359	1.244
2019	0.584	1.327	1.230
2020	0.561	1.178	1.064
2021	0.660	1.385	1.240
2022	0.833	1.692	1.719
2023	0.723	1.593	1.551

Source: [1], [5].

The years 2010 to 2023 brought high volatility in the fuel market. The new decade after 2010 brought economic recovery after the economic crisis in 2008. The high volatility was mainly contributed by weaker economic growth in the middle of the decade, the COVID 19 pandemic, the war in Ukraine and the demand for oil from strong economies (China, India). In the long term, fuel price increases can be expressed as a linear growth trend, which is actually a barometer of global inflation (Fig. 3).

Table 3 provides the average operating costs for small cars with an average fuel consumption of 6.3 l/100 km. The results are based on statistical observations, which come from available professional literature [3].

This literature does not provide mathematical equations for the calculated values in Table 3. The authors of the table considered the purchase of a new car and monitored how the total costs of its operation would develop, i.e. the sum of the purchase price and operating costs, which, in addition to the price of fuel, also consist of maintenance and repair costs [3].

Table 4 and Table 5 present the collected operating data from the monitored vehicle Kia Rio 1.4 LPG and its basic economic indicators.

When comparing petrol/LPG operation, it is shown that in general the return on the initial costs of the LPG conversion is achieved after a run-in period of approximately 30,000 km.

Tab. 3 Statistically predicted fuel costs

Average costs for smaller cars with a petrol consumption of 6.3 l/100 km (€)						
Fuel type	Petrol	LPG	CNG	Diesel	E85	Electro
Reconstruction cost	0	656	1845	0	205	10250
Kilometers traveled						
10 000	1 054	1 456	2 558	1 078	1 255	10 824
20 000	2 107	2 255	3 276	2 157	2 300	11 398
30 000	3 157	3 055	3 989	3 235	3 350	11 972
40 000	4 211	3 854	4 703	4 317	4 395	12 546
50 000	5 264	4 654	5 420	5 396	5 445	13 120
60 000	6 318	5 453	6 134	6 474	6 490	13 690
70 000	7 368	6 248	6 851	7 552	7 540	14 264
80 000	8 421	7 048	7 565	8 635	8 585	14 838
90 000	9 475	7 847	8 278	9 713	9 635	15 412
100 000	10 529	8 647	8 995	10 791	10 681	15 982
150 000	15 793	12 644	12 571	16 187	15 920	18 852
200 000	21 058	16 642	16 142	21 582	21 156	21 718
250 000	26 318	20 635	19 717	26 978	26 396	24 584

Source: [3].

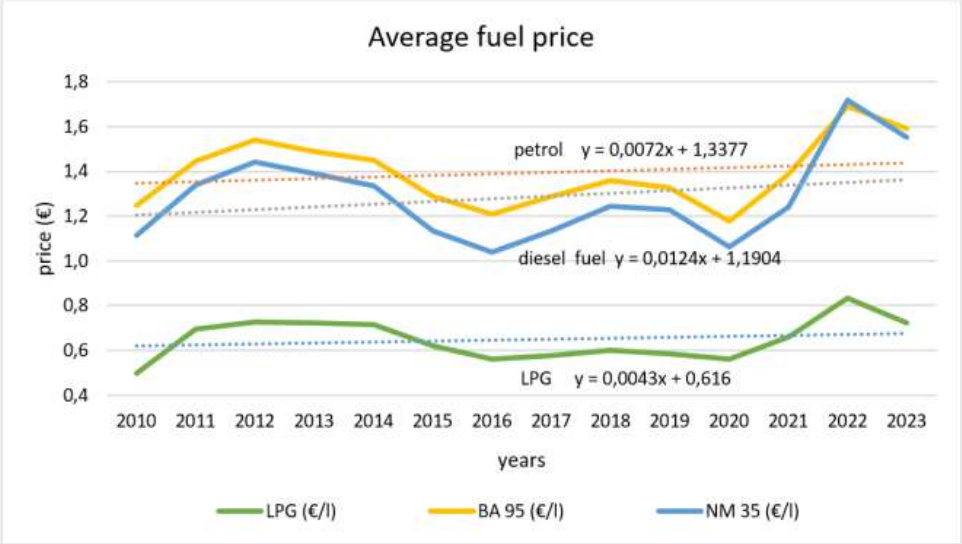

Fig. 4 Fuel price trends in Slovakia 2010-2023
Source: authors.

Tab. 4 Vehicle operating balance KIA Rio 1.4 (2010-2016)

Total balance	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
traveled on LPG (km)	0	2703.05	12165.81	12066.29	17240.9	11332.43	10236.14
traveled on petrol (km)	1611	4966.1	568.19	885.71	1030.1	868.57	1492.86
traveled LPG+petrol (km)	1611	7669.15	12734	12952	18271	12201	11729
consumption LPG (l)	0	213.54	961.1	953.24	1362.03	895.26	808.66
consumption petrol (l)	95.05	177.24	751.31	764.17	1077.99	719.86	692.01
paid for LPG (€)	0	175.78	705.72	710.65	968.66	505.89	421.64
paid for petrol (€)	191.77	713.12	81.73	127.14	149.148	114.94	184.17
added LPG (l)	0	251.46	991.41	1012.52	1365.67	937.99	853.17
added petrol (l)	149.87	521.44	59.66	93	108.16	91.2	156.75
CO_2 emissions LPG (g)	0	356802	1605887	1592750	2275799	1495881	1351171
CO_2 emissions petrol (g)	223929	417556	1770026	1800328	2539669	1695939	1630331
CO emissions LPG (g)	0	1478.57	6654.7	6600.26	9430.77	6198.84	5599.17
CO emissions petrol (g)	625.07	1165.55	4940.79	5025.38	7089.148	4733.988	4550.852
NO_x emissions LPG (g)	0	159.48	717.78	711.91	1017.21	668.61	603.93
NOx emissions petrol (g)	75.72	141.19	598.5	608.74	858.737	573.447	551.263
HC emissions LPG (g)	0	151.37	681.29	675.71	965.49	634.62	573.22
HC emissions petrol (g)	59.61	111.15	471.16	479.22	676.027	451.437	433.973
average LPG price (€)	0	0.698	0.712	0.699	0.706	0.543	0.492
average petrol price (€)	1.279	1.376	1.393	1.398	1.394	1.271	1.175
would pay for petrol (€)	191.77	243.93	1046.51	1068.11	1502.46	914.71	813.39

Source: authors.

Tab. 5 Vehicle operating balance KIA Rio 1.4 (2017-2023)

Total balance	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
traveled on LPG (km)	10736.29	10995.1	7950.57	7892.57	10347.9	7022.95	6402.48
traveled on petrol (km)	285.71	1497.9	785.43	805.43	780.1	1209.05	389.52
traveled LPG+ gasolin.(km)	11022	12493	8736	8698	11128	8232	6792
consumption LPG (l)	848.17	868.61	628.1	623.51	817.48	554.81	505.8
consumption petrol (l)	650.3	737.09	515.42	513.18	656.55	485.69	400.73
paid for LPG (€)	451.36	472.49	352.37	312.36	527.45	482.1	370.03
paid for petrol (€)	115.46	134.64	108.17	101.06	115.45	216.06	72.5
added LPG (l)	836.05	839.18	659.96	626.58	852.99	572.72	528.62
added petrol (l)	89.52	97.78	82.47	84.57	81.91	126.95	40.9
CO_2 emissions LPG (g)	1417190	1451353	1049475	1041819	1365923	927029	845126
CO_2 emissions petrol (g)	1532058	1736527	1214304	1209022	1546792	1144248	944088
CO emissions LPG (g)	5872.75	6014.32	4348.96	4317.24	5660.3	3841.55	3502.15
CO emissions petrol (g)	4276.536	4847.284	3389.57	3374.82	4317.66	3194.02	2635.3
NO_x emissions LPG (g)	633.44	648.71	469.08	465.66	610.53	414.35	377.75
NOx emissions petrol (g)	518.034	587.171	410.59	408.81	523.02	386.9	319.22
HC emissions LPG (g)	601.23	615.73	445.23	441.98	579.48	393.29	358.54
HC emissions petrol (g)	407.814	462.241	323.23	321.83	411.74	304.58	251.3
average LPG price (€)	0.539	0.563	0.534	0.5	0.619	0.839	0.701
average petrol price (€)	1.285	1.377	1.321	1.196	1.414	1.695	1.78
would pay for petrol (€)	835.67	1014.77	680.73	613.93	928.12	823.37	713.3

Source: authors.

Table 6 presents the overall economic balance on an annual basis. The table shows that the vehicle operator had total costs for petrol of € 2,432 and for LPG of € 6,345 during the monitored period.

Tab. 6 Economic balance of operation of KIA Rio 1.4

year	LPG price (€) real	petrol price (€) real	petrol price (€) predict.	annual savings (€)
2010	0	191.77	191.77	0
2011	175.78	713.12	243.93	68.15
2012	705.72	81.73	1046.51	259.06
2013	710.65	127.14	1068.11	230.32
2014	968.66	149.14	1502.46	384.65
2015	505.89	114.94	914.71	293.88
2016	421.64	184.17	813.39	207.58
2017	451.36	38.7	835.67	345.61
2018	472.49	217.64	1014.77	324.64
2019	352.37	108.17	680.73	220.19
2020	312.36	101.06	613.93	200.51
2021	527.45	115.45	928.12	285.22
2022	482.1	216.06	823.37	125.21
2023	370.03	72.5	713.3	270.77

Source: authors.

