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ABSTRACT

of a dissertation for awarding an educational and scientific degree
"Doctor" in the scientific specialty "Economics and Management", in the professional field 3.8 "Economics" on the topic:

ECONOMIC ASSESSMENT AND FUTURE PROSPECTS FOR THE USE OF UNMANNED TECHNOLOGIES SUPPORTING ECOLOGICAL ORIENTATION AND PRECISION AGRICULTURE IN BULGARIA

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I. GENERAL CHARACTERISTICS OF THE DISSERTATION

1.1 Introduction

The relevance of the study is determined by the need to transform modern agriculture towards higher economic efficiency, sustainability and ecological orientation. In the context of a growing population, limited resources and increased requirements for food quality, food security and food souverenity the agricultural sector is faced with the need to implement innovative technological solutions.

In this context, precision agriculture and unmanned technologies are establishing themselves as a key tool for optimizing production processes, increasing efficiency and reducing environmental impact. The unmanned technologies in agriculture are understood to be techniques not driven man using arial and ground base vehicles.

European Union policies, including the Common Agricultural Policy and the European Green Deal, further stimulate this process.

However, regarding the Bulgarian conditions, there are limitations related to the structural features of the sector, limited investment capacity and insufficient empirical base on the cost-effectiveness of these technologies.

The scientific problem is related to the lack of in-depth economic research on the implementation of unmanned technologies in precision agriculture in Bulgaria.

1.2. Object and subject of the study

The main objective of the dissertation is to carry out an economic assessment of the use of unmanned technologies in precision agriculture in Bulgaria and to analyze the prospects for their development in the context of sustainable development and European policies. The object of the study is the agricultural sector of the Republic of Bulgaria, with a focus on maize production as a strategic crop in Bulgaria's agriculture.

The subject of the study is economic efficiency, feasibility and prospects for the development of unmanned technologies as a tool for sustainable management in precision agriculture. The EU definition of sustainable agriculture requires us to assess not only the economic aspect of the new technology, but also to assess its environmental and social aspects. Moreover, for the implementation of the innovative technologies in the individual member States its likewise a key point to assess its institutional aspect. To achieve the set goal, the following main tasks have been formulated:

1. analyzing the theoretical and political prerequisites for digitalization of agriculture;
2. systematization of scientific research in the field;
3. economic assessing the deployment of unmanned technologies (e.g. with corn);
4. benchmarking with conventional technologies;
5. researching the attitudes of farmers and
6. identification of deployment factors and development scenarios.

1.3. Research thesis

The research thesis is that the implementation of unmanned technologies creates prerequisites for increasing economic efficiency, sustainability and resource optimization in crop production, and the degree of their application depends on economic, institutional and technological factors.

1.4. Purpose and tasks of the dissertation

The aim of the study is to carry out an economic assessment of the use of unmanned technologies in precision agriculture in Bulgaria and to analyze the future prospects for their development in the context of the environmental policies of the European Union and the principles of sustainable development in the agricultural sector.

In this regard, for the purposes of the study, unmanned technologies are considered as autonomous or remotely operated technology platforms and/or systems designed to perform tasks without an operator on board, using sensors, communication technologies and software control algorithms.

II. RESEARCH METHODOLOGY

The methodology of the study is based on an integrated analytical approach, including economic, technological, environmental, social and institutional aspects of the site under consideration.

The study is based on the concept of sustainable development, interpreted through its main dimensions - economic, environmental, social and institutional, which allows for a complex and systematic analysis of the studied alternatives. In its general form, the conceptual model includes four main blocks:

1. technological block - considers the technological solutions used and their function in the production process;
2. economic block - covers costs, productivity, resource savings and returns;
3. ecological and social block - includes the effect on the soil, the use of resources, the organization of work and the requirements for qualifications;
4. institutional block - takes into account the influence of the regulatory, organizational and market environment, including transaction costs.

The connections between these blocks are bidirectional. Technological choice affects economic performance, but it is itself determined by institutional conditions, access to capital and organizational capacity of the farm. Likewise, environmental and social effects are not independent of economic efficiency, since they affect yields, additional processing, labor organization and long-term sustainability of production.

The integration of the conceptual model into empirical analysis is carried out through the adaptation of the general theoretical framework to the specific object and methodology of the present research. While the conceptual model outlines the main interconnections between technological, economic and organizational factors in the implementation of unmanned systems in agriculture, the second level of the framework shows their practical application in the context of the dissertation research. The present study focuses on the production of corn in Bulgaria, which was chosen due to the strategic importance of the crop, the high degree of mechanization and the availability of production operations in which the use of unmanned technologies can be economically evaluated and compared with conventional solutions in real production conditions.

The choice of technologies is protected on three grounds. **First**, they are representative of different levels of technological complexity and automation. **Secondly,** they are directly relevant to specific production operations that can be economically compared. **Thirdly,** they allow to analyze not only the technological, but also the organizational and institutional applicability of unmanned solutions in Bulgarian conditions. It is here that it is necessary to clearly emphasize that the comparison between technologies is not carried out on the principle of "*machine versus machine*", due to the differences in the scale, functional purpose and degree of autonomy of the studied solutions. The methodological approach is based on a comparative analysis of the implementation of comparable agrotechnical activities such as ploughing, spraying, harvesting, cultivation, etc., evaluating indicators related to the efficiency, applicability and possibilities for technology integration, as well as the technological and economic results achieved. The comparison is carried out on the basis of a single analytical framework, which includes a comparison by type of operation performed, such as spraying and application of liquid preparations and fertilizers, by functional application in the implementation of specific technological activities in the production of corn, by economic indicators - costs per unit area, labor, energy and fuel consumption, depreciation and return - as well as by technological role between aerial unmanned systems, autonomous ground platforms, conventional ground equipment and manned aviation technologies. This makes it possible to compare solutions of different scale and design through a common benchmark applied to the same production task.

The methods and their sequence in empirical analysis are applied as complementary analytical steps, and not as parallel tools for re-confirming the same results. The following sequence is applied.

At the first stage, a systematic literature review was applied, in accordance with the principles of systematicity and reliability (Snyder, 2019), which clarifies the content of the concept of "unmanned technologies", their place in the system of sustainable and precision agriculture and the existing approaches to their economic evaluation. For the purposes of the analysis, international scientific databases were used, including Google Scholar, Scopus, Web of Science, Elsevier, etc. European and national legal and regulatory frameworks, as well as national and international statistical and institutional sources, including data from the Ministry of Agriculture, the National Statistical Institute, Eurostat, FAOSTAT and the Agricultural Accounting Information Network, are further analysed.

At the second stage, a comparative economic analysis was carried out between unmanned and conventional technologies applicable in the production of corn in Bulgaria. As a reference technology, a John Deere 5505 tractor configuration with a 6-meter trailed sprayer AMAZONE was used, typical for small farms (50-150 ha) at a working rate of about 80-100 l/ha, as well as for medium-sized farms (300-500 ha) at a rate of about 100 l/ha. a tractor with a 12-meter AMAZONE sprayer, the An-2 aircraft, as well as with the NEXAT and XAVER autonomous systems. The comparison was made using unified indicators: cost per unit area (€/ha), application rate (l/ha), energy or fuel consumption, processing time per 1 ha, depreciation charges, labour costs and effect on yield (kg/ha), under identical agro-climatic conditions and an average yield of 5500 kg/ha. It is this unified benchmark that makes it possible to compare technologies of different scales and technological functions.

The economic analysis covers both the direct production costs - fuel, labor, plant protection products, mineral fertilizers and depreciation of equipment, as well as the indirect costs related to the organizational functioning of the farm. An independent analytical component is the transaction costs for searching and processing information, negotiating, coordinating, controlling and monitoring technological operations. Their inclusion extends the assessment beyond purely technological efficiency and allows measuring the real economic feasibility of the compared solutions.

At the third stage, the environmental dimension of the technological choice is analyzed, focusing on the impact of technologies on the soil structure, and the degree of compaction is considered as a factor with a direct impact on yields, the need for additional treatments and long-term productivity. negative externalities.

The fourth stage examines the social dimension, including the impact on the organization and working conditions, the degree of technological renewal and changes in the requirements for the qualifications and competences of the workforce.

At the fifth stage, the institutional dimension is analyzed, which examines the influence of the regulatory, regulatory and organizational environment on the implementation and use of unmanned technologies in agriculture. In this context, the current national and European legal framework, including the regulations related to the use of unmanned aerial systems and the rules for the application of technologies for precision agriculture, is analyzed. factors that influence the diffusion of technological innovation - property rights, regulatory restrictions, administrative procedures and the degree of institutional support.

The empirical part is complemented by a survey aimed at farmers growing corn, which analyzes the attitudes of farmers regarding the implementation of unmanned technologies, the degree of technological readiness and the potential for their integration into sustainable farming practices. For a strategic assessment of the external and internal environment, a SWOT analysis is applied, and in the final stage, a risk assessment is carried out. identifying the main factors limiting the wider use of unmanned systems.

The framework reflects **the triad of interactions between key dimensions of sustainability** and shows that the effects of technology deployment cannot be considered in isolation but should be analysed in the context of complex interlinkages between efficiency, sustainability and institutional environment.

This follows from the fact that the real dependencies between factors are significantly more complex than can be exhaustively presented within the framework of an analytical scheme. For the purposes of the study, these dependencies are conceptually simplified and generalized, which facilitates the analytical process, but at the same time implies a certain loss of detail. is largely conditioned by the quality, reliability and representativeness of the empirical data used. **Limitations in the availability, comparability or relevance of empirical**

information may affect the accuracy of conclusions. However, the methodological framework applied creates a sufficiently reliable basis for economic, environmental and institutional assessment of drone technologies and for subsequent empirical verification.

Justification of the choice of maize production as an empirical focus

In the dissertation, a comparative case study approach is applied in order to assess the possibilities for the implementation of unmanned technologies in Bulgarian agriculture. Within this approach, the choice of a specific crop is of key importance, as it must ensure sufficient analytical comparability between different technological solutions applied under similar production conditions. In this sense, corn was chosen as the empirical focus of the study based on economic, technological and methodological arguments.

