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Environmental and industrial safety risks of modern armed conflicts

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Abstract

Wars have always changed along with society and technology, while people's thinking about war has also constantly evolved. Technological development and industrialization have not only transformed the tools of warfare, but also the way people understand the purpose, means, and consequences of war. Technological development and industrialization over the past two centuries have fundamentally transformed the nature of warfare. As a result of industrialization and technological development, wars have placed an increasing burden on the natural environment, as the means and targets of warfare have become closely intertwined with industrial infrastructure. Industrial and chemical facilities have become strategic targets. The article shows how this change in thinking about war has contributed to nature becoming a key stakeholder in modern warfare. Industrial accidents, oil fires, chemical pollution, and radioactive emissions during military operations threaten not only the civilian population but also the environment. The article analyzes three war case studies. The first took place in Kuwait during the 1991 Gulf War, when the burning of oil wells caused massive air pollution and soil damage. The second examines the environmental consequences of the 1999 bombing of Yugoslavia, where the destruction of industrial facilities and chemical plants caused severe pollution. The third case study examines the bombing of the power plant in Jiyeh during the 2006 Israeli-Lebanese conflict. The analysis highlights that in modern warfare military objectives often override the principle of environmental responsibility, and armed conflicts can exert significant long-term impacts on environmental components. The aim of the article is to explore the nature of environmental risks arising from contemporary armed conflicts and to identify the lessons that can be applied in the practice of disaster management and industrial safety.

Keywords: armed conflicts, industrial safety, war-related environmental pollution, industrial facilities

Introduction

Throughout the history of warfare, nature has always been present as the silent sufferer of human conflict. Even in early forms of warfare, the environment was intentionally damaged in the pursuit of military superiority. Fields were burned and forests cut down to deprive enemy forces of food and raw materials. The destruction of food supplies and the driving off of livestock were integral elements of wartime strategy, as the belligerents used nature itself as a weapon to weapon to achieve victory. This phenomenon is described by war ecology, which examines the interactions between armed conflicts and the environment. During wars, soil, water, and wildlife often fall victim. Industrialization and technological advances have opened up a new dimension to the impact of wars on environmental components. In modern warfare, environmental damage can become global in scale and have a long-term impact on the ecological balance.

From the 19th century onward, warfare increasingly expanded to include the struggle for control over industrial production, energy resources, and economic infrastructure. In modern warfare, the natural environment and industrial infrastructure are closely intertwined, as industrial and chemical facilities form the basis of the economy and have thus become strategic targets. During armed conflicts, the destruction of these facilities not only serves to gain military superiority, but also causes serious and lasting environmental damage. During the wars of the 20th century, the arsenal of warfare continued to expand, and the resulting impacts on the environment intensified accordingly. During the world wars, the concept of the war economy increasingly came to encompass industrial, energy, and transportation systems, and civilian infrastructure became part of the military target set. For example, during the Second World War, bombing campaigns affected not only military plants but also oil refineries, factories, and railway hubs. This marked the emergence of a new dimension of warfare, in which the destruction of industrial capacities became a means of weakening the enemy's economy. Meanwhile, military objectives overrode environmental protection, rendering environmental impacts secondary and largely disregarded consequences. In addition to the increasing prevalence of attacks against civilian infrastructure and industrial facilities, the use of chemical and biological weapons also became more frequent. At the same time, armed forces have grown increasingly dependent on industrial support, as military operations cannot be sustained in the long term without supplies of fuel, energy, and ammunition.

The examination of the environmental impact of war is not only an ecological issue, but also a legal and humanitarian one. The additional protocols to the 1977 Geneva Convention already stipulate that it is prohibited to conduct military operations that cause long-term, serious, and widespread damage to the environment.[1] War-related environmental degradation remains an issue to which the international community continues to struggle to find unified responses. The environmental consequences of modern warfare, however, are not confined to conflict zones; chemical contamination can spread through the atmosphere and water systems, reaching regional or even global scales.

In the following sections, through three case studies, I demonstrate how the environment has become a victim of modern warfare and what lessons can be drawn from these examples for industrial safety and disaster management.

The environmental consequences of wars

From the second half of the 20th century onward, the activities of armed forces have become increasingly dependent on energy supply, fuel logistics, refinery capacities, and chemical industry support. In parallel, the protection of critical industrial infrastructures has become a matter of strategic importance, as the same nodes underpin both a country's economic functioning and its military capabilities. Refineries, chemical plants, power plants, and fuel storage systems not only ensure the supply of military operations but also form the foundations of residential energy services, transportation, and agriculture. Owing to this dual role, these facilities have become targets in modern conflicts. The destruction or damage of an industrial installation simultaneously results in supply disruptions, economic decline, and environmental disaster.

A defining characteristic of modern industrial systems is that they store, process, or transport extremely large quantities of hazardous materials, and wartime conditions further increase the risks associated with their presence. During military operations, the affected areas often become difficult to access, allowing contamination to continue unchecked for days or even weeks. The severity of the environmental consequences depends not only on the type of industrial facility but also on its geographical location. In the case of installations situated near water sources, an accidental oil spill can rapidly escalate into a regional-scale pollution event.

One of the most defining trends in the transformation of modern warfare is that the outcome of armed conflicts is increasingly determined by the operational resilience of industrial and energy systems. The expansion of armed conflicts into domains supported by industrial infrastructure is

consistent with the view that the history of warfare closely follows technological development. Changes in weapons technology, logistics systems, and energy dependence have repeatedly reshaped the nature of warfare, creating the impression that war is capable of adapting to its environment. The objectives and methods of conflicts always align with the technological and societal structures within which they emerge. Consequently, the rise of modern industrial and energy systems not only provides the backdrop for warfare, but also fundamentally shapes its functioning. Advances in weapons technology have increased environmental vulnerability in several ways, enabling targeted attacks on industrial infrastructure. Furthermore, high-impact munitions and missile systems no longer affect only military targets, but also cause significant damage to environmental elements, especially when attacks are directed against facilities that store or process hazardous materials. Such facilities may become targets partly because warfare today is no longer limited to direct confrontation between military forces, but also serves as a means of gaining control over the infrastructures that sustain state functioning. The environmental damage caused during conflicts has now reached levels that raise new interpretative questions even for the classical theory of just war. The proportionality and necessity of the use of armed force has traditionally been based on military and humanitarian considerations, but due to the role of modern weapons and industrial facilities, environmental impact has also become part of the assessment.[2]

The Gulf War

The 1991 Gulf War triggered one of the most severe environmental catastrophes in the history of modern warfare. Iraq's attack on Kuwait and the deliberate destruction carried out during its retreat caused unprecedented economic and environmental devastation. At the end of the war, Iraqi forces set fire to hundreds of oil wells and released vast quantities of crude oil into the desert and the sea. The burning oil wells blazed for months, shrouding the region in massive black smoke plumes. The soot, sulfur dioxide, and heavy metal particles emitted into the atmosphere caused severe air pollution. The lack of natural light and the toxic air made everyday life extremely difficult for months; vegetation died off, and airborne contaminants settled into the soil. Beyond atmospheric pollution, the burning oil wells inflicted profound damage on soil and water quality as well.

1. *Figure: Oil fires in the desert during the Gulf War, Source: https://pure.iiasa.ac.at/id/eprint/7427/1/IR-04-019.pdf*

Crude oil spilled from damaged pipelines and storage tanks created huge oil slicks, which also seeped into deeper layers of the soil. These areas remained unsuitable for agricultural or industrial use for years, and soil regeneration was extremely slow. The oil that reached the Persian Gulf also had a serious impact on marine life. Fish stocks, bird populations, and turtles were wiped out en masse. The Gulf's ecosystem was heavily damaged for an extended period, and both fishing and tourism came to a complete halt. The consequences of the environmental disaster were not only ecological but also significant in terms of public health and society. Air pollution led to a rise in respiratory illnesses, and contamination was detected even in neighbouring countries, as smoke plumes travelled thousands of kilometres. The extent of the environmental degradation was so severe that the remediation of soil and groundwater in Kuwait continued well beyond the turn of the millennium. Biological and physical methods were used during the restoration process, but some of the damage remained permanent. The oil that seeped into the desert sand, the burnt vegetation, and the charred soil changed the structure and water balance of the landscape for a long time. The events in Kuwait are a good example of the extent of damage that acts of war can cause. The purpose of setting fire to the wells was to paralyze the region's economy. Soil and air contamination remained detectable for years, and certain parts of the desert still bear the traces of the conflict today. The case of the Kuwaiti oil fires also offers important lessons from a disaster management perspective. Following the incident, experts from more than thirty countries participated in the years-long

remediation efforts within the framework of international cooperation. The event highlighted the need to reconsider the spatial placement of facilities storing hazardous materials, to reinforce tank farms and pipeline systems, and to incorporate war and terrorism-related risks into industrial safety planning. Another key lesson was that the management of large-scale environmental damage can only be accomplished through international cooperation; therefore, it is advisable to coordinate firefighting, emergency response, and remediation capacities, and to develop a common methodology for addressing contamination originating from hazardous industrial facilities. The Kuwait case also showed that the extent of environmental damage depends largely on how quickly intervention can be initiated and the spread of pollutants prevented. Biological remediation technologies played a significant role in post-war restoration. During the cleanup of the Kuwaiti oil fields, bioremediation using microorganisms was used on an experimental basis to promote the natural breakdown of oil derivatives.[3]

During the restoration process, attempts were made to replant desert vegetation, but even decades later, the contaminated and charred soil in many areas was still unsuitable for vegetation to return. The example of the Kuwaiti oil fires also drew attention to the fact that environmental damage can be used as a deliberate weapon in armed conflicts. The damage caused by the 1991 Kuwaiti oil fires and oil lakes became an important precursor to the contemporary political recognition of environmental risks arising from conflicts, including the targeting of industrial/petrochemical infrastructure.

The 1999 NATO Bombing of Yugoslavia

In the spring of 1999, NATO carried out air strikes on the territory of the Federal Republic of Yugoslavia in order to pressure the Yugoslav leadership into guaranteeing the rights of ethnic Albanians in Kosovo and the wider region. During the military operations, industrial facilities, infrastructure, and energy systems were targeted. The bombing campaign affected refineries, petrochemical plants, and railway bridges as well.[4] n September 1999, a working group of the United Nations Environment Programme (UNEP) identified areas where the bombing of industrial facilities could have caused hazardous material contamination. For example, a petrochemical plant and refinery near Pančevo was hit, and there were signs of soil and water contamination in the surrounding area. The destruction of a refinery near Novi Sad caused a fire and oil products may have entered the soil or water, affecting the Danube water system.[5] According to the UN investigation, there was no ecological disaster affecting the entire region, but there were several serious local

incidents requiring immediate intervention. The environmental damage was most severe in areas where dangerous plants storing large quantities of hazardous substances, such as vinyl chloride, ethylene, ammonia, or sulfuric acid, were hit by bombing.

2. *Figure: Damage to the chemical plant in Pančevo following the bombing, Source: http://news.bbc.co.uk/2/hi/science/nature/323113.stm*

Thousands of tons of toxic substances were released as a result of air strikes on the chemical complex in Pančevo. The toxic gas clouds drifted towards the surrounding populated areas. As the concentration of chlorine and other compounds in the atmosphere exceeded health limits, part of the population had to be temporarily evacuated. The risk was further increased by the fact that the industrial complex was also involved in petrochemical and fertilizer production. Damage to storage tanks and pipeline systems created additional hazards, including the mixing of chemical substances and the potential for explosive reactions. According to the on-site assessment carried out by the UNEP Balkan Task Force in 1999, large quantities of 1,2-dichloroethane, ammonia, and petroleum derivatives were released into the soil and the Danube River. Measurements indicated that water contamination in some locations exceeded permissible limits several times over, and pollutants persisted in the river sediments for an extended period. The investigation also concluded that local water supplies and agricultural areas were affected.[5]

Another severely affected area was Novi Sad, where the oil refinery on the outskirts of the city and its supporting infrastructure sustained multiple strikes. As a result of the bombings, large quantities of crude oil and refined oil products burned or leaked into the soil and the Danube River. The resulting oil pollution posed a threat to the river's water resources and surrounding ecosystems. Soot and heavy metal particles originating from the burned materials entered the atmosphere, creating direct health risks for the population. One of the key lessons of the bombings in Yugoslavia is that attacks on industrial targets make environmental risks a strategic factor in modern warfare. The destruction of civilian infrastructure, especially chemical plants, goes beyond military objectives, as such events can cause humanitarian and ecological crises. The clean-up work took years, and the complete restoration of the contaminated areas has not yet been completed.[6]

When selecting military targets, NATO prioritized strategic war aims and did not always take environmental consequences into account. The Council of Europe (2002) report[7] emphasized that although weapons not prohibited under international law were used during the war, the environmental and health consequences received less attention in military strategy. The report clearly stated that the regulation of environmental damage in war is incomplete in international humanitarian law and that there is a need to develop standards that enforce environmental responsibility even in wartime. The experience of the conflict made it clear that the protection of hazardous facilities must be ensured not only in peacetime. Due to the role played by chemical, energy, and logistics infrastructures in warfare, environmental risks will need to be taken into account even more in future conflicts.

The bombing of the power plant in Jiyeh

In the summer of 2006, during the Israeli-Lebanese conflict, environmental damage occurred that went far beyond the geographical boundaries of the military operations. On July 13 and 15, 2006, the Israeli Air Force launched several strikes on the Jiyeh oil-fired power plant, located about 30 kilometers south of Beirut. As a result of the attacks, the facility's fuel storage tanks exploded and several buildings at the power plant were damaged. The fire burned for more than ten days. The detonation resulted in approximately 10-15 thousand tons of fuel oil spilling into the Mediterranean Sea, which is considered one of the largest coastal oil spills in terms of magnitude. The severity of the incident was further exacerbated by the fact that most of the oil did not flow onto land but directly into the sea. Due to its density and composition, the fuel oil formed a dark, continuous slick floating on the water surface. Due to ocean currents, the oil spill reached the entire central and northern coast of Lebanon, stretching over 150 kilometers.

3. *Figure: Oil pollution after the bombing of the Jiyeh power plant, Source: https://ejatlas.org/print/jieh-power-plant-oil-spill-lebanon*

The heating oil that spilled into the sea contained significant amounts of polycyclic aromatic hydrocarbons (PAHs), which were detected in water samples, mussels, and oysters following the spill.[8] These compounds cause long-term damage to marine life, especially mollusks, fish stocks, crustaceans, and waterfowl. The environmental damage caused by the Jiyeh power plant was not limited to marine pollution. The flames that followed the explosion and the burning that lasted for several days caused significant air pollution. Concentrations of soot, sulfur dioxide, nitrogen oxides, heavy metals, and dioxin derivatives drifted toward the capital. Subsequent on-site investigations and health surveys showed an increase in the number of respiratory irritations, asthma attacks, and eye irritations among the population. In addition, the combustion products generated during the fire were carried by precipitation into the soil and nearby agricultural areas. Beyond the environmental components themselves, the entire coastal infrastructure system was also damaged. Cleanup operations began only weeks later, with the involvement of foreign experts. The response efforts were hindered by the fact that much of the contaminated shoreline consisted of narrow, rocky stretches where physical remediation techniques could be applied only to a limited extent. Collecting the hundreds of thousands of cubic metres of contaminated rock, sand, and soil posed a significant logistical challenge, as Lebanon's available capacities were limited.

From an industrial safety perspective, the Jiyeh disaster highlighted the extreme vulnerability of coastal facilities in the event of military conflict. The large quantity of heating oil stored and the proximity to the sea created conditions in which it was virtually impossible to contain the spread of the pollutant. The tank farm was located directly on the coastline, so when the tanks were damaged, the spilled oil immediately entered the open water. International cooperation was crucial in dealing with the damage, but even so, full recovery was a process that took years. According to several studies, the pollution is still detectable in the sediments of certain areas. The oil spill set back fishing and tourism for years, causing significant economic losses. During armed conflicts, attacks on industrial facilities can cause difficult-to-manage environmental damage, and coastal facilities can pose a particular risk.