The expected costs for petrol without the LPG installation would have reached € 11,391. After the LPG installation, the fuel savings reached € 3,216. After deducting the initial investment for the LPG conversion (€ 970) and the replacement of the LPG tank after 10 years of operation (€ 200), the net savings are € 2,046.

The initial investment in LPG achieved a return in 2014, i.e. 4 years after the conversion to LPG and a run of approximately 40,000 km. When compared with statistically predicted values (Tab. 3 – green cells, where a net saving on LPG of approximately € 3,000 is assumed after reaching 150,000 km), the KIA Rio 1.4 with a run of 137,990 km (since the LPG conversion) and a saving of € 2,046 showed a fuel saving of approximately € 1,000 lower than expected. The reason is mainly the number of cold starts in the prevailing urban operating cycle (80 %). The lower financial saving was also reflected in the awareness of the driver, who deliberately and preventively chose many trips to the petrol mode in order to replace the old, expired petrol in the tank and clean the fuel system. The driver filled up with more expensive premium petrol more often.

A retrospective economic analysis confirmed the return on the initial investment in the LPG system and clearly showed savings. Possible reasons for the relatively lower savings were answered.

4 ECOLOGICAL BALANCE SHEET OF OPERATION PETROL/ LPG

LPG-powered vehicles meet all the emission requirements imposed on them in accordance with the EURO emission standards. However, it is not possible to agree with the frequently published claim that they are always more environmentally friendly than petrol engines [3]. This myth is also refuted by our monitored vehicle KIA Rio 1.4. The homologation report states that the LPG mode has higher values in all emission parameters compared to the petrol mode, except for the CO_2 parameter (Tab. 1).

From an ecological point of view, the CO_2 parameter is the most important, because it makes up the largest mass fraction in exhaust gases (g/km) and is considered a greenhouse gas. This fact is a positive advantage for LPG drives.

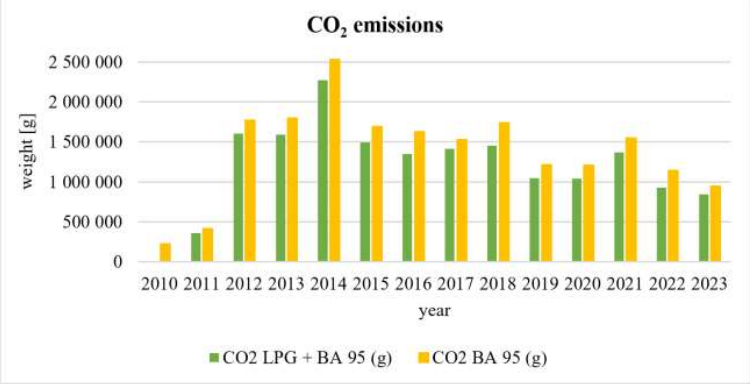

Fig. 5 CO_2 emissions produced (2010-2023)
Source: authors.

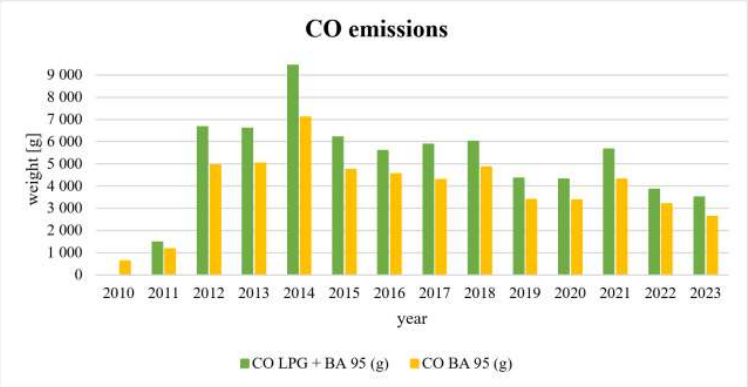

Fig. 6 CO emissions produced (2010-2023)
Source: authors.

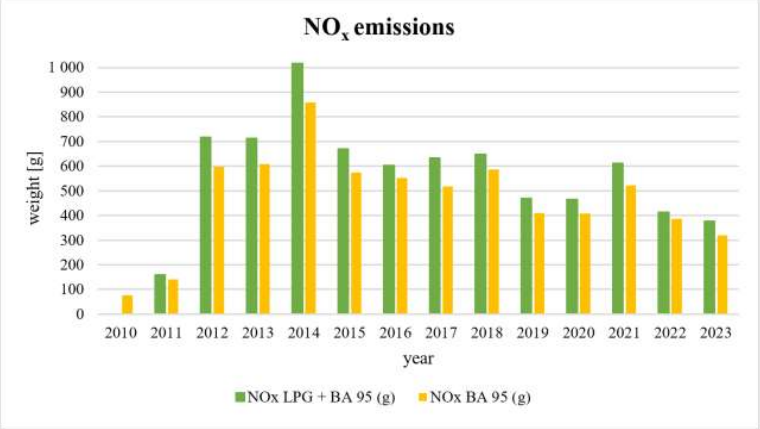

Fig. 7 NO_x emissions produced (2010-2023)
Source: authors.

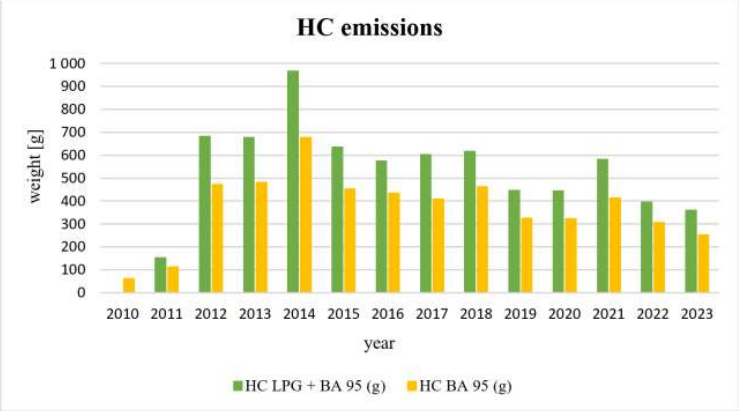

Fig. 8 HC emissions produced (2010-2023)
Source: authors.

The complete ecological balance of the KIA Rio 1.4 is provided by tables 4 and 5. In the graphic representation, these are graphs (figures 5, 6, 7 and 8). Standard statistical methods were used for the ecological retrospective analysis. The graphs (Fig. 5, 6, 7, 8) show that the differences in the impact on the environment between petrol and LPG are not that striking. LPG fuel is more environmentally friendly than petrol in the most monitored parameter CO_2. On the contrary, in the parameters CO, NO_x and HC, the balance of LPG is slightly worse than that of petrol. In particular, the HC parameter declared by the manufacturer in LPG mode is at an increased level compared to engines in the given category.

HC-aldehydes are formed when the engine is cold, at low engine loads, and when the engine is operating with a large excess of air. Aldehydes have a specific odor, corrode the mucous membranes, and have

a harmful effect on the respiratory tract in the human body [7].

In this case too, the engine design has a decisive influence on the nature and amount of emissions. The G4EE engine type proved to be very reliable and economical throughout the entire monitoring period.

5 DISCUSION

The biggest advantages of using LPG are lower emissions, cleaner exhaust gases, longer engine life, lower engine noise and low fuel cost. A significant advantage of LPG is its 5 to 10 % higher octane number than standard gasoline. A higher octane number allows for higher compression and thus greater overall efficiency. LPG has a higher resistance to detonation combustion and a high calorific value (MJ/kg) [13].

The disadvantage of LPG remains the lower volumetric calorific value (MJ/dm3) and lower burning rate than gasoline. LPG combustion is 100 to 150 °C higher than gasoline. LPG is injected into the engine in most cases in the gas phase. These facts lead to a slight decrease in performance by 5 to 10 % compared to gasoline. This disadvantage can be eliminated by the design of direct injection in the liquid phase. These systems for maintaining liquid LPG require high pressure in the system (3 to 5 MPa). Such systems are rarely used due to the complexity of the design, high price and difficult maintenance, because they are unprofitable for ordinary motorists.

Whether a car running on LPG is more environmentally friendly depends on what we are comparing the environmental friendliness against. In order to be able to compare objectively, we cannot only compare the concentrations of certain pollutants in exhaust gases, but we must measure the physically produced quantities of individual exhaust gas components. This can only be measured using special analyzers (CFV, CVS) [3].

Although each vehicle is individual, in the vast majority of cases we find that operation on LPG shows slightly lower amounts of unburned hydrocarbons (HC) compared to gasoline, which results from the fact that we burn only a mixture of propane and butane in the engine, while gasoline represents a mixture of higher-order hydrocarbons [3].

From the point of view of carbon monoxide (CO), we can consider both fuels to be approximately equivalent [3].

In the area of nitrogen oxides (NO_x), LPG is clearly worse, because its production is practically double. These emissions are not a direct product of combustion, but arise secondarily. In addition to residual air, they require a certain temperature, pressure and time to form. The higher the temperature and pressure, the higher the production of this highly toxic pollutant. The disadvantages of LPG engines are the absence of internal cooling and the longer combustion time, which increases the increase in NO_x [3].

On the contrary, a clear decrease of approximately 15 % is reported for LPG emissions of carbon dioxide (CO2), which is the most monitored greenhouse gas today [3].

The monitored G4EE engine (KIA Rio 1.4) is quite individual. In the monitored LPG emissions, it shows worse results in all emissions except CO2 compared to gasoline.

