COLLECTION OF PAPERS
NEW ECONOMY
Volume 3, No. 1, 2025

THEORETICAL AND METHODOLOGICAL PRINCIPLES OF APPLICATION OF AGENT-ORIENTED APPROACH TO MODELING PROCESSES OF LOCAL HROMADAS

Yevgen Kotukh[1*], Maryna Riabokin[2]

Received 26.03.2025. | Send to review 07.04.2025. | Accepted 13.07.2025.

Original Article

[1] National Technical University "Dnipro Polytechnic", Ukraine

[2] Kyiv Institute of Business and Technology, Ukraine

***Corresponding Author:**

Yevgen Kotukh

Email: yevgenkotukh@gmail.com

JEL Classification:
H72, H73, H74, C10, C11, C41, C53

Doi: 10.61432/CPNE0301017k

UDK: 007.5:339.92

ABSTRACT
This article presents a theoretical and methodological framework for applying a multi-agent systems (MAS) approach to modeling the budgeting processes of local hromadas. MAS-based modeling enables consideration of agents' heterogeneity, bounded rationality, and dynamic interaction structures, which traditional models typically overlook. These features allow for a more realistic reproduction of economic processes at the hromada level. The study explores the potential of MAS in solving practical problems such as resource allocation optimization, strategic planning for sustainable development, and strengthening resilience to crises. Particular attention is paid to the development of a budget auction model based on game theory, where economic actors - including local government, enterprises, and residents - engage in a structured competition for resource distribution. The auction mechanism identifies production functions and utility values for each actor, enabling iterative optimization based on predefined efficiency criteria. A proposed simulation framework combines the auction logic with reinforcement learning methods (MARL), where agents improve their strategies through interaction and feedback. The article also outlines a multi-step algorithm for modeling decision-making and coordination processes within the decentralized budget structure. Ultimately, the approach offers tools for more transparent, participatory, and efficiency-driven public finance management. Its implementation can support the digital transformation of local governance, aligning resource distribution with sustainable development goals. The proposed methodology is particularly relevant in the context of Ukraine's decentralization reform and post-war recovery challenges, and it may serve as a foundation for the development of intelligent public finance systems in local hromadas.

Keywords: *multi-agent systems, local hromadas, sustainable development, horizontal alignment, resource allocation*

1. INTRODUCTION

The decentralization reform that began in Ukraine in 2014 has radically changed the system of local self-government and territorial organization of power. This large-scale transformation, based on the principles of the European Charter of Local Self-Government, aimed to transfer significant powers and resources from state bodies to local hromadas. Analyzing the path taken, we can note a number of significant achievements and certain problematic aspects that determined the results of the reform for local hromadas (Kotukh, 2020). The most obvious achievement of decentralization was a significant strengthening of the financial capacity of local hromadas. As a result of changes to the budget and tax legislation, hromadas received stable sources of revenue in the form of local taxes and fees, as well as a share of national taxes. Thanks to financial decentralization, the own revenues of local budgets increased several times compared to the pre-reform period. In particular, local budgets began to receive a significant part of the personal income tax, excise tax, single tax and other revenues. This allowed local authorities to expand financial opportunities to solve urgent problems of hromadas and invest in local development.

A key element of the reform was the formation of a new spatial basis for local self-government through the creation of capable territorial hromadas. The process of voluntary unification of territorial hromadas, and subsequently the completion of the administrative-territorial reform in 2020, led to the formation of 1,470 territorial hromadas instead of more than 11,000 small and mostly financially insolvent local councils. The consolidation of administrative-territorial units allowed to optimize the system of territorial management and increase the efficiency of resource use. This created the basis for a more rational organization of the provision of public services at the local level (Riabokin, Hordei, Novytska, Kotukh, & Kozii, 2022).

The increase in the financial capabilities of hromadas contributed to the intensification of infrastructure development at the local level. A significant number of infrastructure projects were implemented in many hromadas: repair of roads and streets, modernization of lighting and water supply systems, renovation of educational, health and cultural institutions. State support in the form of a subvention for the development of the infrastructure of united territorial hromadas, as well as funds from the State Fund for Regional Development contributed to the implementation of numerous projects that improved the quality of life in many settlements of Ukraine. Decentralization also contributed to the strengthening of local democracy and public participation in solving local issues. The expansion of local self-government powers increased the role of citizens in decision-making at the local level. In many hromadas, mechanisms for participatory budgeting, public hearings, electronic petitions and other forms of public participation were introduced. This contributed to the increase in the accountability of local authorities to citizens and the strengthening of public control over the activities of local self-government bodies. In fact, this changed the paradigm of local self-government in the financial sphere, participants in the budget process in the past became actors and subjects of the budget process.

At the same time, along with positive results, decentralization has also revealed a number of problematic aspects. The problem of managerial capacity has determined the results of decentralization for many hromadas. The shortage of qualified personnel, especially in rural and remote hromadas, limits the possibilities of strategic planning, attracting external resources and effective management. The lack of employees with project management experience, legal and economic education often does not allow to fully use the opportunities that have opened up to hromadas as a result of the reform.

The institutional incompleteness of the reform also affected its results. The unresolved issues of a clear division of powers between different levels of government, especially in the education, healthcare and social protection sectors, create additional challenges for hromadas. Often, hromadas receive new powers without appropriate financial support, which makes it difficult for them to perform their functions. The problem of harmonizing sectoral reforms (educational, medical, and administrative) with the decentralization process remains relevant for the further development of local self-government.

The financial dependence of many hromadas on transfers from the state budget is also a challenge for full decentralization. Despite the increase in their own revenues, a significant part of hromadas remains dependent on subventions and subsidies from the state budget, especially in the areas of education and healthcare. This limits the autonomy of local government and creates risks in the event of economic or political instability at the national level. Reforming the network of educational, healthcare, and cultural institutions in the context of decentralization has also proven to be a difficult task for many hromadas. The need to optimize the network of institutions, which is often accompanied by unpopular decisions to close or reorganize institutions, creates additional social tensions in hromadas. Limited resources do not allow many hromadas to provide the proper quality of services in these areas without significant state support. At the same time, the reform has revealed structural problems of regional development and deepened inequalities between different types of hromadas. To ensure comprehensive success, it is necessary to further improve inter-budgetary relations, strengthen the institutional capacity of hromadas, and continue sectoral reforms. Finding a balance between hromada autonomy and ensuring uniform standards of public service provision throughout Ukraine remains particularly relevant, especially in the context of the war, which has created an additional burden on local budgets and exacerbated regional disparities. Despite the challenges, decentralization remains one of the most successful reforms in modern Ukraine, significantly bringing the country closer to European standards of local self-government and territorial organization of power.