Experience from managing such incidents shows that in conflict-affected regions, damage assessment and intervention are significantly more difficult and slower than in peacetime. Owing to ongoing military operations, neither local authorities nor foreign experts were initially able to access the area surrounding the power plant, and as a result, precise damage assessment could only begin weeks later. During this period, the oil spill continued to spread unchecked, and due to the delayed response a substantial portion of the released oil permeated the coastal sediments, from which removal is difficult even with specialized equipment. Conditions for microbial degradation were also unfavourable along the contaminated shoreline. On the narrow, rocky coastal sections, mechanical removal could not be carried out safely, making the use of manual labour necessary in the affected areas.[9]

Event	Hazardous substances	Quantity	Impact
1991 – Gulf War (Kuwait)	crude oil, petroleum products, soot, sulfur dioxide, heavy metals	several million tonnes of spilled and burned oil	regional air pollution; oil lakes contaminating soil and water; pollution of the Persian Gulf; mass mortality of wildlife; long-term soil degradation
1999 – NATO bombing of Yugoslavia (Pančevo, Novi Sad)	1,2-dichloroethane, vinyl chloride, ethylene, ammonia, sulfuric acid, petroleum products	several thousand tonnes of toxic chemicals; significant oil spills	toxic gas clouds; soil and surface water contamination; long-lasting pollution of Danube sediments; risk of explosive chemical reactions
2006 – Bombing of the Jiyeh power plant (Lebanon)	fuel oil, PAH compounds, soot, combustion by-products	10,000–15,000 tonnes of oil released into the sea; multi-day tank fire	coastal oil pollution extending 150 km; destruction of marine life; air pollution in the Beirut area; decline of tourism and fisheries; sediment contamination

4. *Figure: Comparative table of damage events, Source: author*

The theory of just war and environmental damage

These three events clearly illustrate that the environmental consequences of modern armed conflicts often exceed the immediate objectives of military operations and place a lasting burden on societies and the environment, sometimes spanning generations. The technological and industrial nature of military operations has created a situation in which environmental damage is not merely collateral damage, but in many cases a premeditated consequence intertwined with strategic objectives. This also raises the question of how the deliberate or foreseeable damage to nature fits into traditional and contemporary thinking about war.

Thinking about the moral conditions of war goes back centuries. Early theories of just war focused primarily on the protection of human life, the justification for waging war, and the proportionality of the use of armed force, while the issue of environmental damage was already known to medieval thinkers. The deliberate destruction of agricultural land, water resources, and

forests was considered disproportionate damage even by classical authors. The destruction of natural resources often did not directly serve military purposes and was therefore often considered disproportionate. Environmental protection was not alien to traditional just war thinking. During later armed conflicts, it became increasingly clear that the extent of destruction determines the development of a country's ecological and economic structure for a long time. This realization contributed to the gradual emergence of environmental protection in the theory of just war. Nowadays, environmental protection is becoming an increasingly important issue. Technological advances in modern warfare have created enormous destructive potential. The vulnerability of modern weapon systems and industrial infrastructure together generate consequences that persist for decades after the end of a conflict. Damage to nature is therefore not only an incidental loss, but also a factor that influences the assessment of the proportionality, necessity, and justification of war. Damage to environmental elements has an indirect impact on the living conditions of human communities.[10] The events described in the previous section illustrate that damage to nature often does not stop at national borders. Combustion products spreading through the air, chemicals entering rivers, or oil pollution carried by ocean currents have regional impacts, so environmental damage is not solely a matter for the state involved in the conflict, but becomes a broader issue of international responsibility. The destruction of environmental elements also affects the living conditions of future generations. Even the classic theories of war focused primarily on protecting people living in the present, but today we must also consider the long-term consequences. In modern warfare, protecting the environment can no longer be separated from protecting the population. Permanent damage to natural elements directly affects the functioning of society.

Modern armed conflicts from a disaster management perspective

The successful elimination of industrial disasters occurring during armed conflicts largely depends on the effectiveness of preparedness and prevention activities carried out in peacetime. The course of pollution occurring in wartime conditions is in many ways similar to the risks that must be taken into account in the vicinity of hazardous facilities in peacetime. The major industrial disasters of recent decades have made it clear that their consequences often do not stop at national borders. This highlights the fact that prevention and protection can only be effective if the legal regulations and the procedures, tools and methods used form a coordinated system at international level.[11] In Hungary, the supervision of plants dealing with hazardous substances is carried out in accordance with regulations based on the Seveso III Directive. According to 2022 data, 255 facilities handling hazardous materials operate nationwide; of these, 110 are classified as upper-tier and 145 as lower-

tier establishments.[12] These include petroleum and chemical plants, fertilizer and pharmaceutical factories, and sites that handle large quantities of combustible or toxic materials. Damage to such a facility can easily lead to a disaster with regional or cross-border effects. In the event of damage to hazardous facilities, the time factor plays a decisive role in the response. Examples show that difficulties in responding in the first few hours can multiply the damage in the long term. It is therefore important to maintain the conditions for rapid response in the vicinity of hazardous facilities and to support the system of tools with continuous modernization. At the same time, official supervision and responsible operation also play an important role. Responsible operation includes the preliminary identification and assessment of hazards, the development and continuous updating of internal protection plans, and the regular training of employees to deal with possible extraordinary events.[13] These measures help ensure that in the event of an unexpected incident, the response is faster, more coordinated, and more effective, which can substantially reduce environmental impacts and risks to human health. The protection of hazardous establishments is of strategic importance. In addition, preparing the population directly influences the scale of potential risks. For residents living near hazardous facilities, it is essential to be aware of the potential sources of danger in their surroundings and to understand the relevant behavioural guidelines. Regular preparedness activities can significantly mitigate the consequences of an industrial accident or other emergency situation. Given the growing environmental and industrial risks, preparedness is an indispensable prerequisite for effective response. Since preparedness is not only a regulatory and organisational issue but also a matter of training, the education of public administration leaders plays a crucial role in this system. Decision-makers must possess the knowledge and competencies that enable them to coordinate the activities of various sectors, authorities, and municipalities during wartime or emergency conditions.[14] The practical mastery of decision-making processes ultimately serves to ensure that intervention in an unexpected situation is rapid, coordinated, and professionally sound, regardless of whether it is an industrial accident, a natural disaster, or the indirect effects of an armed conflict.

On the operator's side, preventive measures include all planning, technical, organisational, and management actions aimed at reducing the risk of major accidents, from the identification and reporting of hazardous activities, through the preparation and review of safety documentation, to the operation of safety management systems. In parallel, on the authority's side, permitting, supervision, inspection, and enforcement activities constitute the framework that ensures the effective implementation of prevention. The effectiveness of the prevention system therefore depends primarily on how consistently operators fulfil their obligations and on the authority's ability to

enforce regulatory requirements in a professional and consistent manner.[15] If the prevention and oversight system established in peacetime is strong, the consequences of a potential incident become significantly more manageable.

Summary

Due to the complexity of contemporary industrial and societal systems, the consequences of armed conflicts routinely affect environmental resources, critical infrastructure, and the fundamental conditions required to sustain human life. War-related environmental damage not only spreads beyond the geographical boundaries of the conflict zone but often persists over time as well. In many cases, it results in lasting changes that influence the lives of affected societies for decades. Damage to environmental elements is a recurring feature of modern warfare, intertwined with military strategic objectives. The cases presented also draw attention to the fact that technological progress and the expansion of industrial infrastructure have created a fundamentally new situation. Due to the vulnerability of facilities that store and process hazardous materials, a military operation can easily lead to a serious chemical, industrial, or ecological disaster. This can generate consequences that cannot be managed and eliminated by a single country, but often require coordination at the international level. The issue of environmental damage caused by war also requires new considerations from a moral point of view. In the past, the principles of proportionality and necessity focused primarily on protecting human life and safety. However, modern warfare can cause environmental destruction on such a scale that it indirectly affects the survival of human communities. The destruction of an industrial facility not only destroys the living conditions of the present generation, but also affects the lives of future generations. This justifies making environmental protection an independent aspect of ethical thinking in warfare.

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Inspection and Handling of Postal Shipment Risk - a Case Study

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Abstract

The security of postal networks is of paramount importance today due to terrorism and the spread of new forms of attack, such as letter bombs, and the spread of radioactive or toxic materials. The author of this study will introduce that radiation protection plays a fundamental role in this environment, as radioactive contamination poses an immediate health and environmental risk. The purpose of radiation gates and postal X-ray equipment is to quickly and safely inspect mail, filter out hazardous materials and maintain service continuity. Letter bomb detection systems provide an additional layer of protection by integrating multiple detection methods, such as X-ray imaging and motion detection. Using modern, artificial intelligence-based data analysis and false alarm reduction, the system is able to safely screen large volumes of mail in real time.

Keywords: radiation protection, radiation gate, x-ray device, letter bomb

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1. Introduction

The stability of postal services is of paramount importance for the defense resilience of infrastructures that are important for the defense and security of the country, since the regular flow of mail serves not only the continuity of economic and social life, but also the maintenance of public order and national security. In the modern era, however, postal networks are increasingly becoming tools for terrorism, crime and social unrest, especially in the form of mail containing hazardous materials such as radioactive materials, chemical

agents and components, explosive devices or biological pathogens [1] [2]. The use of radiation protection, radiation gates, X-ray equipment and letter bomb detection devices is therefore not just a technical issue [3], but a fundamental condition for the continuity of service and the safety of the population. The author of this study will introduce that systems installed at key, high-traffic locations of the Hungarian Post Private Limited Company are capable of detecting the presence of gamma and beta radiation, thus immediately screening out shipments suspected of radioactive contamination.

These structures are suitable not only for monitoring shipments, but also for cargo and passenger traffic [4], and alarms are archived by a computer system, thus ensuring the traceability of events. [3]

X-ray parcel scanners provide an additional layer of protection, as they are capable of visually analyzing the internal structure [5] [6] of explosives and other dangerous objects, making their use mandatory in international traffic. X-rays enable detailed mapping of the internal structure [5] [6] and composition of shipments, which is critical for the early detection of potentially dangerous or prohibited contents. The integration of modern digital image processing systems significantly increases the accuracy of detection [7], while optimizing the speed of the screening process, thus minimizing logistical bottlenecks. In addition, precise control of radiation doses guarantees radiation protection for operators and users, contributing to long-term health safety and the sustainable operation of the postal system.

Letter bomb detection devices, such as the SCANMAIL 10K type detectors, use a multimodal approach [8]: they identify suspicious items using a combination of X-ray imaging, weight analysis, motion detection and chemical detection. In domestic processing plants, we can find devices of this or similar type in several places, especially where the mail traffic is above average. In the event of an alarm, the indicated item is examined without opening based on the instructions of the workplace manager, and in parallel, the Firearms Service of the Emergency Police is immediately notified.

The handling of items indicating the presence of dangerous substances requires strict procedures [9]. The characteristics of suspicious items include overstamping, hard touch, oil stains, an unidentified sender, and a “personal” or “confidential” marking, which may prevent the item from being opened by a third party. Upon discovery of a suspicious

shipment, air exchange equipment must be stopped immediately, it is forbidden to move the shipment, expose it to moisture or high temperatures, and use a mobile phone near it. Employees must immediately notify their immediate supervisor and then the remote monitoring service, who will initiate measures by the authorities (e.g. police, disaster management, National Radiation Health Emergency Service). After examining the shipment, the authorities draw up a report and decide on its further fate: seizure, return or subsequent return.

In order to ensure effective protection, postal organizations have introduced not only technical but also organizational and educational measures [2] [10]. Employees receive basic training and annual refresher training, practice the separation and handling of hazardous materials in simulated exercises, and conduct joint exercises with the authorities. The integrated use of radiation gates, X-ray equipment and letter bomb detection devices, as well as close cooperation with the authorities, allows for high-throughput, real-time screening without seriously disrupting the operation of the postal service. Through regular inspections and technical developments, 95% of mail items are controlled, which is a commendable result even in international comparison. For example, the operation of the radiation gate system complies with international standards, and the use of parcel inspection equipment is also mandatory for air transport. The complex protection strategy therefore includes not only the uniform application of technological tools, but also the integration of personal and organizational factors, thus ensuring the continuity of postal services and the safety of the population.

The author of this study aims to comprehensively present theoretical and practical approaches to the investigation and management of security risks related to postal items. Special attention is paid to the role of radiation protection, radiation gates, X-ray equipment and letter bomb detection devices in identifying dangerous substances and devices and in maintaining the security of the postal network. The thesis also aims to explore the operating principles, application possibilities and efficiency of these technologies, with particular regard to the development of integrated, multi-level protection systems. As a result of the research, it is expected that proposals and conclusions will be formulated that may contribute to the development of postal security protocols, minimizing risks and increasing the operational safety of the service. Continuously updated technological tools (CBRN) allow the identification of new threat types, as shown in Figure 1, while regular

training of security personnel guarantees the proper and effective use of technological tools. CBRN devices is a special devices and instruments that are suitable for detecting various chemical, biological, radiological and nuclear materials.

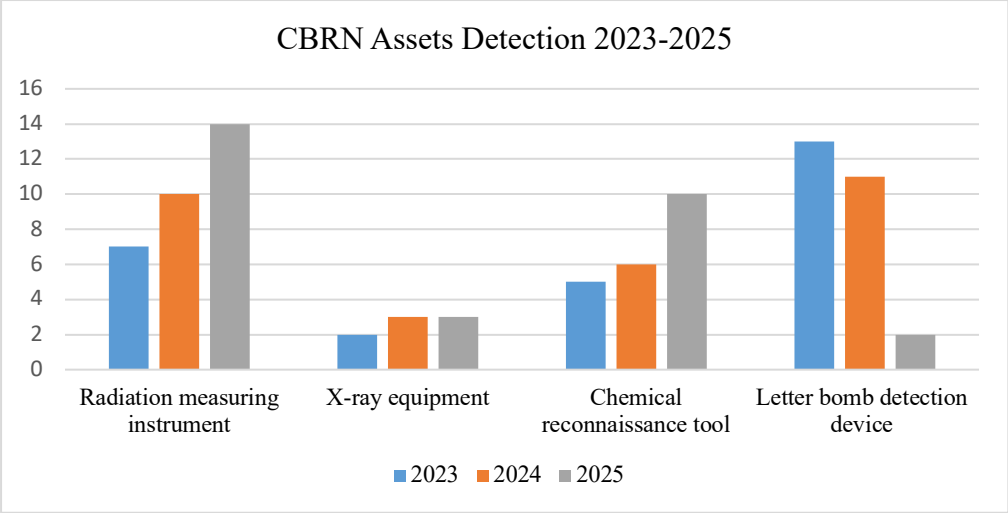

Figure 1. Changes in CBRN equipment used at the post office
Source: author's edit

2. Introduction to Radiation Protection and Radiation Gate Operation

The chapter focuses on the radiation protection principles applied in postal facilities and the operational characteristics of radiation gates. It describes the types of radioactive radiation, the basic principles of detection and measurement, and the technical and safety requirements for the operation of radiation gates in the process of screening mail.

2.1. Basics of Radiation Protection

Radiation protection is the science and practice of protecting against the harmful effects of ionizing radiation. Its aim is to minimize the radiation exposure of individuals, the environment and society. It is guided by three basic principles: justification (only used when unavoidable), optimization (doses are kept as low as reasonably achievable, ALARA principle) and dose limitation (legal limits). Ionizing radiation can be alpha, beta and gamma radiation, each with different penetrating power and hazard. Important dose quantities: absorbed dose (gray, Gy), equivalent dose (sievert, Sv) and effective dose. Radiation protection means: shielding, time protection and distance protection. Activity shows the number of radioactive decays measured in becquerels. Separating internal and external exposure is important for protection. Biological effects of radiation exposures can be deterministic or stochastic. The radiation weighting factor takes into account the type

of radiation and the sensitivity of the organ. In an emergency, special procedures are required to protect responders. The regulation is based on the Atomic Energy Act [11].

2.2. Beam Gate Operation

The operation of the radiation gate is one of the basic technical tools for the security of postal logistics facilities, which actively contributes to the screening and immediate identification of shipments containing radioactive or potentially hazardous materials. During installation, the radiation gate must be placed on the route of passing shipments and packages so that each traffic unit undergoes inspection. The operating personnel must be familiar with the technical operation of the radiation gate and the Hungarian-language operating manual, while following the steps in the protocol in the event of each alarm.