The future is promising for low-emission Bio LPG. This fuel is produced as a by-product in the production of hydrogenated vegetable oil and bioethanol. The production of Bio LPG fuel is possible using today's technologies from food waste and sugar cane used to produce bioethanol. This fuel is produced as a by-product of waste processing. Although LPG is environmentally friendly, it is still a fossil energy source. From a life cycle perspective, Bio LPG is more advantageous than classic petroleum LPG due to its carbon footprint, which is up to 80 % lower. This is also why the European LPG Association considers it an excellent alternative for the future. The assumption by 2050 is that LPG will be produced exclusively from renewable sources. When addressing the issue of alternative fuels, it is important to focus on the entire life cycle of the fuel, from its production to the transfer of energy to the wheels. An example is electric cars, whose carbon footprint is also very dependent on the method of electricity production. The advantage is also the existing infrastructure, where the only difference will be the gradual replacement of classic LPG with Bio LPG. In addition, the fuels can be used in combustion engines, the development of which is currently at a high level. The combination of modern synthetic fuels and Bio LPG thus carries great potential as an alternative fuel source for the future. In Europe, six companies are currently engaged in the production of Bio LPG. Its use does not only apply to transport, it can also find its place in the field of heating buildings, or as a source of energy for a wide industrial area [6].

The LPG perspective does not only apply to petrol engines. High prices of fuel influencing high costs of transport, as well as new norms on toxic substance emissions result in a more intensive search of effective solutions regarding fueling and controlling combustion engines [11]. One of the well-known solutions is fueling the compression-ignition engine with diesel fuel with the addition of LPG [12]. The addition LPG to the diesel oil results in reduction of the harmful compounds emission; at the same time, for economic reasons, there has been rising interest in LPG gas fittings in compressionignition engines observed. Gas fittings offered on the market allow for addition of approximately 30 % propane butane mix. This ratio results mainly from two reasons: because of the liability to the knocking combustion which takes place in bi-fuel supplied compression-ignition engines, and because of the higher exhaust gases

temperature and higher combustion pressure. The result of the above phenomena can be the destructive impact on the combustion chamber's elements and on the exhaust system, as well as influence on noise emission and generated vibrations [8] [9] [10].

6 CONCLUSION

The operating balance of the KIA Rio 1.4 LPG after driving 137,990 km in the petrol/LPG mode clearly confirmed a positive economic return. In this case, a retrospective analysis points to a relatively lower financial return of € 2,046. For comparison, cars in the given performance category show financial savings after driving 150,000 km on LPG of approximately € 3,000 [3]. For a lower-class vehicle with an assumption of urban driving up to 10,000 km/year, this is an adequate result. Engines in this volume category themselves have low average petrol consumption (5.9 l/100). Since they work with indirect fuel injection, when the engine warms up (when consumption is highest), they require a sufficient supply of petrol before switching to LPG mode. The significance of financial savings can be debatable, because satisfaction still depends on the individual requirements and goals of the operator.

In terms of emissions, the KIA Rio 1.4 LPG produced standard results. At the level of the closely monitored CO_2 parameter, the engine recorded a lower carbon footprint than it would have when running on pure petrol.

In other emission parameters, with the exception of HC, there were no significant differences compared to operation on pure petrol.

At the end of this study, we conclude that a vehicle powered by LPG meets all environmental requirements (EURO 4) in terms of emissions. However, this case study dispels the myth that LPG engines are significantly more environmentally friendly than gasoline engines.

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THE IMPACT OF AGING ON THE QUALITY OF BALLISTIC PROTECTION

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Abstract: Ballistic protective materials degrade over time due to environmental exposure, mechanical stress, and natural aging of fibers. While manufacturers specify a limited service life for soft body armor, its actual long-term performance remains insufficiently explored. This study examines the effects of prolonged aging on ballistic resistance by evaluating a soft armor panel that has significantly exceeded its recommended lifespan. Despite visible signs of material degradation, testing indicate that the armor has maintained a certain level of protective capability. These findings suggest that aging alone may not immediately render ballistic protection ineffective, though factors such as fiber deterioration and delamination can influence performance. Further research is needed for better understanding the long-term durability of ballistic materials and their implications for safety standards and practical use.

Keywords: Ballistic protection; Material aging; Body armor durability; Soft armor; Degradation effects.

1 INTRODUCTION

The need for ballistic protection has been evident throughout human history, evolving from rudimentary armor made of leather and metal to advanced synthetic fiber materials used in modern body armor. Historically, early forms of personal protection included chainmail, plate armor, and reinforced fabrics, which were designed to deflect bladed weapons and arrows. However, with the advent of firearms in the late Middle Ages, traditional armor became increasingly ineffective. This led to the continuous development of ballistic-resistant materials, with significant advancements occurring in the 20th century.

Fig. 1 Soviet soldier dressed in SN-42 body armor
Source: https://rarehistoricalphotos.com/soviet-soldier-sn-42-body-armor-1944/

During World War II, researchers experimented with different materials to enhance personal protection against small arms fire. The introduction of nylon and later Kevlar®, developed by DuPont in the 1960s, revolutionized soft body armor by providing lightweight yet highly resistant layers capable of stopping bullets. Over the following decades, improvements in polymer chemistry and fiber weaving techniques led to the development of high-performance materials such as Twaron, Dyneema, and Spectra, which offered enhanced protection with reduced weight. Today, modern body armor is a crucial component of personal protection for military personnel, law enforcement officers, and security forces across the world.

Fig. 2 Kevlar vest by DuPont
Source: https://wholesalemall.ru/product/266908163294

Despite these advancements, soft ballistic armor has a limited service life. Manufacturers typically specify a warranty period of 5 to 10 years, after which the armor is considered to have degraded beyond its optimal protective capacity. However, the actual rate of degradation depends on numerous factors, including:

Environmental exposure (UV radiation, temperature swinging, humidity) Mechanical wear and tear (folding, stretching, impact stress).

Material composition and aging (fiber degradation, chemical breakdown).

While laboratory tests and controlled experiments suggest that ballistic materials are weaken over time, real-world data on long-term durability remain scarce. Many users, particularly in non-military applications, continue wearing body armor beyond its recommended lifespan, what raising questions about its residual protective capability. Does aging alone render ballistic armor ineffective, or does it retain some level of functionality even after years of use?

Answering this question is critical for both individual users and policymakers responsible for setting safety regulations.

This study investigates the long-term effects of aging on soft body armor by examining a ballistic panel that has significantly exceeded its intended service life. By analyzing its structural integrity and residual ballistic resistance, this research aims to provide insights into how aging influences the effectiveness of ballistic protection. The findings could have important implications for the continued use, recycling, or disposal of expired body armor and may contribute to a more informed approach to determining realistic service life expectations for protective equipment.

2 CLASSIFICATION OF BALLISTIC PROTECTION AND RESISTANCE STANDARDS

Ballistic protection generally can be categorized into two main types: soft armor and hard armor. Each type serves for specific purpose and is designed to counter different levels of ballistic threats. The effectiveness of ballistic protection is assessed based on standardized testing protocols that define the level of resistance against various types of ammunition.

2.1 SOFT BALLISTIC ARMOR

Soft ballistic armor is primarily made from woven or laminated synthetic fibers, such as Kevlar®, Twaron, Dyneema or Spectra, which are capable of absorbing and dissipating the kinetic energy of a projectile. Unlike rigid armor plates, soft armor remains flexible, making it ideal for concealable vests, law enforcement gear, and military personnel requiring mobility.

Soft body armor is designed to protect against low – to medium-energy threats, such as:

- Handgun rounds (.22 LR, 9×19 mm, .44 Magnum);
- Shrapnel from explosive devices;
- Fragmentation from secondary projectiles.

Fig. 3 Soft ballistic plates
Source: https://rmadefense.com/store/body-armor/level-3a-body-armor/level-iiia-soft-armor-inserts/

Since soft armor have relied on fiber integrity to stop bullets, its performance can degrade over time due to environmental exposure, moisture, and mechanical stress.

2.2 HARD BALISTIC ARMOR

Hard ballistic armor is composed of ceramic, steel, or polyethylene plates, providing protection against high-velocity rifle rounds and armor-piercing ammunition. These rigid plates are typically inserted into plate carriers or worn in combination with soft armor to increase overall protection.

Hard armor is designed to stop higher-energy threats, including:

- Rifle calibers (5.56×45 mm, 7.62×39 mm, .308 Winchester);
- Armor-piercing projectiles;
- High-velocity shrapnel.

Fig. 4 Hard ballistic plates
Source: protectiongroupdenmark.com/product/pgd-s-lw-icw-super-lightweight-hard-armor-nij-level-3-iii/

Although hard armor offers superior ballistic resistance, it is significantly heavier and less flexible, limiting comfort and mobility for extended wear.

3 BALLISTIC RESISTANCE STANDARDS

Various international standards classify ballistic protection levels based on controlled live-fire tests. These standards help determine the effectiveness of protective materials under specified conditions. Some of the most widely used classification systems include:

- NIJ (National Institute of Justice, USA) – One of the most recognized standards worldwide, defining levels from NIJ Level IIA (low handgun threats) to NIJ Level IV (armor-piercing rifle rounds).
- VPAM (Vereinigung der Prüfstellen für Angriffshemmende Materialien, Germany) – Used in Europe, covering civilian and law enforcement protective equipment.

- STANAG 4569 (NATO Standardization Agreement) – Focused on vehicle armor but also applicable to body armor for military use.
- ČSN 39 5360 (Czech and Slovak Standard) – A classification system used in Central Europe, specifying different resistance levels for personal body armor and protective gear.