First of all, corn is one of the main cereals in Bulgaria and the European Union and occupies a significant share of arable land. It is important for feed production, the food industry and a number of industrial applications, which determines the high economic relevance of the analysis. has wider economic importance.

Secondly, maize production is characterized by clearly structured and repeatable agrotechnical operations, including sowing, fertilization, plant protection and water management. This creates a good basis for the analysis of technologies that are aimed at the precise implementation of specific production activities, localised treatment and more efficient use of inputs.

Thirdly, the row structure and technological features of maize make it suitable for integrating precision farming and automation solutions. Compared to other widespread crops, it provides wider possibilities for the application of different types of unmanned technologies throughout the entire production cycle, and broader economic, environmental and organisational implications of implementing such solutions.

Fourthly, maize is analytically appropriate for a comparative approach, as it can fairly clearly distinguish between operations where conventional and unmanned solutions perform similar functions. This creates prerequisites for a more reliable comparison between different technological options and for assessing their effects on production costs, labour use, resource efficiency and the overall economic performance of the farm.

The choice of maize as an empirical focus is also justified by the specifics of Bulgarian agriculture. Its production is sensitive to climate fluctuations, price volatility and labor constraints, which raises the importance of technologies aimed at more precise management and loss reduction. In this sense, culture provides an appropriate environment for exploring the extent to which unmanned technologies can improve economic efficiency and create prerequisites for more sustainable management of the production process.

Therefore, the choice of maize production is not random, but results from a combination of economic relevance, technological feasibility and analytical suitability. It is these characteristics that make it an appropriate model culture for assessing the opportunities and limitations of the implementation of unmanned technologies in the conditions of Bulgarian agriculture.

Information base, time and geographical scope of the survey

The study is based on a combination of **primary and secondary** sources of information, which creates prerequisites for higher reliability and comparability of results. **The primary data** are formed through a survey among farmers, field observations, analysis of practical cases, participation in demonstration trials and expert assessments. **Secondary sources** include scientific publications, reports of national and international institutions, statistical databases, as well as strategic and normative documents related to digitalization and sustainable development of the agricultural sector. In parallel, political and institutional support for sustainability, innovation and the digital transition in agriculture is being intensified at European level, including through the Common Agricultural Policy, the European Green Deal and the strategy "From farm to table". This dynamic creates a favorable basis for analyzing modern trends and the effects of the implementation of unmanned technologies in agricultural production.

The geographical scope of the survey is limited to the Republic of Bulgaria, and the analysis also takes into account regional differences at NUTS level 2. The country is a relevant subject of study due to the structural polarization of the agricultural sector, uneven technological development and disparities in access to innovation. At the same time, Bulgaria operates within the framework of the common European agricultural policy, which allows for a comparison between national specificities and the strategic goals of the European Union.

A scoreboard and an integrative approach to assess economic, environmental and social effects

In this study, the assessment of drone technologies is based on an integrative approach integrating the economic, environmental and social dimensions of sustainability. The need for such an approach stems from the fact that technological solutions in agriculture simultaneously affect financial results, resource use and labor organization, therefore their effectiveness cannot be evaluated unilaterally or in isolation. The integrative approach serves as a methodological framework for structuring the analysis, selection of indicators and interpretation of results. It tracks not only the direct effects of the deployment of drone technologies, but also the interlinkages between the economic, environmental and social aspects of sustainability. In this way, the assessment goes beyond current economic efficiency and encompasses the potential of technologies to support more precise, resource-efficient and sustainable management of the production process.

The choice of this approach is conditioned by the limitations of one-sided analyses, which consider sustainability only in an economic or environmental aspect. Within the framework of integrative assessment, it is assumed that functional dependencies exist between the different dimensions. Economic efficiency affects investment decisions and the implementation of innovations, environmental effects determine the requirements for production practices and resource use, and social consequences affect the organization of work, qualification requirements and the degree of technological adoption. Therefore, sustainability is seen not only as a result, but also as a direction of development in which unmanned technologies can support the ecological orientation and expansion of precision farming practices in Bulgaria.

For the purposes of the study, a system of indicators has been built, grouped into three main dimensions – economic, environmental and social. The economic dimension includes indicators such as operating costs per unit area, investment and transaction costs, profit, profitability and return on investment. They allow for an assessment of the economic feasibility and effectiveness of the use of unmanned technologies.

The environmental dimension covers indicators related to resource use and environmental impact, including application rates of preparations and fertilisers, energy consumption, degree of precision of operations and impact on soil structure. They assess the potential of technologies to limit resource losses and negative environmental effects.

The social dimension includes indicators related to employment, working conditions, the degree of automation and qualification requirements of the workforce. They make it possible to analyze the impact of technological changes on the organization of work and the adaptability of farmers to innovation.

The data processing is carried out through comparative and evaluative analysis using quantitative and qualitative analytical techniques. Combining these approaches allows for triangulation of results and creates the basis for a more balanced interpretation of the effects of the deployment of unmanned technologies. The analysis is not limited to a description of the current situation, but provides an opportunity for a structured assessment of the potential for wider application of these technologies in different economic and institutional conditions.

Despite its advantages, the approach also has certain limitations. The integrative model inevitably simplifies some of the complex interrelationships between the different dimensions of sustainability. In addition, some environmental and social indicators are difficult to directly quantify, which requires the use of expert assessments and additional interpretation. The results also depend on the quality, scope and representativeness of the available data, which requires analytical caution in formulating conclusions.

Notwithstanding these limitations, the integrative approach allows for a comprehensive and balanced assessment of unmanned technologies in agriculture, taking into account both the direct economic effects and the broader environmental and social consequences of their deployment. This is what makes it an appropriate methodological basis for the current dissertation research.

Methods for Economic Analysis of Unmanned and Conventional Technologies

This section develops a methodological approach for economic assessment of the deployment of drone technologies on farms by applying the transaction cost approach. The choice of this approach is conditioned by the need to assess economic efficiency not only through direct production costs, but also through the costs associated with the organization, coordination and management of the production process.

The economic logic of the analysis is based on an extended understanding of costs, whereby the total costs of the farm are considered as a set of direct, indirect and transactional costs. In this context, the effect of the deployment of unmanned technologies is expressed not only in a change in the cost of production, but also in a potential reduction in the cost of information, coordination, control and decision-making.

The theoretical basis of the analysis is based on the concept of transaction costs within institutional economic theory (Williamson & Masten, 1999); (Masten, 2000). The applied model for their measurement follows the methodology of (Georgiev, M.; Roycheva, A., 2017), adapted to the specifics of farms in Bulgaria.

Within the analysis, costs are distinguished into three main categories. The first category includes direct costs that are directly related to production - seeds, fertilizers, preparations, fuels, labor and depreciation of equipment. The second category covers indirect costs related to administrative services and general management of the farm. The third category includes transaction costs related to the coordination and management of activities, including costs related to information collection and processing, negotiation and monitoring, coordination of production processes, risk and uncertainty management, as well as costs related to planning, change of decisions and dispute resolution.

For quantification purposes, part of the transaction costs is measured using the time cost method. In this case, the time required to carry out management and coordination activities - monitoring, data processing and decision-making is converted into a value equivalent by using an hourly rate of labor. This allows the overall cost structure to include those activities that do not directly manifest themselves as material costs, but have a real impact on the economic efficiency of the farm.

The cost-effectiveness of the deployment of unmanned technologies is assessed through a system of indicators calculated on the basis of total costs and results. Key indicators include profitability as measured by the ratio between profit and total costs, return on investment, expressed by the ratio between additional profit and investment costs, and resource savings as measured by the cost reduction of technology deployment compared to the baseline.

The empirical basis of the analysis is formed through a survey among farmers, through which primary data are collected on the individual components of costs and their dynamics. This information makes it possible both to quantify transaction costs and to analyze the relationship between the technological level of farms and their economic efficiency. The method is applied when comparing unmanned and conventional technological solutions included in the empirical design of the study.

The expected outcome of the implementation of this approach is to identify the extent to which the deployment of unmanned technologies leads to a reduction in transaction costs and an improvement in the overall economic efficiency of farms. The main advantage of the method is that it allows to analyze the impact of technology not only on direct production costs, but also on organizational and management processes on the farm.

The limitations of the method stem from the difficulty in accurately quantifying part of the transaction costs and from the possible subjectivity of the respondents' estimates. Therefore, the results should be interpreted with the necessary analytical caution and in comparison with other sources of information.

Organization and methodology of the survey

For the purposes of the study, a survey was conducted, which collected primary empirical data on attitudes, investment intentions and perceived limitations in the implementation of unmanned technologies in corn production. The survey method allows for standardized collection of information and subsequent quantitative analysis of the behavioral and economic characteristics of farmers.

The main objective of the survey is to assess the degree of readiness of corn producers for the implementation of unmanned technologies in the Bulgarian agricultural sector. Within the framework of the study, the level of awareness, investment intentions, expected economic benefits, as well as the perceived limitations and barriers to technological renewal are analyzed.

The general population of the study covers 14 460 agricultural holdings that have declared areas with maize, and the sampling was carried out through a stratified approach, in which agricultural holdings are grouped according to two main criteria: geographical region (Northern and Southern Bulgaria) and farm size, determined according to the area of corn.

The planned sample size is 114 units, and its size is determined by the method of optimal (Neumann) distribution, which allows minimizing the variance of estimates at a given volume and taking into account the structure of the population. The realized sample size included 35 valid responses from farmers, which corresponds to a response rate of 30.7%. Only the actual valid answers received are included in the analysis. Some of the potential respondents did not participate due to refusal, inaccessibility or other objective reasons. This should be taken into account as a limitation of the study, as there may be selection distortion and limited representativeness of the results. Therefore, the conclusions of the survey should be interpreted primarily in analytical rather than strictly representative terms.