In the event of an alarm, the primary task is to identify, isolate and temporarily store the suspicious shipment safely. The employee operating the radiation gate is obliged to comply with radiation protection protocols, including activating the immediate notification chain - typically to the organization specified in the single-gate management system - and then to report its results to the radiation protection authority. It is important that further handling of found objects containing radioactive isotopes may only be carried out by specialists with specialized qualifications, in accordance with the relevant national and international regulations. [12]

Regular maintenance, system validation, radiation protection monitoring, and periodic training and preparation of operating personnel for emergency situations are key requirements in operational practice. Procedures must be developed based on the domestic guidelines of the International Atomic Energy Agency (IAEA) and the Hungarian Atomic Energy Authority (OAH) [13], thus ensuring efficient and legal operation in accordance with international standards. [14]

The devices used - with particularly high sensitivity - are suitable for detecting gamma radioactive contamination. These devices have a scintillation detector sensitive to gamma radiation. According to the patented measurement method used in the devices, the current value of the background radiation is automatically taken into account to determine the alarm level, the devices used for this purpose take into account the speed and shielding effect of the vehicle, and based on this, the optimal alarm level is determined. A data

packet about the current radiation level and the individual states is sent to the logging computer every half a second. In the event of a significant increase, an alarm signal is sent to the alarm unit located in the service room. The BNS-94H radiation gate developed by Gamma Engineering Co. Ltd. (GAMMA) was installed in the Posta application. [3]

2.3. BNS-94H Beam Gate Structure

The radiation gate can be divided into two functionally separate components that form an organic unit: the detector unit, which detects and measures radiation, and the alarm unit, which, based on the detected values, gives an alarm when the specified threshold values are exceeded.

The installed radiation gate checks the cargo of passing vehicles. The detector unit contains a radiation detector and circuit units, including a microcomputer. The radiation detector of the radiation gate includes a scintillation detector with a built-in high-voltage power supply and preamplifier located in a lead collimator. The radiation detector is placed in a heat-insulating polyurethane foam bed, which protects against shock caused by sudden temperature changes. The circuit units consist of analog circuits, a microcomputer and line drive and protection circuits, in a replaceable card system design. The detector unit is connected to the alarm unit by a multi-core special instrument cable.

The high-sensitivity scintillation gamma radiation detector consists of a ∅ 50x70mm scintillation crystal and a photoelectron multiplier, the pulses of which are amplified by the built-in preamplifier. The high voltage required for the operation of the photoelectron multiplier is provided by a built-in high-voltage power supply. The lead collimator of the detector provides the necessary viewing angle. The measurement time cycle is 0.5 s, which ensures sufficient sensitivity even in the case of a relatively higher speed of movement of the pollution to be detected (30-40 km/h), while an algorithm that also takes into account the detection duration ensures that the sensitivity is automatically increased in the case of slow movement. Its operation is not affected by the instantaneous value of the background radiation, the change in the ambient temperature and the aging of the radiation detector, because the system is self-calibrating. The microcomputer evaluates and transmits data to the PC via a serial line every half a second. In the event of an alarm, it directly controls the alarm unit.

2.4. BNS-94P Package/Person Screening Beam Gate System Operating Principle and Parts

The basic components of the system are the 2-detector beam gate unit and the alarm unit with built-in panel PC. The BNS-94P radiation detection gate developed by GAMMA is a highly sensitive, precision instrument designed for the detection of radioactive sources and nuclear materials. The system integrates two separate scintillation detectors, which are specifically sensitive to gamma and neutron radiation, allowing simultaneous and reliable monitoring of these types of radiation. The operating principle of the device is based on a patented measurement algorithm that optimally sets the alarm thresholds. To do this, it automatically takes into account the current level of ambient background radiation, as well as the relative speed of the object under test and any shielding effects that may affect the strength of the detected signal. This dynamic threshold setting significantly increases the efficiency of the detector, minimizing the number of false alarms. The detection process takes place in half-second measurement cycles, during which it continuously analyzes the incoming radiation intensity. If the system detects a significant deviation from the background values, it provides immediate feedback: the alarm unit signals visually (light signal) and acoustically (sound signal). This allows the operating personnel to react quickly and accurately to potential dangerous situations. Data collection and logging of measurement events are carried out using computer control, which ensures continuous data archiving and retrieval for safety analyses and audits. The IT background supports the integration of the system into larger safety infrastructures and facilitates remote monitoring and maintenance.

In summary, the BNS-94P radiation gate stands out with its high sensitivity, adaptive measurement procedure and fast alarm mechanism, which together make it a reliable and effective tool in nuclear safety applications, such as border crossings, customs checkpoints or the protection of critical infrastructures.

2.5. BNS-92S Radiation Level and Contamination Meter Handheld Instrument

The BNS-92S radiation measuring instrument is a complex, integrated system capable of measuring and evaluating a wide range of radiation parameters. The device measures, among other things, the dose of gamma radiation in Sievert (Sv) and its dose rate in Sv/hour

(Sv/h). It is also suitable for detecting surface contamination associated with a- and β-radiation, and quantifies the concentration of β-particles in radioactive materials.

The device has high sensitivity, which allows for quick and accurate identification of low-level radiation anomalies. The user interface is ergonomically designed, user-friendly and easy to use, allowing for efficient work in a variety of environments. The technical parameters of the device include the ability to configure adjustable alarm threshold levels, which allows for quick adaptation to different safety requirements.

It supports the operator with an audible signal, so the instrument provides immediate warning if the measured values exceed the set limits. The operating temperature range is wide, making the device suitable for a variety of environmental conditions, including extreme and changing climates. The device is built to military standards for reliability and durability, ensuring long-term operation and durability. The BNS-92S uniquely combines two measurement functions in a single unit: it functions as a dosimeter in its carrying case, while it performs a contamination measurement function when removed from the case. This dual mode provides its users with a high degree of flexibility, especially for field measurements. The dose and dose rate alarm levels can be set manually, allowing the operator to precisely control safety protocols. Technical data and user information are displayed on the device's built-in LCD display, which provides easy-to-read, real-time feedback to the operator. In addition, the instrument is capable of computer data communication via a two-way data cable, allowing for digital recording, processing and remote monitoring of data.

In summary, the technical parameters and functionality of the BNS-92S make the device ideal for applications where complex radiation measurements, a fast alarm mechanism and reliable data communication are required, including industrial, civil and military environments.

3. Analysis of Mail Bomb Detection Devices/Mail Inspection Devices

This chapter describes the operation and application of mail bomb and mail inspection systems for mail security. The author of this study will introduce the multimodal detection principles of the devices, such as X-ray imaging, weight and motion analysis, and integrated security processes to help identify suspicious shipments.

Mail bomb detection devices (such as the SCANMAIL 10K) are desktop, compact detector systems that use automated detection methods to identify explosives and other potentially dangerous objects [5] [6] [8], such as mail bombs and sharp cutting tools.

The SCANMAIL 10K is a device belonging to a new generation of microprocessor-controlled desktop mail screening systems. Its design goal is to quickly and reliably screen incoming mail and courier shipments in order to ensure the early detection of potentially dangerous, mail-based explosive devices. The device integrates several detection and signaling modules, which are coordinated by the manufacturer's algorithmic logic. This enables automatic detection of detonator assemblies and other components that can be interpreted as building blocks of explosive devices. The device does not attempt to detect any specific explosive, but rather to identify physical and electronic patterns characteristic of the threat. As a result, the probability of detection is high in different cases, but no system guarantees 100% detection in all possible configurations.

The device automatically generates an alarm if the examined shipment shows characteristics that indicate a potential threat (for example, the presence of detonator assemblies). The alarm logic is calibrated to reduce false alarms caused by common, harmless packaging elements (e.g. staples, paper clips), so the presence of common office objects causes less unnecessary alarms. The sensitivity level of the device is factory-set, so the basic mode is user-friendly and does not require continuous parameter tuning by the operator. The test card included in the package allows the user to check the device's functionality — especially after startup or during periodic checks. The SCANMAIL 10K is easy to operate and does not require special training for everyday use. It is primarily powered by mains power, but also has a built-in battery backup mode, which allows for operation independent of the mains. It has a portable design and can be used immediately when placed on a table. The design of the device does not cause damage to photosensitive films, magnetic tapes or hard drives, so it is considered harmless to them. Mail bomb detection devices used in security checks can be reliably used to identify and filter potential threats, and their operation is based on both relevant scientific knowledge and practical experience. In order to guarantee the security of postal items, various technological solutions are used, which aim to quickly and reliably identify potentially dangerous substances [15] and devices; these methods allow postal workers to check the internal

contents of packages in detail, filter out threatening elements and minimize the number of false alarms.

• Metal Detectors: These devices are used to detect metal parts, such as detonators or batteries, which may be part of explosive devices. They work quickly and efficiently, but the presence of metal in itself does not constitute a threat (e.g. paper clips).

• X-ray Imaging: X-ray technology provides a detailed image of the internal contents of packages. It helps postal workers identify wires, cables, or unusual packaging, indicating suspicious items.

• Explosive Trace Detection (ETD): This method detects traces of explosives on the surface of packages. It is very sensitive, so it can indicate a threat even if the explosive is hidden in the shipment.

4. Introduction to X-ray Device

The radiation protection of persons exposed to radiation in the public or at work must be optimised, with the aim of keeping the personal doses, the probability of radiation exposure and the number of persons exposed to radiation as low as reasonably achievable, taking into account current technical knowledge and economic and social factors.

The requirements of the operating instructions issued by the manufacturers must be observed during the integration and use of parcel inspection equipment in postal technology. Only X-ray equipment in perfect technical condition may be operated. As confirmed by certificates, no radioactive material may be released into the external environment, thus excluding public radiation exposure. It also applies that in the case of equipment used in given postal facilities, the employees involved do not need to be provided with a dose level indicator device. No special protective measures are required. Inspection of shipments is an essential obligation due to air transport and customs inspection, so disassembly and non-destructive shipment inspection can be performed at the installation site.

4.1. Purpose of the Radiological Activity

The purpose of using X-ray equipment is to screen postal items. [16] Outgoing items are screened for aviation security purposes, to detect anything that is not allowed in the

shipment. Incoming items are screened for the purpose of determining the customs procedure.

4.2. Technologies Using Ionizing Radiation

The operation of the X-ray equipment for parcel inspection is carried out at the designated location, in compliance with the rules prescribed for the consignments. The chapter contains the most significant technological processes related to the screening of consignments.

This chapter discusses the operation and application of X-ray equipment that ensures the fast and safe screening of postal consignments. The author of this study will introduce the operating principle of the equipment, its role in identifying hazardous materials, and the requirements for efficient and safe operation to ensure the continuity of postal service. The inspection from an aviation security perspective takes place in the protected, internal areas of the facility and in the related external zones closed off by security boundary elements. The use of the device is justified so that explosives, weapons, or other objects and materials that are dangerous to civil aviation and capable of committing an illegal act are filtered out of the postal consignments, and their entry into the closed area of the airport or on board the aircraft is prevented. In normal mode, the device operator checks the image of the unit carriers (mail items) at the screen workplace with the HI-SCAN 100100V aviation security device and makes sure that the air transport does not contain any abnormal content from a security point of view. If the screener does not find any suspicious signs or devices, objects, or materials that are dangerous to the safety of air transport, in that case he stamps the box markers, bag functions, and address labels of the unit carriers with the stamp assigned to him; thereby he declares that the checked mail items are suitable for air transport.

If it cannot be determined with complete certainty that the contents of the postal item do not contain any prohibited material, device or object, or if there is a suspicion of any prohibited or prohibited content, or if the item contains such a high-density material that it prevents detailed examination of the content, the affected unit or postal item must be removed from the technological process immediately and, in order not to jeopardize the transmission time of other items, it must be placed in a separate room and in a separate storage. The set aside unit/units/ are subjected to further inspection on the HI-SCAN 7555i

aviation security equipment in the separate room. If during the inspection there is still reasonable suspicion of a given item, only the item that gives rise to suspicion may be retained after the unit is opened.

4.3. Equipment Description

In postal security processes, as shown in Table 1, Smiths Heimann HI-SCAN 100100V, HI-SCAN 7555i and Astrophysics XIS 100X devices play a key role in the fast and reliable screening of mail. These systems enable detailed inspection of the internal contents of packages, identification of potentially dangerous objects, metal parts or suspicious packaging elements, and support postal workers in making decisions during security procedures. The different devices are adapted to different sizes of mail, throughput and detection capabilities, thus ensuring effective, continuous control in the postal network. [17]

Table 1. Screening equipment used at the post office
Source: author's edit

Machine Type	Accessories	Application
Smiths Heimann HI-SCAN 100100V	NAS (network-connected storage unit)	Aviation security screening
	LinkSys Ethernet switch, 8 port	
	Mobile data storage unit	
	CTP Test Piece ECAC European Standard (test bag)	
Smiths Heimann HI-SCAN 7555i	Ceia PD 140V hand-held metal detector set (3 pcs)	Aviation security screening
Astrophysics XIS 100X	-	Customs clearance of incoming shipments

5. Summary and Conclusions

The effectiveness of security systems in the postal sector is multidimensional and depends on several factors, including technological sophistication, integration, international coordination, and continuous development and training. Modern sensor technologies — such as X-ray imaging, beam gates and chemical trace detection systems — enable the rapid and accurate identification of hazardous materials, [18] such as explosives and radioactive components. The use of artificial intelligence and machine learning further increases the accuracy of early threat detection and optimizes control processes in a dynamically changing security environment. [19]

Integrated security systems, which bring together different components (e.g. CCTV, alarm systems, access control), allow for comprehensive, proactive protection. In addition, international cooperation and standardization, in accordance with the Universal Postal Union (UPU) and European Union (EU) guidelines, play a fundamental role in enhancing the security of cross-border parcel delivery. Technological innovation and employee training together ensure the adaptability and sustainable efficiency of the systems. The combination of these measures not only increases security, but also improves operational efficiency and cost-effectiveness through automation and process optimization, thereby enabling faster and more accurate package handling, which directly contributes to increased customer satisfaction. Increasing the security of postal transport in Hungary is of critical importance in terms of minimizing the threats and ensuring the reliability of logistics processes. In order to enhance security, it is essential to integrate modern technological solutions — including X-ray imaging, beam gates and artificial intelligence-based sensor systems — into processing processes, as well as to use automation to increase efficiency and reduce human errors. Modernizing the legal and data protection frameworks, employee training and improving customer awareness together ensure the consistent implementation of security protocols. Furthermore, international cooperation and infrastructure development — such as the use of automated delivery points — contribute to increasing the resilience of the postal chain. The application of combined measures overall promotes the reliability and sustainable security of postal services in a dynamically changing threat environment.

The effectiveness of postal inspection systems is a key factor in maintaining the security and reliability of the sector. The summary highlights that modern technological

solutions, such as X-ray detectors, beam gates and chemical detectors, significantly contribute to the accurate and rapid identification of hazardous materials, such as explosives and radioactive elements. In addition, the use of AI and machine learning allows for early detection of threats and the optimization of security processes. In order to improve the effectiveness of the systems, the development of integrated security systems, which combine video surveillance, alarms and access control to form a coherent, proactive protection strategy, is of paramount importance. International cooperation, in particular under the auspices of the UPU and the EU, further strengthens the security of cross-border shipments through uniform standards and cooperation mechanisms.

Continuous technological innovation and regular, targeted training of security personnel guarantee that an effective response to the latest challenges is created. The use of automated systems not only increases cost efficiency by optimizing human resources and time, but also results in faster, more accurate customer service, which directly improves service quality and customer satisfaction.

Together, these factors ensure that postal control systems meet modern security requirements, thereby supporting the sustainable and reliable operation of the postal sector in a challenging environment.

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Multipolarity and Geopolitical Room for Maneuver: An Assessment of Hungary's Foreign Policy and Civil Protection Resilience in Light of the Primakov Doctrine

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Abstract

This paper examines the relevance of the Primakov Doctrine to Hungary's foreign policy strategy, with particular focus on the country's positioning within an increasingly multipolar international order. While Hungary remains a member of the Euro-Atlantic community, since 2010 its foreign policy has progressively emphasized the development of strategic ties with Eastern powers—most notably Russia, China, and Turkey. This tendency aligns thematically with the core principles of the Primakov Doctrine, which promotes balancing between great powers, the reinforcement of national sovereignty, and the rejection of a unipolar world order.

The study argues that a foreign policy orientation grounded in multipolarity presents Hungary with significant opportunities, but also exposes the country to considerable economic, political, and security-related risks. The Eastern Opening policy has facilitated the development of alternative economic relations and regional cooperation frameworks, even as tensions with the European Union and NATO have intensified. Special attention is given to Hungary's foreign policy ambition to act as a mediator within the Central European and Balkan regions.

Importantly, the implications of geopolitical balancing are not limited to foreign policy, but are also highly relevant to civil protection and national resilience. In a global context shaped by hybrid threats, energy infrastructure vulnerabilities, and supply chain disruptions, foreign policy choices have a direct impact on the

functionality of systems responsible for civilian safety. The study concludes that maintaining equilibrium between East and West is not only a strategic imperative, but also a matter of public security—necessitating the close integration of foreign policy and civil protection capacities in Hungary's national strategy.