These standards ensure that protective equipment is tested under realistic conditions, helping military forces, law enforcement agencies, and security personnel choose appropriate armor based on operational requirements.

3.1 CSN 39 5360

The Czech standard **CSN 39 5360** was introduced in 1996 and developed by the Czech Testing Office for Firearms and Ammunition based on extensive ballistic testing, primarily for police applications. It defines the classification and testing of protective equipment against bullets, fragments, and stabbing weapons. Although officially withdrawn in 2018, it is still considered highly relevant due to its strict requirements and regional specificity.

The scope of the standard covers:

- Bullet resistance, evaluated by penetration or non-penetration, as well as the depth and volume of the backface signature in a backing material simulating human tissue.
- Fragment resistance, assessed using the V_{50} parameter, i.e., the average velocity at which 50 % of the projectiles perforate the sample.
- Edged and stabbing weapon resistance, tested with specific impactors (knife, spike, ball) under TON I–III classifications.

The standard defines seven ballistic resistance classes (TBO 1–7), each corresponding to a specific caliber, bullet type, and impact velocity. These include both Western calibers (e.g., 9 mm Luger, .44 Magnum, .223 Remington) and typical Eastern Bloc calibers such as 7.62 × 39 mm (AK-47) and 7.62 × 54 mm R.

One of the distinctive features of ČSN 39 5360 is its stringent trauma limits, which are significantly stricter than those found in the widely used NIJ 0101.06 standard. The maximum allowed backface signature depth is 25 mm, with a maximum trauma volume of 8 ml (roughly equivalent to about 2 mm in NIJ terms). This makes the standard one of the most demanding in terms of injury prevention.

In summary, although ČSN 39 5360 is no longer valid as an official technical standard, it remains as an important reference point. Its rigorous approach highlights the need for protective equipment, not only to stop projectiles, but also to minimize blunt trauma, providing a higher margin of safety for the wearer.

Tab. 1 Czech CSN 39 5360 standard

Czech CSN 39 5360				
TBO	Caliber	Bullet type	Velocity (m/s)	Bullet weight (g)
1	.22 lr	FMJ Pb core	300 +/- 10	2,6
2	9 mm Luger	FMJ Pb core	410 +/- 10	8
2 cz	7,62x25mm	FMJ Pb core	470 +/- 10	5,5
3	.357 Magnum	FMJ Pb core	430 +/- 10	10,2
3 cz	9mm Luger	FMJ Pb core	440 +/- 10	6,45
4	.44 Magnum	FMJ Pb core	440 +/- 10	15,6
4 cz	7,62x25mm	FMJ Pb core	550 +/- 10	5,5
5	.223 rem.	FMJ	920 +/- 10	4
5 cz	7,62x39mm	FMJ	710 +/- 10	8
6	.308 win.	FMJ	830 +/- 10	9,5
6 cz	.223 Rem	AP	950 +/- 10	3,95
7	.308 win	AP	820 +/- 10	9,8
7 cz	7,62x54mm R	AP	860 +/- 10	9,75

Source: authors.

3.2 Comparison with NIJ 0101.06

Ballistic protection standards differ from regions, with the Czech ČSN 39 5360 and the American NIJ 0101.06 being among the most significant. While both aim to ensure the reliability of protective equipment, their scope, methodology, and evaluation criteria vary.

The Czech standard, valid from 1996 to 2018, included a broad classification system not only for bullets but also for fragments and stabbing weapons. It introduced seven ballistic resistance classes (TBO 1–7) and set very strict limits for blunt trauma (backface signature). The NIJ 0101.06 standard, introduced in 2008 and still widely used today, defines ballistic resistance levels IIA, II, IIIA, III, and IV, focusing primarily on bullet threats.

A key difference lies in the trauma limits: while NIJ allows a maximum backface signature depth of 44 mm, ČSN restricts this to 25 mm depth and 8 ml volume, making it one of the strictest standards in terms of injury prevention.

Tab. 2 Comparasion of ČSN 39 5360 and NIJ 0101.06

Parameter	ČSN 39 5360	NIJ 0101.06
Validity	Introduced 1996, withdrawn in 2018 (still used as a reference in Central Europe)	Published in 2008, currently valid (superseded by NIJ 0101.07 under preparation)
Primary focus	Comprehensive: ballistic (bullets), fragment (V_{50} method), and stabbing threats	Ballistic protection against bullets only
Classification system	**TBO 1–7** (Ballistic Resistance Classes)	Levels IIA, II, IIIA, III, IV
Backface signature	≤ 25 mm depth and ≤ 8 ml volume (very strict trauma criterion)	≤ 44 mm depth (depth criterion only, more permissive)
Evaluation criteria	Penetration/non-penetration, backface signature depth and volume, material damage	Penetration/non-penetration, backface signature depths
Rogional significance	Standard for Central and Eastern Europe; still referenced for strictness	Globally recognized, dominant reference for procurement and certification
Overall strictness	Very demanding in terms of trauma and inclusion of Eastern Bloc calibers	Less strict trauma requirement, but broader international acceptance

Source: authors.

In summary, ČSN 39 5360 was one of the strictest ballistic standards in Europe, particularly in limiting blunt trauma and including Eastern Bloc calibers. Although it is no longer officially valid, it remains an important reference point in evaluating the durability and safety of protective equipment. On the other hand NIJ 0101.06 has gained worldwide recognition and continues to serve as the dominant benchmark for ballistic testing.

4 FACTORS INFLUENCING THE DEGRADATION OF BALLISTIC PROTECTION

The effectiveness of ballistic protection is not permanent and gradually decreases over time. The degradation of protective materials is influenced by several factors that act individually or in combination, ultimately reducing their ballistic resistance and reliability.

4.1 Enviromental exposure

Protective fibers such as Kevlar®, Twaron, or Dyneema are sensitive to long-term environmental effects. Ultraviolet (UV) radiation causes chain scission and loss of tensile strength in aramid fibers. Humidity and water absorption accelerate hydrolysis, particularly in Kevlar, leading to fiber weakening. Temperature swinging between heat and cold induces thermal stress, which can compromise the structural integrity of laminates.

4.2 Mechanical stress and wear

In service, soft armor panels are subject to repeated folding, compression, stretching, and local impacts. Over time, these mechanical stresses break down the fiber weave and reduce the uniformity of ballistic resistance. Delamination of laminated layers may occur, leading to localized weak points that are more susceptible to penetration.

4.3 Natural aging of fibers

Even in ideal storage conditions, ballistic textiles undergo natural chemical aging. Oxidation processes reduce the molecular weight of polymer chains and alter their mechanical properties. Studies have shown that aramid fibers can lose a significant portion of their tensile strength after more than 10 years, even without visible signs of damage.

4.4 Contamination and operational factors

Exposure to sweat, body oils, cleaning agents, or other chemicals may alter fiber chemistry and accelerate degradation. Operational use, such as long-term wearing under variable conditions, contributes to micro-damage and surface abrasion, which are difficult to detect but critical for performance.

4.5 Combined effects

In practice, degradation rarely occurs due to a single factor. Synergistic effects (e.g., UV radiation combined with high humidity, or mechanical stress combined with chemical exposure) accelerate material deterioration. As a result, ballistic panels may lose protective capability earlier as we expected or conversely, it will retain some level of functionality beyond the manufacturer’s declared service life.

5 TESTED MATERIAL

For the purpose of the experiment, a soft ballistic panel of class TBO 3 was used, originating from a Kirasa body armor vest manufactured in 2001. The panel significantly exceeded the manufacturer's declared service life. Structurally, it consists of multiple layers of aramid fibers in fabric form, enclosed in a protective textile cover. During the time of testing, the panel was more than 20 years old.

5.1 Storage and operational conditions

The ballistic panel had been stored for a long period under standard conditions, during which it may have been exposed to environmental influences such as:

- UV radiation,
- temperature and humidity fluctuations,
- mechanical stress related to handling and operational use.

Visible signs of degradation were observed on the surface, including discoloration, local wear of the textile cover, and partial deformation of the layers.

5.2 Testing procedure

Ballistic tests were carried out in accordance with the requirements of the ČSN 39 5360 standard for evaluating resistance against small arms. The following types of ammunition were used:

- 9 × 19 mm Luger,
- .357 Magnum,
- .22 LR.

The shooting was performed at a distance of 10 m, with repeated shots of each caliber aimed at different parts of the panel. Standard service firearms corresponding to the tested calibers were used for firing.

6 EXPERIMENT

Ballistic tests conducted on the TBO 3 soft ballistic panel (Kirasa vest, year of manufacture 2001) demonstrated that even after more than two decades of service/storage, the panel retained its protective capability. The tests were carried out with 9 × 19 mm Luger, .357 Magnum, and additionally .22 LR ammunition. No perforations occurred in any of the tests. The measured Backface Signature (BFS) values did not exceed 5 mm, which is significantly below the thresholds defined by ČSN 39 5360 (25 mm / 8 ml) and NIJ 0101.06 (44 mm). Projectile velocities were recorded using a Garmin Xero chronograph, ensuring precise control of input parameters.

Fig. 5 The experiment setup
Source: authors.

Fig. 6 Xero C1 PRO Chronograph
Source: https://cdn.myshoptet.com/usr/www.polovnictvostefanik.sk/user/shop/big/7100-3_garmin-xero-c1-pro-chronograph.jpg?680e297b

Fig. 7 9mm Luger round, used during the experiment
Source: authors.

Tab. 3 Ammunition used during the experiment

Ammuntion	Velocity (m/s)	Kinetic Energy (j)	Perforation	BFS (mm)
9x19mm Luger	360	518	NO	≤ 5
. 357 Magnum	400	800	NO	≤ 8
.22 LR	320	133	NO	0

Source: authors.