The data collection was carried out through e-mails and an online platform (Google Forms), which allows covering respondents from different regions of the country and facilitates the processing of information. The collection and processing of the data from the survey 2024-2025

The survey tool has been developed in accordance with the conceptual model of the research and provides a clear link between research objectives, empirical questions and analytical variables. The questionnaire includes two main blocks.

The first block covers variables characterizing the structural profile of the farms - geographical location, size of the cultivated area, area with corn, resource provision (labor force and equipment) and level of technological provision. These indicators play the role of explanatory variables and allow the formation of comparative groups in the analysis.

The second block is aimed at examining the behavioural attitudes and investment intentions of farmers, including variables measuring the willingness to use and purchase unmanned technologies, investment intentions, the expected amount of public financial support, as well as perceived constraints. Among the main constraints are considered the high cost, lack of practical experience, perceived risk, administrative difficulties and possible impact employment.

The questions in the questionnaire are formulated mostly with closed answers. Both dichotomous 'yes/no' variants and different categories of responses, including ranges and grades, were used. This allows for a more accurate measurement of attitudes and creates conditions for subsequent quantitative analysis, grouping of respondents and verification of dependencies between the structural characteristics of farms and the attitude towards the implementation of unmanned technologies.

In addition, as methods **for processing and analysis of empirical data**, comparative cost analysis, transaction cost analysis, SWOT analysis and scenario modeling, χ^2 chi-square analysis are applied, and each of these methods performs a specific role in the general analytical framework.

χ^2 chi-square analysis is used in surveys in socio-economic research, as it works with categorical data and belongs to the group of nonparametric statistical methods (Babbie, 2020). The method is applied to establish the presence or absence of a statistically significant relationship between two categorical variables. In the context of this study, it makes it possible to assess whether the observed differences in farmers' attitudes can be related to the structural characteristics of farms.

In addition, the limitations of χ^2 analysis should also be taken into account. First of all, the test allows to establish the presence or absence of a relationship between the variables, but does not provide information about the causal relationships between them. Secondly, the reliability of the analysis depends on the categorization of observations, and at low frequencies in individual cells it is possible to reduce statistical stability. Thirdly, a limitation is the sample size of 35 valid responses, which leads to a lower statistical power of the test and requires caution in the interpretation of the results. In this context, χ^2 analysis is mainly used to identify trends and dependencies, rather than to derive statistically representative conclusions about the population. Despite these limitations, the χ^2 test is an appropriate tool for categorical data analysis and allows for a reasonable empirical assessment of the relationships between the structural characteristics of farms and their readiness for the deployment of unmanned technologies.

In addition, comparative cost analysis, transaction cost analysis, SWOT analysis and scenario modeling are applied.

In this study, strategic analysis is not based on a single method, but on a set of complementary analytical approaches that perform different functions in the general research logic. In this sense, some of them serve to synthesize empirical results, others - to structure the analysis of the external and internal environment, and still others - to model future directions of development.

The SWOT analysis was used as a tool for summarizing and systematizing the results of the empirical analysis related to the implementation of unmanned technologies in Bulgarian agriculture. Its main function is to synthesize the identified factors in a structured form, covering both the economic and institutional aspects of the process.

Използването на SWOT анализа е обусловено от необходимостта да се интегрират резултатите от количествения анализ, икономическата оценка и анализа на институционалната среда. В този смисъл методът не се прилага като самостоятелен доказателствен инструмент, а като средство за интерпретация и стратегическо обобщение на емпиричните резултати.

SWOT analysis is based on several main sources of information:

1. the results of the survey among farmers;
2. the results of statistical analysis, including χ^2 analysis;
3. the results of the economic assessment and analysis of transaction costs;
4. analysis of the institutional and regulatory environment;
5. data from the scientific literature.

The development of the SWOT analysis involves systematizing the factors into four main categories:

1. Strengths - internal economic and organizational advantages, such as increased efficiency, resource savings and improved manageability of production processes;
2. Weaknesses - internal constraints, including high investment costs, lack of practical experience and limited access to technology;
3. Opportunities - external factors related to the economic and institutional environment, such as access to finance, digitalization policies and support for innovation;
4. Threats - external risks, including market uncertainty, regulatory constraints and administrative barriers.

To limit the subjectivity in the formation of the SWOT matrix, a verification procedure was applied by comparison between different sources of information. The factors were checked against the results of the survey, statistical analysis and economic assessment, as well as against data from the scientific literature and institutional analysis.

SWOT analysis is not used to prove dependencies, but to interpret them in a broader economic and institutional context. The main limitation of the method stems from its qualitative nature and from the possible subjectivity in the classification of factors.

Top-down and bottom-up approach as a framework for structuring analysis

The **top-down and bottom-up** approaches are used as a complementary framework for structuring the analysis of the implementation of unmanned technologies in Bulgarian agriculture. The top-down method is applied as a tool for analysis of the external economic, institutional and regulatory environment in which the technological modernization of the sector takes place. support, the regulatory framework and conditions for digitalization of agriculture, as well as financial instruments supporting investments in new technologies. The role of the method is to identify external opportunities and limitations to the implementation of unmanned technologies and to assess the extent to which the institutional environment creates incentives or barriers to the use of drones and other precision technologies on farms.

The bottom-up method has been used for empirical analysis of the behavior and characteristics of farms. The role of the method is to provide an empirical basis for the study and to show the real state of implementation of unmanned technologies at the farm level. Unlike the top-down approach, which analyzes the external environment, this method reveals internal factors and limitations. It follows logic from the particular to the general, and on the basis of microeconomic data, generalizations for the sector are derived (Kintsch W. , 2005); (Kintsch W. P., 2011); (Casazza & Pianigiani, 2016). The combination of the two approaches allows for a comparison between the external institutional environment and the internal logic of economic behavior, and the analysis covers both the policies and conditions for support, as well as the real constraints, decisions and investment attitudes of farmers.

Backcasting as a Scenario Modeling Method

The method of backcasting has been used for strategic modeling of the future development of the implementation of unmanned technologies in Bulgarian agriculture. Unlike traditional predictive approaches, which are based on extrapolation of current trends, backcasting starts from a predefined desired future state and derives the necessary conditions and steps to achieve it.

Within the framework of the study, the desired state is associated with a wider deployment of unmanned technologies, characterized by higher efficiency, reduced transaction costs and more sustainable production management. On this basis, the necessary economic, institutional and technological prerequisites for the realization of such a transformation are identified.

The role of the method is to link empirical results with future opportunities for the development of the sector and to outline realistic scenarios for technological modernization. It assesses what policies, investments and organisational changes would support the wider deployment of unmanned technologies. The limitations of the method stem from its dependence on the chosen vision of the future and on the analytical interpretation of the conditions for its achievement.

ABCD method as a tool for arranging strategic analysis

The ABCD method (Awareness - Baseline - Creative solutions - Decide) has been applied as a tool for structuring strategic analysis. The method has been developed within the framework of the Framework for Strategic Sustainable Development (Broman & Robert, 2015); (Broman & Robèrt, 2017) and is used not as an independent evidentiary method, but as a logical scheme for arranging the analysis in successive stages.

In the context of the study, the individual stages perform the following functions:

Awareness - formulation of a vision for the implementation of unmanned technologies in Bulgaria and awareness of the strategic need for technological modernization;

Baseline - analysis of the current state based on empirical data, economic assessment and institutional analysis;

Creative solutions - development of possible solutions and scenarios, including by applying backcasting;

Decide - setting priorities and outlining practical directions for action.

The method serves as a framework that consistently arranges the results of economic, statistical and institutional analysis and translates them into strategic conclusions.

Framework of the five levels of sustainability

Within the framework of the dissertation research, this framework is applied to assess the economic, environmental and institutional effects of the deployment of unmanned technologies. It creates a link between empirical analysis and strategic decisions related to the sustainable development of the agricultural sector (Bachev, H.; Ivanov, B.; Sarov, A., 2020); (FAO, 2021c).

The combined use of SWOT analysis, top-down and bottom-up approaches, backcasting, ABCD method and the five-level framework allows for the construction of a multi-layered strategic perspective on the implementation of unmanned technologies in Bulgarian agriculture. Each of these methods performs a different function - from synthesizing empirical results, through structuring the analysis of the environment, to modeling future development opportunities.

Limitations and assumptions of the study

Despite the application of a combined methodological approach, this study is associated with certain limitations and assumptions that should be taken into account when interpreting the results. They stem from the nature of the data used, the specificities of the sample, the research design chosen and the analytical methods applied.

The study is based on a combination of primary and secondary data. The primary information is collected through a survey and includes assessments, attitudes and perceptions of farmers, which suggests the presence of a subjective element. Secondary data are extracted from scientific publications, institutional sources and statistical databases, including the Ministry of Agriculture, the NSI, Eurostat and FAO. Therefore, some of the outcomes related to perceived benefits, limitations and willingness to deploy unmanned technologies should be interpreted as indicative assessments and not as directly proven causal dependencies.

The empirical analysis is based on 35 valid answers, and the sample includes farms of different sizes, but with a stronger representation of medium and large farms. This creates a risk of distortion of results in the direction of higher technological readiness and investment capacity. Due to the limited size and structure of the sample, the results cannot be statistically summarized for the entire general population of agricultural holdings in Bulgaria, but mainly allow for the identification of trends and dependencies.

Initially, the study envisaged conducting economic experimental field trials (EEFT), based on the principles of experimental economics through the formation of control and test groups on real farms. The implementation of this framework was hampered by restrictions during the COVID-19 pandemic, which did not allow controlled experiments to take place. As a result, the analysis is based on survey data, observations, participation in demonstration trials and secondary sources, rather than directly measured experimental results.

The analysis is focused on a model crop - maize, chosen because of its wide distribution and the potential for the implementation of unmanned technologies. This limits the possibility for the results to be automatically transferred to other crops with different production and technological specifics. In addition, specific pricing, technological and organisational assumptions reflecting a particular market and economic context are used in the analysis.

The main assumptions of the study include the adoption of functional comparability between conventional and unmanned solutions in certain production operations, the use of specific technological and price parameters, as well as the choice of corn as a model crop for assessing the possibilities for the implementation of unmanned technologies in Bulgarian agriculture.