One of the most obvious problems was the uneven development of hromadas. Financial decentralization led to significant differentiation of hromadas in terms of budget security. Hromadas with developed industry, large enterprises or located near regional centers received significantly greater financial opportunities compared to peripheral, rural hromadas. The existing distribution mechanism seeks to completely equalize budget security, but only smoothes out the largest disparities, preserving the difference between „rich“ and „poor“ territories, is carried out according to a clear formula, is based on only one tax, which simplifies the system and does not allow taking into account many factors and aspects in the development of hromadas. Despite the mechanisms of horizontal equalization (basic and reverse subsidies), significant disparities in the development of territories remain an urgent problem. The digitalization of the state‘s financial sector, the introduction of the latest financial technologies, the accumulation and ability to process huge amounts of data, as well as artificial intelligence technologies have created the prerequisites for changing approaches and improving planning and implementation mechanisms in the budget process.

Thus, an urgent scientific and practical task is to study the possibilities of an innovative approach to modeling the economy of local hromadas, based on the use of multi-agent systems (MAS). Unlike traditional economic models, MAS allow us to take into account the heterogeneity of agents, their bounded rationality, and complex interaction networks. This provides a more realistic and detailed reproduction of economic processes at the hromada level (Muyambiri, 2025).

The aim of this study is to develop theoretical and methodological foundations for the use of multi-agent systems for modeling the budgeting process of local hromadas. The most promising applied approach in this regard is the use of game theory and the proposal of a business game in the auction format.

2. LITERATURE REVIEW

The application of agent-oriented approaches to modeling local hromada processes represents an emerging interdisciplinary field combining computer science, economics, public administration, and sustainability studies. Multi-agent systems (MAS) have emerged as powerful tools for addressing complex resource allocation problems in distributed environments. Zhang et al. (2019) provide a selective overview of multi-agent reinforcement learning (MARL), highlighting that most successful reinforcement learning applications involve multiple agents. Research demonstrates that MAS can decentralize traditional centralized resource allocation, enabling more efficient distribution across complex networks.

Studies show that multi-agent systems provide promising platforms for decentralizing resource allocation, particularly where economic dispatch and unit commitment play critical roles in system operation. Efficient resource allocation mechanisms enable proper use of limited resources to achieve optimal objectives, with game theory providing mathematical foundations for analyzing interactive behavior. Current studies indicate that MARL faces challenges including computational complexity, non-stationarity, coordination, and performance evaluation, requiring solutions for scalability and trustworthiness for practical implementation.

Participatory budgeting represents one of the most ambitious participatory innovations of recent decades, enabling hromada members to collectively decide budget allocation. Systematic literature reviews reveal that PB has evolved through various phases, focusing on democratic governance, citizen engagement, and resource allocation efficiency. Research utilizing Korean local government data demonstrates strong evidence that public participation in budgetary processes significantly affects fiscal outcomes. Studies indicate that meaningful citizen participation requires two-way dialogue between government and citizens, with public managers' perceptions significantly influencing PB process success.

Game theory has made important contributions to public economics, particularly where standard competitive models provide inadequate analytical frameworks. The Public Goods Game serves as a standard experiment for analyzing tension between individual incentives and collective benefits. Game-theoretic techniques explain various financial phenomena, including capital structure decisions and resource distribution mechanisms. Research demonstrates that rational individuals in public goods games tend to contribute fewer resources, highlighting free-rider problems in public resource allocation.

Recent advances in reinforcement learning have led to significant progress in multi-agent applications, though theoretical foundations for MARL remain relatively limited. MARL has been applied to resource allocation problems including computation offloading, energy management, and network resource distribution, with challenges remaining regarding non-stationarity and partial observability. Theoretical arguments suggest that decentralization can make government more accountable and responsive to citizens. Research indicates that centralization and decentralization represent compatible governance concepts, with public administrators driven by values such as accountability, efficiency, responsiveness, and innovation.

Various optimization mathematical models are used to model the cost allocation process. The choice of the appropriate model depends on the specifics, strategic goals, and the level of interaction between participants in financial processes. In (Kotukh & Riabokin, 2025), a comparative analysis of common models used for the allocation of investment resources and subsidies was carried out.

One of the newest and innovative approaches is multi-agent reinforcement learning (Zhou, Zhang, & Luo, 2023), which is able to adapt subsidy policies in real time based on market reactions. The use of artificial intelligence enables dynamic analysis of the optimal allocation of financial resources, but this method requires large amounts of data and complex computing resources. It is relevant in the areas of dynamic allocation of subsidies to maintain stable prices for agricultural products. Combining the capabilities of multi-agent systems (MAS) with game theory will provide hromadas with promising budgeting tools. In the context of the involvement of territorial hromadas, it can provide significant advantages when planning the involvement of new innovative approaches in investing in sustainable development projects (Riabokin & Kotukh, 2025a).

Studies demonstrate that governance quality significantly impacts public sector efficiency, with human resources, democracy, corruption, and digitalization affecting performance. Research on local government efficiency reveals significant variations in service delivery costs, with privatization and public sector reforms showing potential for cost savings. Recent approaches to public sector productivity emphasize moving beyond cost-efficiency focus toward innovation-enhancing measures and digital transformation (Lemaallem & Saadi, 2025).

Research on SDG 11 emphasizes creating inclusive, safe, resilient and sustainable cities and hromadas, with local action essential for achieving sustainable development goals. Studies demonstrate that local action can accomplish things other governance levels cannot, with proximity to problems enhancing collective motivation for sustainable solutions. Research explores how citizen-generated data can support local environmental SDG monitoring, emphasizing community participation importance in sustainability initiatives.

Current literature reveals gaps in integrating multi-agent systems with participatory governance mechanisms. While individual components have been extensively studied, limited research examines the intersection of MAS, game theory, and participatory budgeting in local hromada contexts. Research suggests that achieving SDGs requires alignment between conceptualization, implementation, and evaluation, with transformative learning and robust partnerships across sectors. Future studies should focus on empirical validation of theoretical models in real-world local governance settings and examine how digital transformation can enhance participatory processes while maintaining democratic legitimacy and hromada ownership.

The literature reveals growing recognition of agent-based approaches' potential for enhancing local hromada resource allocation. While significant theoretical foundations exist across multiple disciplines, empirical evidence for integrated approaches remains limited. Future research should focus on developing and testing comprehensive frameworks that combine multi-agent systems, participatory governance, and sustainable development objectives in local hromada contexts.

3.MATERIALS AND METHODS

The result of the functioning of the economy is the production and distribution of goods that form product flows. The annual period of economic planning for most economic actors is determined by a number of historical, legal, organizational and psychological factors. First of all, the legal and fiscal system in most countries of the world, including Ukraine, is built on the annual budget cycle. The fiscal year as the basis of budget planning and reporting sets the time frame for state bodies, which are subsequently projected onto other economic actors. Tax reporting and obligations associated with fiscal periods encourage enterprises and organizations to synchronize their own planning cycles with the budget year. It is obvious that budget processes are continuously linked to economic processes and relations.