Keywords: Primakov doctrine, multipolarity, Hungarian foreign policy, civil protection, national resilience

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Introduction

The end of the Cold War brought about a fundamental transformation in the international political system. The previously unchallenged dominance of the United States in global affairs has increasingly come under scrutiny, particularly following the 2008 financial crisis and the geopolitical shifts of the 2010s [1]. In this context, Russia began to develop a new foreign policy strategy, one of the key components of which was the doctrine associated with Yevgeny Primakov, formulated in the 1990s. The core objective of the Primakov Doctrine is to counterbalance American and Western dominance and to promote a multipolar global structure in which multiple centers of power maintain equilibrium [2].

Over the past two decades, Hungary's foreign policy has exhibited a clear effort to strike a balance between Eastern and Western orientations—particularly since 2010. The country has actively sought to diversify its foreign relations, building increasingly close ties with Russia, China, and other Eastern powers, while maintaining cooperation with the West. This strategic realignment fits within the conceptual framework of the Primakov Doctrine and has had a notable impact on Hungary's geopolitical room for maneuver. The central question, however, is whether this direction ultimately supports or undermines Hungary's long-term interests within the European Union and NATO.

This study investigates the extent to which the Primakov Doctrine has influenced Hungary's foreign policy strategy, with specific attention to the principles of multipolarity, regional cooperation, and the pursuit of geopolitical balance.

Analyzing Hungary's geopolitical maneuvering space through the lens of multipolarity and the Primakov Doctrine is essential from the perspective of civil protection. Hungary's foreign policy orientation—particularly its strategy of balancing between global powers—has direct implications for the country's security posture, energy dependencies, and the protection of critical infrastructure. In a multipolar world marked by rising hybrid threats and increasing strategic uncertainty, it is imperative to anticipate geopolitical risks and to strengthen defensive mechanisms aimed at safeguarding civilian security.

The pursuit of geopolitical balance is not merely a matter of theoretical or diplomatic discourse—it plays a crucial role in the practical implementation of national resilience. The instability inherent in a multipolar world system has the potential to undermine state-level essential service structures, including energy, drinking water, and food supply, as well as the operability of public services, the reliability of public communication, and the responsiveness of crisis management systems. The consequences of strategic uncertainty thus extend beyond the traditional scope of national security, significantly impacting public safety and the sustainability of public health capacities.

Based on these premises, it can be concluded that there is a strong causal relationship between Hungary's foreign policy room for maneuver and the functional capacities of its civil protection system. The reconfiguration of global power relations and strategic orientations directly influences the state's adaptive capabilities in times of crisis—whether economic shocks, unconventional forms of warfare, or cybersecurity incidents. In this context, civil protection must be understood as extending beyond the conventional domain of domestic security and as forming an integral component of foreign policy strategy.

1. The Primakov Doctrine and Hungary's Foreign Policy Identity

The Primakov Doctrine emerged in the mid-1990s, as Russia sought a new foreign policy strategy in the aftermath of the collapse of the Soviet Union. Yevgeny Primakov—who served as foreign minister and later as prime minister—argued that in the post-Soviet era, Russia should not submit to the dominance of the United States and the West. Instead, he advocated for the creation of a world order characterized by multiple power centers that would maintain equilibrium among themselves.

The doctrine was grounded in the idea that Russia should strengthen its ties with other regional powers—primarily China, India, and the states of the Middle East—and reassert its influence in the post-Soviet space [3]. It also called for Russia to develop alternative cooperation mechanisms to counter Western alliance systems, such as the Eurasian Economic Union and the Shanghai Cooperation Organization. These initiatives contributed to the construction of a new foreign policy narrative for Russia, distinct from the pro-Western orientation it briefly adopted in the early 1990s [4].

Following the democratic transition, Hungary's foreign policy was clearly aligned with the West. The country joined NATO in 1999 and became a full member of the European Union in 2004. These steps reinforced Hungary's commitment to Euro-Atlantic integration and firmly anchored its foreign policy identity to the West. After 2010, however, signs of a strategic reorientation became increasingly visible. The so-called "Eastern Opening" strategy aimed to diversify Hungary's foreign relations and to strengthen economic and political ties with states such as Russia, China, and Turkey [5].

The influence of the Primakov Doctrine on Hungarian foreign policy is most evident in the growing emphasis on multipolarity. Since 2010, Hungary has increasingly demonstrated through its diplomatic actions a vision of itself not merely as an EU member state, but as an autonomous geopolitical actor capable of navigating among competing global powers. This approach was reflected in Hungary's energy cooperation with Russia—for instance, in the Paks II nuclear power plant expansion project, implemented by the Russian state company Rosatom and largely financed by Russia.

Another important element of Hungary's foreign policy strategy is the increasing role of regional cooperation. The Visegrád Four (V4) alliance has gained prominence in recent years within Hungarian strategic thinking, particularly through closer ties with Poland—although these were recently weakened due to the outcome of Poland's latest elections. At the same time, Hungary has promoted political initiatives that, while not directly derived from the Primakov Doctrine, reflect similar themes of developing an alternative strategic path within the EU. On multiple occasions, Hungary has found itself in conflict with the European Commission and other Western partners in the name of defending national interests.

Hungary's emphasis on multipolarity has resulted in a dual-track approach: it seeks to maintain strong economic and political ties with the European Union while simultaneously attempting to carve out an alternative foreign policy space through its Eastern Opening. However, this strategy entails serious challenges—particularly within the frameworks of EU and NATO membership. The critical question is how long Hungary can maintain this delicate balance without facing long-term geopolitical and economic risks.

2. Multipolarity and Strategic Opportunities for Hungary

The application of multipolarity in Hungarian foreign policy reflects a tendency that thematically resonates with the core principles of the Primakov Doctrine—particularly the aim of balancing among great powers and expanding national room for geopolitical maneuvering.

A multipolar international system envisions a global structure in which multiple centers of power coexist and counterbalance one another. This concept holds particular appeal for Hungary, which, due to its size and geopolitical position, is not among the global superpowers, yet can potentially enhance its strategic autonomy by navigating between competing power blocs.

Hungary's "Eastern Opening" policy follows this logic. Over the past decade, the country has deliberately sought to strengthen its economic and political relations with states such as Russia, China, Turkey, and the countries of Central Asia. The Eastern Opening has not only been significant in terms of trade, but has also provided a geopolitical alternative to the perceived dominance of the West [6]. Within the conceptual framework of the Primakov Doctrine, Hungary's foreign policy shift can be interpreted as a form of "independent diplomatic maneuvering," allowing the country to

develop a multi-vector foreign policy and avoid falling under the exclusive influence of any single great power bloc.

Multipolarity also offers potential economic advantages for Hungary. In recent years, Russia and China have made significant infrastructure and energy-related investments in the country, which the Hungarian government has framed as a key element of economic diversification. Hungary's participation in China's Belt and Road Initiative and its energy cooperation with Russia—particularly the expansion of the Paks II nuclear power plant—demonstrate efforts to leverage Eastern economic and technological opportunities [7]. Through such strategic partnerships, Hungary not only gains material benefits, but may also enhance its diplomatic standing both within and beyond the European Union.

However, pursuing multipolarity also entails notable challenges. Both the European Union and the United States have repeatedly expressed criticism regarding Hungary's Eastern Opening, especially in light of growing Russian and Chinese influence. The EU's rule-of-law mechanisms and the withholding of certain financial resources illustrate that Western partners view Hungary's increasingly autonomous foreign policy with concern. Furthermore, Chinese and Russian investments carry inherent political risks: excessive economic dependence on these countries may constrain Hungary's strategic autonomy in the event of future international conflicts or economic crises.

As a result, Hungary's foreign policy strategy must carefully balance between competing interests. While the principle of multipolarity offers Hungary the opportunity to expand its geopolitical room for maneuver, it is evident that this strategy is only sustainable insofar as it does not jeopardize the country's core economic and political interests. The European Union remains Hungary's most important trading partner, and the Hungarian economy remains significantly reliant on EU funds. In this context, the success of Hungary's foreign policy depends on its ability to maintain productive relations with both Western and Eastern powers—without irreparably damaging its standing with either side.

3. The Primakov Doctrine and Hungary's EU Policy

Certain directions within Hungary's foreign policy—particularly regarding its relationship with the European Union—demonstrate thematic or tactical parallels with elements of the Primakov

Doctrine, especially in the context of promoting a multipolar world order and balancing between global powers. Although Hungary formally committed to European integration with its accession to the EU in 2004, its foreign policy in recent years has included several initiatives that diverge from the mainstream political and economic orientation of the Union.

In the past decade, the Hungarian government has frequently voiced criticism of EU institutions, particularly on issues related to rule-of-law mechanisms, migration policy, and joint decision-making procedures. A recurring narrative in Hungary's foreign policy communication suggests that the country would benefit from a looser form of EU cooperation—one that grants greater national sovereignty. This position reflects the core principles of the Primakov Doctrine, which likewise seeks to dismantle hegemonic global structures and elevate the importance of sovereign decision-making.

One of the most tangible examples of conflict with the EU has been the suspension of financial transfers. On several occasions, the European Commission has delayed or withheld funding allocated to Hungary, citing concerns over rule-of-law compliance. In response, the Hungarian government has argued that EU institutions are leveraging financial mechanisms as tools of political pressure aimed at restricting Hungary's sovereign foreign policy choices.

As tensions between Hungary and the EU persist, the country has increasingly sought to develop alternative economic and political alliances. Hungary has advocated for closer cooperation with BRICS countries and has strengthened relations with Eastern partners such as China and Russia. However, this strategy entails considerable risks, as Hungary's economy remains heavily dependent on the EU, and its relationships with Eastern states cannot fully substitute for access to EU markets and investment flows.

Overall, the influence of the Primakov Doctrine on Hungary's EU policy has produced an ambivalent situation. While Hungary is striving to pursue a more autonomous foreign policy path, it remains deeply embedded in the EU's economic and political structures. This duality will likely shape the future trajectory of Hungarian foreign policy: the central question is how long such a balancing strategy can be sustained amid an increasingly polarized international political environment.

4. Regional Impacts: Hungary and Central Europe

The influence of the Primakov Doctrine extends not only to Hungary's foreign policy but also to the broader geopolitical dynamics of the Central European region. Hungary shares its regional space with countries such as Poland, the Czech Republic, and Slovakia, all of which engage in some degree of balancing between global power centers, though they approach the East–West geopolitical divide in markedly different ways.

The Visegrád Cooperation (V4) has gained momentum in recent years, particularly during debates within the EU and in response to the migration crisis. Poland and Hungary have emerged as close allies in advocating sovereigntist positions within the EU; however, their foreign policy orientations diverge significantly. While Poland pursues a consistently Atlanticist strategy, prioritizing close military and political ties with the United States, Hungary has sought to apply a strategy rooted in multipolarity, attempting to balance relations among major powers. As a result, Hungary's increasingly close relationship with Russia has generated tensions within the Polish–Hungarian axis, as Poland regards Russia as a historical threat, while Hungary tends to approach it as a pragmatic economic and political partner.

Slovakia and the Czech Republic have followed yet other paths. Slovakia seeks to balance Western and Eastern interests but continues to emphasize its firm commitment to EU and NATO integration. The Czech Republic, meanwhile, has increasingly adopted a pro-Western orientation in recent years, particularly under the current government, whose foreign policy priorities reflect a clearer alignment with EU and NATO principles.

In the Balkans, Hungary has taken on an especially active role—one that aligns well with the strategic logic of the Primakov Doctrine. Serbian–Hungarian relations have become particularly significant in recent years, especially in the domains of energy and infrastructure cooperation. Hungary has made major investments in Serbia and has strengthened political ties with the government of President Aleksandar Vučić. Serbia's foreign policy has traditionally navigated among the EU, Russia, and China, providing Hungary with an opportunity to position itself as a regional intermediary.

For Hungary, one of the greatest challenges in regional cooperation lies in maintaining a multipolar foreign policy in a context where neighboring countries follow divergent geopolitical

preferences. The coherence of the V4 has been strained by differing approaches to Russia and China, while Hungary's mediating ambitions in the Balkans—although strategically promising—may simultaneously limit its maneuvering space within the EU if its orientation shifts too far eastward.

5. Critique of the Primakov Doctrine and Risks for Hungary

While the application of multipolarity in Hungary's foreign policy offers certain strategic opportunities, it also presents a range of critical challenges and potential risks. The most pressing dilemma lies in how Hungary can reconcile a foreign policy strategy inspired by the logic of the Primakov Doctrine with its long-standing commitment to Euro-Atlantic integration.

From an economic perspective, the European Union remains Hungary's most important partner. A substantial portion of Hungarian exports is directed toward EU member states, and EU funds play a fundamental role in the development of the national economy. Although economic relations with Russia and China are also significant, they cannot fully substitute the benefits of EU-based cooperation. This means that the success of Hungary's foreign policy depends on its ability to maintain a balanced relationship with both its Western and Eastern partners [8].

On the political level, Hungary's multipolar foreign policy approach risks leading to a degree of isolation within the EU. In recent years, Hungary has repeatedly clashed with EU institutions, particularly over rule-of-law disputes and its relations with Russia. While the geopolitical strategy associated with the Primakov Doctrine encourages the pursuit of alternative forms of international cooperation, a significant drift from the EU's mainstream political direction could ultimately weaken Hungary's capacity to assert its interests in the Union's decision-making processes.

From a security standpoint, maintaining equilibrium between NATO membership and bilateral relations with Russia presents an additional challenge. For countries such as Poland and the Baltic States, Russia is perceived as an existential threat. In contrast, Hungary has adopted a more pragmatic, economy-driven approach toward Russia. This divergence may lead to tensions within NATO, particularly in the event of a future Russia–Europe confrontation.

One of the most significant risks of applying the Primakov Doctrine to Hungarian foreign policy is the potential erosion of Hungary's geopolitical room for maneuver if it fails to effectively

balance its Eastern and Western relations. Should the country's multipolar strategy distance it too far from the decision-making centers of the EU and NATO, this may, in the long run, diminish Hungary's political influence and economic leverage within the international system.

6. Hungary as a Mediating Power?

One possible consequence of a foreign policy approach inspired by the Primakov Doctrine is the strengthening of Hungary's role as a mediator—positioning the country as a bridge between East and West, particularly in the context of relations between Russia and the European Union.

In recent years, Hungarian diplomacy has undertaken several initiatives pointing in this direction, including mediation proposals related to the conflict between Ukraine and Russia. However, such a mediating role can only be credible if Hungary is perceived as a trustworthy negotiating partner by both Western and Eastern actors. Persistent conflicts within the EU and Hungary's increasingly close ties with Russia may cast doubt on its ability to act as an objective and effective intermediary.

One of Hungary's greatest challenges in the coming years will be to define its place within a multipolar world order while maintaining its Euro-Atlantic commitments. The Primakov Doctrine may offer a strategic framework that inspires Hungarian foreign policy maneuvers, but long-term success will ultimately depend on the country's ability to preserve a delicate balance between its relationships with both Western and Eastern partners.

7. Summary and Conclusions

The parallels between the Primakov Doctrine and Hungary's foreign policy strategy over the past decade demonstrate that Hungary has consciously moved toward a geopolitical trajectory aimed at exploiting the benefits of multipolarity. The Eastern Opening policy, the development of alternative economic partnerships, and the pursuit of balance between Western and Eastern powers all reflect foreign policy logic consistent with the conceptual framework laid out by the Primakov Doctrine.

One of Hungary's key foreign policy challenges is reconciling the obligations arising from EU membership with its increasingly active engagement with Eastern powers. Global geopolitical shifts—especially the deepening conflict between Russia and the West and China's growing influence—are creating a new strategic environment [9] in which Hungary must preserve its diplomatic flexibility by adopting a multidirectional foreign policy. This approach would allow Hungary to act not only as an EU member state but also as an autonomous geopolitical actor in its own right.

This study has shown that while a multipolarity-driven strategy offers several advantages, it also entails significant risks. From an economic standpoint, Hungary remains heavily dependent on the European Union, and although Eastern partnerships are playing an increasingly important role, they cannot fully substitute access to EU markets and financial resources. Politically, persistent conflicts with EU institutions and diverging approaches within NATO may gradually weaken Hungary's ability to assert its interests in these organizations.