The use of a combined methodological approach allows complementarity and triangulation of the results from different sources and analytical methods, which contributes to a more balanced and comprehensive assessment of the problems under study.

III. EMPIRICAL RESEARCH

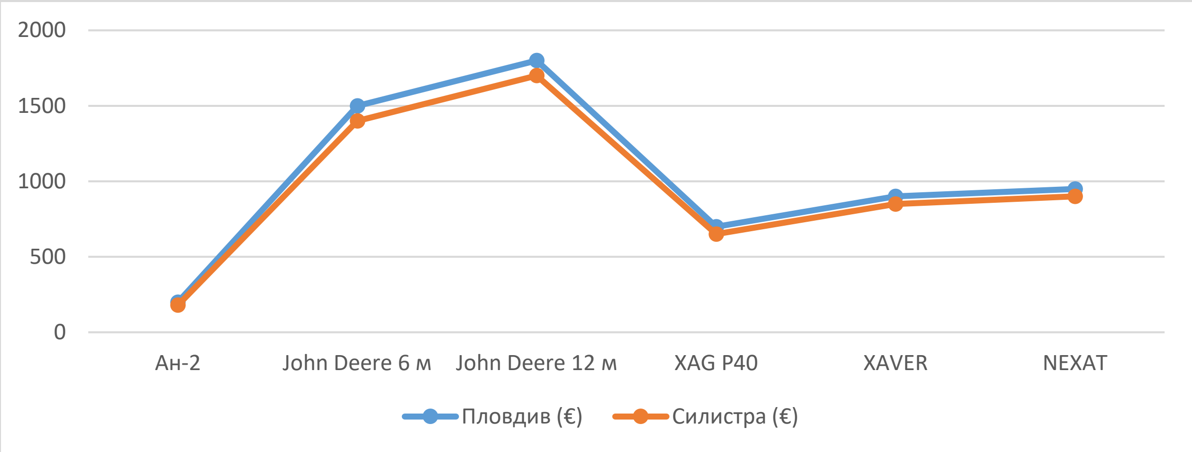
3.1. Economic Assessment of Unmanned and Conventional Technologies

Based on the developed methodological framework, a case study of corn production in Bulgaria was carried out in order to assess the economic feasibility of unmanned technologies compared to conventional solutions. The analysis covers the direct production and transaction costs associated with the implementation, use, training, coordination and management of the various technological configurations.

The results show that the costs of the main inputs of seeds, fertilisers and plant protection products remain similar between technologies. Significant differences are mainly formed in the costs of spraying, fuel/energy and technological implementation. The highest costs are observed in aviation technology, while drones and tractor trailed solutions achieve lower values per unit area.

The economic effect of unmanned technologies is mostly manifested through optimization of the "spraying" operation, reduction of overlap, more precise application of resources and lower energy intensity. Transaction costs are also essential. In the 'purchase' model, they are higher due to the need for integration, training and support, while in the 'service' or 'rental' model, part of these costs are transferred to an external supplier. The choice of technology directly depends on the scale of the farm: in small and medium-sized farms, services and rent are more suitable, and in larger farms, investment in own equipment can be economically justified.

Figure 1: Graphical presentation of transaction costs by technologies used in Plovdiv and Silistra regions



Source: own research

The graphical presentation shows that technologies with a higher degree of automation require higher upfront and organizational costs but offer the potential for long-term resource optimization.

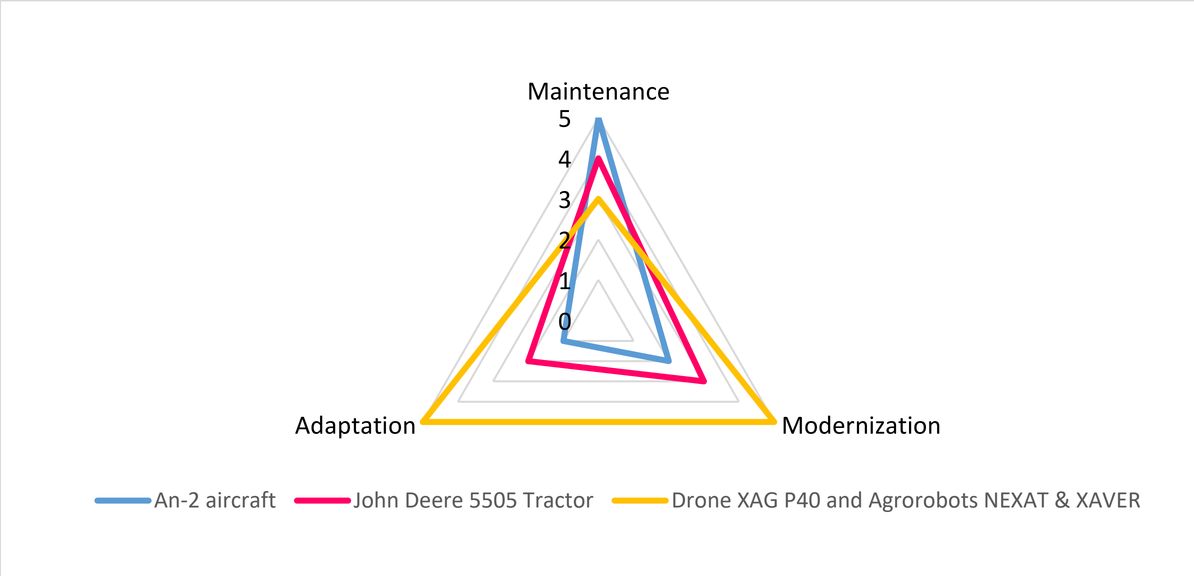
In summary, the cost-effectiveness of unmanned technologies is determined by both direct production costs and transaction costs and the access model. The hybrid model is regarded as an integrated approach that combines the advantages of both models in order to achieve greater efficiency and sustainability in their application. The most effective approach is the model in which unmanned technologies are applied selectively in activities with high optimization potential, while conventional mechanization retains its leading role in the implementation of core field operations.

3.2. Impact of unmanned technologies on production efficiency

Production efficiency is evaluated through indicators of productivity, time efficiency, adaptability and impact on yield. It is considered as the ability to carry out agrotechnical operations in a timely, accurate and resource-efficient manner. The results show a clear distinction between the technologies. Aviation technology provides the highest area productivity and the shortest processing time, which makes it suitable for large areas and short agrotechnical windows. However, this advantage is accompanied by higher energy intensity and lower precision.

Tractor configurations show a positive effect of a larger working width, which increases productivity and reduces consumption per unit area. The XAG P40 drone has a lower area performance, but is distinguished by high accuracy, low energy consumption and good applicability in fragmented or hard-to-reach terrains. The NEXAT and XAVER robotic systems have lower current performance, but offer automation, repeatability and long-term optimization potential.

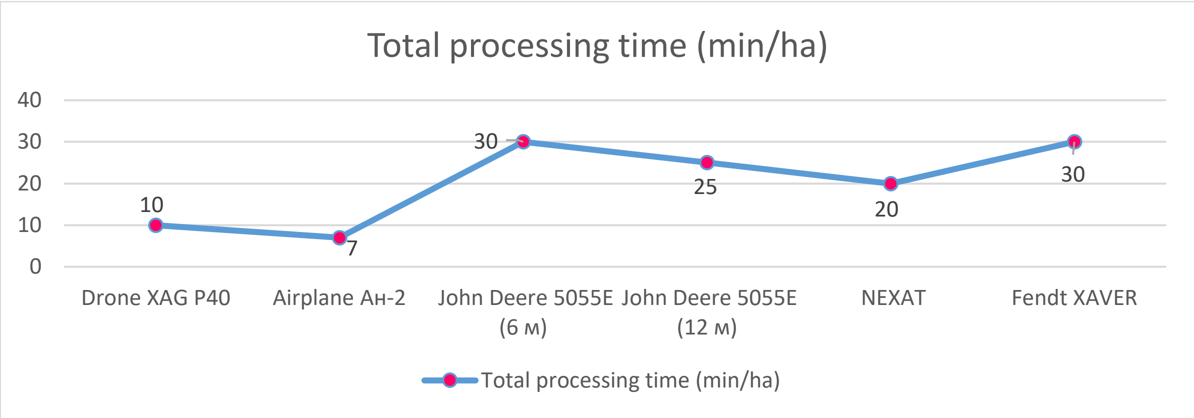
Figure 2: Visualizations of the factor's maintenance, modernization and adaptation of unmanned and conventional technology



Source: own research

The analysis shows that unmanned and robotic technologies have a higher potential for modernization and adaptation, while conventional solutions are more limited but easier to manage organizationally. A positive relationship between technological precision and production result has been established. Unmanned and autonomous technologies create prerequisites for higher yields through better compliance with agrotechnical deadlines and more precise application of resources.