One of the most important characteristics that determine the economic potential and capabilities of an enterprise is its production function. The production function hereinafter refers to the relationship between the quantity of products produced of a given quality and the resources spent on their production. It is determined by both endogenous and exogenous factors that control the production process. Endogenous factors include: equipment with basic equipment and organization of the technological process, which ensures the efficient use of equipment for processing incoming resources, and availability of production personnel. Exogenous factors include the demand for products, prices for products and resources, which are determined by market conditions, as well as the tax policy of the state, and in exceptional cases, a government order, which is usually distributed on a competitive basis.

Each change in the model of manufactured products causes a change in the internal environment of the enterprise. These changes are accompanied by social processes of a local nature, which are projected on the market as a whole. Usually, the market‘s reaction to these changes has local significance. The entire market, due to its great inertia, cannot adequately respond to rapid changes. Only a change in product generations, which affects the production activities of entire industries, is reflected in the market situation, since the creation of a new generation of products in any industry is correlated with a radical restructuring of enterprises. It is accompanied by a change in the main production equipment, in which new generation products are manufactured. The production of new types of main equipment stimulates changes in the activities of industries that produce equipment. Therefore, the social consequences of changes in the production of goods caused by the creation of new generations of products affect market processes, affect the interests of wide circles of the population and provoke industrial crises.

The changes brought about by the production of products for new purposes in a number of industries are affecting the activities of many enterprises and the economies of states. They affect the entire infrastructure of industry and inspire changes in the lives of people. The crisis caused by the restructuring of the country‘s economic infrastructure in wartime conditions is spreading to the life of territorial hromadas. There are changes in the way of life of hromadas hosting IDPs and enterprises, where new production sectors are being created, the transport system and communication system are changing, and living standards are changing. Correlated changes in industrial production of economic blocs are reflected in the development of production relations on a state scale. The destruction of established economic and social relations causes serious upheavals in the economies of countries. There is a redistribution of spheres of influence and accumulated wealth. Population migration is accelerating. Usually, under conditions of total destruction of the economic potential of certain regions, also associated with the destruction of the old way of life and production, the change in the energy base of the economy is accelerating. Restructuring, accompanied by the rise and fall of production, determines new laws of social development. All contradictions caused by changes in the economic potential of hromadas are reflected in the market. All contradictions are focused in market processes. Their diversity is dictated by the strict laws of economics.

Modern democratic processes put forward new requirements for local governance, and one of the key tools for transforming local government is participation. Participation (or participatory democracy) in local government and budget relations is an important mechanism for involving citizens in decision-making processes at the local level. This is a complex socio-political phenomenon that involves the active involvement of citizens in decision-making processes, in particular in the field of budget relations. Participation in local government is not only a management tool, but also an important step towards the development of civil society, increasing the efficiency of local government and strengthening democratic values.

The main forms of participation include several key practices. First of all, this is participatory budgeting - an innovative mechanism that allows residents to directly influence the distribution of part of the local budget. No less important are public hearings - public meetings during which residents have the opportunity to directly communicate with representatives of local authorities, discuss budget proposals and provide their own feedback. In Ukrainian realities, the legal basis for the development of participation is laid by a number of legislative acts, in particular the Law of Ukraine „On Local Self-Government", the Budget Code and methodological recommendations of the Ministry of Regional Development. The true effectiveness of participation depends on the readiness of both authorities and citizens for constructive cooperation.

Participation in budgetary relations is a modern and important element of patronizing the development of leading industries of local hromadas and concentrating in the hands of the authorities funds sufficient to meet the socio-economic needs of the community. Such a task is usually solved with the involvement of a certain circle of public experts. The competition of opinions and visions of community development of experts with the vision of representatives of local self-government bodies motivates to look at this process from the position of modeling a business game, an auction of proposals, as an optimization problem. It is in this vein that it makes sense to introduce the concept of an actor of economic relations, which are individuals (citizens) living in a local hromada, legal entities (enterprises) registered in the territory of the hromada - responsible for paying taxes on the results of their activities, as a result of the production of public goods, as well as local self-government bodies responsible for the distribution of public goods (taxes) and management of community property for the provision of public services. It is using the example of financial bodies of local hromadas that we will further explore the involvement of actors in modeling using the game.

The goal of the auction is to allocate subsidies and investments in a typical link in such a way that the efficiency of using funds that have the center of the link is maximized. This means that, taking into account the utility and limited cost of the goods (products and services) produced, the efficiency is maximized.

The calculation is carried out using the game module „auction", which is used to coordinate the interests of players and the center of any link in the expenditure part of the budget structure.

The central link organizing the game has some resource that it must distribute among the players. Each of the players is characterized by its production function, on which we are particularly interested in two points that reflect the regimes in which production volumes are minimal and maximal.

In real conditions, the player's production function is unknown to the partners. It is hidden by the player from the rest of the process participants, including the center. Therefore, at the initial stage of the game, the center must identify it for all players who represent the units involved in the distribution. (Often, the analytical expression of this function is unknown even to the players who represent this element).

In the context of the local hromada economy, the production function can be considered as a mathematical model of the relationship between the volume of public goods/services provided and the budget resources spent. We formulate the production functions of the local hromada according to the following criteria (See Table 1).

In the work (Riabokin & Kotukh, 2025b), an analysis of the compliance of the production functions of local hromadas with the goals of sustainable development was conducted. At this stage, it is advisable to introduce the concept of public product as an integrated indicator of hromada utility.

In the future, for theoretical justification by modeling the optimization of the allocation of budget funds, assessing the effectiveness of expenditures and planning hromada development, we will use this integral indicator of the above functions. However, it is quite clear that in practical application, actors of economic relations can optimize funds in terms of sustainable development goals and, under such circumstances, production functions should be considered separately, by direction, and then there will be a municipal public product, an administrative public product, an investment, a social, etc.

Table 1 - Production functions of local hromada

Function	Function description
The function of providing municipal services	the relationship between spending on a particular area and the quantity/quality of services provided.
Administrative production function	the efficiency of local government depending on administrative costs
Investment function	the relationship between capital expenditures and the infrastructure/ fixed assets created
Social production function	the relationship between social spending and social indicators (e.g., poverty level, availability of services).
Ecological function	the relationship between environmental expenditures and ecological indicators/outcomes

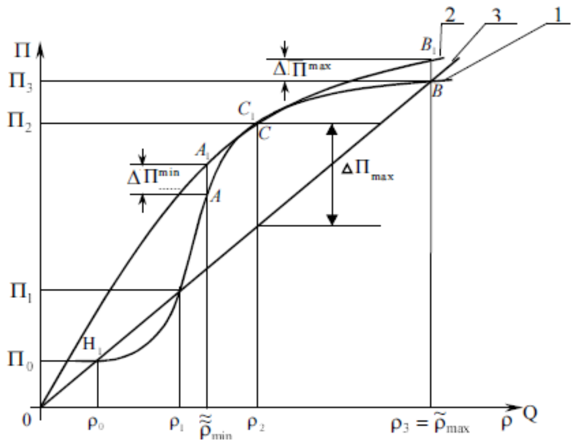
Source: developed by the authors

Thus, we conduct the simulation considering the local hromada as an economic actor with a single public product, where the price of all working capital is taken as a single resource. This, of course, will not give efficiency in optimization, but will provide an opportunity to consider the approach in general terms. Our approach is based on the proposal being considered in (Dabagyan, 2000).