All BFS values represented only about 11–32 % of the allowed thresholds according to ČSN and NIJ, indicating a substantial margin of safety.

Fig. 8 The ballistic panel after the experiment
Source: author.

Fig. 9 The ballistic panel after the experiment.
Source: authors.

6.1 Impact Energy Calculations

Kinetic energy of projectiles was calculated using:

$$E_k = \frac{1}{2}mv^2, \quad (1)$$

$$E_{k\,9mm} = 518\ \text{J},$$

$$E_{k\,357\ Magnum} = 800\ \text{J},$$

$$E_{k\,22LR} = 133\ \text{J}.$$

6.2 BFS in relation to standards

All measured BFS values were significantly lower than the limits allowed by ČSN (25 mm) and NIJ (44 mm). In practical terms, this means that the observed deformations accounted for only a small fraction of the allowable trauma depth. Even the highest value (8 mm) for .357 Magnum remained comfortably within safe margins, indicating that the risk of serious behind-armor blunt trauma would be minimal.

6.3 Analysis of results

The panel, though manufactured in 2001, continued to meet protective requirements. This suggests that aging alone does not inevitably lead to critical loss of ballistic resistance, particularly under controlled storage conditions.

The low BFS values demonstrate effective energy dissipation. Literature generally considers BFS below 10 mm as unlikely to cause severe blunt trauma injuries, which is consistent with the present observations. As expected, .357 Magnum produced the highest deformation, corresponding to its greater kinetic energy. Nevertheless, the BFS remained well within acceptable safety thresholds. The .22 LR case confirmed the opposite extreme, with minimal deformation due to its low energy.

Visual inspection showed localized fiber damage but no significant delamination of layers. This indicates that the laminate structure continued to distribute loads effectively, even after more than 20 years of service life.

Fig. 10 Projectiles stopped by panel
Source: authors.

Fig. 11 Projectiles stopped by panel
Source: authors.

Fig. 14 9mm projectile after hitting the panel
Source: authors.

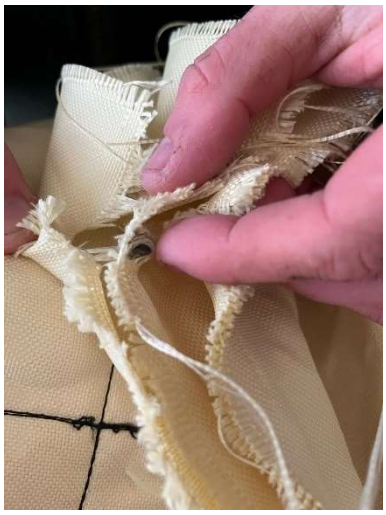

Fig. 12 Projectiles stopped by panel
Source: authors.

Fig. 15 9mm projectile after hitting the panel
Source: authors.

Fig. 13 Projectiles stopped by panel.
Source: authors.

Fig. 16 BFS in antishock panel
Source: authors.

6.4 Practical implications

The outcomes highlight that older ballistic panels may retain sufficient protective capability beyond their declared service life. This supports the concept of condition-based assessment, where serviceability is verified through periodic testing rather than determined solely by chronological age. However, conservative approaches remain advisable until broader datasets confirm these results across multiple samples and storage conditions.

7 CONCLUSION

This study evaluated the residual ballistic performance of a TBO 3 soft ballistic panel taken from a Kirasa body armor vest manufactured in 2001, more than twenty years past its declared service life.

Ballistic testing with 9×19 mm Luger, .357 Magnum, and .22 LR ammunition demonstrated complete stoppage of all projectiles.

The measured Backface Signature (BFS) remained low—≤ 5 mm for 9 mm and .22 LR and 8 mm for .357 Magnum—well below the maximum limits specified by both ČSN 39 5360 and NIJ 0101.06 standards.

These results confirm that, under suitable storage conditions, aging alone does not necessarily degrade the ballistic resistance of aramid-based soft armor to a critical degree.

The findings highlight that even after two decades the tested panel retained substantial energy-absorption capability and provided protection that comfortably exceeds international requirements.

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ANALYSIS OF MODULAR ROD FRAME CONSTRUCTION FOR THE 3D-PRINTED MULTIROTOR UAVs

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Abstract: The presented article deals with the analysis of the modular unmanned aerial vehicle (UAV) components, which were designed so to be convenient for the assembly of the UAV in the various multicopper configurations. Thanks to the proposed modular UAV design it is possible to quickly create the tricopter, quadcopter and also hexacopter configurations and to achieve the required parameters or characteristics, such for example weight, payload, manoeuvrability, stability, redundancy etc., regarding the specific UAV mission. The structural analyses for two types of materials convenient for the 3D printing production, namely ABS plastic and titanium alloy were performed. From the analyses results, the most critical parts of the UAV construction were identified. From the analyses results it can be concluded that if heavier payloads will be carried by the UAV or more demanding dynamic manoeuvres will be expected, it is necessary to use more expensive plastic materials even for the prototyping purposes and laboratory testing at least for the most mechanically stressed components, such for example the arms.

Keywords: Unmanned aerial vehicle; Multirotor configuration; Structural analysis; Fatigue analysis; Buckling analysis.

1 INTRODUCTION

An unmanned aerial vehicle (UAV), commonly known as a drone, is an aircraft with no human pilot, crew, or passengers on board. It can be controlled remotely with various levels of autonomy. UAVs were originally developed for military applications and are especially advantageous for the missions dangerous for humans. Nowadays, they had become an essential part of militaries, but this technology expanded also to many non-military applications [1].

The UAV structural design is usually dependent on its specific application [2]. In addition to the missile launching or bomb dropping applications, they are often used for the monitoring or surveillance applications, both, in high and also low altitudes [3]. However, UAV application for the logistic [4], delivery [5], supply or rescue missions has also an increasing trend. In addition to the fixed-wing configurations often inspired by the conventional aircrafts [6], very popular have became multi-rotor configurations usually manufactured in versions involving from three up to the eight rotors [7]. However, the most popular is the quadcopter configuration, therefore, research in this area is very extensive and involves for example design of coaxial tilt-rotor UAVs [8] or reconfigurable UAVs with controlled rolling and turning [9]. A remarkably interesting design is presented in [10], which allows to the modular quadcopter to disassemble into two BI copters during the mid-air operation. Morphing design can be advantageous also for the applications requiring for example rapid perching [11]. Other research presents the perching mechanism based on the bio-inspired bat-like design [12]. The combination of the bio-inspired configuration together with the possibility of morphing can be found in [13] and presents the quadrotor design inspired by the eagle claw for dynamic grasping.

The extensive advances in the 3D printing technologies have led to the design and development of UAVs manufactured by this additive technology. Research in this area is focused on the topology optimization or generative design that can be used for the whole UAV frame optimization [14], [15] or for the UAV components, such for example portable drone arms [16] or winching systems [17].

Our research is focused on the design of the modular structure, which significantly extends the application possibilities of the UAVs and significantly reduces the UAV costs, as various configurations can be assembled from the same components manufactured by the 3D printing.

2 MODULAR UAV DESIGN

As it was mentioned, the most important requirement for our multicopter UAV design was its modularity. This requirement involves the design of the unified structural components for three different UAV configuration, namely tricopter, quadcopter and hexacopter configuration. Other important requirements that were considered, were sufficient load capacity, flight characteristics and control of the vehicle, due to the which the attachment of the rotors involves the possibility of the movable attachment.

UAVs with different numbers of rotors meet the various application requirements. While a tricopter has a lower load capacity and stability, it excels in the manoeuvrability. On the contrary, with an increasing number of rotors, the load capacity and stability increase, but the manoeuvrability decreases.

In addition to the structural design itself, it is necessary to consider also the material, from which the UAV will be manufactured. Titanium, or more specifically its alloy Ti_6Al_4V was chosen as the material for the main structural components, due to its low weight and high strength, which prevents large elastic deformations. The main disadvantage of the titanium is its price. For this reason, the plastic materials can be used for the non-demanding applications, research and development activities and fabrication of prototypes. In our case, the ABS plastic was chosen to produce the prototype to verify the UAV functionality and flight characteristics. The mechanical properties of the chosen materials are summarized in Tab. 1.

Tab. 1 Mechanical properties of the materials

Material	**Ti_6Al_4V**	**ABS plastic**
ultimate tensile strength (MPa)	950	37
tensile yield strength (MPa)	880	30
compressive yield strength (MPa)	970	N/A
Young's modulus of elasticity (GPa)	113.8	1.92
Poisson's ratio (-)	0.342	N/A

Source: https://asm.matweb.com/

One area where ABS plastic shows a weakness in the outdoor applications is in exposure to ultraviolet (UV) radiation. ABS plastic UV resistance in its natural form is relatively poor and prolonged UV exposure causes ABS to degrade due to the photo-oxidation process, which breaks down the polymer chains. As a result, ABS tends to discolourise, the material surface loses impact strength and toughness and can start to crack. The rubbery butadiene components and other segments oxidize, and the material embrittles.

However, multiple solutions to make ABS viable for outdoor use have been developed [18]:

- UV stabilizer additives such as UV absorbers or HALS – (Hindered Amine Light Stabilizers) are mixed into the ABS resin to absorb harmful UV radiation or to neutralize free radicals to slow down the degradation process.
- Protective coatings, paint or coat sprays with inhibitors block UV light by shielding the plastic from UV rays, since the sun will hit the paint layer instead of the polymer.
- Co-extruded UV-resistant acrylic or ASA (Acrylonitrile Styrene Acrylate) layer can be bonded to the ABS in some manufacturing processes like ABS sheet extrusion or co-moulding.
- Additives like carbon black can improve UV endurance, because carbon black pigment is an excellent UV absorber – it dissipates UV energy as heat. Therefore, black ABS components tend to last much longer in the sun than white or light-coloured ones.