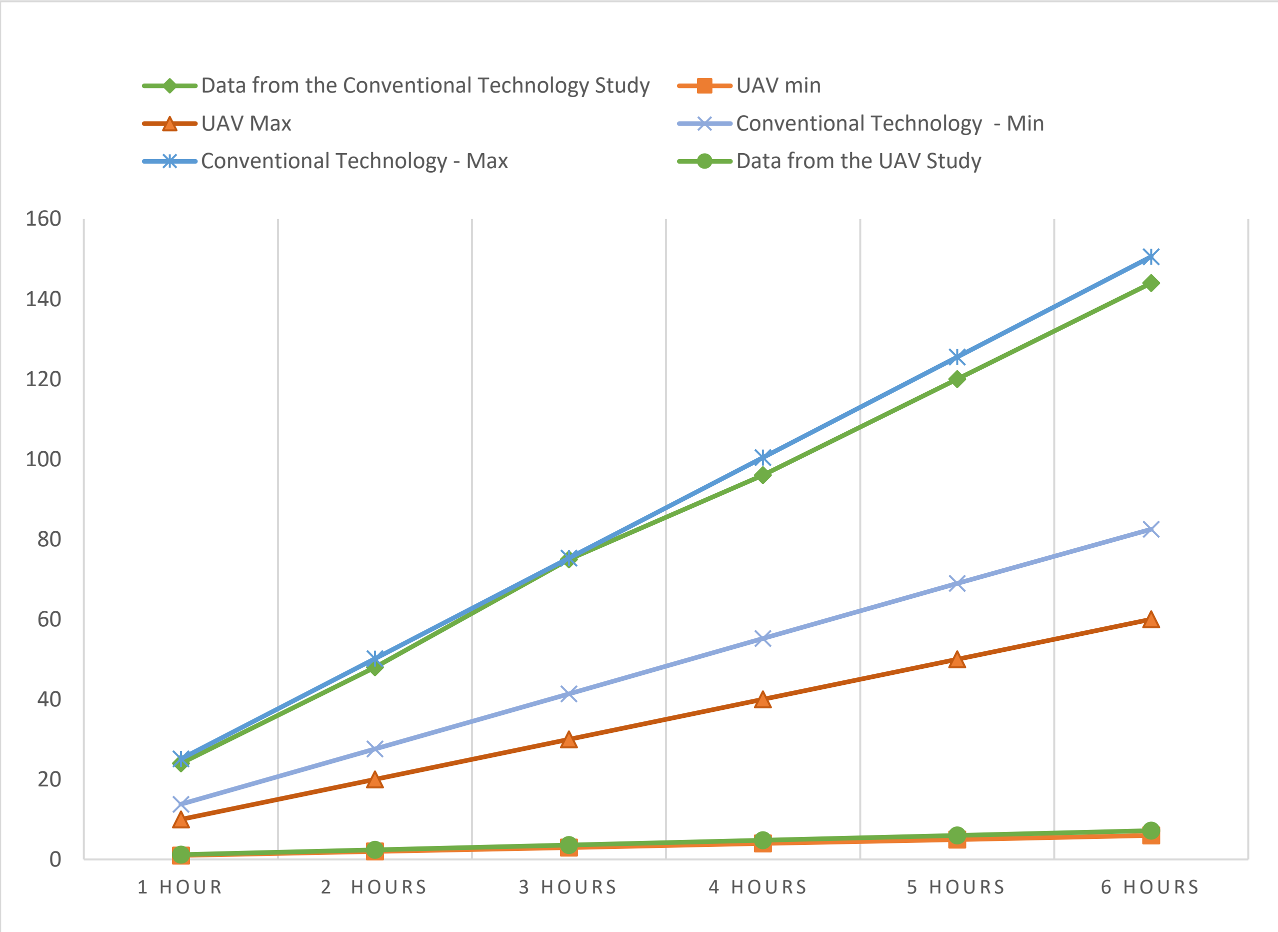
Figure 3: Production function with time factors in comparative analysis of conventional and unmanned spraying technology



Source: own research

Observations on the application regarding fastes processing time show that maximum speed and maximum precision may not match in all cases. However aviation and drone technologies are more suitable for short agrotechnical windows, while tractor and robotic solutions provide greater stability and control.

Figure 4: Comparison of area (acres per hour) of conventional field sprayers and unmanned aerial vehicles (UAVs) with sprayers



Source: Data from our own case study. Ordinate: The covered area (in hectares). Abscissa: Spray Hours

In summary, conventional technologies retain an advantage in terms of area productivity, while unmanned and autonomous systems have a higher potential for precision, flexibility and adaptability. The most effective is the hybrid model, which combines the advantages of both approaches.

3.3. Environmental effects of the application of unmanned technologies

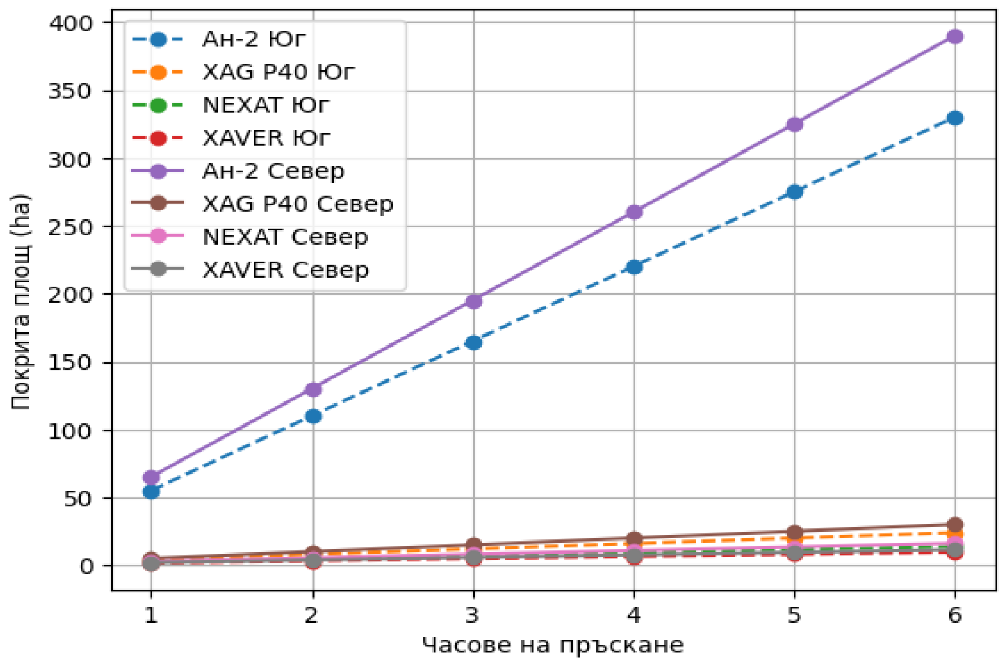
Environmental effects were analyzed using indicators of soil compression, overlap, spray drift and energy intensity. Environmental efficiency is seen as the ability of technology to limit the negative impact on the environment while maintaining production results.

Soil compression is a key environmental indicator, as it affects soil porosity, aeration, infiltration, and long-term productivity. Unmanned aerial technologies, the XAG P40 drone and the An-2 aircraft practically eliminate the risk of compression, since they have no contact with the soil. Robotic systems occupy an intermediate position: XAVER has minimal impact, while NEXAT concentrates the load through controlled movement and long permanent fixed lineal leaving 95 % of the arable soil uncompacted.

Conventional technologies demonstrate high area productivity in well-configured areas, but this advantage does not take into account environmental factors such as overlap, drift and impact on the soil. Unmanned technologies feature high precision thanks to GPS and RTK navigation, which reduces overlap, application losses and energy consumption.

In the analysis of the production function with a "time" factor, the dynamics of the cultivated area under conventional and unmanned technologies in Northern and Southern Bulgaria were studied spraying part of the production process. The comparison was made on the basis of empirical data from two farms in the village of Boyanovo and the district of Silistra, which allows taking into account the regional differences in the structure of agricultural areas.

Figure 5: Comparison of area productivity with conventional and unmanned technologies in Northern and Southern Bulgaria



Source: own case study research

The data show a linear relationship between working hours and cultivated area across all technologies, but also significant differences between regions. The An-2 aircraft has the highest area capacity of up to 330 ha in 6 hours in Southern Bulgaria and up to 390 ha in Northern Bulgaria. This is due to the large working width and high speed, especially in large and compact units. The XAG P40 drone occupies an intermediate position, while NEXAT and XAVER have lower values, but offer higher precision, lower resource consumption and a more favorable environmental profile.

On a regional basis, higher productivity is found in Northern Bulgaria due to the larger and more compact areas in the region of Silistra. In southern Bulgaria, where terrain is more fragmented, the relative advantage of unmanned technology is increasing in operations requiring accuracy and adaptability.

In summary, conventional technologies have an advantage in area productivity, especially in Northern Bulgaria, while unmanned technologies are more effective in precision operations and complex terrain conditions typical of Southern Bulgaria.

3.4. Social and organizational aspects of implementing unmanned technologies

The implementation depends not only on their technical and economic characteristics, but also on the social and organizational conditions on the farms. Important factors are producer attitudes, perceived risk, trust in digital technologies, access to training, institutional support and organisational capacity. Social acceptance is related to the willingness of farmers to change established practices. The implementation of drones and agrorobots is not only a technical, but also an organizational solution that requires new knowledge, adaptation of work processes and restructuring of activities.

Organizational capacity, technical support, management readiness and personnel with digital skills are of key importance. The transition to digital agriculture is changing work processes and strengthening the role of data in management.

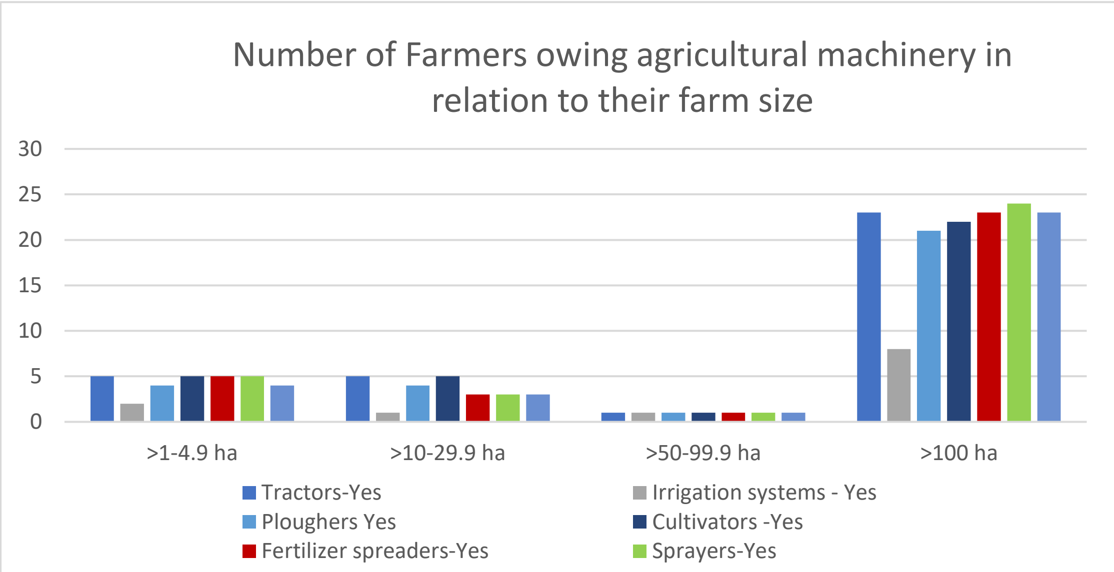
Training and consultancy support reduce uncertainty and accelerate technology adoption. The lack of practical experience and information remains a significant barrier, while demonstration activities and expert assistance facilitate adaptation.