The regional context also presents significant challenges. Within the framework of Visegrád cooperation (V4), Hungary's unique position—attempting to maintain strong relations with both Poland and Russia—has created internal tensions. While Hungary's mediating role in the Balkans presents certain opportunities, a shift too far eastward could ultimately erode its position within the EU.

Hungary's evolving foreign policy direction reflects thematic similarities with the strategic logic of the Primakov Doctrine, yet the relationship between the two cannot be interpreted as a direct or intentional adoption. The country's primary challenge will be to position itself effectively within a multipolar world order without becoming isolated from the European Union. If Hungary succeeds in maintaining a balanced relationship with both Western and Eastern actors, its geopolitical relevance may increase, enabling it to serve as a meaningful bridge between East and West. However, if a strategy inspired by the Primakov Doctrine drives Hungary too far from Euro-Atlantic structures, the long-term consequences could include diminished economic stability and reduced political influence.

The coming years will determine whether Hungary can sustain this strategic balance or whether the global redistribution of power will force a realignment in its foreign policy orientation. One thing is clear: the process of global multipolarization has accelerated, and Hungary now finds

itself in a position where strategic flexibility and careful planning will be essential to advancing its national interests.

In a multipolar world—where diplomatic alignments, economic networks, and strategic alliances directly influence a nation's vulnerability profile—civil protection capabilities must also be viewed as a component of foreign policy. Accordingly, future Hungarian foreign policy must consider not only the pursuit of geopolitical balance but also the long-term sustainability of national resilience.

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Examining the Seveso Safety Management System using the Fault Tree Analysis method

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Abstract

The aim of this study is to develop a methodological approach for supervising the Safety Management System (SMS) using Fault Tree Analysis (FTA). The main research question is how the complex structure of the SMS can be reduced so that supervisory activities remain targeted and risk-based. Our hypothesis is that fault tree analysis is suitable for identifying weak points in the system that determine safety performance. The method applies a deductive logical approach: following the formulation of the top event, key elements and basic events are identified, and then critical fault combinations are determined through qualitative evaluation. Based on the results, supervisory focus areas and priorities for risk-reduction measures can be defined, supporting the effectiveness of operational and regulatory inspections. The author's intention is to establish a methodological foundation that, in the long term, contributes to strengthening safety culture and reducing the risk of major industrial accidents.

Keywords: dangerous plant, dangerous substance, safety management system, Fault Tree Analysis, disaster prevention, industrial safety.

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Introduction

Hazardous substances present in establishments handling dangerous materials, as well as the activities involving them, constitute potential sources of environmental hazards to the population living in the vicinity, and to both the built and natural environment [1]. In Hungary, the regulatory control of risks arising from such activities is governed by Act CXXVIII of 2011 on disaster management and the amendment of certain related laws [2], together with its implementing regulation [3].

The regulatory framework classifies establishments handling hazardous substances into two categories based on the quantities of dangerous substances present simultaneously: lower-tier and upper-tier establishments. In addition to the requirements set forth by the SEVESO Directive [4], Hungarian legislation also defines a third category: establishments operating below the threshold quantities. These designated establishments must demonstrate, within their safety documentation, that the risks arising from their activities have been reduced to an acceptable level and that they are adequately prepared for emergency response in the event of an accident. As part of this documentation, establishments handling hazardous substances are required to verify the existence and maintenance of a Safety Management System (SMS) that meets the prescribed content requirements. The purpose of the SMS is to establish and maintain a structured regulatory framework aimed at preventing major accidents involving hazardous substances, permeating all internal regulations of the organisation. Its proper functioning is of paramount importance for safety performance, as highlighted by research conducted by the Major Accident Hazards Bureau of the European Commission's Joint Research Centre, which revealed that a significant proportion of major accidents involving hazardous substances -approximately 85%- can be attributed to human error and deficiencies in the management system [5]. Accordingly, the SMS can be identified as one of the most critical tools for preventing major accidents related to hazardous substances.

Extensive research has examined the impact of continuous auditing activities on the quality of maintaining other management systems [6], and the findings clearly confirm the positive effect of regular supervision. Consistent with this observation, it has also been demonstrated in the case of the Safety Management System (SMS) that well-designed, complex, and regular internal and external inspections are indispensable prerequisites for the maintenance and development of the system [7].

However, auditing and inspecting the Safety Management System (SMS) presents considerable challenges for both the operator and the competent authority due to its complexity. Consequently, to achieve its intended purpose -namely, ensuring the operational safety guarantees of establishments handling hazardous substances- regular and well-planned supervisory activities are indispensable. The examination of complex systems can only be accomplished through reduction, whereby the functioning of the system is assessed by the inspector(s) using a sampling-based approach. Under this methodology, conclusions regarding the overall performance of the system are drawn from the evaluation of the sample; therefore, the sample fundamentally influences the outcome of the assessment. It follows that the planning of supervisory activities, and particularly the selection of samples, requires exceptional expertise and attention. If the sample examined is not adequately representative, incorrect conclusions may be drawn regarding system performance, which could ultimately compromise safety performance.

As a result of the above, the operational safety guarantees of establishments handling hazardous substances can only be ensured through the maintenance of a well-functioning and continuously supervised Safety Management System (SMS). Due to the complexity of the management system, comprehensive supervision covering every individual element is not feasible; therefore, the application of reduction and simplification is unavoidable. Excessive or improperly executed reduction may compromise the outcome of the audit activity and, consequently, the safety performance of the hazardous establishment. For this reason, it is advisable to examine reduction procedures applicable to the supervision of the SMS, which can serve as the basis for developing an appropriate inspection methodology. In this article, the author presents a methodology supporting reduction in connection with the Safety Management System.

1. Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a deductive, logic-based method applied to identify and evaluate safety risks within systems [8]. The method was first introduced in 1962 by Bell Telephone Laboratories and the United States Air Force for the safety analysis of an international satellite system, and later became widely adopted in the nuclear, chemical, and aviation industries [9; 10]. In Hungary, its first application is attributed to Gyula Fáy, who employed the method in 1978 for the analysis of combustion processes [11]. The primary objective of the analysis is to uncover the causal chain leading to an undesired event -referred to as the top event- and to determine the logical

relationships among the individual basic events contributing to its occurrence. Owing to its structural design, the deductive, top-down nature of the method is evident, as it begins with a generally defined system and proceeds to examine specific basic events and their impact on the system.

The graphical model describing the logical relationships among basic events employs so-called logic gates (AND, OR). An AND gate is applied when the simultaneous occurrence of all basic events is required to trigger the output event, whereas an OR gate indicates that the occurrence of any single basic event is sufficient. Following the construction and evaluation of the fault tree, the impact of basic events on the top event can be determined and ranked, enabling the identification of so-called critical basic events that fundamentally influence system performance. Knowledge of these critical basic events allows for the optimisation of risk-reduction measures [12].

An advantage of Fault Tree Analysis lies in its deductive nature, which makes it suitable not only for examining technological or technical failures but also for identifying organisational and regulatory deficiencies. As a result, it serves as one of the key tools for conducting a comprehensive system-level analysis [8]. In this context, technological failures refer to physical equipment and software non-conformities, organisational deficiencies encompass human factors, while regulatory non-compliance denotes deviations in the application of operational procedures and governing regulations.

The application of the analysis method can generally be described as a unified process consisting of the following structured steps:

1) Definition of the top event
2) Identification of the immediate causes/events leading to the top event
3) Further decomposition of identified events down to the level of basic events (events that cannot be further broken down)
4) Determination of the logical relationships between events
5) Evaluation of the fault tree

Following the construction of the fault tree, its evaluation can be performed using either quantitative or qualitative methods. In the quantitative approach, after determining the occurrence probabilities of individual basic events, their risk can be calculated and ranked by considering the logic gates. It is important to note that numerous studies highlight the challenges associated with

estimating the occurrence probabilities of basic events [13, 14, 15]. For human-related factors, methods are available for probability estimation (e.g., HEART – Human Error Assessment & Reduction Technique) [16]; however, quantifying organisational deficiencies remains an extremely significant challenge. In contrast, qualitative analysis focuses on identifying the most critical fault combinations by examining so-called “cut sets” composed of basic events. This process involves analysing the event sequences leading to the top event and assessing the role and frequency of individual basic events within these pathways [17].

Due to the nature and applicability of the evaluation methods, the qualitative approach is particularly suitable for the fault tree analysis of regulatory frameworks and can therefore be applied to the examination of the Safety Management System implemented in establishments handling hazardous substances.

2. Safety Management System (SMS)

The objective of the SEVESO Directive (2012/18/EU) is to prevent major accidents involving hazardous substances and, in the event of their occurrence, to mitigate their consequences through the continuous provision of protective measures, the availability of pre-established intervention mechanisms, and training aimed at ensuring their proficient application [4]. To foster the development of the indicated safety culture, the Directive prescribes the maintenance of a Safety Management System (SMS), which formally records safety objectives as well as the entirety of organisational and technical measures applied during daily operations.

The implementation of the SEVESO Directive into Hungarian legislation is ensured by Government Decree 219/2011 (X. 20.) and related legal provisions [2]. In line with the EU Directive, these regulations also prescribe requirements for the Safety Management System (SMS); however, in order to allow adaptation to the specific characteristics of individual establishments, they do not include standardized, detailed provisions regarding its structure [18]. While this implementation provides a high degree of flexibility for operations, it poses significant challenges during supervisory activities. Therefore, the SMS is not merely a formal requirement but a fundamental instrument of safety culture, integrating regulatory expectations into practical application [19].

As a result of the practical approach, the key elements of the SMS structure have been defined, which collectively ensure the effectiveness of the system. These include [20]:

- Organisation and Personnel: Clear definition of responsibilities and roles. This includes managerial commitment, appropriate training, and the development of a safety culture.
- Identification and Assessment of Major Accident Hazards: Detecting potential hazards and conducting risk assessments are essential for prevention. This ensures that all critical points within the establishment are known and manageable.
- Operational Control: Regulation and supervision of operational processes guarantee that safety requirements are effectively implemented in practice. This includes maintenance, monitoring of technological parameters, and compliance with standards.
- Management of Change and Protective Planning: Assessing the safety implications of all modifications—whether technological, organisational, or regulatory—is crucial. Protective planning involves the development of preventive and mitigation measures.
- Performance Evaluation (Monitoring): Continuous monitoring and assessment of safety performance enable early detection of deficiencies and identification of improvement opportunities.
- Audit and Review: Regular inspections and reviews ensure compliance and support the continuous improvement of the management system.

Given that the primary function of the Safety Management System (SMS) is to establish safety guarantees and ensure their practical implementation, continuous supervision of its compliance and effectiveness is indispensable for proper operation. Recognising the practical nature of the SMS and the critical role of supervisory activities, several methodological guidelines have been issued by the National Directorate General for Disaster Management (NDGDM) for specific areas—such as maintenance [21], subcontractor management [22], and incident investigation [23]. Nevertheless, both official and internal supervisory activities continue to pose significant challenges.

Due to the diversity in the content and format of SMSs developed by operators, the quality of inspections is significantly influenced by the individual inspector and their professional preferences. Therefore, it is justified to establish a unified, risk-based inspection methodology that focuses on the critical points of the system and provides a representative assessment of the SMS's compliance and effectiveness.

3. Fault Tree Analysis of the Safety Management System (SMS)

Based on the points previously discussed, the critical role of supervising the Safety Management System (SMS) and the associated challenges have been highlighted. Considering the importance of audit activities in maintaining proper functionality, as well as the practical indispensability of the SMS in fulfilling its purpose, an inadequately supervised system poses a significant risk to the population living in the vicinity of the establishment, as well as to the built and natural environment. To prevent this, there is a clear need for methodological development that facilitates the supervision of SMSs in various establishments handling hazardous substances, thereby ensuring the practical maintenance of safety guarantees.

Due to the complexity and variability of the Safety Management System (SMS), its supervision presents considerable challenges. Given the magnitude of risks arising from inadequate functioning of the SMS, it is essential to develop a methodology that ensures regular supervisory activities and supports the sustainable operation of the system. This can only be achieved through methodological development based on reduction and simplification, while paying particular attention to ensuring that, despite simplification, the method remains capable of verifying safety guarantees at an appropriate level.

Several studies have examined the applicability of Fault Tree Analysis in the context of quality management [24, 25], confirming its broad potential for use. Consequently, Fault Tree Analysis proves suitable for the examination of the Safety Management System (SMS), while also accounting for risks arising from simplification. The following section provides an overview of the fault tree analysis of the Safety Management System.

In the course of fault tree analysis, the first step is to define the top event, which constitutes the subject of the investigation [26]. When examining the Safety Management System (SMS), the top event can be designated as “Inadequate implementation of the Safety Management System in a SEVESO establishment.” This formulation reflects that the objective is not to analyse a specific technical failure, but rather to identify deficiencies in the functioning of the SMS as a complex system. Consequently, the fault tree analysis focuses less on technical failures and more on the impact of organisational and regulatory deviations.

After defining the top event, the next step is to identify the immediate events (causes) that may lead to its occurrence. These are the events that can trigger the top event. In the case of examining the Safety Management System (SMS), based on the structured framework prescribed by legislation, these causes can be traced back to the previously presented key elements of the system. Given that the top event has been designated as inadequate functioning of the system, the corresponding events at this level can be represented as the inadequate functioning of each key element, as follows:

- Deficiency in organisation and personnel
- Deficiency in risk analysis
- Deficiency in operational standards
- Deficiency in protective planning
- Deficiency in performance monitoring
- Deficiency in documentation

After listing the immediate triggering events, it is necessary to examine the events that cause these, proceeding down to those that can no longer be decomposed. These indivisible events are referred to as basic events, which form the subject of further analysis. Such events directly contribute to the occurrence of the higher-level events represented in the fault tree.

Following the graphical representation of the fault tree, the logical relationships between the listed events are described using logic gates (AND, OR). In practice, additional logic gates are also applied (e.g., k/n gate – the occurrence of any k events among the input events ensures the occurrence of the output event; Inhibit gate – the output event occurs only if the input event and the event drawn to its right both occur) [26]. However, the interpretation of these special connections is not relevant for the present analysis and will therefore not be addressed further. When using an AND gate, all input events must occur for the output event to take place, whereas with an OR gate, the occurrence of any input event leads to the occurrence of the output event.

As a result of the graphical representation of the fault tree, the basic events leading to the occurrence of the top event can be identified; however, this alone does not ensure the determination or ranking of their significance. Nevertheless, establishing a priority order is indispensable for developing a supervisory methodology. Based on this priority order, elements subject to supervision can be defined by filtering out basic events that have negligible impact on the proper functioning of

the Safety Management System (SMS) and focusing on critical basic events. Audit activities concentrated on these critical elements provide guarantees for ensuring the proper operation of the SMS.

The identification of these critical elements can be achieved through the evaluation of the fault tree. Both quantitative and qualitative methods are available for fault tree evaluation. As previously discussed, the quantitative approach is of limited applicability in the examination of regulatory frameworks due to the difficulty of determining occurrence probabilities. Consequently, the analysis of the SMS fault tree can be performed using a qualitative evaluation, which involves examining event cut sets to identify critical basic events—so-called weak points. These basic events fundamentally determine the occurrence of the top event and therefore play a key role in defining risk-reduction measures.

As a result of this line of reasoning, all basic events (failure causes) leading to the inadequate functioning of the SMS can be identified, and by evaluating these, the critical events (root causes) can be designated. Based on these critical basic events, a supervisory methodology can be developed to ensure the proper operation of the SMS.

4. Applicability od results

The construction of the fault tree for the Safety Management System and the identification of its weak points is not merely a theoretical analytical method but a practical decision-support tool that offers significant advantages for both operators of establishments handling hazardous substances and supervisory authorities. Fault tree analysis enables the systematic identification of risks embedded within the SMS structure through logical interrelations, thereby revealing the most critical points on which supervisory and audit processes can specifically focus. This approach facilitates the maintenance and assurance of system functionality and, indirectly, the continuous guarantee of safe operation.

For operators, knowledge of weak points enables priority-based risk reduction. Based on the results of the analysis, measures can be defined that not only serve to prevent major accidents but also strengthen emergency preparedness. Information derived from fault tree analysis provides an objective foundation for investment and maintenance decisions, as well as for strategic planning at the managerial level, as it reveals system vulnerabilities and development needs.

For authorities, the application of this method also offers significant advantages. Fault tree analysis supports the determination of a risk-based inspection focus, thereby enhancing the efficiency of supervisory activities and making compliance assessment more targeted. Data obtained from the analysis contribute to legislative and methodological development, as well as to the evaluation of emergency preparedness. Overall, the identification of weak points not only strengthens safety culture but also optimizes operational and supervisory processes, which in the long term significantly reduces the risk of major industrial accidents.