In economics, the relationship between the cost of production and the price of the consumed generalized resource is expressed by the relationship $\Pi = \frac{k_1}{1 + k_2 e^{-k_3 P}}$,

where P - current cost of the product; P - cost of the resource; $k_i, i = 1,2,3$ - constant coefficients.

Figure 1 – Graph of the function of the dependence of the cost of production and the price of the product*



*Source: developed by the authors

The graph of the function is presented in Fig. 1. In Fig. P o – minimum integral indicator of product cost, P 1 – basic integral indicator of product cost, P 2 – optimal product cost; P 3 – maximum product cost;

The corresponding values of the price of resources for the production of the product are plotted on the x-axis.

With sufficient accuracy for approximate calculations at the system design stage, in the operating mode of local government functioning according to production functions, the schedule can be approximated by a power function.

When implementing the auction process, it is necessary to take into account that the volume of the public product is determined by a public resource, which can be dated from the state budget but also from the local hromadas own public funds. Therefore, the volume of the public product is a function of these sources. In general form, we present it as $\prod = f\left(\rho_{дотацій} + \rho_{власнийфонд}\right)$, where $\rho_{дотацій}$ - the amount of subsidies, $\rho_{власнийфонд}$ - the cost of own funds used for the production of the public product. In this function, the weight of $\rho_{дотацій}$ can vary from zero to 100%. Since when distributing subsidies we are interested in the efficiency of the subsidies allocated to the actor, when determining the production function, $\rho_{власнийфонд}$ we will consider the value as a constant parameter. Then the value of the public product can be represented as a function $\prod = F\left(\rho_{дотацій}\right)$, where P - the cost of the produced product, $\rho_{дотацій}$ - the amount of subsidies.

The auction game consists of two components – identification of the production functions of the actors by the center, which are refined with each step, and multi-step solution of the optimal distribution problem. By the center we mean the conditional arbiter of the game, which establishes the rules and compliance of actions with the rules. First, the initial identification of the production function for each actor is carried out in the form of a working section of its analytical expression, given by the formula $\prod_{ij} = s_{ij}\rho_{ij}^{\alpha_{ij}}$, where $\prod_{ij}$ - the cost of production produced by the j-th player of the i- ro level, ρ_{ij} - the amount of subsidy allocated to the j- ro actor of the i- ro level, s_{ij} and α_{ij} - the parameters of the production function. To highlight a working area on the production function, experts of the corresponding element of the system indicate two points where the value of the produced goods is equal to $\prod_{ij\ \min}$ and $\prod_{ij\ \max}$. For each value we can compose equalities $\prod_{ij\ \min} = s_{ij}\rho_{ij\ \min}^{\alpha_{ij}}$ and $\prod_{ij\ \max} = s_{ij}\rho_{ij\ \max}^{\alpha_{ij}}$. In this case, the parameters of the production function s_{ij} and α_{ij} are unknown and must be determined. By taking the logarithm of the ratio $\prod_{ij\ \min} = s_{ij}\rho_{ij\ \min}^{\alpha_{ij}}$ and , $\prod_{ij\ \max} = s_{ij}\rho_{ij\ \max}^{\alpha_{ij}}$ it is necessary to determine the function for each element $\prod_{ij} = s_{ij}\rho_{ij}^{\alpha_{ij}}$. To approximate the production function on the working area $\prod_{ij\ \min} - \prod_{ij\ \max}$ by the expression $\prod_{ij} = s_{ij}\rho_{ij}^{\alpha_{ij}}$, it is necessary that the angular coefficients of the points with coordinates $\prod_{\min}$, $\prod_{\max}$, $\rho_{\min}$, $\rho_{\max}$ satisfy the condition $\frac{\prod_{\min}}{\rho_{ij}} > \frac{\prod_{\max}}{\rho_{ij}}$. Secondly, based on the parameters determined s_{ij} and α_{ij} for all, j the optimal value of the functional is determined $E_i = \frac{\sum_{j=1}^{m_{ij}} s_{ij}\rho_{ij}^{\alpha_{ij}}}{P_i^0} \to \max$, where $P_i^0 = \sum_{\forall j}\rho_{ij}$. Here E_i is the efficiency of the node, which is determined by the production function, which is maximized under the constraints defined for each actor in the form of inequalities $\rho_{ij_{\min}} \le \rho_{ij} \le \rho_{ij_{\max}}$ specified by the actor in the process of identifying the production function. Another constraint is the inequality $P_i^0 = \sum_{\forall j}\rho_{ij}$ given to the center after the iteration of the game in the past. Let us write the functional in the following form using the Lagrange multiplier method:

$$\sum_{j=1}^{m_{ij}} s_{ij}\rho_{ij}^{\alpha_{ij}} + \lambda\left(m_i^0 - \sum_{j=1}^{m_{ij}}\rho_{ij}\right) \to \max, \text{ where } \rho_{ij}\Big|_{\min} < \rho_{ij} \le \rho_{ij}\Big|_{\max} \text{ and } P_i^0 = \sum_{j=1}^{m_{ij}}\rho_{ij} \quad (1)$$