Other reason for the material selection was the material and technical equipment of our laboratories. For the initial UAV prototype production, the ABS material was used. However, after finishing the process of the 3D printer modification [19], materials with the improved mechanical properties such for example PC-ABS material, which is a combination of the polycarbonate and ABS can be used for the UAV manufacturing. The most demanding components can be produced using the high-performance thermoplastics such as the PEKK, PEEK, PEI. However, their price is significantly higher comparing to the prices of the commonly available plastic materials. The comparison of the mechanical properties of these materials can be found in [19].

2.1 UAV Structural Components

The design of the modular UAV involves the following components: base, arm and its parts (fixed and movable end parts), component for the engine attachment, base cover, base plate and landing gear leg.

The base component (Fig. 1) is a thin-walled structure to which the arms, landing gear legs, cover and base plate are attached. The loads from all these components influence the base. The internal part of the base is used for the placement of the on-board electronics, sensors and other equipment necessary for the completion of the various tasks. In the three-rotor and six-rotor configurations, the arms are attached to the base on one side (in the three-rotor configuration only three slots are used) and the base plate and landing gear legs are attached on the opposite side. In the four-rotor configuration, the base is simply rotated, and the arms are attached to the opposite side as in the previous case. This arrangement of attachments allows to use the same base for all configurations.

The arm (Fig. 1) is a rod structure to which the engine is attached via a replaceable end part. It transfers loads from the engine to the base and can be used for all structural configurations. In the arm structure a free space for the servo motor for the control of the movable end part of the arm was allocated. The arm is fixed to the base with a segmented attachment and secured in this position by a cover screwed to the base.

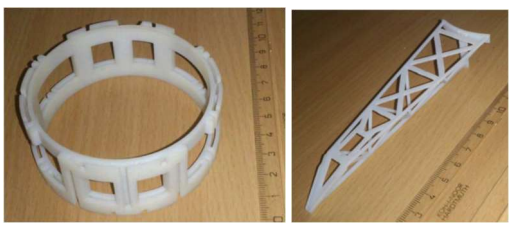

Fig. 1 Base component (left) and arm (right) manufactured from the ABS plastic material
Source: authors.

The end part of the arm can be equipped with the fixed end part (Fig. 2), which is attached by the groove and secured by two crews. This part is used for the quadcopter and hexacopter configuration, as these configurations do not require the tilt of the rotor.

The movable end part of the arm results from the requirement to have at least one of the three engines of the tricopter movable to ensure the tilting. The movable end part involves the interconnecting part, which is attached to the arm via the groove and two screws and involves the circular groove, in which the end part is accommodated and tilted. In the top part there is a gearing for the tilting of the engine using the servo.

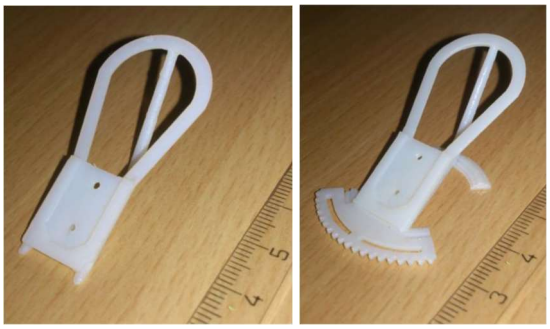

Fig. 2 Fixed (left) and movable (right) part of the arm manufactured from the ABS plastic material
Source: authors.

The component for the engine attachment is a plate structure for the direct attachment of the engine to a fixed or movable end part of the arm by screws.

In addition to protect the onboard equipment of the base and improve the aerodynamic characteristics of the vehicle, the base cover also serves to secure the arms in the base by screws.

The base plate closes the internal space of the base component from the bottom and serves for the attachment of the onboard sensors, electronics or other equipment or payload. It also serves as a support for the landing gear legs.

The landing gear leg is a rod structure attached by two screws to the base component used to transfer landing loads to the base and to absorb impacts occurring during the landing. For this reason, the landing gear leg is intentionally designed to be unstable and is expected to undergo large elastic deformations. It is also the structural component that is expected to be destroyed during the hard landing, and its goal is to protect other parts of the structure from damage.

The whole design of the particular UAV components is in details presented in [20].

2.2 UAV Configurations

There are many UAV configurations inspired by the conventional helicopters, either with a single large rotor or two propellers rotating in opposite directions. However, the helicopter configurations of UAVs are not so popular, as their control requires a considerable amount of skill. On the other side, multicopters use the regulation of the speed of rotation of particular rotors and their control is much easier.

However, with the increasing number of rotors, it is usually necessary to place onboard more electronics and sensors and to design a larger frame to house the additional electrical and mechanical components. This weight is not negligible; therefore, the UAV need to generate more thrust, thus requiring more power from the batteries. This means that UAVs with more rotors must also have larger batteries, which has a significant impact on the total weight. Other problem is that the added parts make the multi-copter more expensive.

Tricopters with only three rotors usually lack the thrust and lift power, and therefore, they have small payload capacity. For this reason, tricopters are typically very small and lightweight. This might be interesting to specific applications, however, tricopters are harder to fly than quadcopters. The lack of paired propellers means that the tricopters are equipped with more complex yaw mechanism.

The tricopter configuration shown in Fig. 3 is the most manoeuvrable configuration, however, its load capacity is the lowest. Considering the proposed engine – propeller system with the thrust of 1.5 kg[3] and calculated weight of the titanium construction of approx. 3 kg (the weight of the construction components together with the engines, batteries, and onboard electronics), the load capacity of this configuration is approx. 1 – 1.5 kg. Against conventional tricopter configuration, in this design there is a possibility to tilt all three rotors, which reduces the deflection of one rotor necessary for the compensation of the reactive moment of one of the rotors and increases the UAV controllability.

Fig. 3 Tricopter configuration
Source: [20].

The popularity of quadcopters is based on the perfect combination of price and ease of use. They excel in a relative cheapness of components, stability, compactness, and a minimum complexity of their components. The thrust-to-weight ratio is sufficient for the use of suspension camera systems. At the same time, their manoeuvrability and weight remain very good and can be used also for aerobatics flights, and their stability is sufficient also for the aerial photography. For these reasons, it can be expected that quadcopters will remain dominant multicopter configuration. The expected weight of the titanium quadcopter shown in Fig. 4 from the bottom view is 3.5 kg.

Fig. 4 Quadcopter configuration
Source: [20].

Hexacopters or even octocopters are the most stable, expensive, and heavy configurations. However, also hexacopters can be advantageous for specific applications because in spit of the added weight, UAVs with more rotors can generate higher lift in comparison for example with the quadcopters. With this capability, these UAVs are convenient for carrying various payload types. Regarding the excellent stability, they can be used also for the high-quality shooting, aerial mapping and for the most demanding applications, as the operational robustness of hexacopters and octocopters is thanks to the redundancy superior. Considering failure of one engine, the UAV with lower number of rotors can fly out of control and crash. In a hexacopter or octocopter, there is at least one rotor that is considered redundant. This means that the UAV can still stay airborne even if one rotor fails. However, the flight performance is in this case usually limited, but sufficient to recover the UAV safely. This can be critical for specific applications. The calculated weight of the hexacopter configuration shown in Fig. 5 and Fig. 6 is approx. 4 kg for the titanium construction.

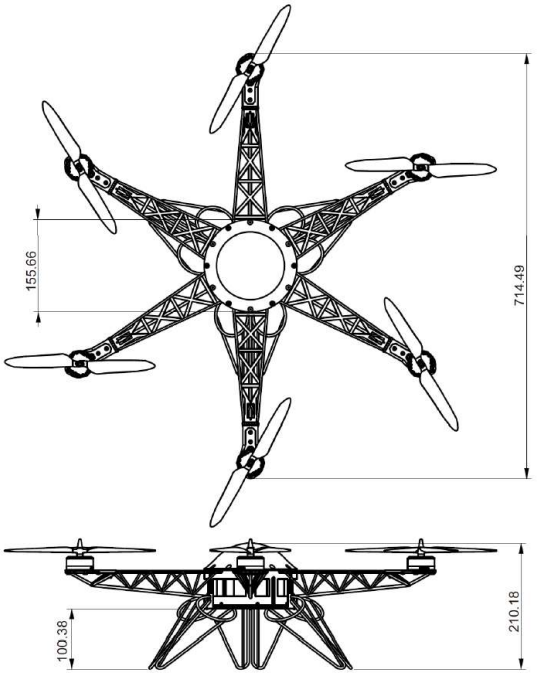

Fig. 5 Hexacopter configuration – top and side view
Source: authors.

Fig. 6 Hexacopter configuration
Source: [20].

3 ANALYSES AND RESULTS

For the simulations, the volume 3D models were created and subsequently, the linear analyses were performed. As the simulation models were symmetric, for the analyses purposes, only the sections of the models involving the arm and a part of the base were applied and the rest of the model was represented by the boundary conditions. As a result of this simplification, it was possible to significantly reduce the time necessary for the analyses.

All structural analyses were performed in the Creo Simulate software [21].