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The flagship of chemical defence of the Hungarian Defence Forces: the HDF 102nd CBRN Defence Regiment

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Abstract

Effective defence against Chemical, Biological, Radiological, and Nuclear (CBRN) threats demands seamless integration of legal frameworks and operational capabilities. Building on the author's preceding publication [1] – analyzing NATO standards (STANAG 4701, AEP-66) interoperability and Hungary's domestic legal environment – this second installment examines their practical implementation in the Hungarian Defence Forces (HDF).

The study conducts a capability-based analysis of the HDF 102nd CBRN Regiment's operational prowess under NATO SIBCRA (Sampling and Identification of Biological, Chemical, and Radiological Agents) protocols, demonstrating how international doctrines translate into reality via specialized equipment and structure. Highlighting the unit's "dual-use" versatility in military operations and civil emergencies – exemplified by biological decontamination modules during the COVID-19 pandemic – the article underscores its role in national resilience.

Field evaluation of SIBCRA procedures reveals the Regiment as Hungary's "hard power" pillar, bridging legislative intent and effectiveness while bolstering NATO interoperability against evolving CBRN risks.

Keywords: HDF 102nd CBRN Defence Regiment, operationalization, SIBCRA, NATO interoperability, dual-use capability

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Introduction

The author's previous study provided insights into the international and domestic legal frameworks governing SIBCRA. Below follows its practical implementation within the HDF. Among the special capabilities of the HDF, Chemical, Biological, Radiological, and Nuclear (CBRN) defence holds strategic significance. The custodian, knowledge centre, and executive force of this capability is the HDF 102nd CBRN Defence Regiment, re-established on January 1, 2023, within the framework of the Defence Force Reform. The unit is not without precedents: its creation stemmed from the merger of the HDF 93rd Petőfi Sándor Chemical Defence Battalion and the HDF Görgei Artúr Chemical Defence Information Centre (HDF GAVIK), as well as the modernization of existing capabilities [2]. With this step, a centralized organization was established that meets both NATO alliance requirements and domestic security challenges.

Historical roots and the legacy of the namesake

The ethos of the regiment is deeply rooted in Hungarian military history. The legal predecessor organization, the Royal Hungarian Army Gas Defence Battalion, was established on October 1, 1937 – a date still honoured today as the Unit Day. The chemical defence soldiers of the modern era proudly bear the name of Major General (Posthumous) László Sodró, who is considered the "father" of the Hungarian chemical warfare specialized branch [3].

László Sodró's life path is an exemplary model of professional dedication and military steadfastness. After graduating from the renowned Ludovika Academy and serving on the front lines in World War I, he acquired the most modern gas defence knowledge of the era in Germany. Upon returning home, he implemented this expertise as the commander of the Gas Defence School and the 101st Motorized Chemical Battalion. In World War II, during the siege of Budapest, he held his ground to the very end, subsequently enduring Soviet captivity as a prisoner of war and suffering through forced labour camps [4]. His legacy obliges the current personnel to maintain the highest professional standards.

Organizational structure and stationing system

The regiment's operation is realized through a dual stationing system, built on the synergy of the "executive force" and the "scientific background" [5].

- *Székesfehérvár* (the operational centre): The Regiment Headquarters and the majority of executive subunits are located here. The backbone of the organizational structure is formed by the CBRN Defence Battalion, which includes the special CBRN Defence Company and the Support Company. Heavy equipment, decontamination capacity, and mobile reconnaissance forces are concentrated here.

- *Budapest* (the scientific and command base): The capital hosts the regiment's strategic analytical and scientific centre, the HDF Chemical Defence Information Centre (HDF CDIC/VIK). This organization integrates special capabilities: operating within its framework are the HDF HAVARIA Laboratory Department, responsible for the operational identification of samples; the Operational Assessment Department, functioning as the centre for data collection and analysis; and the HDF Disaster Management Department, ensuring liaison and information sharing with civil authorities [2].

Personnel: Competence requirements and training system

The HDF 102nd CBRN Defence Regiment is one of the most demanding units of the HDF, not only technically but also from a human resources perspective. The conditions for filling positions are determined by a strict domestic legal environment (e.g., the Act on the Legal Status of Defence Personnel, MoD Decrees). Expected competencies vary depending on the position, but their common basis is high-level professional preparedness and a safety-conscious mindset [6].

- *Leadership Personnel* (Command Level): Responsible for the planning and direction of operations; the requirements for them are the highest. Regarding their education, a higher education qualification including CBRN defence knowledge (e.g., the Military Leadership specialization of the National University of Public Service, Faculty of Military Science and Officer Training – NKE-HHK) is a basic requirement. This must be supplemented by appropriate radiation protection qualification (comprehensive level), which, beyond analyzing complex situations, enables the staff to coordinate – among others – the National Nuclear Emergency Response System (ONER) and NATO decision-making mechanisms, and to cooperate effectively with partner agencies (e.g., Disaster Management NBIÉK) [7].

- *Subordinate Officers* (Squad/Platoon Leader Level): For this level, higher education and a comprehensive level radiation protection qualification are also basic requirements. Their

knowledge must cover, among other things, the proper operation of equipment used during decontamination and reconnaissance tasks, as well as sampling and identification procedures.

- *Enlisted Personnel*: At this level, the emphasis is on skill-level task execution, the confident use of individual protective equipment, and the physical and psychological endurance indispensable for prolonged work in protective suits.

The training system does not stop at the classroom: the personnel are regular participants in Live Agent Training (LAT) exercises held at international (Kruševac, Serbia) and NATO-accredited (Zemianske Kostoľany, Slovakia) training centres, where they test their knowledge in real radiation and chemical environments [8].

The "HAVÁRIA" capability: nuclear emergency response

One of the most versatile elements of the Regiment, directly serving the protection of the civilian population, is the HDF HAVARIA Laboratory Standby Service. This special, multidisciplinary unit was established to manage, among other things, nuclear accidents (e.g., events affecting the Paks Nuclear Power Plant or radiological incidents). Its operation takes place within the framework of the Defence Disaster Management System (HKR) [9].

The HDF HAVARIA Laboratory Standby Service is not merely a standby unit but a complex response system:

- *Reconnaissance*: It is capable of immediately creating radiation maps and defining hazard zones.

- *Monitoring / Prevention of Spread*: To inhibit the further spread of contamination – in cooperation with the AMAR (Automatic Measuring and Data Acquisition System) team – it deploys road checkpoints (Radiation Portal Monitors). Their task is the screening of personnel and equipment exiting the zone, separating the contaminated ones for subsequent decontamination (which is the task of the Székesfehérvár subunits).

- *Medical Support*: It cooperates closely with the radiological experts of the HDF Medical Centre (HDF MC) in the fields of dose assessment and the treatment of radiation casualties (iodine prophylaxis, chelation therapy) [10].

Operational procedures in practice

The regiment's operational activity is strictly based on the relevant NATO STANAG standards and doctrines. This ensures interoperability with allied forces. The process can be divided into three main phases, executed by the regiment's subunits (Reconnaissance and Decontamination platoons):

- *Reconnaissance and Zoning (Survey):* Reconnaissance vehicles (e.g., VS BTR-80) delimit the Hot, Warm, and Cold zones using closed-system measurements. The goal is localizing the contamination source and modeling propagation direction (e.g., gas cloud or radioactive plume) based on meteorological data [11].

- *Sampling and Identification (SIBCRA):* Specially trained sampling teams apply a double packaging technique to avoid cross-contamination. On-site identification is aided by handheld detectors (e.g., Thermo Fisher RIIDEye) and chemical identification devices (e.g., FTIR and RAMAN spectrometers, portable GC-MS HAPSITE), while samples are transported to the laboratory for definitive analysis [12].

- *Decontamination:* Decontamination platoons deploy Decontamination Stations. The process includes the phased cleaning of personnel and equipment (e.g., using DS-10 team decontamination kits, DECOCOM 3000 containers), ranging from chemical treatment to the final instrumental check (Check-Out) [13].

Technical equipment and instrumentation: the arsenal of precision defense

The equipment of the HDF 102nd CBRN Defence Regiment is a blend of traditional, battlefield-proven technique and modern high-tech instruments adapted from civilian cutting-edge technology. This technical symbiosis covers the full spectrum of the CBRN defence task system, from rough decontamination to molecular-level analytics [2].

- *Vehicle technology and decontamination systems*

Mobility and intervention capability are based on vehicles and decontamination systems.

- Combat vehicles: The backbone of reconnaissance is provided by the armored VS BTR-80 combat vehicles.

- Special technical equipment: Operational capability is supplemented by specially equipped standby vehicles and evaluation vehicles that also perform mobile laboratory functions.

- Decontamination technology**:** High-capacity tasks are handled by DECOCOM 3000 container systems and battalion-level decontamination trailers. This capability is complemented by precision and tactical tools:

1. Figure: Decontamination of vehicle during CBRN training. Source: https://defence.hu/news/the-bravest-

  - The *Cristanini Sanijet 921* is a versatile decontamination unit capable of cleaning even the most sensitive surfaces with low-pressure steam and special chemicals [14].

  - Certain professional tools of the *Kärcher product family* ensure the effective application of decontaminants and the removal of surface contamination, proving the military applicability of civilian high technology [15].

- *Individual protection*

The survivability of personnel is ensured by the modernized version (fielded in 2021) of the 93M protective suit, the 96M protective suit kits developed for decontamination personnel with enhanced chemical resistance, and state-of-the-art filter gas masks [16].

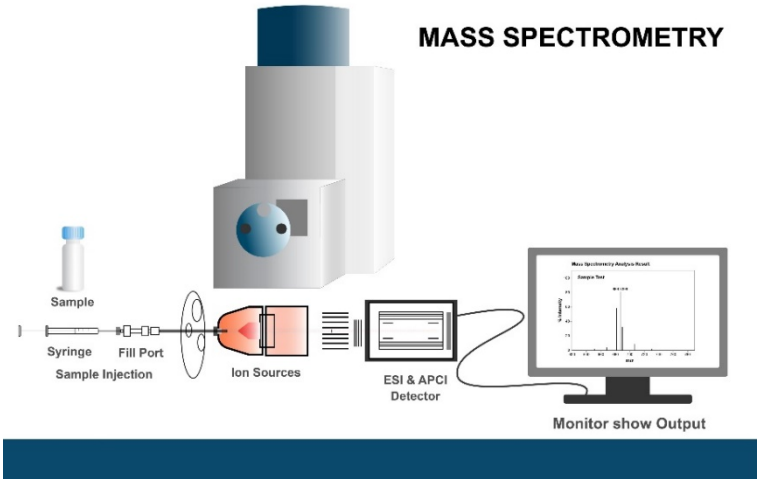
- *Instrumental analytics and detection*

The Regiment's reconnaissance and laboratory capability is divided into three main threat directions (chemical, radiological, biological), featuring both portable battlefield devices and deployed large-scale instruments.

- Chemical Reconnaissance

The identification of chemical agents is a multi-stage process ranging from rapid tests to laboratory confirmation.

- Portable (Field) Instruments**:** Soldiers' immediate decision-making is supported by colorimetric detection kits (detector tubes, indicator papers). More advanced identification is performed by devices capable of molecular-level analysis:
  - *IMS (Ion Mobility Spectrometry)*: The basis of battlefield gas detection [17].
  - *Flame Photometric Devices*: Tools for traditional but reliable detection.
  - *FTIR and RAMAN Spectroscopy*: These handheld devices operate with laser and infrared technology. While RAMAN is capable of non-contact identification through packaging, FTIR requires direct contact with the sample.
  - *Portable GC-MS:* The mobile version of gas chromatography-mass spectrometry represents the peak of field analytics.
- Deployed (Laboratory) Instruments**:** The final, legally binding identification of samples (confirmatory identification) is performed with large-scale instruments:
  - *GC-MS*: Gas Chromatography-Mass Spectrometry (the main instrument of the laboratory).
  - *LC-MS*: Liquid Chromatography-Mass Spectrometry.
  - *ICP-MS*: Inductively Coupled Plasma Mass Spectrometry, enabling elemental-level analysis.



2. Figure: The process of mass spectomety measurement.

Source: Made bv the author with AI (Gemini)

- Radiological reconnaissance

The detection of invisible radiation ranges from dose measurement to isotope-selective identification.

- Detectors and Dosimeters:
  - *Surface contamination meters*: GM (Geiger-Müller) tube or scintillation-based probes for localizing contamination.
  - *Dose rate meters*: Devices with GM tubes and proportional counters for measuring the intensity of the radiation field (e.g., SSM-1 devices).
  - *Personal dosimeters*: The protection of personnel is ensured by electrochemical (direct reading) and authority-approved (accredited measurement) dosimeters.
- Analyzers (Spectroscopy):
  - *Portable scintillation detectors*: Rapid isotope identification in the field (e.g., RIIDEye devices).
  - *HPGe (High Purity Germanium) detectors*: Semiconductor-based detectors represent the peak of gamma spectroscopy. Although they

fundamentally require laboratory stability, the Regiment possesses a movable configuration, thus capable of deploying laboratory precision near the incident site [18].

- Biological Reconnaissance

Since the identification of biological agents is time-consuming, the emphasis is on rapid screening.

- Rapid Tests**:** On-site sampling teams use single-agent (specific) and simultaneous (multiplex) immunochromatographic tests, which are capable of indicating the presence of the most dangerous pathogens (e.g., anthrax, plague, ricin) within minutes, pre-screening samples for further PCR examinations [19].

Deployments and special training in real life

CBRN defence does not exist in laboratory isolation but is tested in the harsh reality. Throughout its history, the HDF 102nd CBRN Defence Regiment and its predecessor organizations have proven on numerous occasions that doctrinal knowledge can save lives in live situations. Below, we review the critical deployments and special training exercises that have elevated the Regiment to become one of NATO's recognized professional workshops.

- Live Deployments: When Defence Activates

In recent decades, the Regiment (and its predecessor) has functioned as the "heavy artillery" of domestic disaster management but has also stood its ground on the international stage.

- The Red Sludge Disaster (2010) – The Master Exam of Domestic Decontamination

The industrial disaster affecting the region of Devecser and Kolontár represented one of the greatest logistical and professional challenges for modern Hungarian chemical defence. The complexity of the remediation efforts and the coordination of on-site forces required unprecedented logistical organization [20]. When the highly alkaline, caustic red sludge flooded the area, chemical defence subunits worked in shifts on the terrain for weeks.

3. Figure: CBRN intervention during the Red Sludge Disaster (2010) in Kolontár Made by the author with AI (Gemini)

- The Task: The goal was not only decontamination but also the prevention of secondary dust formation, which could have caused severe respiratory injuries to the population.
- Execution: The units cleaned vehicles, residential houses, and roads with decontaminants applied by high-pressure equipment, neutralizing the caustic alkali. This deployment demonstrated that military chemical defence is capable of intervening on an industrial scale even in civil disaster situations.

- The Invisible Enemy: COVID-19 Pandemic Operations (2020-2021)

Biological defence (the "B" component of CBRN) rarely comes to the forefront, yet during the pandemic, the Regiment played a key role.

- The Task: Executing disinfection and biological decontamination tasks in the country's critical institutions.
- Execution: The unit established special "Biological Decontamination Teams" that performed comprehensive disinfection in nursing homes, hospitals, and schools. The protocol of personal decontamination was tested live here as well: soldiers had to work in infected zones ("Hot Zones") while hermetically isolating themselves

from the virus, then undergo strict, multi-stage decontamination upon exiting the zone [21].

- Veterinary Prevention: Managing African Swine Fever (ASF)

Although avian influenza often receives great publicity in civil disaster management, the Regiment's operational experiences in this field are primarily linked to defence against African Swine Fever (ASF) and the enforcement of preventive regulations.

- The Task: Preventing the spread of the epidemic during logistical and troop movements, with particular regard to cross-border operations and international traffic.

- Execution: The focus of the operation was the strict, preventive disinfection and decontamination of military technical equipment prior to border crossings, ensuring biological security. This capability was supplemented by special sampling and decontamination tasks executed in cooperation with law enforcement agencies and institutions (e.g., in relation to the Foot-and-Mouth Disease affecting artiodactyls), during which the Regiment's professional staff supported the work of partner authorities [22].

- International Engagement: NATO NRF Readiness

One of the Regiment's most important international "deployments" is its participation in the NATO Response Force (NRF). Although this fundamentally means standby duty, it imposes live operational requirements.