At this stage, resource normalization is performed and therefore we assume that $Đ^0 = 1$. Under these conditions, the Lagrange function is defined as follows $\sum_{\forall j} {}_0 s_{ij}\rho_{ij}^{\alpha_{ij}} + \lambda\left(1 - \sum_{\forall j}\rho_{ij}\right) \to \max$, where ρ_{ij} - in this expression the values of resources are already normalized. Differentiating this function by ρ_{ij} we get ${}_0\alpha_{ij0}s_{ij}\rho_{ij}^{{}^0\alpha_{ij}-1} - \lambda = 0$, where $j = \overline{1,n_i}$ and therefore $\rho_{ij} = \left(\frac{\lambda}{{}_0\alpha_{ij0}s_{ij}}\right)^{1/{}_0\sigma_{ij}}$, where $i = \overline{1,n_i}$ and ${}_0\sigma_{ij} = {}_0\alpha_{ij} - 1$. From the condition $\sum_{\forall j}\rho_{ij} = 1$ we have $\sum_{j=1}\left(\frac{\lambda}{{}_0\alpha_{ij0}s_{ij}}\right)^{1/{}_0\sigma_{ij}} = 1$. Having solved this equation with respect to λ, we will find a solution that satisfies us, which we will substitute into ${}_0\alpha_{ij0}s_{ij}\rho_{ij}^{{}^0\alpha_{ij}-1} - \lambda = 0$ and determine the values of the resource allocation plans $Đ^0$. The solution does not satisfy the constraint $\rho_{ij_{\min}} \le \rho_{ij} \le \rho_{ij_{\max}}$. To satisfy the constraint, we will compose the sets ${}^0K_1 = \left\{\rho \mid \bar{\rho}_{ij} > \tilde{\rho}_{ij}\right\}$, ${}^0N_1 = \left\{\rho \mid \tilde{\tilde{\rho}}_{ij} \le \tilde{\rho}_j \le \tilde{\rho}_{ij}\right\}$, ${}^0K_{11} = \left\{\rho \mid \tilde{\tilde{\rho}}_{ij} > \rho_{ij}\right\}$ and ${}^0N = {}^0K_1 + {}^0N_1 + {}^0K_{11}$, where $\tilde{\tilde{\rho}}_{ij} = \left(\rho_{ij}\right)_{\min}$, $\tilde{\rho}_{ij} = \left(\rho_{ij}\right)_{\max}$, ${}^0N$ - the total number of actors of the i-th link. In order to take into account, the constraints center must first satisfy the requests of the actors included in the set ${}^0K_1$. We define a resource for the actors from this set $\hat{\rho}_{ij} = \tilde{\rho}_{ij}, \forall i \in {}^0K_1$ and then for the remaining requests actors the constraint has the following form: $\sum_{\forall j \in N \setminus K_1^0} \left(\frac{\lambda}{{}_0\alpha_{ij}{}_0 s_{ij}} \right)^{1/{}_0\sigma_{ij}} = {}^1P = P^0 - \sum_{\forall j \in K_1^0} \rho_{ij}$, where K_1^0 is the set of actors who received the maximum permissible amount of resources $\rho_{ij} = \tilde{\rho}$. Let's solve the simplified problem of optimal distribution for actors from the set $\notin K_1$. It is simplified after satisfying the requests of actors from the set K_1. The new distribution, in addition to the actors included in the set ${}^0K_1$, will contain an additional number of actors who need to be given resources in the amount of $\tilde{\rho}_{ij}$. Having satisfied all the performers who $\tilde{\rho}_{ij} < \rho^{\exists}{}_{ij}$, we will compose the sets ${}^1K_1, {}^1N_1$, where ${}^1K = {}^0K_1 + \Delta^0 K_1$, and are $\Delta^0 K_1$ the actors who reached the constraint after solving the previous problem. Repeating the approximation for the requests included in the set ${}^1K_1$, we will achieve that on the q-th approximation $\Delta^q K_1 = 0$, if under these conditions the set ${}^qK_1 \in \varnothing$, then the problem is solved. If, ${}^qK_1 \neq \varnothing$, then the problem arises, either to exclude actors from further iterations, ${}^q\rho_{ij} < \tilde{\tilde{\rho}}_{ij}$ or to allocate them additional resources (from the reserve fund of the center) in the amount $\tilde{\tilde{\rho}}_{ij}$ and continue the iterations of successive approximations. This dilemma, in our opinion, is outside the modeling process and belongs to the problems in the field of financial policy and therefore, in our opinion, is solved outside the proposed model, therefore it is not considered at this stage. Approximation iterations continue until all resources are allocated.

4.RESEARCH RESULTS

Before we consider the algorithm of the multi-agent model, let us summarize the process of the budget auction. The process of the budget auction begins with the announcement by the center of the starting values of the parameters of all actors. Then the center assigns a queue according to which it will conduct bargaining with the actors, and invites the j-th player in the queue to name new values of his parameters $\rho_{ij}, \prod_{ij}$, which, according to the strategy of the next, j-th player, should improve his state in terms of resource allocation. Before announcing a new plan, the actor estimates his capabilities. A generally accepted approach to the estimation is to calculate the production function. To determine the parameters of $\alpha_{ij} s_{ij}$ the next approximation q in $\prod_{ij\ \min} = s_{ij}\rho_{ij}^{\alpha_{ij}}{}_{\min}$ and $\prod_{ij\ \max} = s_{ij}\rho_{ij}^{\alpha_{ij}}{}_{\max}$ instead of $\prod_{\min}, \rho_{\min}, \prod_{\max}, \rho_{\max}$ iteratively substituted values $\left(\prod_{ij}^{q-1}\right)_{\min}, \left(\rho_{ij}^{q-1}\right)_{\min}$ and new proposals of the actor $\prod_{ij}^q, \rho_{ij}^q$. After that, the center calculates the next, optimal distribution. If the proposal of the j -th player increases the efficiency of the system by an amount greater than some predetermined amount δ, then the proposal of the y-th player is accepted. From this iteration, the plans $\prod_{ik}^q = f\left(\rho_{ik}^q\right), k \in \left\{\overline{1, m_{ij}}\right\} \setminus j$ of the other actors are adjusted according to the new optimal solution. If the new plan does not improve the efficiency of the system, the actor is offered to make the next attempt. However, the actor is free to announce any new plan that does not go beyond the working area of the characteristic and to demand the corresponding value of the resource. After a certain (pre-agreed) number of attempts, the center stops the dialogue with the j-th actor and announces the results of the auction. There are two possible options for the center's decision: the actor's proposal is rejected, since it does not increase the functionality of the center, or it is accepted. In this case, the distribution, which is made taking into account the new values of the parameters of the j-th player, is reported to all actors. Then the center passes the move to the next actor. After completing the first round of negotiations with all actors and correcting the plan according to acceptable amendments, the center continues the game with performers who wish to further improve the plan. Iterations continue until all actors leave the auction. After the auction ends, the center announces the agreed decision. In a single-resource problem, when only cost is considered, the change in the situation is depicted in Fig. 2, where curve 2 corresponds to the original production function of the actor. That is, the proposed solution assumes that the utility of the goods produced by all its actors is determined by their monetary value. But in reality, the utility and cost of goods may not coincide. This is easy to prove by analyzing only stable cases.

For example, Public natural resources: Forests, lakes, parks have high utility for the hromada (recreational value, ecological services, quality of life), but their market value often only takes into account potential commercial exploitation.

Historical and cultural sites: Old buildings, monuments, or local traditional practices may have relatively low market value but extremely high utility as a source of hromada identity and social cohesion.

Infrastructure with externalities: Schools, hospitals, community centers create positive externalities (better education, health, social capital) that are not fully reflected in their market valuation.

Non-profit utilities: Water systems, local transportation may have low profitability (cost), but are critical utilities for the functioning of the hromada.