The implementation of unmanned technologies is a complex process dependent on the interaction between technological, economic, social and institutional factors. Successful integration requires the development of human capital, organizational capacity and a supportive institutional environment.

3.5. Results of the survey among farmers

To verify the social and organizational factors, a survey was conducted among maize farmers. The aim was to establish attitudes towards unmanned technologies, perceived benefits and limitations, investment readiness and differences according to the characteristics of farms. The results show a concentration of corn production in Northern Bulgaria, where larger farms with higher mechanization and better access to investment prevail. In Southern Bulgaria, farms are smaller and with lower mechanization, which limits the direct implementation of capital-intensive technologies. Larger farms have a more developed machinery park, while small and some medium-sized farms are more suitable for services, shared use and cooperative access.

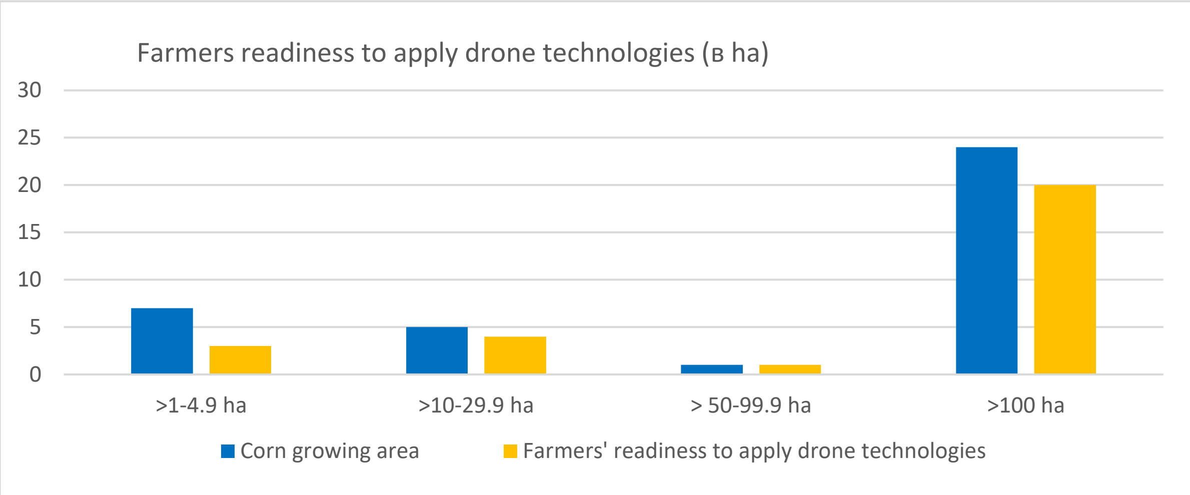
Figure 6: Owned agricultural machinery of the interviewed maize growers



Source: Data from its own study. Ordinate: Number of agricultural holdings. Abscissa: Farm Executions

The data show that technical equipment status increases with the size of the farm, which confirming the importance of scale for technological modernization. The main limitations to implementation are the high cost, insufficient practical experience, lack of training and administrative burden. With agrorobots, technological complexity and investment uncertainty are of additional importance.

Figure 7: Farmers' willingness to use sustainable technologies according to the size of the cultivated area (ha)



Source: Data from own research. Ordinate: Number of agricultural holdings. Abscissa: Intentions/willingness of maize farmers (grouped by strata) to apply BT

The χ^2 independence test carried out shows that there is no statistically significant relationship between farm size and readiness to deploy unmanned technologies, as $p = 0.839 > 0.05$. This means that interest in them is determined not only by scale, but also by awareness, expected economic impact, access to finance and practical experience. About 71.4% of respondents declare their intention to use drones, while the share of agrorobots is 54.1%. Drones are perceived as a more affordable and applicable solution in the short term, and agrorobots as a longer-term perspective. The strongest interest is in monitoring, plant protection, pest control and optimization of agrotechnical operations.

In summary, the survey shows a positive attitude towards the implementation of unmanned technologies in corn production, but the main barriers remain the high cost, lack of practical experience, insufficient training and administrative burden.

3.6. Regulatory, institutional and market barriers to deployment

The integration of unmanned technologies depends on the institutional environment that determines the conditions for their use. The analysis is based on the concepts of transaction costs, property rights, and market failures.

The results show an asymmetry in the regulatory framework. The use of drones is relatively well regulated by European legislation, while agrorobots and autonomous ground systems fall into a more fragmented legal environment. Lack of clarity on safety, liability, certification and operation creates institutional uncertainty.

Table 1: SWOT analysis of the institutional and regulatory environment for unmanned technology in Bulgaria

Strengths	Weaknesses
Compliance with European regulations Improved precision in agriculture Supporting innovation Established structure for registration and training	Complexity of administrative procedures Limited access to training Expensive equipment Lack of awareness
Opportunities	**Threats**
Increasing efficiency in agriculture. Expansion of training programs Access to additional funding Development of specialized geofences	Regulatory uncertainty Competition from other technologies Cybersecurity risks Insufficient infrastructure in rural areas

Source: Data from our own study

The SWOT analysis shows that the strengths are related to compliance with European regulations, support for innovation and opportunities to increase precision. Weaknesses include administrative complexity, limited access to training, high cost of equipment, and insufficient awareness. The opportunities are related to European funding, training programs, specialized geofences and the expansion of precision agriculture, and the threats of regulatory uncertainty, cyber risks, dependence on external suppliers and weak infrastructure in rural areas.

Administrative procedures, registration, licences, operator training and data management increase transaction costs, especially for small and medium-sized farms. Also an important issue is the ambiguity about the ownership and use of data generated by drones and digital systems. Market constraints are manifested through limited access to finance, underdeveloped markets for specialised services and uneven technological infrastructure. For some farms, therefore, external services, rent, shared use and cooperative forms are more suitable.

The convergent findings confirm the importance of farm size, investment capacity, digital infrastructure and institutional support. Divergent aspects show that drones are more flexible and affordable for medium-sized and fragmented farms, while robotic systems are more suitable for large and capital-backed producers.

In summary, the successful integration of drone technologies depends on a balance between technological capabilities, economic feasibility, social readiness and institutional support. Their deployment should be a step-by-step process based on business logic, digital infrastructure, training and targeted public policy.

IV. STRATEGIC PERSPECTIVES AND MODELS FOR THE IMPLEMENTATION OF UNMANNED TECHNOLOGIES

4.1. SWOT assessment of the environment for the implementation of unmanned technologies regarding intensive and extensive agricultural systems in Bulgaria

The SWOT assessment **(***see table 20 of the dissertation***)** shows that Bulgarian agriculture has significant potential for technological modernization through drones and autonomous ground systems, but this potential is unevenly distributed between different types of farms. The applicability of drone technologies depends on the scale of the farm, the degree of mechanization, investment capacity, digital preparation and institutional support.

In intensive agriculture, typical for larger and highly productive farms, unmanned technologies have the highest applicability. They contribute to increasing production efficiency, optimizing resources, reducing costs and expanding precision agriculture. The large scale allows for faster return of investment (ROI) and easier integration of drones and agrorobots.

In extensive agriculture, deployment is more limited due to the smaller scale of farms, lower mechanisation, limited access to finance, insufficient technological preparation and weaker data capacity. Demographic problems in rural areas have an additional impact.

For smaller and extensive holdings, flexible models such as external services, shared use of machinery, cooperative forms and regional demonstration projects are therefore more suitable. They reduce investment risk and facilitate access to innovative solutions.

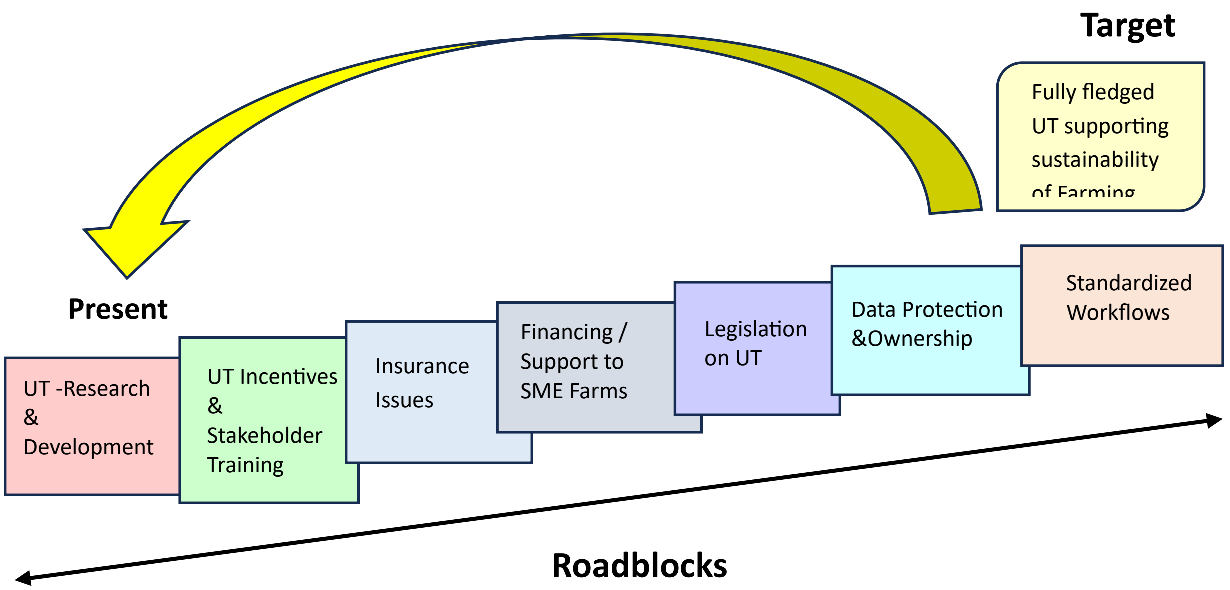
4.2. Opportunities for the development of unmanned technologies in Bulgarian agriculture

The development of unmanned technologies depends on the interaction between economic, institutional, technological and social factors. A clear regulatory framework, access to investment resources, digital competences, digital infrastructure and data governance and protection rules are key. The analysis shows that the implementation in Bulgaria will most often be realized through flexible organizational forms of external services, shared use of equipment and cooperative models. This is due to the dual structure of the agricultural sector, in which there are many small farms and large production units.