3.1 Strength Analyses

The strength analyses were performed to determine the maximum stresses in the structural components at the maximum static load from the engine thrust. All analyses were performed for two

types of materials, namely for the ABS plastic and titanium. The arm was loaded with a force of 15 N at the point of the groove used for the attachment of the end part of the engine, which corresponds to the engine thrust of 1.5 kg.

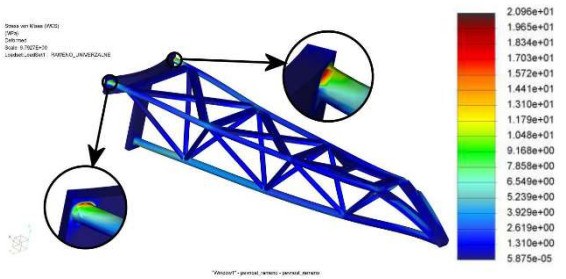

Fig. 7 Strength analysis of the arm from ABS plastic
Source: authors.

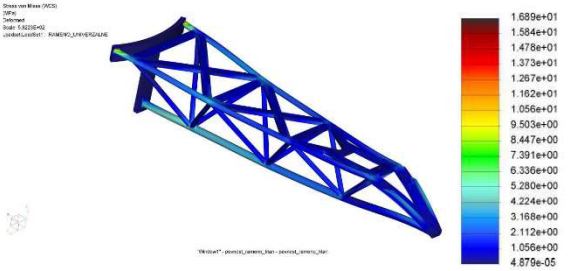

Fig. 8 Strength analysis of the arm from titanium
Source: authors.

The analyses proved the ability of the structure to transfer this static load without structural failure for both materials. The maximum stresses in the ABS plastic arm (Fig. 7) were approximately 21 MPa, which is below the ultimate tensile strength of 37 MPa and even this value is lower than the tensile yield strength (30 MPa). However, this calculated value indicates that this limit could easily be exceeded considering the impact of dynamic stresses. Since the simulated load represents a load at the limit of the vehicle's payload capacity, the UAV made of this material is convenient for example for the flight tests, ideally with no additional or only light payload. The stresses in the titanium arm (Fig. 8) achieved the value of approx. 16 MPa, but its ultimate tensile strength is up to 950 MPa, so this material is according to the assumption suitable for the UAVs even carrying heavy payloads.

The base load was simulated by the loading in a point corresponding to the location of the engine, which was attached to the base by idealized elements in the form of the weight links. Through these elements, the loads were transferred to the base and thus simulated the placement of the arm.

The loading force was the same as in case of the arm (15 N). And similar were also the resulting stresses that achieved in the base made of ABS plastic (Fig. 9) and also of titanium (Fig. 10) the values of about 20 MPa, which means that the conclusions from the analysis of the arm about the unsuitability of the ABS plastic for the higher payloads are the same.

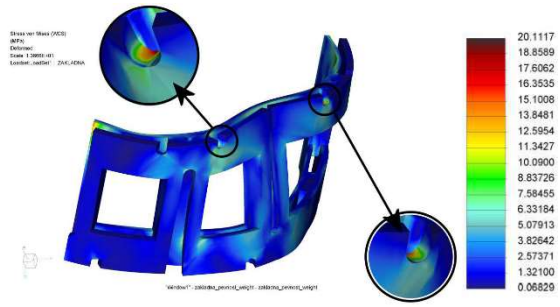

Fig. 9 Strength analysis of the base from ABS plastic
Source: authors.

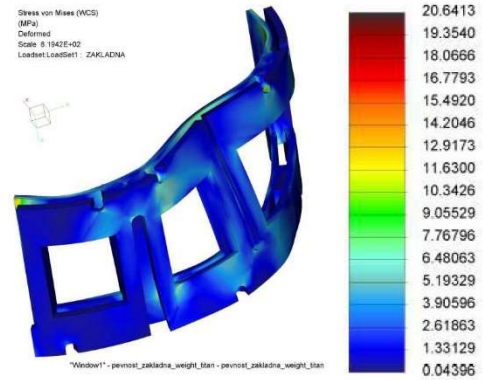

Fig. 10 Strength analysis of the base from titanium
Source: authors.

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The movable end part of the arm was loaded in the same way as the fixed one. In addition to this analysis, also the analysis in the full deflection was performed. This deflection during the flight does not exceed 30°, but the force was applied with an angle of 45° into the engine attachment part.

The maximum load of the structure made of ABS plastic considering the perpendicular force was 39 MPa (Fig. 11) and considering the force acting from an angle of 45°, it was 57 MPa (Fig. 12). However, these high values shown in the legend were influenced by the boundary conditions and these values were identified only in the local points. These values can not be considered as relevant for the calculations; in general, from the analysis results it can be seen that the calculated values are below the ultimate tensile strength values and therefore it can be concluded that this part will not fail in practice.

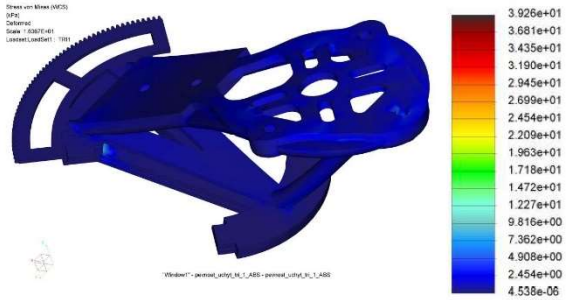

Fig. 11 Strength analysis of the movable end part of the arm from ABS plastic with no defection
Source: authors.

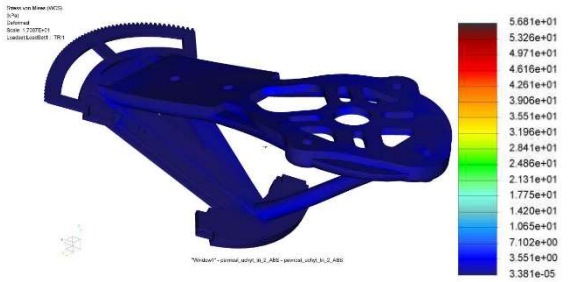

Fig. 12 Strength analysis of the movable end part of the arm from ABS plastic with maximum defection
Source: authors.

The strength analysis of the fixed end part is not necessary, because it is identical to the movable one, and the same applies to the analysis of these parts of the structure made of titanium, which has several tens of times higher strength than ABS plastic.

3.2 Modal Analyses

Modal analysis was used to determine the natural frequencies of the UAV structure and to determine the vibration shapes that occur at these frequencies. For the ABS plastic structure, the first 4 vibration shapes were determined at the frequencies of 67.424 Hz, 70.477 Hz, 202.58 Hz and 271.79 Hz. For the titanium structure, the natural frequencies were as follows: 215.597 Hz, 227.706 Hz, 722.779 Hz and 969.524 Hz. It would be possible to determine also other natural frequencies and vibration shapes, but these vibration shapes are very unlikely due to the high natural frequencies. In Fig. 13 – Fig. 16, the modal analysis results for the ABS plastic are shown. The results for the titanium material are similar and differs in the calculated natural frequencies. The calculated natural frequencies were subsequently applied as the input values for the following analyses.

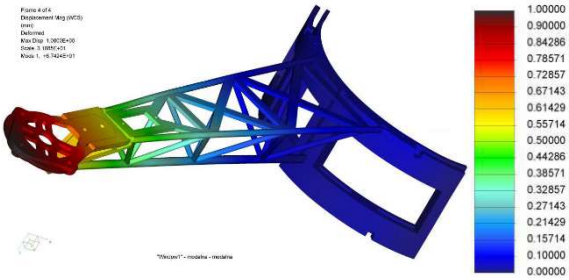

Fig. 13 First mode of vibration (ABS plastic)
Source: authors.

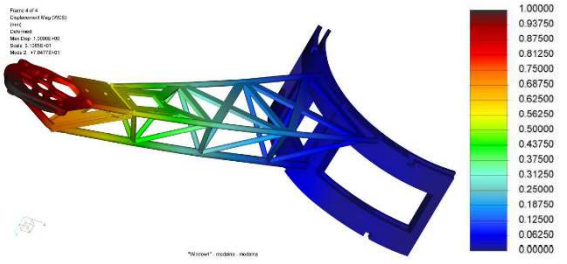

Fig. 14 Second mode of vibration (ABS plastic)
Source: authors.

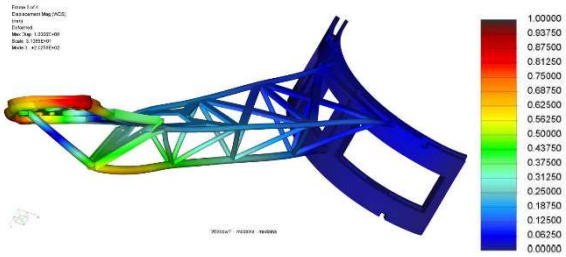

Fig. 15 Third mode of vibration (ABS plastic)
Source: authors.

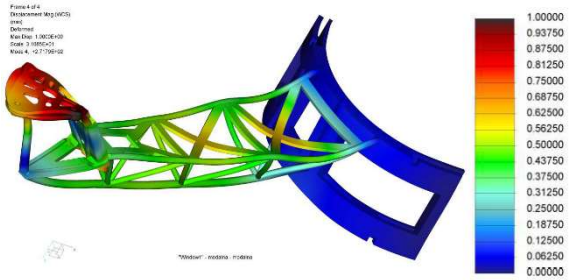

Fig. 16 Fourth mode of vibration (ABS plastic)
Source: authors.

However, the modal analysis does not provide quantitative information about the magnitude of the deformation or stresses. The main goal of the modal analysis was to determine the natural frequencies. If the excitation frequencies coincide with the natural frequencies, they will cause the structure to vibrate at its natural frequency, which will lead to the resonance.