Public Land: The value of common lands for grazing, local festivals, or community gatherings is difficult to quantify monetarily, although their utility for social cohesion can be high.

Public goods with time inconsistency: Investments in sustainable development, renewable energy may have low current commercial value, but high long-term utility for future generations.

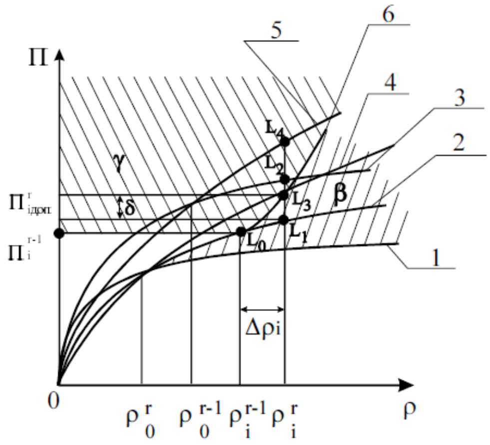
Traditional land use practices: In many hromadas, traditional forms of land use exist with low market efficiency but high socio-cultural value and environmental sustainability.

Hromada digital and information assets: Local databases, archives, and information exchange systems have high functional value, but are difficult to commercially value.

General utility theory was developed by Von Neumann allows us to model these differences through the concept of expected utility and subjective preferences, but it is important for hromadas to develop their own assessment mechanisms that take into account both economic and social, cultural and environmental dimensions of „utility" . An interesting direction for future research is the methodology for determining weighting factors that would allow us to take utility into account when conducting an auction.

Fig. 2 shows a graphical representation of the proposed scenario, where γ is the permissible and β is the forbidden regions of the scenario. Point L_0 depicts the plan proposed to the jth actor as a result of the previous solution of the optimization problem. The new proposal will change the position of the representation point: it will either remain on the old production function, or be located below or above this curve. In the first two cases, the center immediately rejects the proposed plan, since it cannot be better than the optimal one determined after the previous move (i.e., the result is either already known or belongs to the forbidden region). If the point is located above the curve, it will make a new calculation of the optimal plan for the entire system. If the calculation shows that increasing the player's plan will not lead to an improvement in the center's functional by a predetermined amount (δ >0), the proposal will be rejected. If the functional increases by an amount greater than δ, the proposal will be accepted. Depending on which of the parameters of the production function α_{ij} or s_{ij} changes in connection with the proposal of a new plan by the j-th actor, its representation point will move to one of the characteristics depicted in Fig. 2 as curves. The transition to curve 4 (point L_3) will occur with an increase in parameter s_{ij}, the point L_2 on curve 3 — with a decrease in the value of parameter α_{ij}. If it moves to curve 5 (point L_4), then both parameters will change. But even in these cases, the center can agree to a change in the plan if its functionality increases by a value greater than δ. Thus, a change in the plan acceptable to the center can occur only if the condition is met with the redistribution of the resource $0 < \delta < \delta_{ij} - \Delta_i$, where δ_{ij} is an increase in the plan of the j-th player, and Δ_i is the total decrease in the plans of the players from the set $\{j_i\} \setminus j$. In Fig. 2, such a redistribution corresponds to the representation point lying above curve 6.

Figure 2 – Graphical representation of the proposed scenario



Source: developed by the authors

Curve 6 is the locus of points dividing the entire region into two parts. It is obvious that only plans corresponding to points lying in the region above curve 6 are acceptable to the center. After the game is over, the center will determine the refined parameter values $\prod_{ij}(\rho_{ij}), \rho_{ij}$ and make a resource allocation consistent with the capabilities of all actors.

Combining the described auction algorithm with multi-agent reinforced learning methods (Multi-Agent Reinforcement Learning (MARL) could create a powerful adaptive resource allocation system. Each actor (agent performer) is implemented as a reinforcement learning agent. The center is also implemented as a center agent that optimizes the allocation rules. Agents learn to optimize their bid strategies over time. Thus, we formalize the environment and rewards through:

State – current resource allocation, requests from other agents, history of previous iterations

Action – creating a request for resources.

Reward is a combination of resources received and the implemented plan, taking into account the utility function.

In the practical part of the study, it is proposed to consider practical approaches to implementation, namely:

1. Decentralized approach (Independent Learners). In this approach, each agent autonomously learns to optimize its application strategy. This would have advantages in ease of implementation and scalability, but there may be disadvantages with learning and coordination.

2. Centralized learning, decentralized execution. Under this approach, agent training occurs centrally using complete information, and during the auction, agents act autonomously using the learned strategies. Such a solution is proposed to be built using the MADDPG, QMIX, COMA methods.

Below we present the budget auction algorithm directly. (Fig. 3). The algorithm is designed to be executed in the topology of a multi-agent system model. The role of actors here is played by the agents-executors, and the agent-center performs the functions of the center.

The dialogues of the executing agents with the agent-center begin with determining the initial parameters for the budget auction and agreeing on the cost of the goods. After that, the agent-center:

1. Announces the start of the budget auction, indicating the amount of the allocated resource.
2. Warns about the rules of the game and reminds of the penalties imposed in case of their violation.
3. Assigns a queue of dialogues with performing agents.
4. Asks, in turn, each executing agent to name the limiting values of the optimal plans for the players $\prod_{min}, \prod_{max}$ and the corresponding values of the required resources ρ_{min}, ρ_{max}.
5. Identifies for each agent -executor the values of the parameters $_0\alpha_{ij}$ and $_0 s_{ij}$ and the boundaries of the working area of the characteristic.

6. Optimizes the production plan and resource allocation based on these values.

7. Announces these values of the initial distribution plan to the executing agents, specifying the initial values of ${}^{0}\prod_{ij}$ and ${}^{0}\rho_{ij}$.

8. The agent center informs the executing agents of the planned indicators obtained at the previous stage of the procedure and invites the next executing agent to the budget auction.

9. Request from the center agent about the feasibility of changing the plan.

10. If no changes are needed, go to 13, otherwise return to 4.

11. Request from the center agent about the amount of the request for the resource.

12. Input by the jth agent-executor of his request for the resource.

13. Identification of a new production function of the agent -executor passing through the point where $\prod_{i} = \prod_{i\min}$, $\rho_i = \rho_{i\min}$ and a new point proposed by the agent -executor.

14. Calculation of the permissible production volume by the center j-th executive agent.

15. Notification by the center agent to the j-th execution agent about the possibility or impossibility of satisfying its request.

16. Request from the executing agent for an acceptable plan.

17. Notification of the agent to the center about the minimum permissible production volume j- th the agent -executor corresponding to the previously entered request for the resource.