- The Task: Initially, the Regiment's task was to provide a SIBCRA team and a laboratory decontamination team, which over the years merged into a single capability: a SIBCRA team with self-decontamination capability, deployable anywhere in the world within 2-5 days upon NATO orders.

- Significance: This "deployment" validates the Hungarian capability in the eyes of allies. Hungarian soldiers here perform security duties not only based on national but on NATO standards (STANAG), within a multinational environment, ready to handle either combat gases or radiological threats in conflict zones [23].

- The Peak of Preparation: Training and Methodology

For the above deployments to be successful, the Regiment applies training methods that increase psychological and physiological stress to the extreme.

- "Toxic Valley" Exercise – Slovakia

This is one of the most important annual pilgrimages for Hungarian CBRN soldiers. Due to strict environmental protection regulations prohibiting the release of live warfare agents (e.g., Sarin or VX gas) into the environment in Hungary, soldiers deploy to the Zemianske Kostoľany training ground in Slovakia.

  - Methodology (LAT - Live Agent Training): This is training with real agents. There is no simulation here. Soldiers work with real, lethal nerve agents and blistering agents [24].

  - The Essence of Training: Although psychological stress and strengthening trust in protective equipment are fundamental, the main goal of the exercise is international interoperability. The SIBCRA teams of participating nations can learn each other's Standard Operating Procedures (SOP) here and coordinate sampling techniques to ensure seamless cooperation in a live NATO operation.

- "Purple Field" – Serbia (Kruševac)

The series of exercises held in Serbia holds similarly high significance. Since the location falls outside the jurisdiction of the European Union, the different regulatory environment provides an opportunity for the safe use of warfare agents exceeding the quantities applied in the Slovakian exercises.

- Operational Advantage: The larger quantity of active agents allows for the realistic practice of unit-level (squad, platoon) reconnaissance procedures.

- Practical Benefit: Soldiers here can execute not only detection but also Real Decontamination procedures involving the full technical chain, which would be feasible only to a limited extent on domestic training grounds during peacetime [8].

4. Figure: HDF 102nd CBRN Defence Regiment during the Serbian–Hungarian military exercise codenamed Purple Field 2024, in Kruševac, Serbia. Source: https://defence.hu/news/cbrn-defence-troops-

- "Purple Ray" (Bíbor Felhő/Bíbor Kristály) – Domestic Complex Tactical Exercise

This is the Regiment's (and its predecessor's) own large-scale domestic exercise, often executed in the "ruin city" of the Bakony Hills.

- Methodology: Simulation of asymmetric warfare. During the exercise, soldiers must face not only chemical contamination but also attacks by "enemy" forces (OPFOR), IED (Improvised Explosive Device) threats, and the challenges of urban warfare.

- The Essence of Training: A chemical defence soldier is primarily a soldier. Here they practice how to decontaminate during a firefight, or how to rescue a casualty from a radiation-contaminated area while the convoy is under attack [25].

Thus, it is evident that the work of the HDF 102nd CBRN Defence Regiment (and its predecessors) goes far beyond theoretical preparation. The deadly silence of Toxic Valley, the red dust of the Red Sludge, and the invisible threat of COVID are all milestones that forge this special capability into steel. The symbiosis of training and deployments ensures that when the siren sounds, science and courage step into action simultaneously.

Conclusions

This two-part study provides a comprehensive overview of Hungary's CBRN defence capabilities, spanning the theoretical foundations of NATO standardization and legal governance to the practical realities of field operations. The detailed analysis of the HDF 102nd CBRN Defence Regiment demonstrates that the unit functions not merely as an executor of orders but as a complex, adaptive system capable of meeting the rigorous demands of both AEP-66 standards and domestic crisis management regulations. The synergy between the doctrinal compliance outlined in the first article and the technical readiness detailed here – exemplified by modern reconnaissance and decontamination assets – confirms that the HDF maintain a credible, combat-ready CBRN capability. Looking ahead, integrating autonomous technologies represents the Regiment's next evolutionary phase. While human oversight remains essential for final decision-making and laboratory analysis, robotic "forward outposts" significantly mitigate risks. Thus, the chemical defence soldier of the future will excel not only in protective equipment but also in managing complex robotic systems and interpreting sensor fusion data. This evolution positions Hungary's CBRN defence at the international forefront, balancing the legal-doctrinal framework established in the previous article with the technological adaptability demanded by 21st-century challenges.

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The Role of Precision Forestry and Drone Technology in Optimizing Forest Management Processes

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Abstract

The aim of this study is to examine the role of digital data processing methods and unmanned aerial vehicles (UAVs) applied in precision forestry, with particular regard to the development potential of forest management processes. The research presents the significance of geographic information systems, remote sensing, and artificial intelligence in modern forest management. The study is based on a quantitative methodology, using an online questionnaire for data collection. Based on a sample of 281 domestic forest managers, the study analyzes the practical use, advantages, and limitations of drone technology. According to the results, the use of digital tools is widespread (71.2%); however, only 21% of respondents currently use drone technology, although 70.5% plan to introduce it. The greatest barriers are the regulatory environment (71.2%), lack of training (56.5%), and high costs (54.2%). The study highlights that digitalization and data-driven decision-making play a key role in achieving sustainable and efficient forest management.

Keywords: precision forestry, UAV, drone technology, GIS, digitalization, forest management, artificial intelligence, geoinformatics

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Introduction

The technological developments of recent decades have fundamentally transformed the methods and approach of forest management. Digitalization, the advancement of information technology systems, and the emergence of

automated data processing solutions have made it possible to make traditional forestry procedures more efficient and accurate. However, the continuous increase in the volume of data generated during the management of forest ecosystems presents new challenges for professionals, as processing this data is no longer feasible using traditional methods. Consequently, modern technologies capable of rapidly processing and interpreting data are playing an increasingly important role. [1]

Precision forestry represents an innovative approach based on the integrated application of various digital technologies. Its aim is to optimize the management of forest stands, increase the efficiency of management processes, and minimize environmental impacts. The combined use of geographic information systems (GIS), remote sensing technologies, and unmanned aerial vehicles (UAVs) enables detailed and highly accurate surveys of forest stands, which significantly contributes to improving decision-making processes. [2]

The development of drone technology has opened a new dimension in forest data collection and monitoring. UAVs equipped with advanced sensors such as multispectral and LiDAR sensors are capable of providing high-resolution, spatially and temporally accurate data. This data makes it possible to determine the structural characteristics of forest stands, monitor growth processes, and detect various risk factors early, such as pests and pathogens. The use of drones is particularly advantageous when surveying hard-to-reach areas where traditional data collection methods are of limited applicability. [3]

The growing social and economic demand for sustainable forest management further reinforces the need to apply modern technologies. Climate change, the increasing frequency of forest damage, and the need for more efficient use of resources represent challenges to which traditional methods no longer provide adequate answers. Precision forestry offers an opportunity for managers to make decisions based on real-time and accurate data, thereby increasing the efficiency and sustainability of forest management. [4]

The aim of this study is to examine the extent to which digital technologies used in precision forestry – with special regard to drone technology and data processing systems – contribute to the optimization of forest management processes. The research places particular emphasis on the practical application of these technologies, their advantages and limitations, as well as exploring future development opportunities. The study is based on a questionnaire survey conducted among a sample of 281 domestic forest managers, which quantitatively presents the current state and development trends of digitalization.

Literature Review

The emergence and development of precision forestry are closely linked to the advancement of geographic information and remote sensing technologies. In modern forestry practice, methods that enable the collection, processing, and analysis of large volumes of spatial and temporal data are playing an increasingly important role. The application of these technologies fundamentally contributes to a more accurate understanding of forest stands and to increasing the soundness of management decisions.

Recent innovations in remote sensing have become one of the most important tools in forest management, as they allow the noncontact observation of study areas. Using procedures based on the measurement of electromagnetic radiation, uniform, high-resolution datasets can be created that are suitable for examining the structural and health status of forest stands. Measurements taken in different spectral ranges provide information on vegetation condition, biomass quantity, and the presence of various stress factors. [5]

The use of photogrammetry and LiDAR (Light Detection and Ranging) technology represents a significant advance in the accuracy and detail of forest data collection. Photogrammetry enables the production of high-resolution orthophotos and digital surface models, which serve as important foundations for forestry mapping and planning tasks. LiDAR is an active remote sensing method capable of creating three-dimensional point clouds using laser pulses. These point

clouds provide extremely detailed information about forest stand structure, including canopy height, density, and vertical layering. [6]

Zoltán Zboray pointed out that by using LiDAR-based systems, the spatial location of individual trees can be determined with high accuracy, which is of fundamental importance for growing stock estimation and forest stand structure analysis. This type of data enables finer-level planning of forest management, which is one of the cornerstones of the precision approach. [6]

Geographic information systems (GIS) play a key role in integrating and analyzing forestry data. Managing information from different sources – such as remote sensing data, field measurements, and registry systems – within a single system enables complex analyses to be performed. GIS-based systems support, among other things, the preparation of timber harvesting plans, the planning of reforestation processes, and the assessment of environmental impacts. Such systems help optimize interventions. In the right hands and with appropriate competencies, geographic information systems go beyond empirical limitations and thus represent the future of sustainable forest management. [4]

In recent years, the use of unmanned aerial vehicles (UAVs) has increased significantly in forest management. One of the greatest advantages of drones is that they can quickly and cost-effectively collect high-resolution data over large areas. Anderson and Gaston emphasize that UAV technology is a particularly effective tool for environmental monitoring and forest stand assessment, as it enables the production of detailed and up-to-date data. [7]

The use of drones is not limited to data collection; it is increasingly being integrated into complex data processing systems as well. Modern UAV platforms are capable of carrying multispectral and thermal camera sensors, which allow the health status and stress reactions of forest stands to be examined. This type of data is particularly important for the early detection of pests and diseases, as well as for

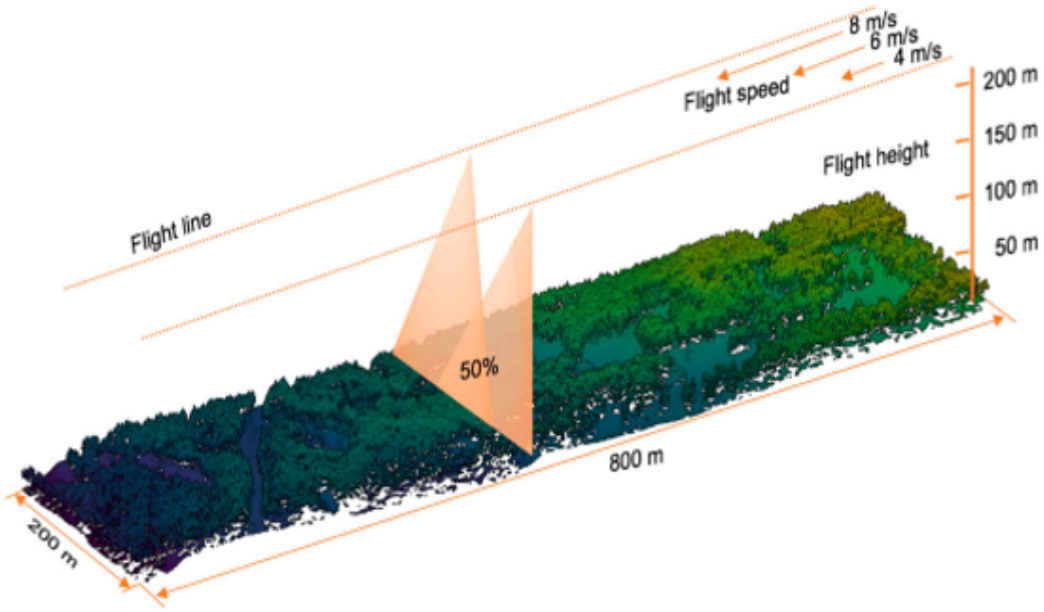


Illustration of the optimal application of the UAV LiDAR system (Tianyu Hu et al., 2021)

planning targeted interventions.

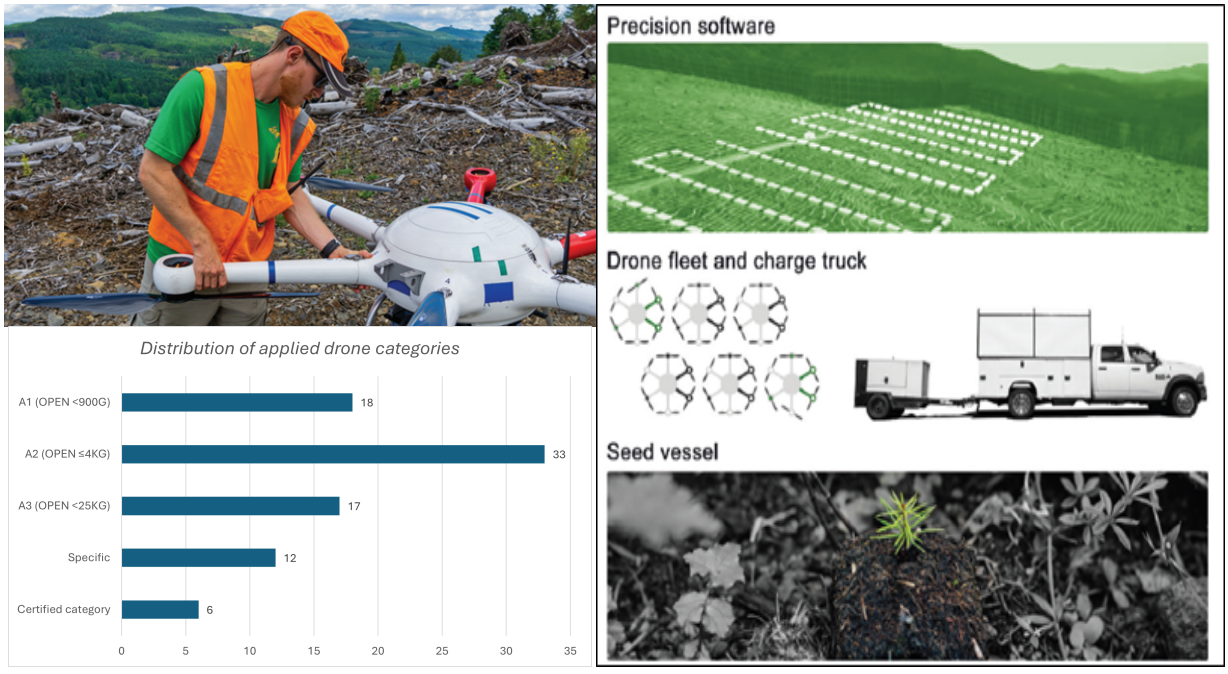
Tianyu Hu and his colleagues demonstrated that the combined use of LiDAR and UAV technologies enables the determination of key forest stand parameters such as tree height, diameter at breast height, crown diameter, and above-ground biomass. By producing these real and accurate parameters in a digitized manner, traditional estimation methods can become obsolete. This approach significantly increases measurement accuracy while reducing time and resource requirements. [8]

Recent development directions include the integration of digital technologies, one of the defining elements of which is the Forest 5.0 concept. This approach is based on the application of artificial intelligence, IoT-based systems, and big data analytics, enabling the automation and optimization of forest

management processes. The goal of Forest 5.0 is not only to increase efficiency but also to enforce sustainability considerations and mitigate the effects of climate change. [9]

However, digital transformation also comes with many challenges. Ferenc Facskó [1] pointed out that one of the biggest problems is the lack of integration between different systems. In addition, high investment costs and technological complexity are highlighted as barriers to widespread adoption. Udvaros and Forman conducted a detailed analysis of European Union drone regulations, which impose strict limits on the use of UAVs, especially in protected natural areas. [10]

A new generation of forest regeneration is represented by the integration of LiDAR-based surveying and targeted seeding technology. LiDAR sensors mounted on drones create 3D maps with centimeter accuracy, and algorithms analyze these maps to identify microhabitats where seedling survival is most likely. Seeding is not done by traditional broadcast sowing but using seed capsules containing a nutrient-



Custom-designed DroneSeed hexacopter (Matthew Aghai and Tiffani M., 2020)

rich, moisture-retaining growing medium that protects the seed from drying out and from pests – a kind of specialized intensive seedling cultivation technology. Special carrier-seeding drones deliver the capsules precisely to the designated locations

using compressed air "guns," ensuring proper embedding in the soil. This method can significantly increase the efficiency of artificial regeneration, especially in hard-to-reach or damaged (post-fire) areas. Overall, it can be concluded that the technological foundations of precision forestry are already in place, but their integrated and widespread application still presents many challenges. The key to future development lies in reducing the gap between technological advances and practical application.