3.3 Fatigue Analyses

These analyses were performed for the main structural components to identify the critical parts of the structure with the risk of fatigue cracking after a certain number of load cycles. The load cycle was defined as peak-to-peak, it means as alternately symmetrical cycle with a sinusoidal waveform. This type of stress represents the worst possible case and does not occur in practice.

The fatigue analysis of the arm made of ABS plastic showed the expected location of the fatigue crack in the area of the connection of the rod elements to the segmental attachment to the base. For this material, the calculated number of cycles to failure was approximately $10^{4.31969}$ (Fig. 17), which corresponds to the value of 20 878 cycles, for which there is a probability that fatigue cracks occur. The results of the fatigue analysis of the titanium arm (Fig. 18) confirmed the same locations of the expected fatigue crack, however, the expected number of cycles to failure was up to $10^{19.1228}$, which is a value that greatly exceeds the required number of cycles.

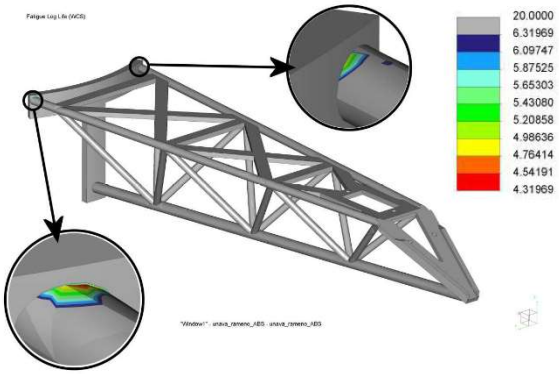

Fig. 17 Fatigue analysis of the arm from ABS plastic
Source: authors.

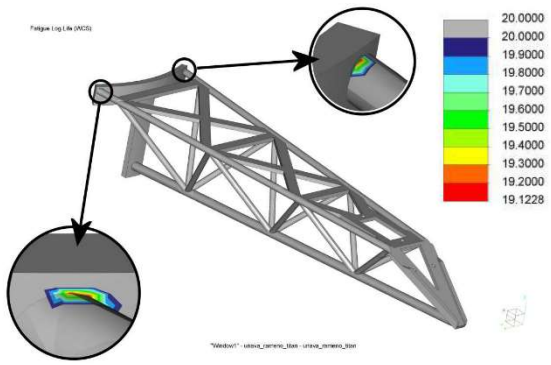

Fig. 18 Fatigue analysis of the arm from titanium
Source: authors.

The fatigue analyses of the base were performed under the same load and conditions as the fatigue analyses of the arm. The results of the analysis were similar; for the plastic base, the number of cycles to failure was $10^{3.63639}$ (Fig. 19), which corresponds to the value of only 4 329 cycles, for which there is a probability that the fatigue crack occur. For the titanium, the calculated number of cycles to failure was $10^{18.1616}$ (Fig. 20), which again greatly exceeds the required number of cycles to failure. The expected fatigue crack was located in the cutout for the arm rod component.

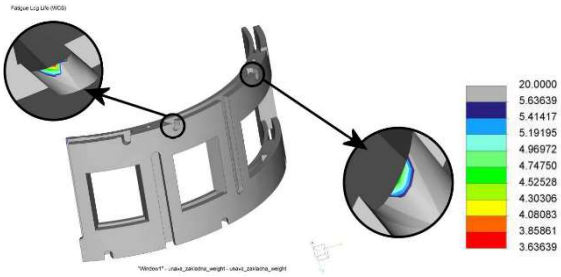

Fig. 19 Fatigue analysis of the base from ABS plastic
Source: authors.

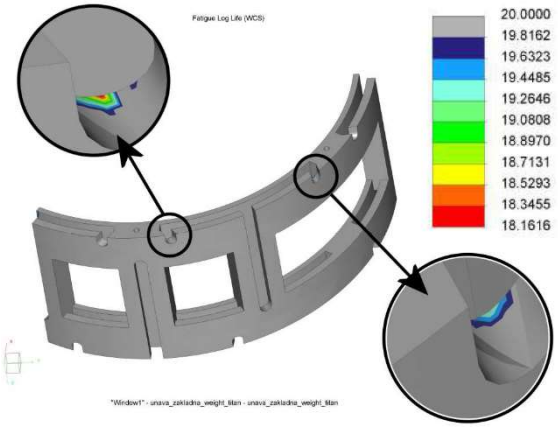

Fig. 20 Fatigue analysis of the base from titanium
Source: authors.

3.4 Buckling Analyses

The buckling analysis determines the critical load at which the structure loses stability and illustrates the shape of the deformation of the structure that occurs when its stability is lost. From the shape of the main structural components, it follows that this analysis is relevant only for the arm, as the loss of its stability occurs earlier, or at a lower load.

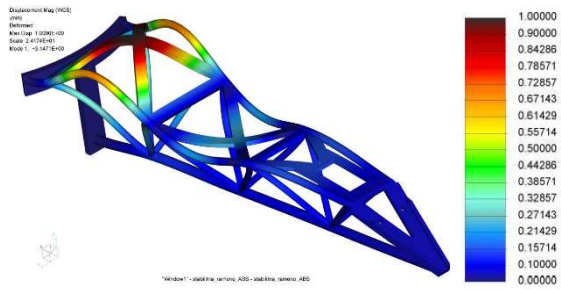

Fig. 21 Buckling analysis of the arm from ABS plastic
Source: authors.

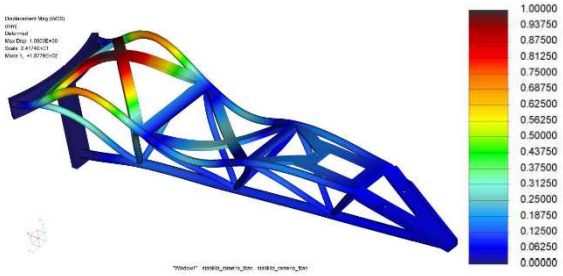

Fig. 22 Buckling analysis of the arm from titanium
Source: authors.

The analysis results show that the loss of stability of the arm from the ABS plastic occurs at 3.2 times of the static load (Fig. 21). For the titanium arm, this value of buckling load factor (BLF) is 187 times of the static load (Fig. 22).

The analyses results showed that the location of the loss of stability is in the upper part of the arm. This construction component was therefore identified as the most critical part of the UAV, as the expected dynamic loading acting on the structural components during the manoeuvres will be approx. 2 or 3 times higher in comparison to the calculated static loading and will achieve values of more than 40 MPa for the ABS plastic material, which is the value higher than the tensile yield strength. Therefore, for the more demanding applications requiring dynamic manoeuvres, it will be necessary to select plastic materials with better mechanical properties.

4 CONCLUSION

The main requirement for our UAV design was its modularity. This was achieved to a high degree, since the two main structural components can be used for the multicopter configurations in the form of tricopter, quadcopter and also hexacopter. This allows to assemble the most convenient multicopter configuration regarding to the given flight task.

Particular structural components were analysed from several aspects, involving the static strength, fatigue and buckling analyses for two different materials, which can be used for the UAV manufacturing using the 3D printers.

As a result of the performed analyses, the ABS plastic is a material convenient for the manufacturing of the functional prototypes due to its low weight and low price and for the applications, in which the overall price without the need of heavy additional payload is determining. However, considering the performed analyses results, for the most mechanically stressed components, such for example the arms, it will be necessary to use more expensive plastic materials, especially if heavier payloads will be carried or demanding dynamic manoeuvres will be expected. Similarly, the ABS plastic material is convenient only for the manufacturing of the prototype and is not convenient, if the long operational life is required. However, the main advantage of this material is that it can be easily recycled and repeatedly used for the prototyping purposes, which is very advantageous, if multiple UAV designs and modifications need to be tested in the laboratory conditions. The titanium alloy is convenient for the manufacturing of the UAV, which is heavier but nevertheless allows the vehicle to carry a significant payload. Also, the strength properties of the titanium are incomparably better in comparison to the ABS plastic.

Other problems and requirement for the improvement and optimization will be revealed by practical tests of the UAV prototype. For example, it may be necessary to focus on the solution of the machining technologies of the contact and sliding surfaces of the structure, to apply UV-stabilization technology for the ABS material to mitigate the UV degradation risk or their manufacturing from other suitable and available materials.

However, materials with better mechanical properties, such for example PEKK, PEEK or PEI, are much more expensive and therefore, they will be applied only for the production of the most critical UAV components, such for example arms.

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3. Length of the article should not exceed 6 pages in defined format. Microsoft Word text editor must be used for writing. Articles must be written using Times New Roman, single line spacing and follow the following form: Title -12 point bold capital letters aligned to the center. Full author´s (co-author´s) name – 10 point normal letters aligned to the center. Abstract – 9 point normal letters, extent 3-5 lines. Keywords – 9 point normal letters. The article text – 10 point normal letters. Contact - full author´s (co-author´s) name, affiliation, e-mail – 9 point normal letters at the end of the article. The article text will be written in 2 columns format with a 75 mm column width and 10 mm empty space separating the columns. The first line of each paragraph must be shifted 5 mm to the right.

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6. Equations in the text are also to be written using the equation editor. (Equation must be typed in Microsoft Equation, which is an integral part of Microsoft text editor.) They must be numbered. Numbers are to be enclosed in parentheses and aligned to the right margin of a column.

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8. References must be fully and accurately documented (according to ISO 690). References should be quoted in the text in square brackets and listed in the order they have appear in the text.

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