18. Request from the center agent about the advisability of continuing the dialogue.

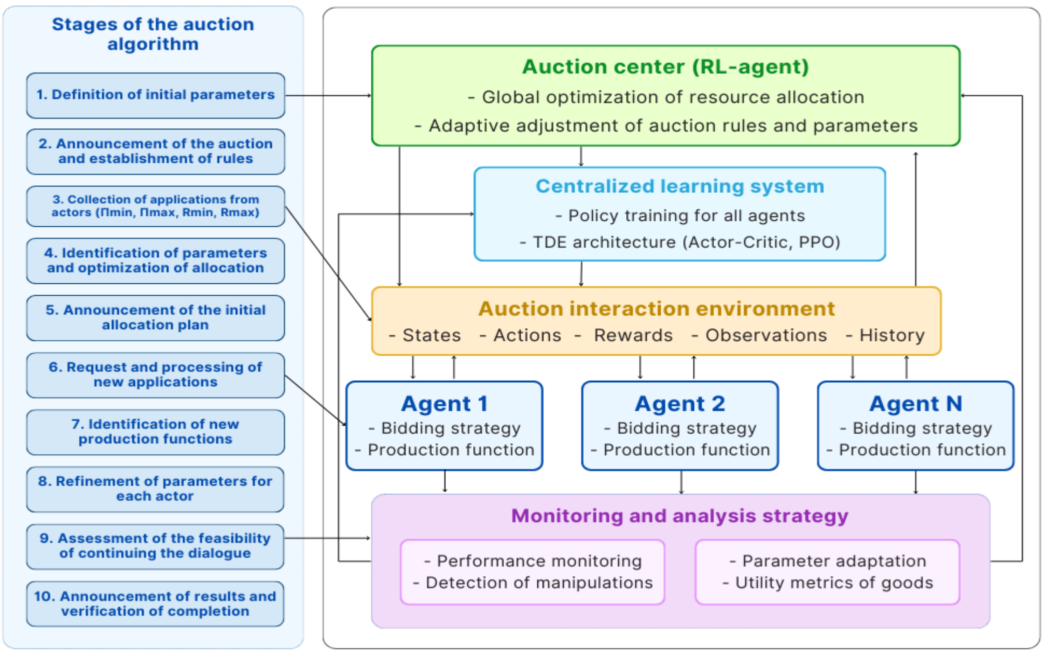
19. If continuation is required, go to 4, otherwise go to 13.

20. Request from the center agent about the appropriateness of refusing to choose to continue the steps and returning to the plan of the previous step.

21. Announcing the result of the game with the j-th agent-executor.

22. Transition to dialogue with j+1-th agent-executor and transition to 8.

Figure 3 – Budget auction algorithm based on a multi-agent model



Source: developed by the authors

The budget auction ends when none of the implementing agents expresses a desire to change their planned indicators for the next, full cycle. The resulting structure of budget allocation is optimal to the extent that the control figures and restrictions determined by experts, the upper level of the resource allocation subgraph, and the acceptability of the agreed boundaries of the working areas of the production characteristics of the elements are optimal. In order for the allocation in the local budget system to be optimal, it is necessary that all actors at all levels of budgeting be represented by agents and participate in the budget auction. Obviously, it is necessary to methodologically and programmatically ensure the lowest level of actors (the village represented by the village headman and the village community), although now most small settlements no longer have their own budget. It is also necessary to work out production functions that correspond to different sustainable development goals separately. This will make it possible to measure the results obtained at the stage of budget implementation and compare them directly with the sustainable development goals. In this way, the distribution of subsidies and investments is optimized, which forces all elements of the link to work in such a way that their efforts are aimed at maximizing the functionality of the center, taking into account the usefulness for the center of the goods produced by the actors.

5. DISCUSSION

The theoretical framework and methodological foundations presented in this study establish a solid foundation for the application of multi-agent systems to local hromada budgeting processes. However, several critical areas require further development to translate these theoretical concepts into practical, implementable solutions. The most immediate priority for future work involves the empirical validation of the proposed multi-agent budget auction model through controlled pilot implementations. We propose conducting pilot studies in one or two Ukrainian local hromadas that demonstrate varying characteristics in terms of population size, economic development level, and administrative capacity. The selection criteria for pilot hromadas should include willingness to participate in innovative governance experiments, sufficient administrative infrastructure to support data collection, and representative socio-economic profiles that reflect the broader Ukrainian local government landscape.

The pilot testing phase will serve multiple objectives, providing empirical data on the practical feasibility of implementing the multi-agent auction mechanism in real budgeting scenarios, allowing for the collection of performance metrics that can validate the theoretical assumptions underlying the model, and revealing practical challenges and opportunities for model refinement that cannot be anticipated through theoretical analysis alone. The pilot studies should be designed as controlled experiments with clear baseline measurements, intervention protocols, and outcome evaluation frameworks. Data collection should encompass both quantitative metrics such as budget allocation efficiency, participant satisfaction scores, and time-to-decision measurements, as well as qualitative assessments including stakeholder feedback, process observations, and administrative burden evaluations. This empirical evidence will be crucial for refining the model parameters, validating the production function specifications, and demonstrating the practical value proposition of the multi-agent approach.

Recognizing the significant variation in digital capacity and technical expertise across Ukrainian local hromadas, future work must prioritize the development of scaled-down and modular versions of the proposed model. This adaptation strategy acknowledges that while the full multi-agent implementation may be optimal for hromadas with advanced technical infrastructure, many local governments require more accessible entry points to participatory budgeting innovation. The simplified version should maintain the core theoretical principles of the multi-agent auction while reducing computational complexity and technical requirements. This could involve developing preset agent strategies that eliminate the need for complex machine learning algorithms, implementing rule-based decision support systems that can operate with minimal computational resources, and creating standardized templates for production function estimation that require basic input data readily available in most hromadas.

The modular approach should allow hromadas to implement components of the system incrementally, beginning with basic participatory mechanisms and gradually incorporating more sophisticated multi-agent features as their capacity develops. This progression model should include clear upgrade pathways, compatibility standards between modules, and comprehensive training materials that enable local administrators to manage the system independently. Future research should also explore hybrid implementation models that combine digital multi-agent tools with traditional participatory methods, ensuring that hromadas with limited digital infrastructure can still benefit from the improved decision-making processes that the model facilitates.

The complexity of multi-agent systems and auction mechanisms presents significant communication challenges that must be addressed to ensure broad adoption and stakeholder understanding.

Future work should prioritize the development of intuitive visualization tools that make the algorithmic processes transparent and accessible to non-technical stakeholders, including community members, local officials, and oversight bodies. The visualization framework should include interactive dashboards that allow real-time monitoring of the auction process, clear flowcharts that explain the decision-making logic in accessible language, and simulation interfaces that enable stakeholders to explore different scenarios and their outcomes. Particular attention should be paid to visualizing the production function identification process, the resource allocation optimization, and the feedback mechanisms that drive system learning and adaptation.