The connections between my research topic and disaster management can be found in both the fields of fire protection and industrial safety [11]. In addition to examining the issue of forest fire protection, it is worth mentioning the professional field of resilience of critical organizations and infrastructures [12]. This activity is of course closely related among others to prevention and disaster management activities in the agricultural and industrial sectors, because the systems of measures are similar to those used in the prevention of industrial and transportation accidents [13,14].

Materials and Methods

The aim of the research was to examine the digital technologies used in precision forestry, with particular regard to the practical dissemination and application possibilities of drone technology in Hungary. The study was based on a quantitative methodology, which allowed for the statistical analysis of respondents' opinions and experiences, as well as the identification of general trends.

Data collection was carried out using an online questionnaire via the Google Forms platform. During the compilation of the questionnaire, the main topics identified in the literature review were incorporated, thereby ensuring the theoretical foundation and relevance of the research. The questions were designed to be clear, interpretable, and based on practical experience.

The data collection took place between 27 december 2024 and 21 March 2025. The questionnaire was sent out in a targeted manner to professionals working at domestic state-owned forest enterprises and major private forest managers. The

sampling was not random but based on expert (targeted) sampling, which ensured that respondents had relevant professional experience in the subject under investigation.

A total of 281 evaluable responses were received. The ownership distribution of the sample (61.6% state-owned, 38.4% private) is close to the structural ratios of domestic forest management, which increases the generalizability of the results. Based on the professional experience of the respondents, it can be stated that a significant proportion of the respondents are experienced professionals: 52.3% have more than 10 years of professional experience. This ensures that the responses are based on sound practical experience.

The questionnaire consisted of a total of 25 questions, which can be grouped into several thematic blocks. The first block concerned the general characteristics of the respondents, including professional experience, job title, and the size of the forest area managed. The second block examined the use of digital technologies and IT systems, with special attention to the application of geographic information systems and data processing solutions. The third block focused on the use of drone technology, including the frequency of use, areas of application, as well as the identification of advantages and barriers.

The question types were mixed: closed questions (single-choice and multiple-choice), Likert-scale evaluations, and open-ended questions were all included in the questionnaire. The use of the Likert scale allowed for the quantitative measurement of respondents' attitudes and opinions, particularly regarding the perceived usefulness and applicability of the technologies.

During data processing, descriptive statistical methods were applied. For the responses to each question, frequency distributions and percentage shares were determined, which made the main trends easily understandable. Quantitative data analysis was carried out using simple statistical tools, as the primary aim of the research was to map the current situation rather than to establish complex models.

For the open-ended questions, qualitative content analysis was applied. In doing so, the responses were sorted into thematic categories, and then recurring patterns and key findings were highlighted. This allowed the quantitative results to be supplemented with deeper, interpretive insights.

During the research, special attention was paid to the reliability and validity of the data. Although the online questionnaire method enables fast and efficient data collection, an important limitation is the self-report nature of the responses, which may bias the results. Nevertheless, the relatively large sample size and the professionally relevant respondent group contribute to the reliability of the results.

Overall, the chosen methodology proved suitable for achieving the research objectives, as it allowed for a comprehensive examination of the current state of technologies used in precision forestry, as well as the identification of development directions.

Results

The results of the questionnaire survey provide a comprehensive picture of the digitalization level of domestic forest management, as well as the current situation and future prospects of modern technologies, particularly the use of drones.

Prevalence of digital technologies

Based on the results, it can be stated that the use of digital technologies is already widespread in domestic forest management. Of the respondents, 71.2% (200 persons) regularly use some kind of digital tool or system in their daily work, while a further 26.3% (74 persons) use such opportunities occasionally. Only 2.5% (7 persons) stated that they do not use digital technologies at all.

This proportion clearly indicates that digitalization is no longer just a complementary element but has become an integral part of modern forest management practice. The high proportion is particularly significant given that the forestry sector has traditionally been more conservative and slower to adapt technologically.

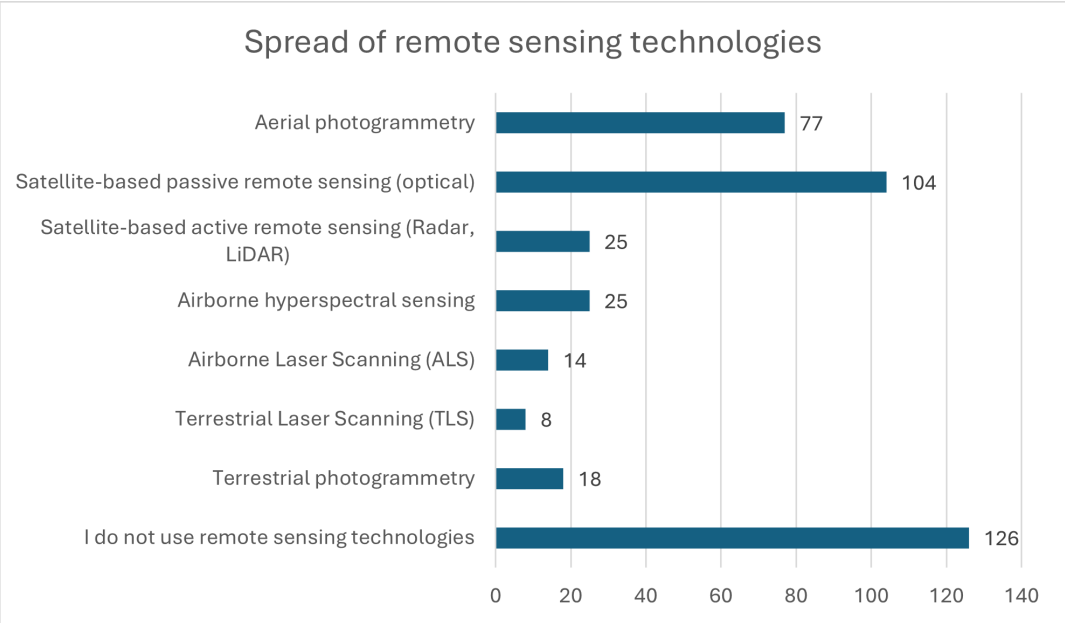
Among the systems used, the domestically developed ESZR (Forestry Professional System) stands out, which is used by 93% of respondents (252 persons). This shows that domestically developed systems fit practical needs well and play a dominant role in forestry data management. In addition, the use of QGIS is also significant (57.6%, 156 persons), indicating the growing popularity of open-source geographic information systems. The use of Google Earth Engine (53.9%, 146 persons) also indicates that cloud-based data processing and the management of large spatial datasets are increasingly appearing in practice.

Respondents highlighted more efficient management (69.4%), cost efficiency (65.1%), and time savings (54.1%) as the most important advantages of digital systems. This suggests that digitalization provides benefits primarily from an economic and operational perspective, while sustainability aspects (26.0%) currently receive less emphasis in practical assessment.

Application of remote sensing technologies

The use of remote sensing technologies is less common. Of the respondents, 46.8% (126 persons) do not use such solutions at all, indicating that the spread of these technologies is still limited.

Among those who use remote sensing, traditional passive optical satellite solutions dominate (37.0%, 104 persons). This is followed by aerial photogrammetry (27.4%, 77 persons), which provides higher-resolution data. More advanced active remote sensing technologies, such as LiDAR, appear at much lower rates (5–9%), which can be explained by high costs and the need for specialized expertise.



Spread of remote sensing technologies (own diagram)

This result indicates that although technological possibilities are available, their widespread application has not yet been realized in practice.

Integration of data management systems

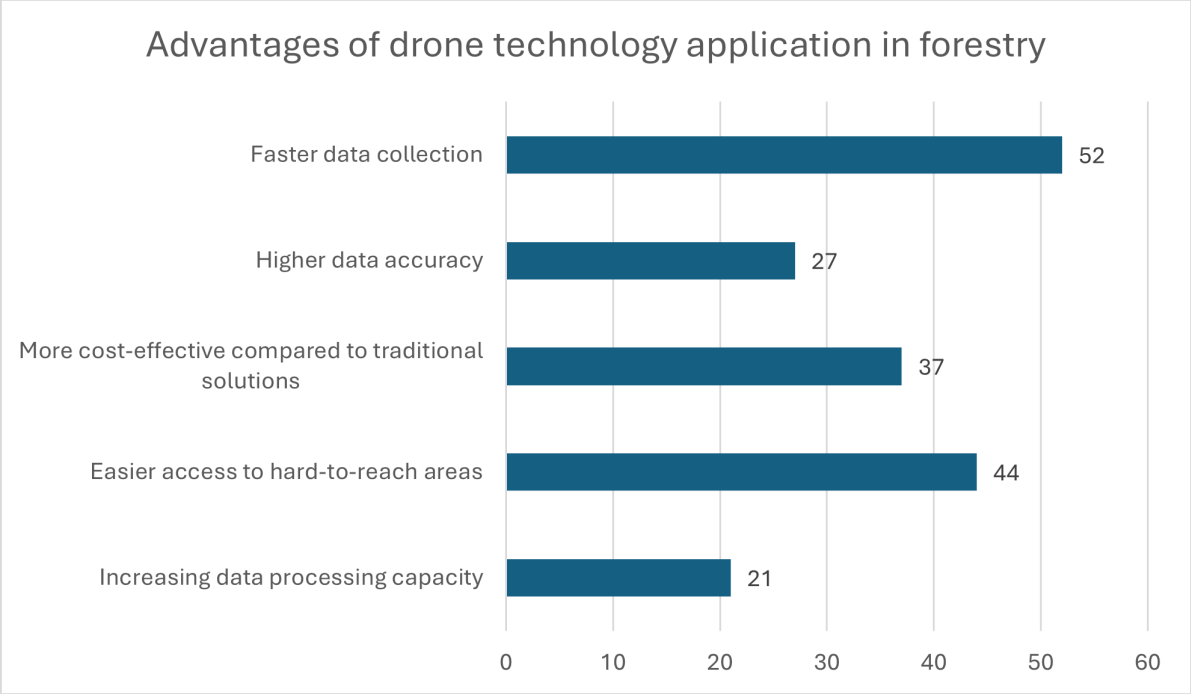
The level of integration of data management systems is a key factor in the efficient operation of precision forestry. According to 72.6% of respondents (204 persons), the systems they use are only partially integrated, meaning that data linking is often done manually.

Only 19.6% (55 persons) reported having fully integrated systems, indicating that automated data flow is not yet common. This is particularly problematic when processing the large volume of data collected by drones, where the lack of integration results in significant time and resource demands.

Application of drone technology

The current level of drone technology adoption is relatively low. Only 21% of respondents (59 persons) use UAV devices in their work. At the same time, openness to the technology is extremely high, as 70.5% of respondents (198 persons) plan to introduce it in the future.

This result clearly shows that the application of drone technology is on the verge of a rapid growth phase, which is currently limited primarily by external factors.



Advantages of drone technology application in forestry in Hungary (own diagram)

Among the application areas of drones, taking aerial photographs (76.3%) and forest stand assessment (74.6%) dominate. In addition, plant protection (52.5%) and pest monitoring (49.2%) also play a significant role, indicating that drones are used not only for mapping but also for operational tasks.

The most important advantages perceived by respondents include faster data collection (88.1%), surveying hard-to-reach areas (74.6%), and cost efficiency

(62.7%). These advantages clearly show that drone technology plays a key role primarily in increasing efficiency.

Application barriers and development needs

The greatest barrier to the spread of the technology is the regulatory environment, highlighted by 71.2% of respondents. In addition, high costs (54.2%) and lack of training (56.5%) are also significant limiting factors.

Among the development needs, the necessity of specialized education and knowledge development clearly stands out (89.7%), indicating that one of the most important prerequisites for technological advancement is the availability of adequate human resources.

The majority of respondents (70.1%) expect improvements in the efficiency and sustainability of forest management from digitalization, which clearly reflects a positive attitude toward these technologies.

Discussion

Based on the results of the research, it can be stated that the use of digital technologies is already widespread in domestic forest management. Of the respondents, 71.2% regularly use digital tools, which is consistent with Ferenc Facskó's [1] findings that managing large volumes of forestry data is no longer efficiently feasible with traditional methods. Thus, digitalization is not just an opportunity but a necessity in the sector.

At the same time, the results also highlight that significant differences can be observed in the prevalence of different technologies. While the use of GIS-based systems is widespread and received high usefulness ratings, the use of remote sensing technologies and especially drones is still limited. This duality suggests that the digitalization of forest management is currently in a transitional phase, where basic technologies are already stably present, but the integration of innovative solutions is not yet complete.

The lower prevalence of remote sensing technologies (46.8% do not use them) suggests that there is still a significant gap between technological possibilities and practical application. This can be partly explained by costs and the lack of necessary expertise, but it also indicates that technology adoption is influenced not only by technical factors but also by organizational and educational factors.

In the case of drone technology, a particularly interesting duality can be observed. The current usage rate is low (21%), while the proportion of those planning to introduce it is outstandingly high (70.5%). This indicates that professionals are open to innovation, but actual application is limited by external barriers. Anderson and Gaston [7] previously pointed out that UAV technology has significant potential in forest management, particularly in data collection and monitoring. The results of the present research confirm this potential but also indicate that domestic application has not yet reached the international level.

The most important advantages of drone use, such as rapid data collection, surveying hard-to-reach areas, and cost efficiency, are consistent with those described in the literature, which confirms the practical relevance of the technology. At the same time, the frequency of use (mostly monthly application) suggests that drones have not yet been fully integrated into daily workflows.

One of the most significant barriers to technological application is the regulatory environment, highlighted by 71.2% of respondents. This result is consistent with the findings of Udvaros and Forman [10], according to whom European Union drone regulations impose complex and strict limits on usage. This is particularly true in forest management, where work is often carried out in areas subject to nature conservation restrictions.

The lack of training also emerged as a determining factor. Of the respondents, 56.5% highlighted the importance of specialized training in digital data management, while 89.7% did so among development needs. This suggests that the biggest limitation to technological development is not the lack of available tools but the lack of appropriate expertise. Based on the open-ended responses, it is

clearly evident that the problems are not limited to device usage but also extend to data processing and interpretation.

The deficiencies in the integration of data management systems (only partially integrated according to 72.6% of respondents) are particularly critical for precision forestry. The Forest 5.0 concept is based on data-driven operation and automated decision-making, which can only be achieved with properly integrated systems. However, based on the current situation, data flow remains fragmented, which significantly reduces the efficiency of the technologies.

Based on the results of the research, it can be stated that domestic forest management is in a transitional technological state. Basic digital systems are already widespread, but the application of innovative solutions such as drones, LiDAR, or artificial intelligence is still limited. The key to future development lies in the simultaneous improvement of technological, organizational, and educational factors.

Conclusions

The aim of the research was to examine the role of digital technologies applied in precision forestry, with a particular focus on drone technology, as well as to explore their practical adoption and development potential. Based on the results, it can be clearly concluded that digitalization already plays a significant role in Hungarian forestry; however, the level of application of individual technologies varies considerably.

The widespread use of digital tools (71.2%) indicates that the sector is open to innovation, and modern IT solutions have already been integrated into everyday practices. In particular, the application of geographic information systems can be considered well-established, playing a fundamental role in data management and decision support.

In contrast, the use of remote sensing technologies and drones cannot yet be considered widespread. Although the current rate of drone usage is relatively low (21%), the high intention for future adoption (70.5%) clearly indicates significant

growth potential. This trend suggests that drones may become key tools in precision forestry in the near future.

The research also highlighted that the main barriers to technological advancement are not primarily technical limitations, but rather the regulatory environment, high investment costs, and the lack of appropriate expertise. The training needs identified by respondents emphasize that human resource development is crucial for the effective implementation of these technologies.

It is also important to highlight the lack of integration in data management systems, which significantly limits the full exploitation of the potential of precision forestry. The absence of unified, integrated systems increases the complexity of workflows and reduces the efficiency of data-driven decision-making.

Among future development directions, particular emphasis is placed on the integration of artificial intelligence, IoT-based sensor networks, and drone technology. Together, these can enable the realization of the Forest 5.0 concept, which aims to establish an intelligent, sustainable, and data-driven forestry model.

Overall, it can be concluded that the development of precision forestry is clearly moving toward digitalization and automation. While the technologies are already available, their widespread and effective application requires an appropriate regulatory framework, economic support, and the development of professional training. The results of this research contribute to a better understanding of the state of digitalization in Hungarian forestry and provide a foundation for the development of future strategies.

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