The developed risk profile includes investment, technology, personnel, regulatory, cybernetic and climate risk. The most significant are high initial costs, uncertain returns, shortage of specialists, dependence on external suppliers and uncertainties in the regulatory framework. On this basis, four development scenarios have been formulated. The first envisages the preservation of traditional agriculture but carries the risk of technological lag. The second is related to the partial and phased implementation of unmanned technologies in activities with high added value. The third implies a complete digital transformation but requires significant investment and strong institutional support. The fourth is a hybrid model, in which unmanned technologies are gradually introduced into existing production systems.

Comparative analysis shows that it is the hybrid model that is most realistic in the short and medium term, as it combines the advantages of conventional mechanization and innovative technologies, while reducing investment risk.

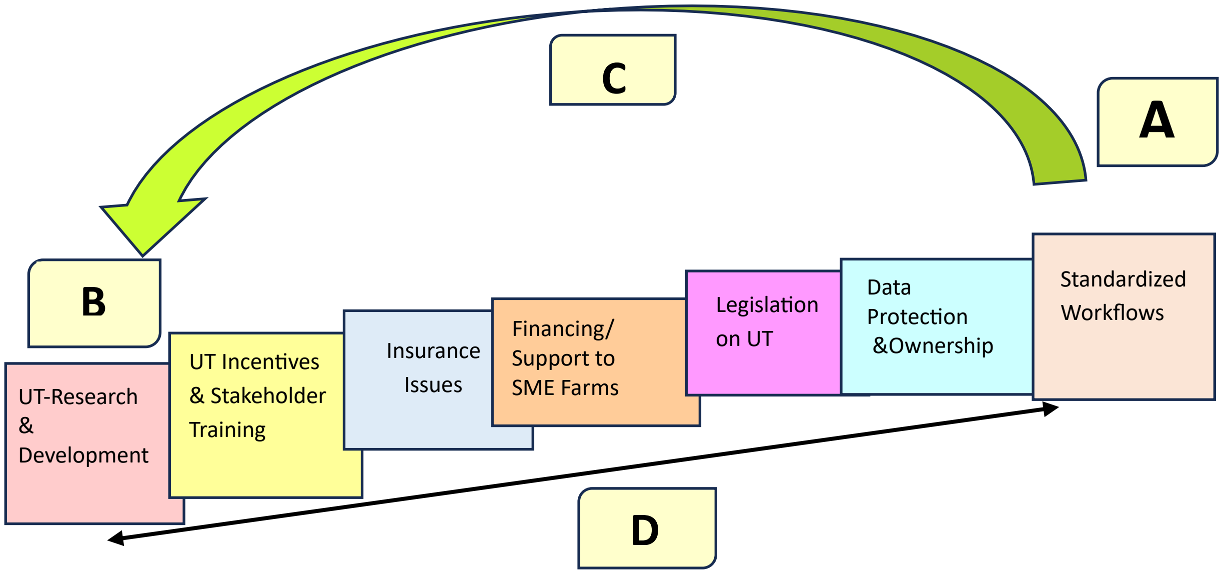
Figure 8: Diagram of the Inverse forecasting method used for the implementation of unmanned technologies



Source: Data from our own study

The reverse forecasting method outlines the main stages for achieving the desired future state of research, training, financial support and regulatory regulation. The analysis shows that the lack of standardized procedures and lengthy regulatory processes can slow down implementation.

Figure 9: Diagram of the ABCD method



Source: Data from our own study

The ABCD method structures the process into four stages: formulating a vision, assessing the current state, developing solutions and setting priorities. The results show that successful integration depends on the simultaneous development of scientific base, human capital, financial access and regulatory certainty.

The scenario analysis of costs has been applied as a tool to assess the economic efficiency of the deployment of unmanned aerial vehicles (UAVs) in agricultural production. By comparing conventional technology and different levels of partial deployment of UAVs (0-80%), the cost per unit area for individual agrotechnical operations, using a hybrid approach, is calculated.

The results show that the optimization potential is mainly concentrated in spraying and fertilizing, while the main field activities remain dependent on conventional mechanization. It is found that with an increase in the share of unmanned technologies, overall costs decrease, which confirms the existence of a positive economic effect.

In summary, the most effective is the hybrid deployment model, which allows the selective use of UAVs, reduction of investment risk and gradual technological adaptation, while contributing to increasing the competitiveness of agricultural holdings.

4.3. Author's tool for assessing the applicability of unmanned technologies at business level

The main objective of the developed tool is to provide a practical assessment model through which farmers can analyze the applicability of a particular technology to the characteristics of their farm, compare different technological alternatives and obtain a summary assessment of the effectiveness and sustainability of the investment.

The instrument is conceptually linked to the sustainable development approach and integrates the economic, environmental and social dimensions, complemented by the institutional and technological context. In this sense, it represents a practical interpretation of the scientific results of the dissertation research in the form of an applicable analytical model.

The structure of the instrument is consistent with the principles of sustainable development and is conceptually linked to the UN Sustainable Development Goals (SDGs), with economic criteria (link to SDG 8 and SDG 9) reflecting the objectives related to economic growth and innovation, environmental (link to SDG 12, SDG 13 and SDG 15) to sustainable resource management and environmental protection, and social (link to SDG 4 and SDG 10) with the development of human capital and social sustainability. This allows for the integration of global sustainable development goals into the process of evaluating technological solutions at the farm level. In this way, the tool integrates the global Sustainable Development Goals into the process of evaluating technological solutions at the farm level. Methodologically, the instrument combines a linear structure of indicators and the method of weight sum. The evaluation is carried out on a scale from -3 to +3, with negative values indicating an adverse influence, and positive values indicating a higher degree of correspondence between the technology and the characteristics of the farm.

In the basic version of the instrument, the weights are distributed as follows: economic criteria - 53.3%, environmental criteria - 26.7% and social - 20.0%. This distribution is derived based on the results of the empirical research carried out within the framework of the dissertation, as well as on the logic of the process of technological implementation at the farm level.

Economic criteria receive the highest weight 53.3%, because in the conditions of Bulgarian agriculture, it is financial expediency that is the most common primary motive when deciding on the implementation of a new technology.

Table 2: Design of an instrumental model for self-assessment of the sustainability of agricultural holdings in Bulgaria based on the models of linear description and weight sum.

Self-Assessment Guide for stakeholders regarding the Sustainability assessment of innovative agricultural machinery including the application of Unmanned Technologies (Model-Template)																
Assessment Aspects of Agricultural Sustainability		Individual Score Weight of Criterium (in %)	*Negative Scores for meeting the expectations of Stakeholders*					*Optimum*	*Positive Scores for meeting the expectations of Stakeholders*					Unweighted Total Score	Weighted Total Scores of Assessment	*Comments*
Criterium			Characteristics/ Traits of criterium	Summary Negative Scores	-3	-2	-1	0	1	2	3	Summary Positive Scores	Characteristics/ Traits of criterium			
Economic	C1	50	high	-3	-3							0	low	-3	-1.5	Please
	C2	5	don't like	0						2		2	like	-2	0	Please
	C3			0										0		Please
	Cn...	X3		-3	-3							0		-3		Please
Ecological	C1										3	-3		-3		Please
	C2			1	3	2						0		1		Please
	C3			0								0		0		Please
	Cn...			0								0		0		Please
Social	C1			0								0		0		Please
	C2			0								0		0		Please
	C3			0								0		0		Please
	Cn...			0								0		0		Please
Total Scores of Assessment		100%												100%		

Source: Data from the doctoral student's own research and author's development

The analysis of the survey results shows that high investment costs, access to finance, payback period and the risk of inefficient investment are among the most significant factors that determine farmers' behaviour. This is particularly true for small and medium-sized farms, which are more sensitive to capital risk and limited access to credit and investment resources.

Environmental criteria receive 26.7% as their importance increases in the context of European green transformation policies, precision agriculture and sustainable management of natural resources. However, at individual farm level, environmental benefits are often perceived as secondary to economic justification, except in the case of organic production, environmental certification or participation in specialised measures and schemes.

Social criteria receive 20.0% because they affect occupational safety, the need for training, the quality of the working environment and the transformation of work functions. Although they are not a leading motive for investment, their role is significant in the conditions of labor shortage, the need for qualification and increased safety requirements when working with detergents and equipment. The proposed scheme is a flexible basic model that can be adapted to the specificities of a particular farm. For example:

1. in the case **of small farms** , the weight of economic criteria may increase;

2.in the case **of organic farms**, the burden of environmental performance may be increased;

3.In **large high-tech farms** , the importance of automation, data integration and operational efficiency can be increased.

The proposed weighting system is a flexible model that can be adapted to the specifics of the specific farm. For example, in the case of small farms, economic criteria may carry more weight, while in the case of organic farms, the importance of environmental performance increases.

The developed applicability matrix is based on the results of economic analysis, survey research and strategic methods. Its construction takes into account the size of the farm, mechanization, investment capacity, organizational readiness and access to technology.

The matrix shows that small farms are more suitable for using external services with a drone, medium-sized farms for a combined model, and large and capital-backed farms for the integration of drones, autonomous systems and platforms for precision farming.