Additionally, future work should develop comprehensive communication strategies that explain the benefits and mechanisms of the multi-agent approach to diverse audiences. This includes creating educational materials for community members, training protocols for local administrators, and policy briefs for regional and national government officials. The goal is to build broad understanding and support for the innovative approach while addressing potential concerns about complexity and technological dependence.

To demonstrate the practical value and robustness of the proposed model, future research must develop comprehensive performance measurement frameworks and conduct extensive scenario analysis. The performance metrics should encompass multiple dimensions of public budgeting effectiveness, including allocative efficiency in terms of how well resources are distributed according to community priorities, dynamic efficiency regarding how quickly the system adapts to changing circumstances, democratic legitimacy measuring the extent to which all stakeholders feel adequately represented, and administrative efficiency evaluating the cost and complexity of operating the system. Key Performance Indicators should be developed for each component of the multi-agent system, including agent learning rates, auction convergence times, stakeholder satisfaction levels, and budget outcome quality measures. These metrics should be benchmarked against traditional budgeting approaches to provide clear evidence of the model's value proposition.

The scenario analysis framework should examine system performance under various socio-economic conditions, including economic crisis situations, demographic changes, infrastructure disruptions, and varying levels of stakeholder participation. This analysis will be crucial for understanding the model's robustness and identifying potential failure modes or adaptation requirements. Future work should also develop stress-testing protocols that evaluate system performance under extreme conditions, such as sudden population changes due to conflict-related displacement, economic shocks that dramatically alter resource availability, or technological failures that compromise system functionality.

6.CONCLUSION

To position the proposed multi-agent approach within the broader landscape of participatory governance innovation, future research should conduct comprehensive comparative analyses with existing international frameworks for participatory budgeting and resource allocation. The comparative analysis should examine successful participatory budgeting implementations in countries with similar development profiles to Ukraine, innovative digital governance initiatives that have achieved scale in European contexts, and multi-agent system applications in public administration from global best practice examples.

This comparative work should also explore opportunities for international collaboration and knowledge exchange, potentially developing networks of local governments that are experimenting with similar approaches. Such collaboration could accelerate learning, reduce implementation costs, and build broader momentum for participatory governance innovation. Future research should explicitly develop the connections between the multi-agent budgeting model and the United Nations Sustainable Development Goals, particularly those related to sustainable cities and hromadas, reduced inequalities, and partnerships for the goals. This integration requires developing specific methodologies for incorporating SDG indicators into the production function specifications and auction mechanisms, including monitoring frameworks that track how budget allocations contribute to sustainable development outcomes, creating incentive structures that reward decisions aligned with sustainability objectives, and establishing reporting mechanisms that demonstrate local contributions to global development goals.

The successful completion of this comprehensive research agenda will transform the theoretical contributions of this study into practical tools for enhancing democratic governance and resource allocation efficiency in Ukrainian local hromadas. The phased approach, beginning with pilot testing and progressing through model refinement, visualization enhancement, performance validation, and international comparison, provides a clear pathway for advancing both theoretical understanding and practical application of multi-agent systems in public administration. The lessons learned and tools developed through this work have the potential to influence participatory governance innovation far beyond the Ukrainian context, contributing to more effective, democratic, and sustainable public administration worldwide.

REFERENCES

Zhang, K., Yang, Z., & Başar, T. (2019). Multi-agent reinforcement learning: A selective overview of theories and algorithms. https://arxiv.org/abs/1911.10635

Zhou, Z., Zhang, C., & Luo, J. (2023). Multi-agent reinforcement learning: Methods, applications, visionary prospects, and challenges. https://doi.org/10.1109/TIV.2024.3408257

Lemaallem, H., & Saadi, A. (2025). Productivity and Trade Openness: a Sectoral Analysis of Morocco's Economy. *Economics - Innovative And Economics Research Journal,* 13(2), 529–551. https://doi.org/10.2478/eoik-2025-0052

Dabagyan, A. V. (2000). Theory and models of economic and social-political waves. Kharkiv: Intekhprom. http://opaco.btu.kharkiv.ua/cgi-bin/cgiirbis_64.exe?LNG=&Z21ID=&I21DBN=EK&P21DBN=EK&S21STN=1&S21REF=&S21FMT=fullwebr&C21COM=S&S21CNR=20%20&S21P01=0&S21P02=0&S21LOG=1&S21P03=K=&S21STR=%D1%81%D0%BE%D1%86%D0%B8%D0%B0%D0%BB%D1%8C%D0%BD%D0%BE%2D%D0%BF%D0%BE%D0%BB%D0%B8%D1%82%D0%B8%D1%87%D0%B5%D1%81%D0%BA%D0%B8%D0%B5%20%D0%BF%D1%80%D0%BE%D1%86%D0%B5%D1%81%D1%81%D1%8B

Kotukh, E. V. (2020). E-governance as a new paradigm of public administration. Investments: *Practice and Experience*, 3, 122–127. 10.32702/2306-6814.2020.3.122

Kotukh, Y., & Riabokin, M. (2025). Current problems of modeling resource allocation processes in the conditions of digitalization of the public financial sector [Conference paper]. Economics and Management 2025: Prospects for Integration and Innovative Development, 3, 80–84. Dnipro: Bila K. O. https://confcontact.com/2025-ekonomika-i-menedzhment/Zbirnyk-konferentsiyi-2025-Tom-3.pdf

Riabokin, M., & Kotukh, E. (2025). RWA-tokenization as a tool for sustainable economic development of local hromadas [Conference paper]. VIII International Scientific and Practical Conference "Modern Trends in the Development of Financial and Innovation and Investment Processes in Ukraine", Vinnytsia, Ukraine. https://conferences.vntu.edu.ua/index.php/fiip/fiip2025/paper/viewFile/23188/19185

Muyambiri, B. (2025). South African Private Investment and Economic Growth: Impact of FDI Inflows and Outflows. *Economics - Innovative And Economics Research Journal*, 13(2), 485–505. https://doi.org/10.2478/eoik-2025-0051

Riabokin, M., & Kotukh, E. (2025). Typology of production functions of local hromadas in the context of achieving sustainable development goals [Conference paper]. VIII All-Ukrainian Scientific and Practical Conference "Actual Problems and Prospects for the Development of Accounting, Analysis and Control in a Socially Oriented Enterprise Management System", Poltava, Ukraine. P.916-919. https://drive.google.com/file/d/1CUl0jrhFAI_1c5uZ6-cAaRodM_stjklx/view?usp=drive_link

Riabokin, M., Hordei, O., Novytska, O., Kotukh, Y., & Kozii, N. (2022). Peculiarities of the budget process under martial law. *Economics and Region*, 4(87), 275–281. https://journals.nupp.edu.ua/eir/article/download/2809/2217 DOI: 10.26906/EiR.2022.4(87).2809