Table 3: Example of application of the author's tool for self-assessment of technological alternatives in agriculture

Group criteria	Weight %	Rating Assessment Alternative A (Own drone)	Weighted value	Rating Assessment Alternative B (external drone service)	Weighted value
Economical	0,533	2	1,07	3	1,60
Eco-friendly	0,267	2	0,53	2	0,53
Social	0,200	1	0,20	1	0,20
General assessment	**100**	-	**1,80**	-	**2,33**

Source: Author's development based on the model for assessing the applicability of innovative technologies.

The above example compares two alternatives: own investment in a drone and the use of an external service. The results obtained show that both are applicable, but the external service receives a higher overall rating due to lower financial risk, lack of significant upfront costs and lower requirements for technical and organizational capacity.

In summary, the developed tool represents a significant author's contribution, as it builds a practical connection between the theoretical analysis of the sustainable implementation of technologies and the real management decisions at the level of agriculture. Through it, scientific statements and research results are transformed into an applicable analytical model, supporting the process of evaluation and selection between different technological alternatives.

The integration of a system of criteria, justified weights and an indicative application mechanism shows that the tool goes beyond a conceptual model and takes on the character of a practically applicable tool for analysis and decision-making. Its structure allows adaptation to different types of farms, production conditions and technological solutions.

In this way, the instrument creates the basis for a step-by-step, economically justified and strategically oriented integration of unmanned technologies in Bulgarian agriculture, while taking into account the economic, environmental, social and institutional aspects of sustainable development.

V. CONCLUSIONS AND RECOMMENDATIONS

Based on the analysis carried out, it can be summarized that the sustainable implementation of unmanned technologies in Bulgarian agriculture requires coordinated actions at institutional, sectoral and economic level. Technological transformation should be seen as a step-by-step process encompassing production practices, resource management, work organisation and the institutional environment.

The main conclusion is that the hybrid model is the most suitable for Bulgarian conditions, in which unmanned technologies are selectively used in activities with high added value, and conventional mechanization retains a role in the main field operations. This approach reduces investment risk, allows for the accumulation of experience and creates conditions for gradual modernization.

The main barriers are related to high upfront costs, digital skills shortages, limited service infrastructure, administrative burdens and uncertainties around data management and protection. Therefore, successful implementation requires not only investments in technology, but also in knowledge, training, organization and management capacity.

At the institutional level, it is recommended to improve the regulatory framework for drones and autonomous ground systems, reduce the administrative burden and develop targeted financial instruments such as subsidies, grants, vouchers, preferential loans and shared financing.

At sectoral level, the development of technology-as-a-service models, cooperative forms of technology use and regional demonstration centres are needed. This is particularly important for small and medium-sized farms, which can access technology without significant own investment.

At farm level, a phased deployment is recommended after an individual assessment of economic feasibility, frequency of use, organisational capacity and expected returns. The greatest effect is achieved when drones and agrorobots are integrated into a system for monitoring, data analysis, resource management and control of production risks.

In conclusion, unmanned technologies can become a real tool for modernization, resource efficiency and competitiveness of Bulgarian agriculture only by combining a predictable regulatory environment, access to funding, practical trainings, sectoral cooperation and strategic adaptation at farm level.

VI. CONTRIBUTIONS OF THE DISSERTATION RESEARCH AND APPLICABILITY OF THE RESEARCH RESULTS

Scientific and theoretical contributions

As a result of the dissertation research, the following scientific theoretical contributions can be formulated:

1. An integrated conceptual framework for analysis of the implementation of unmanned technologies in agriculture has been developed, which brings together economic, production, environmental, social and institutional factors. This framework builds on existing approaches and considers the process of technological adaptation as a complex and multifactorial phenomenon.
2. The theoretical understanding of the role of the institutional environment in the implementation of innovations in the agricultural sector through the application of concepts from the institutional economy, including transaction costs, property rights and market failures, in the context of unmanned technologies is enriched.
3. It has been proven that the deployment of unmanned technologies does not follow a universal model, but is a differentiated process depending on the structural characteristics of agricultural holdings, including size, level of mechanization, investment capacity and organizational readiness.
4. A theoretical formulation for a hybrid model of technological integration has been developed, in which unmanned technologies are combined with conventional mechanization, thus ensuring a balance between innovation, economic efficiency and manageable risk.
5. The theoretical understanding of the relationship between precision agriculture and unmanned technologies has been expanded, with the latter seen not as stand-alone solutions but as part of a wider digital ecosystem for managing agricultural production.

Scientific and applied contributions

On the basis of the research conducted, the following scientific and applied contributions have been made:

1. An author's tool for assessing the applicability of unmanned technologies at the level of agriculture has been developed, which allows a comparative analysis of technological alternatives by integrating economic, environmental, social and institutional criteria.
2. A matrix has been created for the selection of technological solutions according to the type of farm, which offers a differentiated approach to the implementation of unmanned technologies depending on the scale, resources and organizational capacity.
3. A scenario model for the development of unmanned technologies in Bulgarian agriculture has been developed, including four alternative scenarios that reflect different combinations of institutional support, economic profitability and technological readiness.
4. An empirical analysis of the attitudes, barriers and investment readiness of farmers has been carried out, which provides a real basis for assessing the implementation process and identifying key constraints.
5. A model has been developed for assessing the economic efficiency of the implementation of unmanned technologies by analyzing the costs and the potential for their optimization in agricultural production.
6. Practical recommendations for the sustainable deployment of unmanned technologies at three levels institutional, sectoral and economic are formulated, which can be used in the development of policies and management decisions.

Applicability of the research results

The applicability of the results of the study is expressed in the formulation of scientifically based and practically applicable guidelines for more effective implementation of unmanned technologies in Bulgarian agriculture. Based on the strategic analyses, the SWOT assessment, the scenario approach, the risk assessment and the developed implementation models, recommendations aimed at creating conditions for sustainable, cost-effective and organizationally feasible use of unmanned technologies (drones and agrorobots) in the agricultural sector are derived.

The results of the study can be used in the development of public policies, sectoral strategies and management practices related to digitalization and technological modernization of agriculture. They contribute to a deeper understanding of the factors that influence the implementation process of unmanned technologies, as well as the economic, organizational and institutional conditions necessary for their successful integration.

At the national level, the results can support the development of policies to promote precision and digital agriculture through financial incentives, investment programs, trainings and the creation of a regulatory framework for the use of unmanned systems. They can be used in the formation of strategies to increase the competitiveness of Bulgarian agriculture, to optimize resource efficiency and to stimulate sustainable production practices.

At European level, the results of the survey are in line with the priorities of the Common Agricultural Policy of the European Union, the Green Deal and strategies for digital and sustainable transition. They can serve as an analytical basis for the development of specific measures and models aimed at accelerating digitalisation in agriculture, reducing environmental pressures, using resources more efficiently and fostering innovation in the agricultural sector at European and Member State level. In this context, the deployment of drone technologies can contribute to achieving higher productivity, sustainability and adaptability of agricultural systems within the framework of European policies for smart and green agriculture.

The applicability of the results of the dissertation research also has a pronounced practical, applied, analytical and managerial nature, which is expressed in the development of the author's instrumental model for assessing the applicability and sustainability of unmanned technologies on agricultural holdings. The developed model provides a practical analytical framework for comparing different technological alternatives and assessing their economic efficiency, environmental sustainability and organizational applicability to the characteristics of a particular agricultural holding.

The model integrates economic, environmental and social criteria, complemented by the technological and institutional context, and is linked to the principles of sustainable development and the UN Sustainable Development Goals. The system of indicators and weights has been developed on the basis of the results of the empirical research and the specifics of Bulgarian agriculture.

The results of the survey can be used both at the level of agriculture and in the development of policies and programs for digitalization, technological modernization and sustainable development of agriculture. At European level, the model is applicable in the context of the Common Agricultural Policy, the Green Deal and smart and precision farming strategies.

In this sense, the developed author's tool is a practically applicable mechanism for analysis, strategic planning and decision-making at various levels related to the implementation of unmanned technologies in agriculture.

The study shows that technological transformation in agriculture is a complex and step-by-step process that affects not only production practices, but also resource management, labor organization, investment planning and adaptation to the changing market and regulatory environment. In this context, the developed models and analytical conclusions can serve as a basis for strategic decision-making both at institutional and sectoral level, as well as at the level of an individual agricultural holding, in accordance with the conditions of the agricultural sector in Bulgaria.

The systematization of recommendations in the institutional, sectoral and economic directions creates an opportunity for better coordination between public policies, market organization and management decisions of farmers. This is important for accelerating the processes of technological modernization, increasing the competitiveness of farms and limiting differences in adaptation capacity between different groups of producers.

The results of the study were popularized among the scientific community through the publication of 3 articles and 1 scientific report.

PUBLICATIONS RELATED TO THE DISSERTATION

1. Grozdanova, D., & Georgiev, M. (2021). Balance between the European Union and Bulgarian legislation as regards the agricultural land versus food sovereignty. In Proceedings of the XVII International May Conference on Strategic Management (IMCSM21) (pp. 267-277).

2. Covid-19 Measures. Institutional "Errors", Transaction Costs and Adaptation in the Agriculture. (2021). Bulgarian Journal of Agricultural Economics and Management, 66(1), 21-31. https://agriacad.eu/ojs/index.php/bjaem/article/view/2289

3. Georgiev, Minko and Grozdanova, Dafinka, Acquisition and Inheritance of Agricultural Land in Bulgaria - From Fragmentation Towards Consolidation (November 25, 2020). Journal of Agricultural and Environmental Law, Vol. 15 No. 29, pp. 66-84 (2020), Available at SSRN: https://ssrn.com/abstract=3741323

4. Georgiev, M., Grozdanova, D., Ivanova, B., Beluhova-Uzunova, R., & Shishkova, M. (2022). Agricultural land, rent seeking and transaction costs. Scientific Papers Series Management, Economic Engineering in Agriculture and Rural Development, 22(2), 345-351.